Fully Depleted CCDs for Spectroscopy

Natalie Roe

Detectors For Astronomy 2009

ESO Garching

Outline

- Overview of LBNL fully-depleted CCD technology
- Advantages/Disadvantages
- Recent Spectrograph Deployments
  - Keck LRIS upgrade
  - SWIFT instrument on Palomar Hale 200”
  - SDSS BOSS spectrograph upgrade

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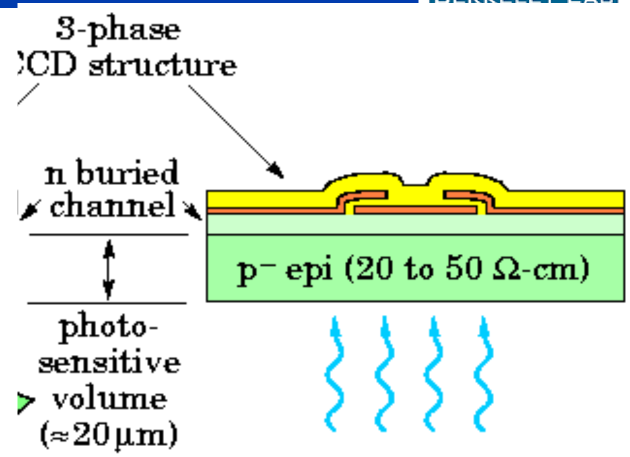
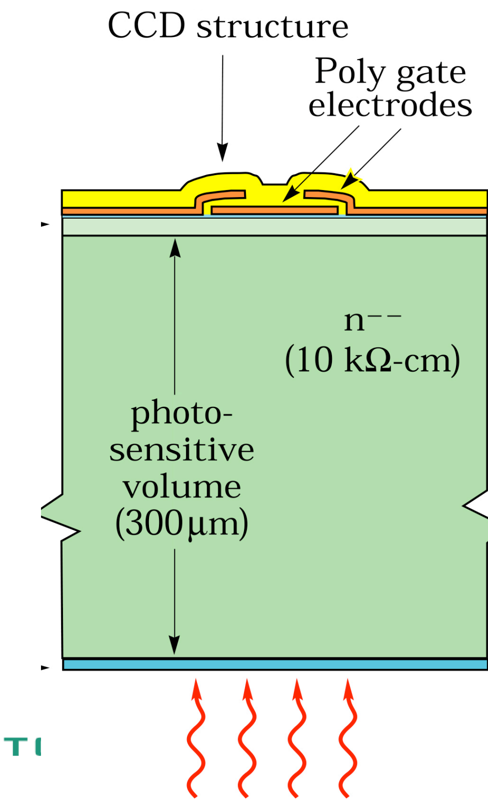
LBNL Fully Depleted CCDs

- **The fully-depleted CCD was invented by Dr. Steve Holland at LBNL in the mid 1990's**
  - **First devices fabricated at the LBNL Microsystems Laboratory on high-resistivity n-type silicon, ~300 μm thick**
  - **Thick gettering layer is deposited on backside at beginning of fabrication for low dark current**
  - **After front-side processing, wafers are thinned and a transparent conductive window is deposited for fully depleted back-illuminated operation**
  - **Recent design improvements allow for HV bias operation to reduce charge diffusion (4 μm rms for 200 μm thick device)**
- **Patents Issued**
  - U.S. Patent 6,259,085 "Fully Depleted Back Illuminated CCD", Jul. 10, 2001.
  - U.S. Patent 6,025,585 "Low-resistivity photon-transparent window attached to photosensitive silicon detector", Feb. 15, 2000.
  - U.S. Patent 7,271,468 "High-voltage compatible, fully-depleted CCD", Sept 28, 2007

Fully Depleted CCD Design

- Conventional scientific CCDs are thinned, back-illuminated n-channel devices with ~10-20 μm epitaxial depletion region
- LBNL CCDs are thick, back-illuminated fully-depleted p-channel devices
  - 100 – 300 μm depletion region
  - Pixel size 9 – 30 μm
- Advantages of fully-depleted CCDs include
  1. higher QE over broader wavelength range than previous astronomical grade CCD's
  2. reduced fringing at long wavelengths
  3. small, controllable point spread function
  4. p-channel is 10x more radiation tolerant than n-channel CCDs (important for space applications; see talk by C. Bebek)
- Disadvantages
  - Higher pixel rate of cosmics, Compton e-'s





Fully-depleted CCD Fabrication

- **LBNL CCD fabrication is a partnership between DALSA Semiconductor and the LBNL MicroSystems Lab (MSL)**
  - **DALSA has been supportive of process flow changes for yield improvement & design R&D**
- **MSL facilities at LBNL include**
  - **Class 10 clean room for CMOS fabrication**
  - **Class 1000 clean room for cold-probing, packaging**
  - **CCD test lab with 5 dewars, QE, diffusion & reflectometry test equipment**

LBNL CCD Process Flow

CCD processing at DALSA Semiconductor (150 mm wafers)

- ~ 80% of the fabrication done at DALSA (commercial foundry)
- Partially processed wafers sent to LBNL
- Thinned to desired final thickness (200 – 250 μm typically)
- Remaining processing steps at LBNL on thinned wafers

All processing done at DALSA

21 wafers per lot sent to LBNL for back illuminated CCD processing

3 “control” wafers fully finished at DALSA for each lot

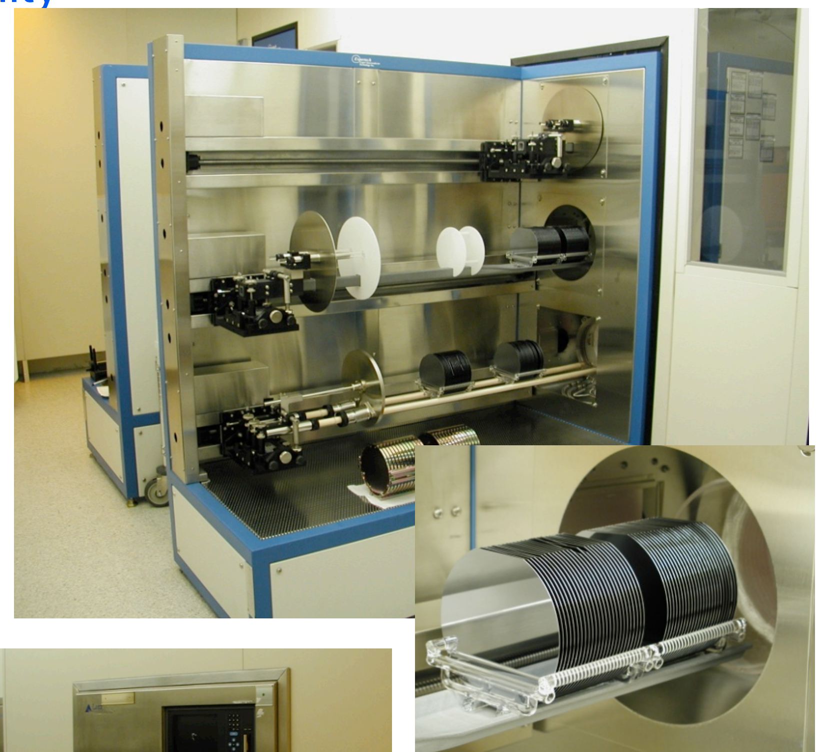
Thinned (200 – 250 μm), back-illuminated CCD

Thick (~ 675 μm), front-illuminated CCD

(QC, HV testing, irradiation)

LBNL MicroSystems Laboratory

- Class 10 semiconductor fabrication facility
  - —150 mm wafer capability



Projection aligner lithography system
Beta Squared Lithography (P/E)

Dielectric plasma etcher
Lam 4520 XLE

Atmospheric and low pressure chemical vapor deposition furnaces
Expertech (Thermco)

Technology Transfer

- Preferred method for transfer of fully depleted CCD technology transfer is via licensing of LBNL Patents
  - Licenses issued to Digirad, Fairchild
  - Patent applications in process in Europe and Japan
- Less preferable technology transfer method is via LBNL publications and presentations
  - But, very effective based on recent progress:
    - Hamamatsu is producing fully depleted, back-illuminated, p-channel CCDs for the Subaru telescope and for x-ray astronomy groups
    - e2V has described efforts in fully depleted CCD fabrication
    - MIT Lincoln Laboratory has produced 75 μm thick fully depleted CCDs for Pan-STARRS (orthogonal transfer array)

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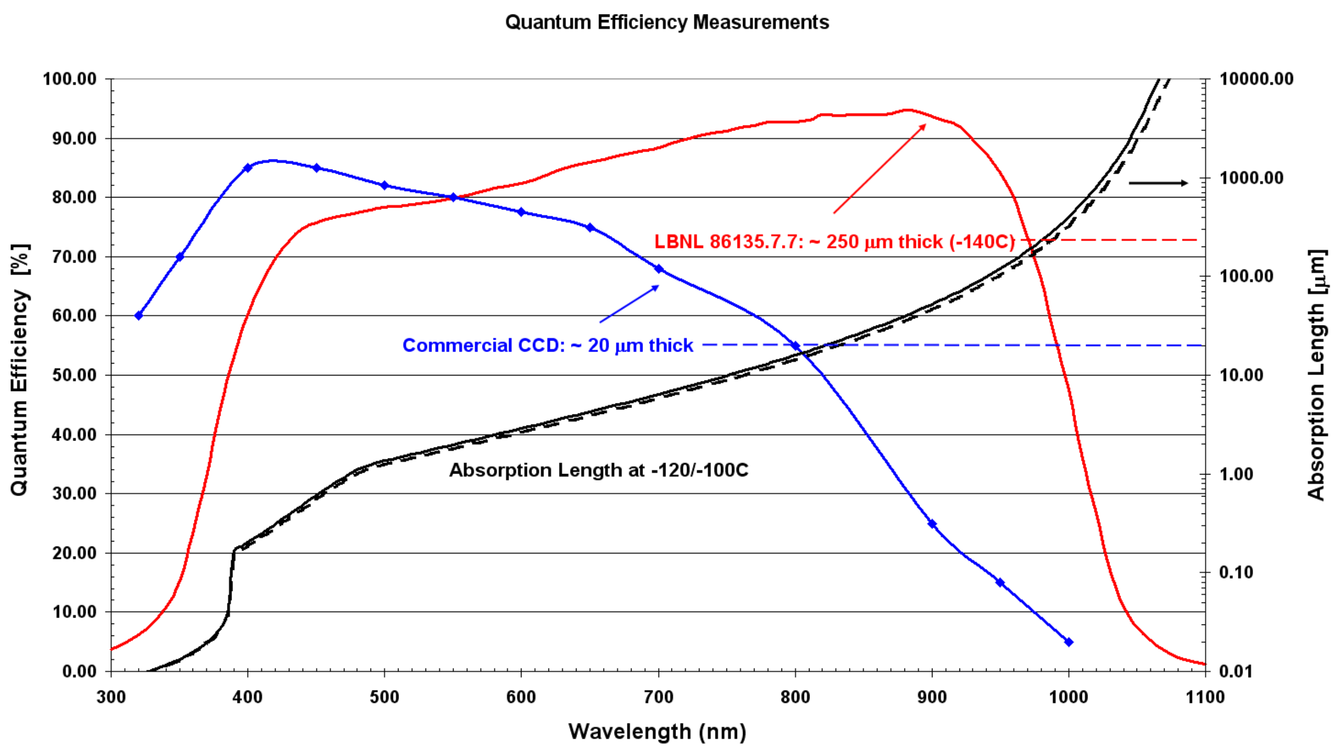
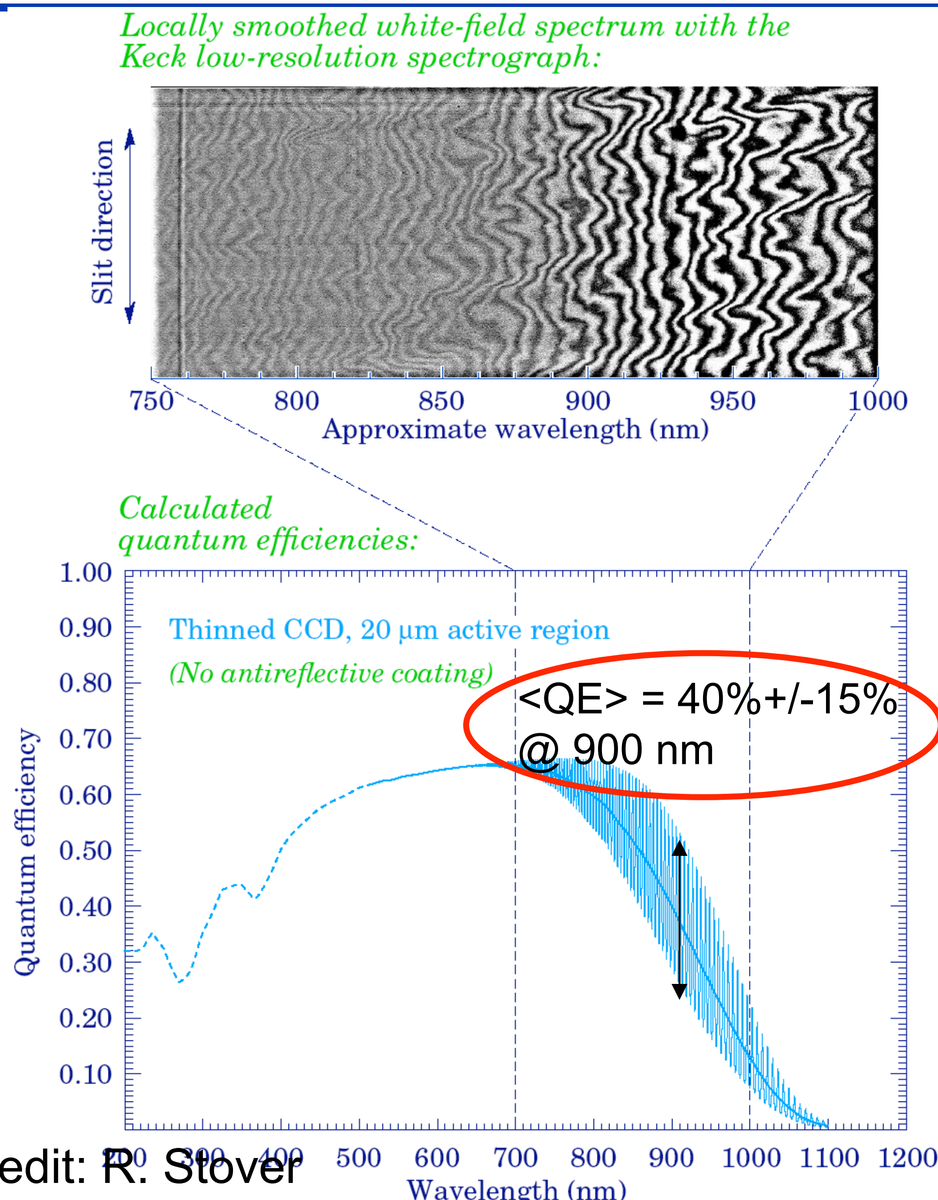
Quantum Efficiency

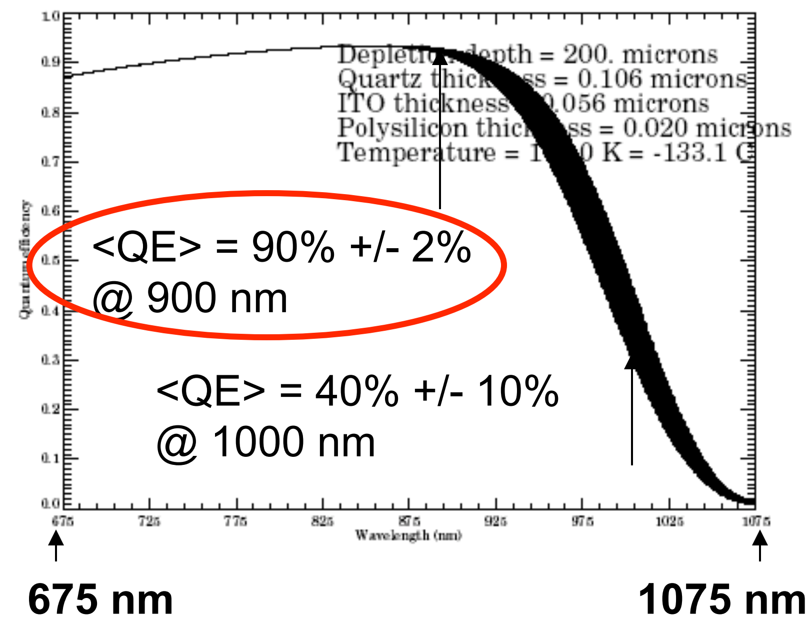


- 250 µm thick detector at -140C
- 2 layer anti-reflection coating: ~ 600A ITO, ~1000A SiO2
- Optimization of AR coating is ongoing – see talk by D. Groom
- We are collaborating with JPL on blue-enhanced conductive backside coatings using molecular beam epitaxy - see talk by S. Nikzad.

Fringing Reduced to 2% at 900 nm



Simulation of fringing in 200 μm thick CCD



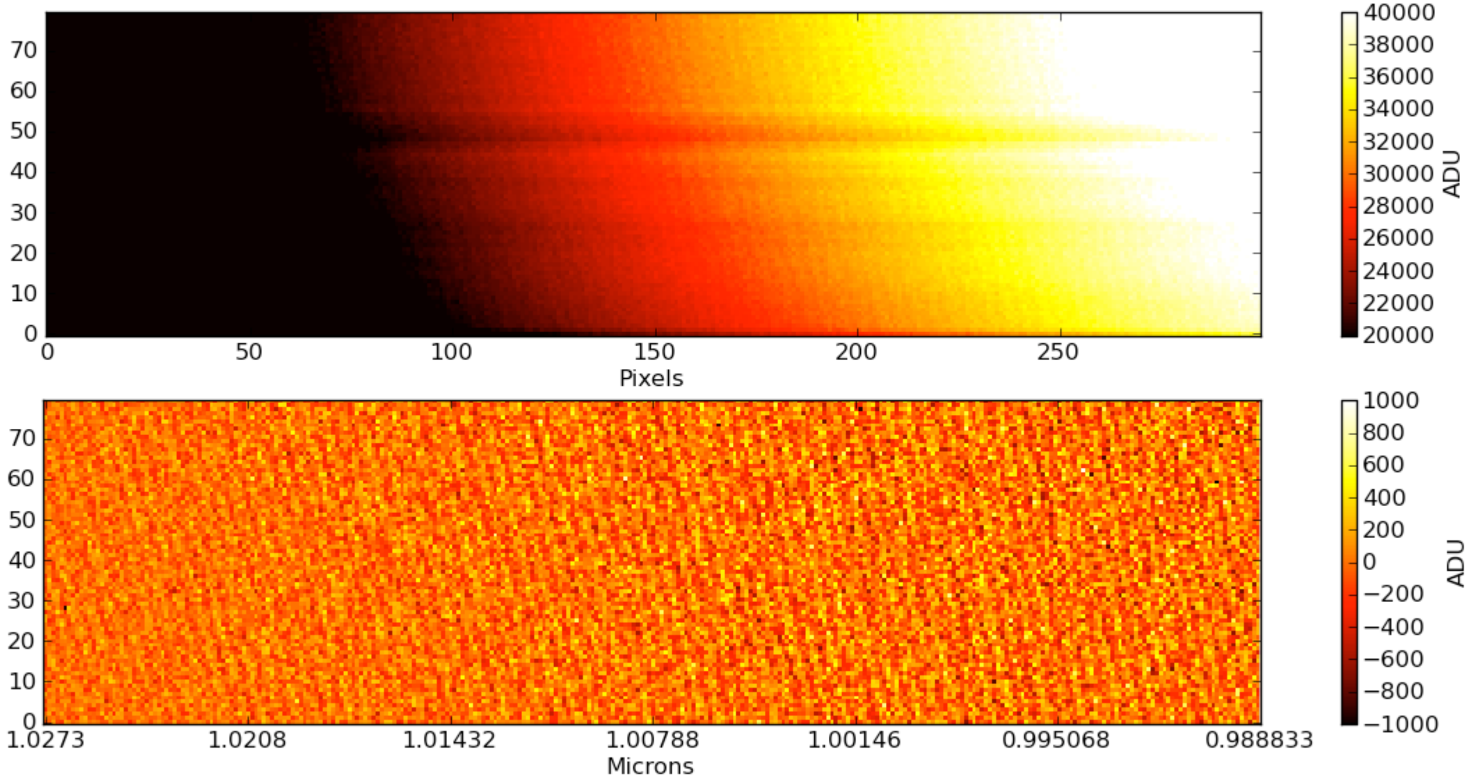
Simulation of fringing in 20 μm thick CCD

Credit: R. Stover

Credit: Don Groom

Fringing on 250 μm thick 4k x 2k measured: ~2-3% at 1 μm

residual fringing after subtracting a low-order (10th) polynomial fit to the blackbody spectrum



40,000 ADU

20,000 ADU

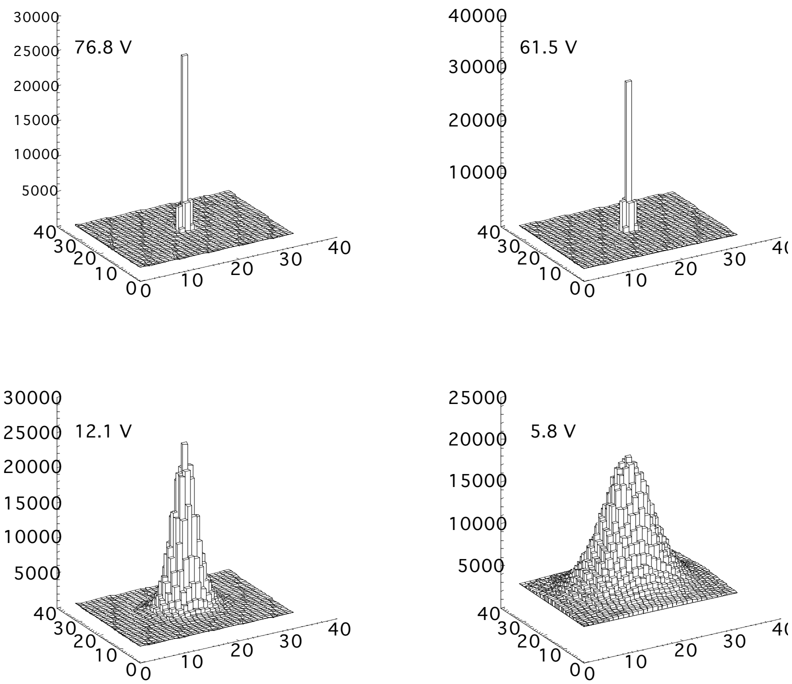
1,000 ADU

-1,000 ADU

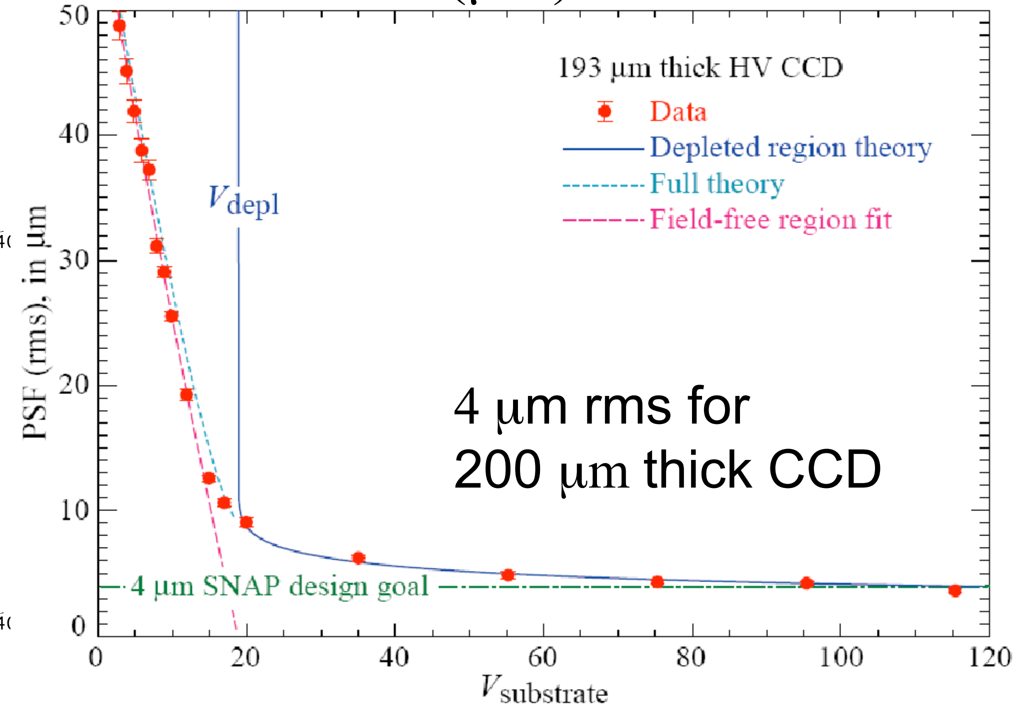
10,273A ← 9888A

Credit: Tim Goodsall, SWIFT/Palomar

“Dial in” Point Spread Function with bias voltage – can apply >100V



RMS PSF (µm) vs Vsubstrate

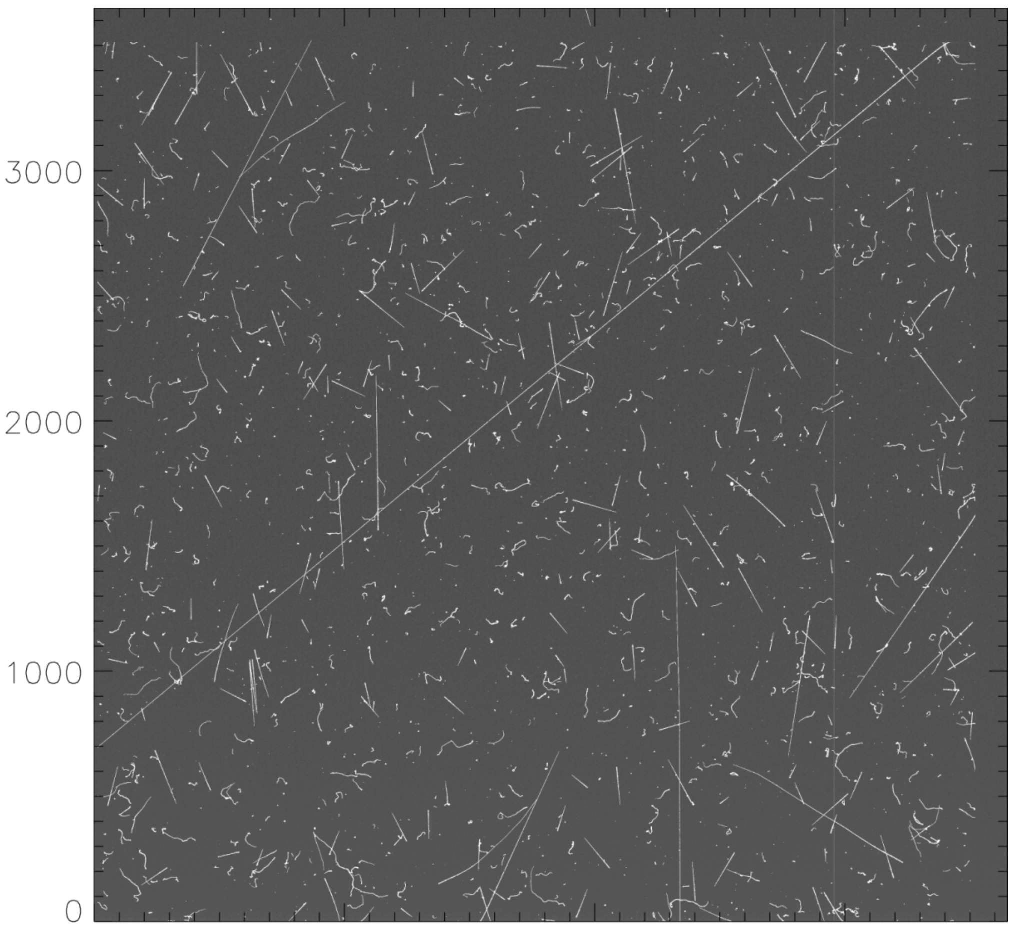


x-y axis: pixel number
z axis; arbitrary units
1100 x 800 back-illuminated CCD, 15 µm pixels

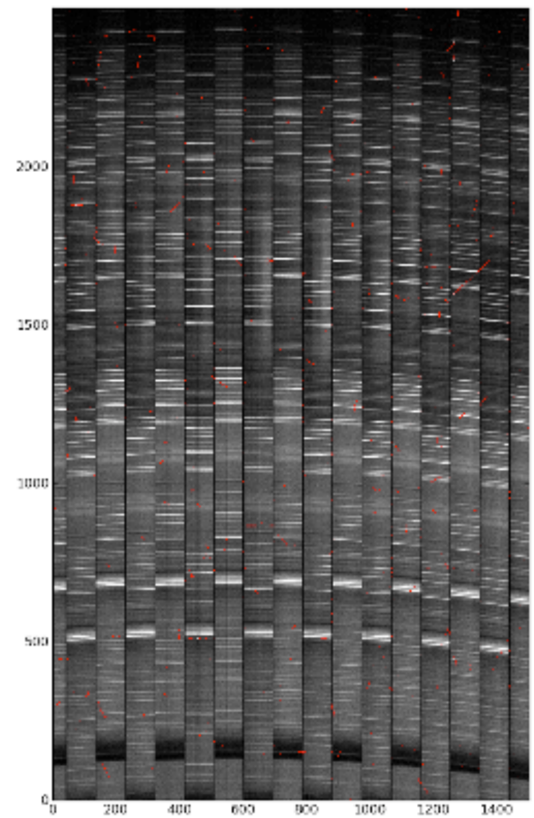
“Improved Spatial Resolution in Thick, Fully Depleted CCDs with Enhanced Red Sensitivity”
by J. A. Fairfield, presented at 2005 IEEE/NSS meeting

Cosmics in 650 μm thick CCD, 30” dark exposure

CCD 107409.16.11, 650 μm thick, fully depleted at 207V – 30 min exp.



Cosmics can be eliminated by combining multiple exposures, and through use of pattern recognition software, eg LA Cosmic, as demonstrated below on SWIFT spectra (Tim Goodsall)



Dark current at -140C is 0.63 e-/pixel-hour

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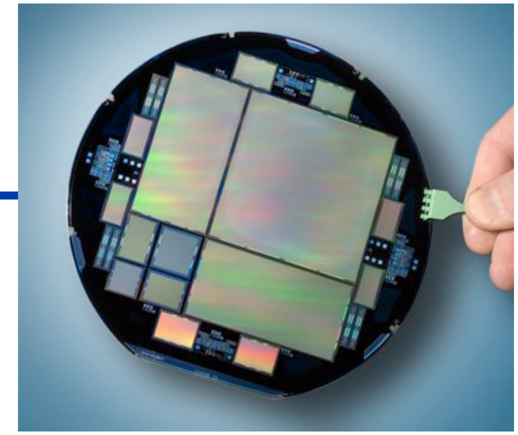
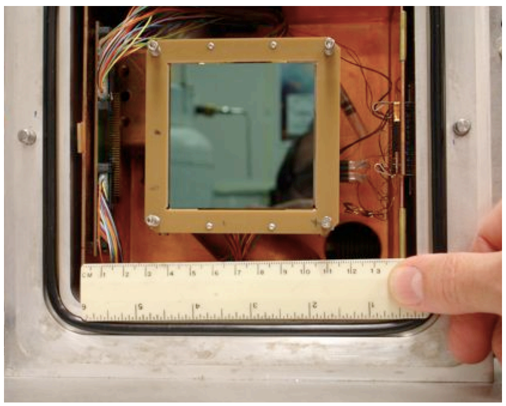
Spectroscopic Requirements for CCDs

- Broad wavelength coverage
  - Near-infrared coverage especially important for high redshift objects
- Low read noise and dark current for spectroscopy of faint sources requiring long exposures
- Fast optics => very good flatness on device surface
- A single large format device is often all that is needed
  - led to development of a very flat, but non-buttable package for 4k x 4k and 4k x 2k CCDs at LBNL

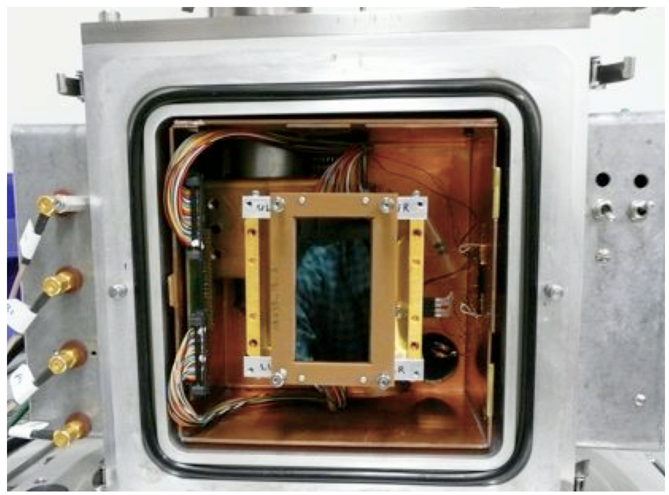
4k x 4k, 4k x 2k CCDs



- **6” wafer with 1 4k x 4k, 2 4k x 2k’s and 1 2k x 2k**

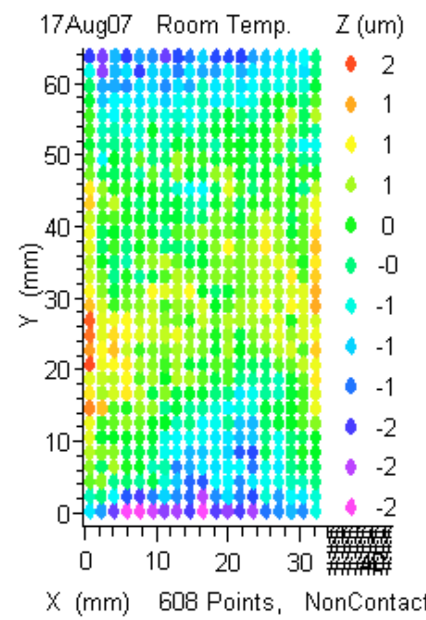


Packaged 4k x 4k
in dewar at LBNL



Packaged 4k x 2k
in dewar at LBNL

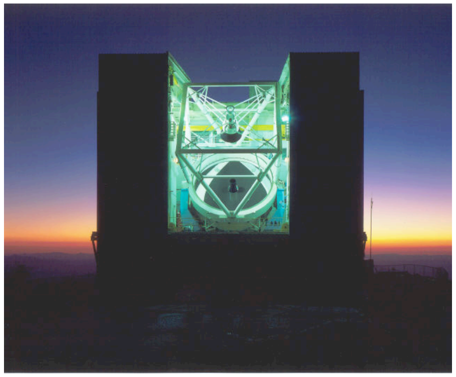
4k x 2k flatness
+/- 2 um



Spectroscopic Deployment of LBNL CCDs

Kitt Peak/Mayall 4m
MARS and RC spectrographs

Keck 10m
LRIS upgrade



MMT 6.5m/Mt. Hopkins
Red Channel spectrograph

Sloan Digital Sky Survey
spectrograph upgrade

Lick Observatory/Mt Hamilton
Hamilton Echelle spectrograph

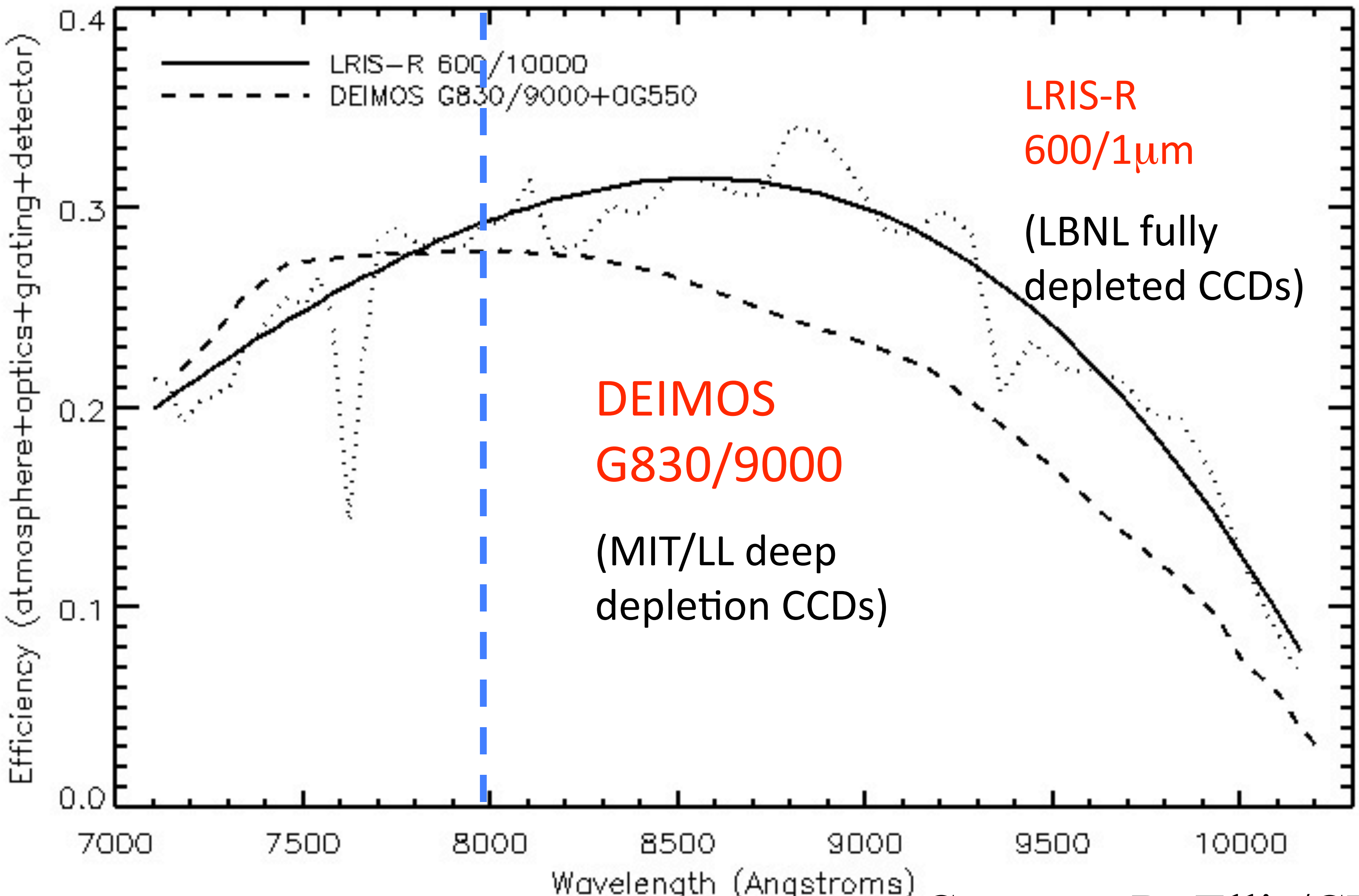
Palomar Hale 200"
SWIFT spectrograph

LRIS Upgrade

- Low Resolution Imaging Spectrograph, commissioned in 1993
- "the most in-demand and scientifically productive instrument of our entire suite at Keck Observatory" – Keck Director Taft Amandroff
- Red side upgraded with 2, 2k x 4k 15 μm pixel CCDs
  - fabricated on 4" wafers at LBNL MSL
  - packaged at UC/Lick by R. Stover in a buttable package
- First light in June 2009

DEIMOS vs LRIS-R

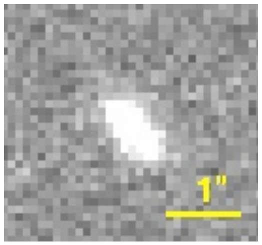
Efficiencies from June LRIS-R run (Drew Newman)

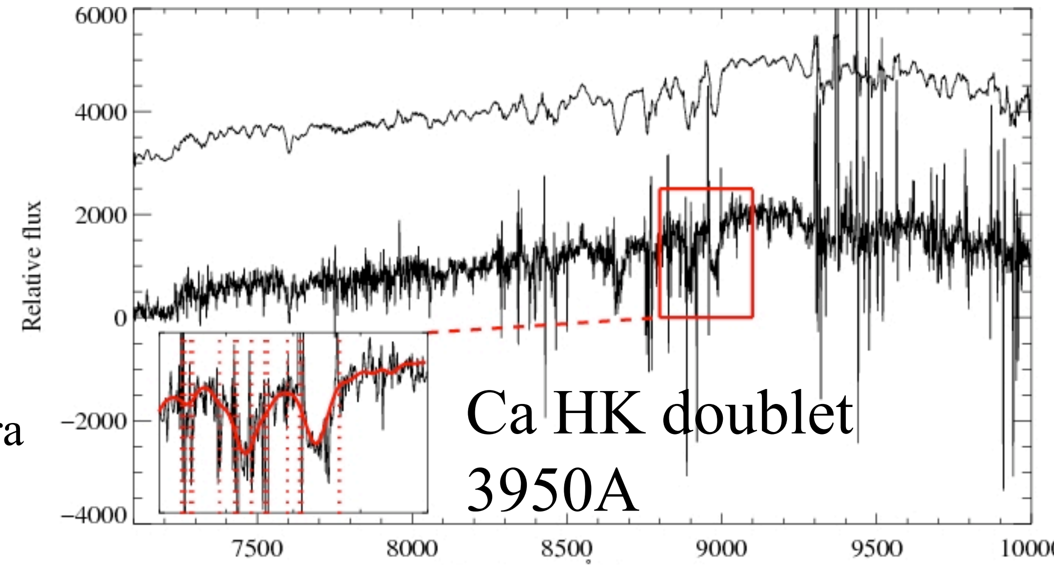


Courtesy R. Ellis/CIT

Measuring Galaxy Masses at z>1 through absorption line dispersion

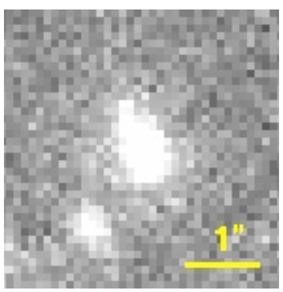
I=23.0 z=1.263 σ =187 km s^{-1}





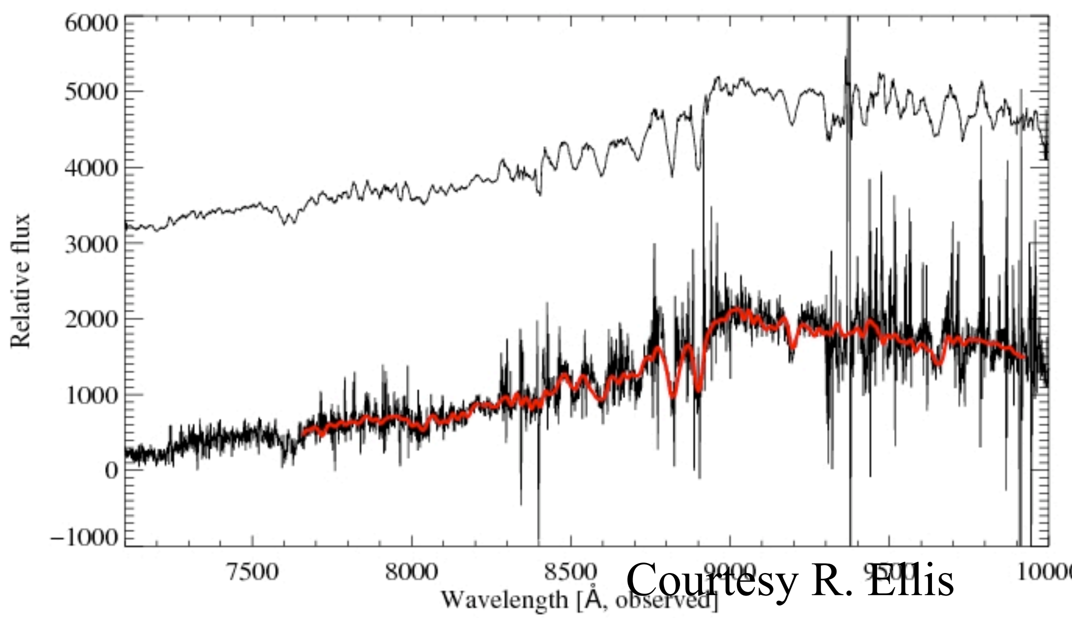
"These are the best absorption-line spectra ever at these redshifts, I think."
– Richard Ellis/CalTech

I=22.5 z=1.242 σ =230 km s^{-1}



600/1μm t=12 hrs

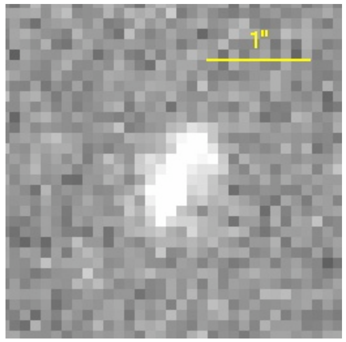
(A. B. Newman et al, in prep.)

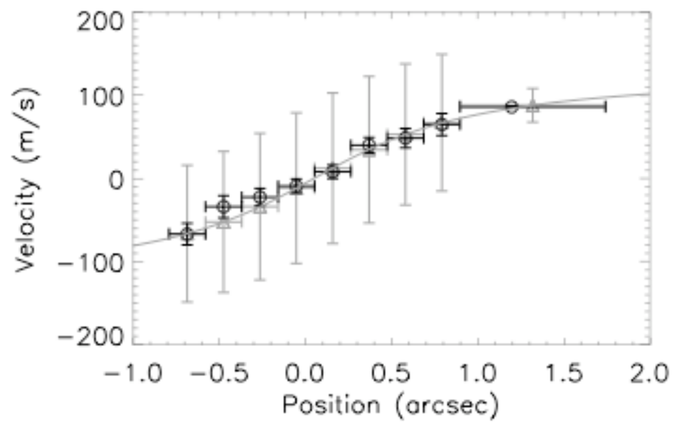


Courtesy R. Ellis

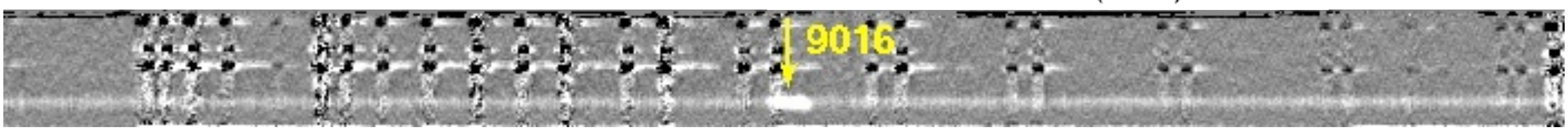
Galaxy Rotation Curves at z>1 from emission

I=23.8 z=1.68

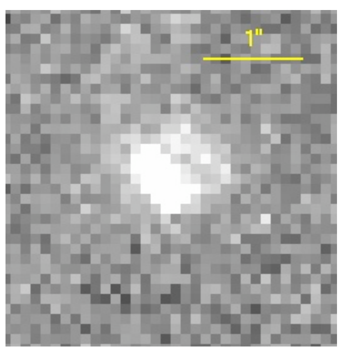


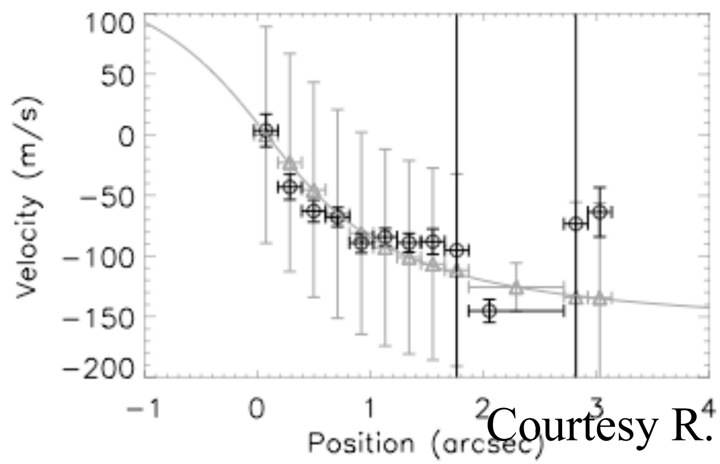


OII doublet
3727 A



I=23.1 z=1.42

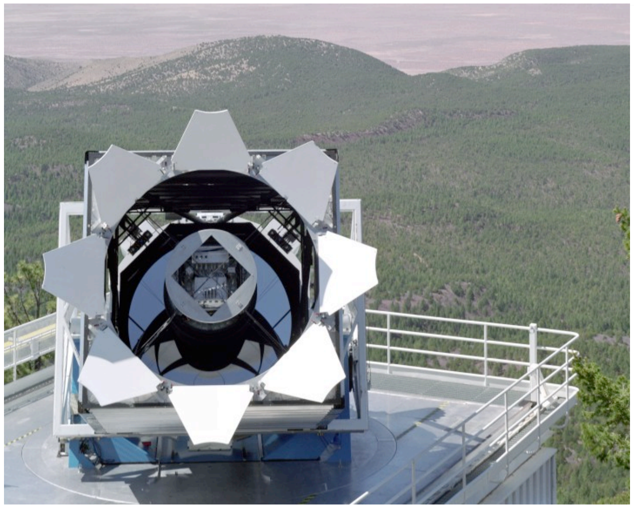




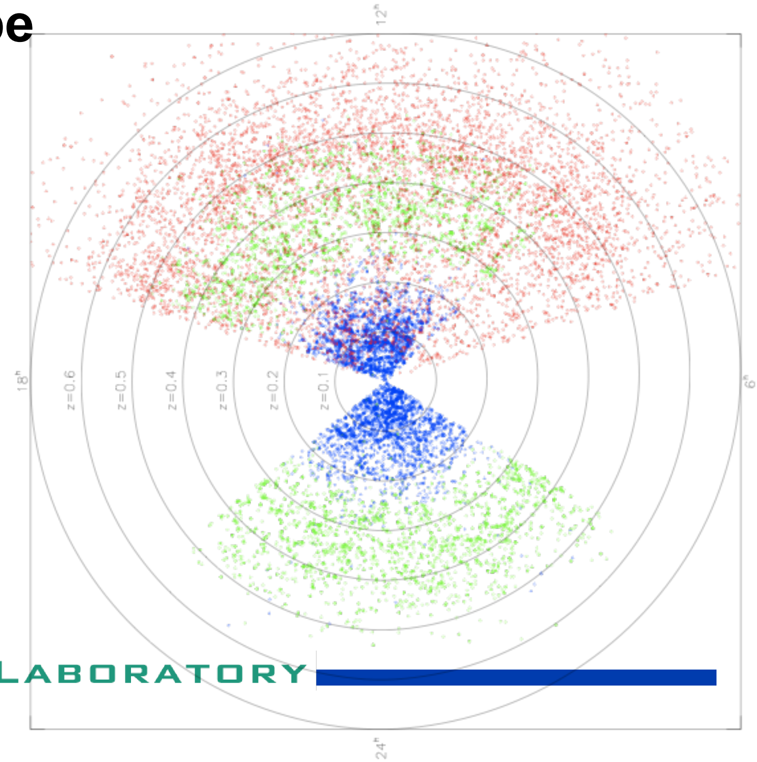
600/1μm t=12 hrs (Newman, Miller et al)

Courtesy R. Ellis/CIT

BOSS Spectrograph Upgrade

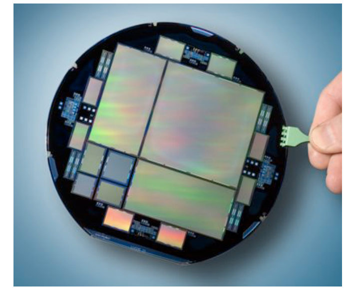


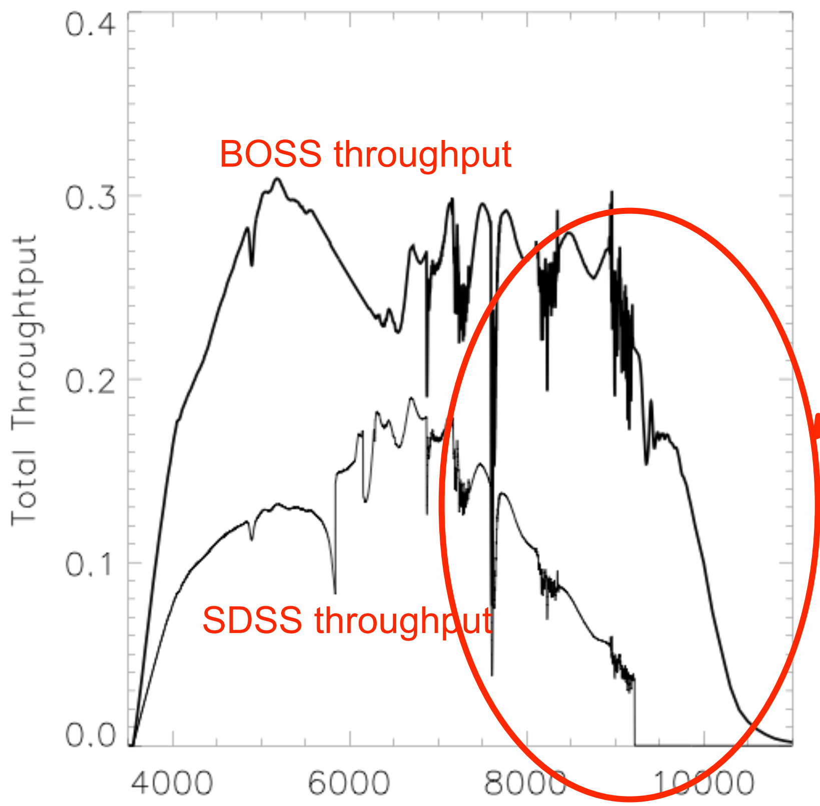
- **SDSS-III is an all-spectroscopic 3rd generation Sloan Digital Sky Survey**
  - **Support from NSF, DOE, Sloan and >30 member institutions and participation groups**
- **BOSS is the flagship SDSS-III survey**
  - **5 years dark time at APO 2.5m telescope**
  - **Data taking started in September 2009**
  - **BOSS will hone the precision on dark energy parameters using baryon acoustic oscillation technique**
    - **red-shift determinations of 1.5M galaxies at $0.5<z<0.8$**
    - **Lyman-α forest measurements of 150,000 quasars at redshifts $2.3<z<2.8$**



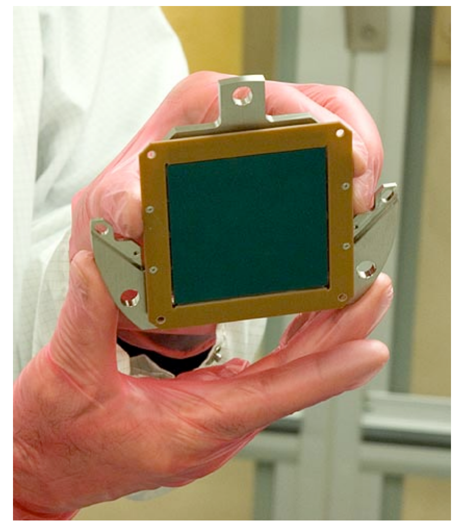
BOSS Spectrograph upgrade

- **Increase number of fibers from 640 to 1000**
- **Significant improvement in throughput**
  - **More sensitive CCDs from LBNL (red) & e2v (blue)**
  - **Better gratings and dichroics**





Fully depleted NIR-sensitive LBNL CCD: improved throughput above 7000A



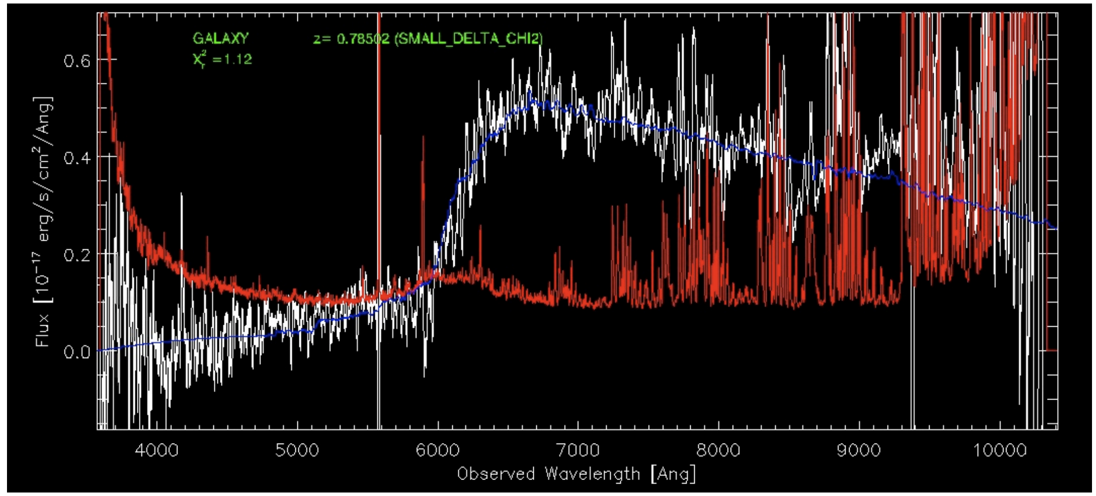
4k x 4k LBNL CCD

BOSS CCD Performance

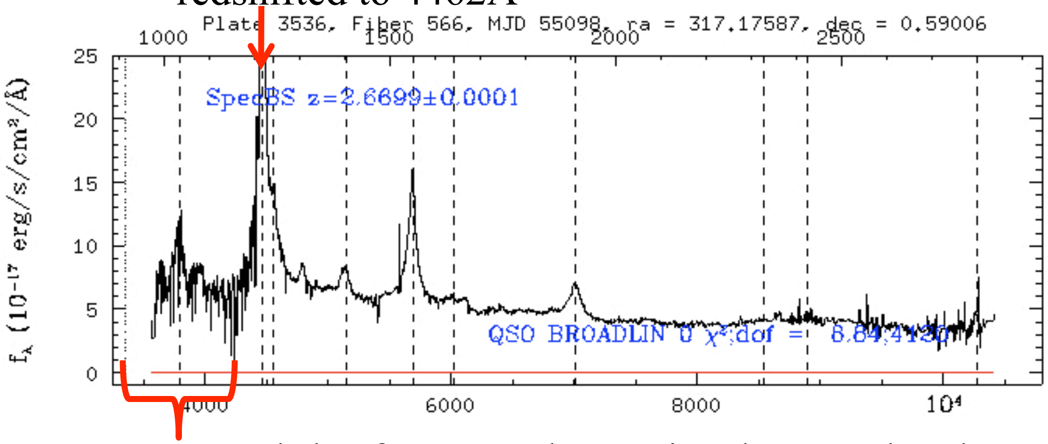
		4k x 4k LBNL CCD		4k x 4k e2v CCD	
Parameter	**Requirement**	**Red 1**	**Red 2**	**Blue 1**	**Blue 2**
Read Noise	Blue: < 3 e- Red: < 5 e-	2.1 e- 2.2 e- 2.5 e- 2.1 e-	2.5 e- 2.5 e- 2.4 e- 2.4 e-	1.8 e- 1.6 e- 1.7 e- 1.8 e-	1.8 e- 2.2 e- 1.9 e- 1.8 e-
Dark Current	Blue: < 4 e-/pix/hr Red: < 8 e-/pix/hr	~1e-/pix/hr	~1e-/pix/hr	1 e-/pix/hr	1.5 e-/pix/hr
Cosmetics	< 15 bad cols	2 bad cols	0 bad cols	0 bad cols	4 bad cols

BOSS Commissioning Spectra

Luminous red galaxy at z=0.78 (galaxy in white, sky bkgd in red)



H-alpha emission at 1216A, redshifted to 4462A



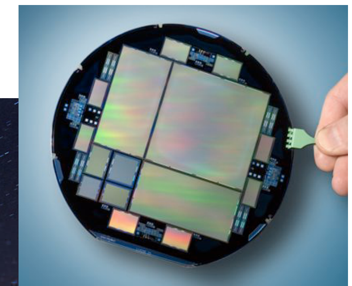
Quasar at z = 2.67

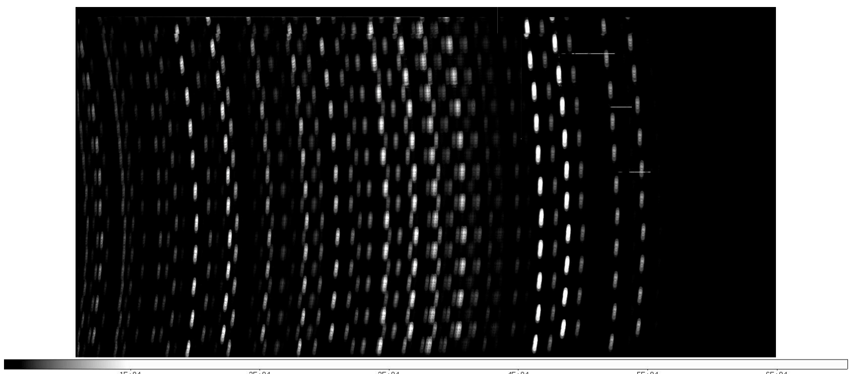
Lyman-alpha forest – absorption by H_2 clouds tracing the distribution of large scale structure in the universe

Thanks to Shirley Ho

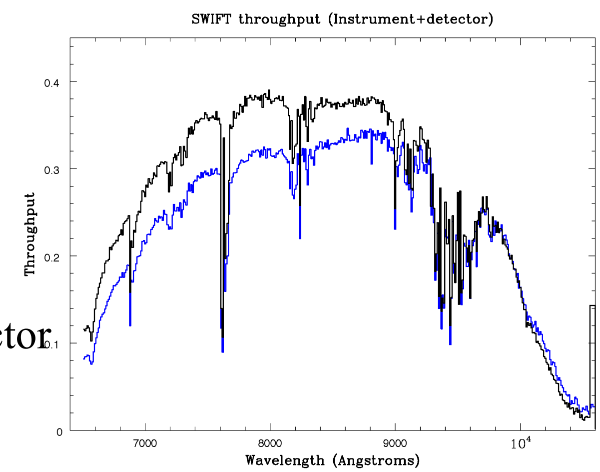
SWIFT Spectrograph at Palomar

- **SWIFT is an I and Z band (6500-1000 μm) IFU spectrograph built by Oxford Univ, available for community use on Palomar Hale 200” telescope with AO – PALMAO system (JPL)**
- **Uses 2 4k x 2k 15 um pixel LBNL CCDs**
- **Key science: kinematics of z<1.7 galaxies, weighing super-massive black holes, 5<z<7 Ly-alpha emitting galaxies**



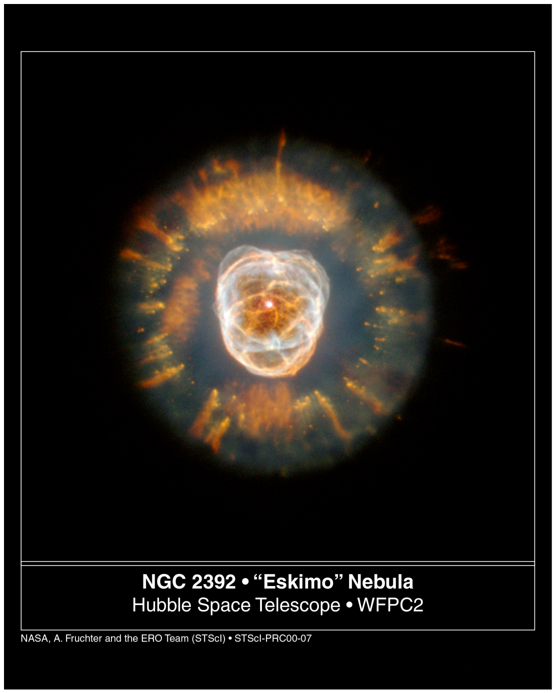


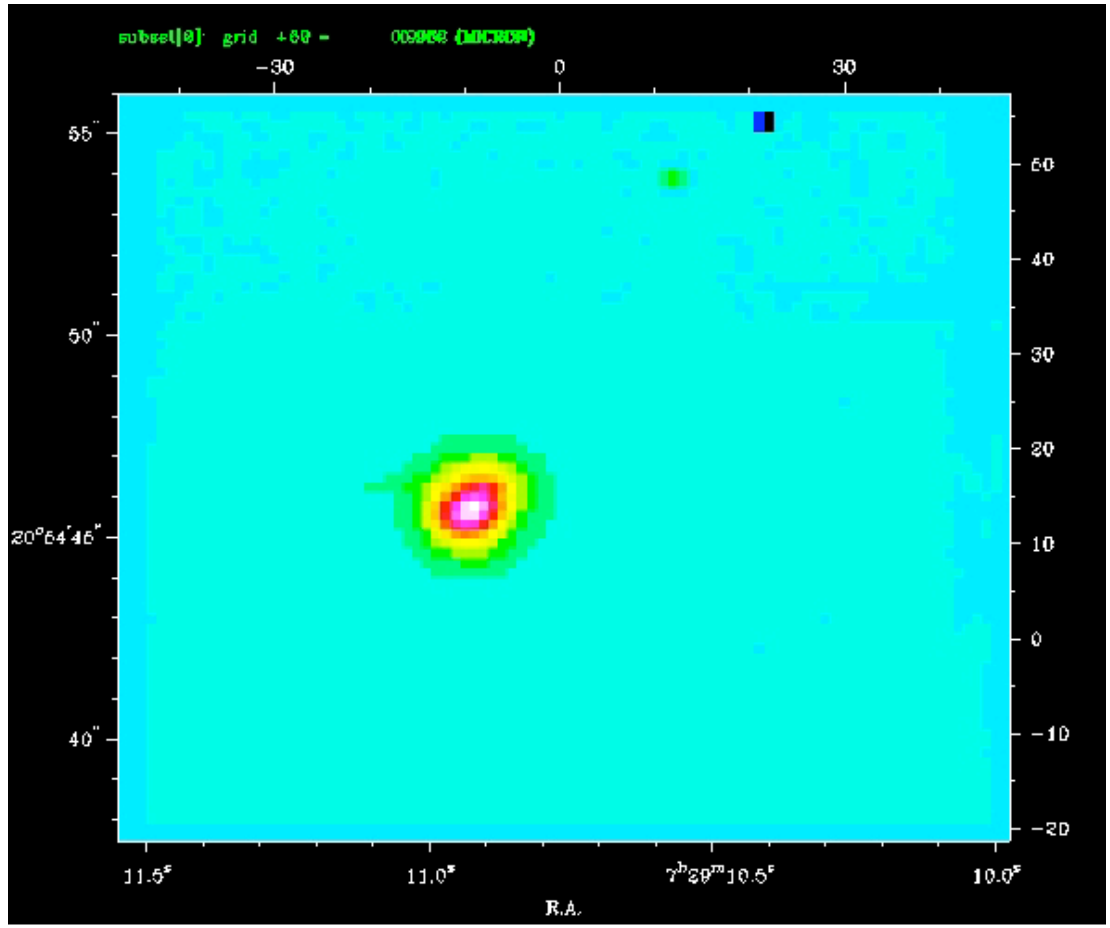
Arc lamp exposure showing dispersed spectra of 44 x 89 “spaxels”



Beyond 9000 Angstroms, SWIFT is at least twice (and probably thrice) as sensitive as a typical observatory spectrograph with a standard CCD detector array. Black curve is science grade CCD; blue is engineering grade.

SWIFT: Eskimo Nebula at 9066-9078A

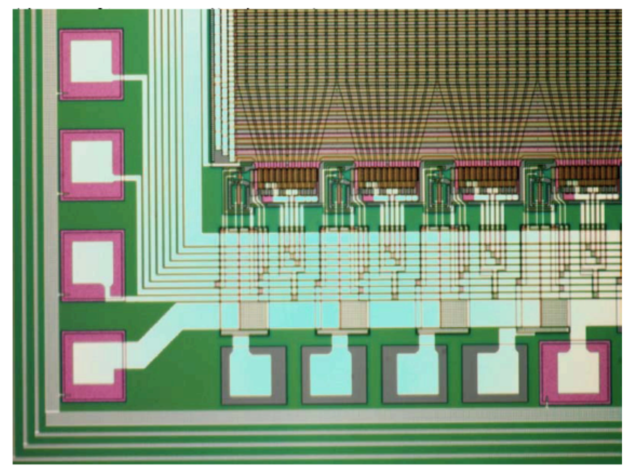




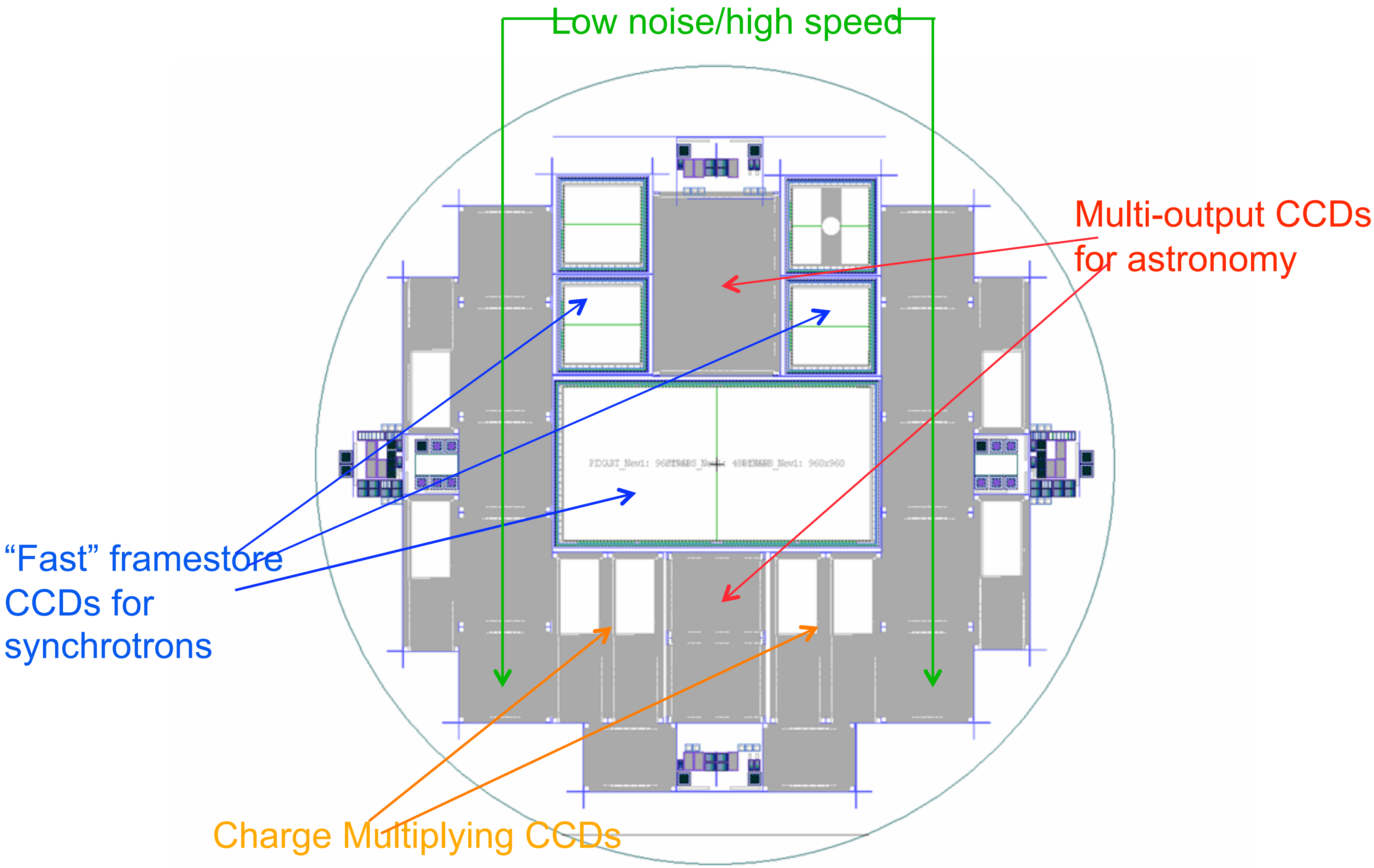
Scanning the Sulfur-III emission in 1A steps reveals kinematics

LBNL R&D Directions

- We are pursuing several avenues for improved CCD response
  - Thinner TiN CCDs for reduced diffusion
  - Charge multiplying CCD for single photon sensitivity
  - Fast CCD with multiple outputs
  - Lower noise output transistors
  - Higher speed output transistors
  - Combinations of the above in a single device



R&D Wafer layout – submitted September 2009



Conclusions

- Fully depleted CCDs have many advantages for astronomy
- Spectroscopic applications have especially benefitted from good near-IR coverage, low fringing at long wavelengths
- Expect to see more applications of fully depleted CCDs in imaging cameras as well
  - PanSTARRS (MIT/LL), SuprimCam (Hamamatsu), Dark Energy Survey (LBNL), LSST.
- Design improvements are ongoing at LBNL.