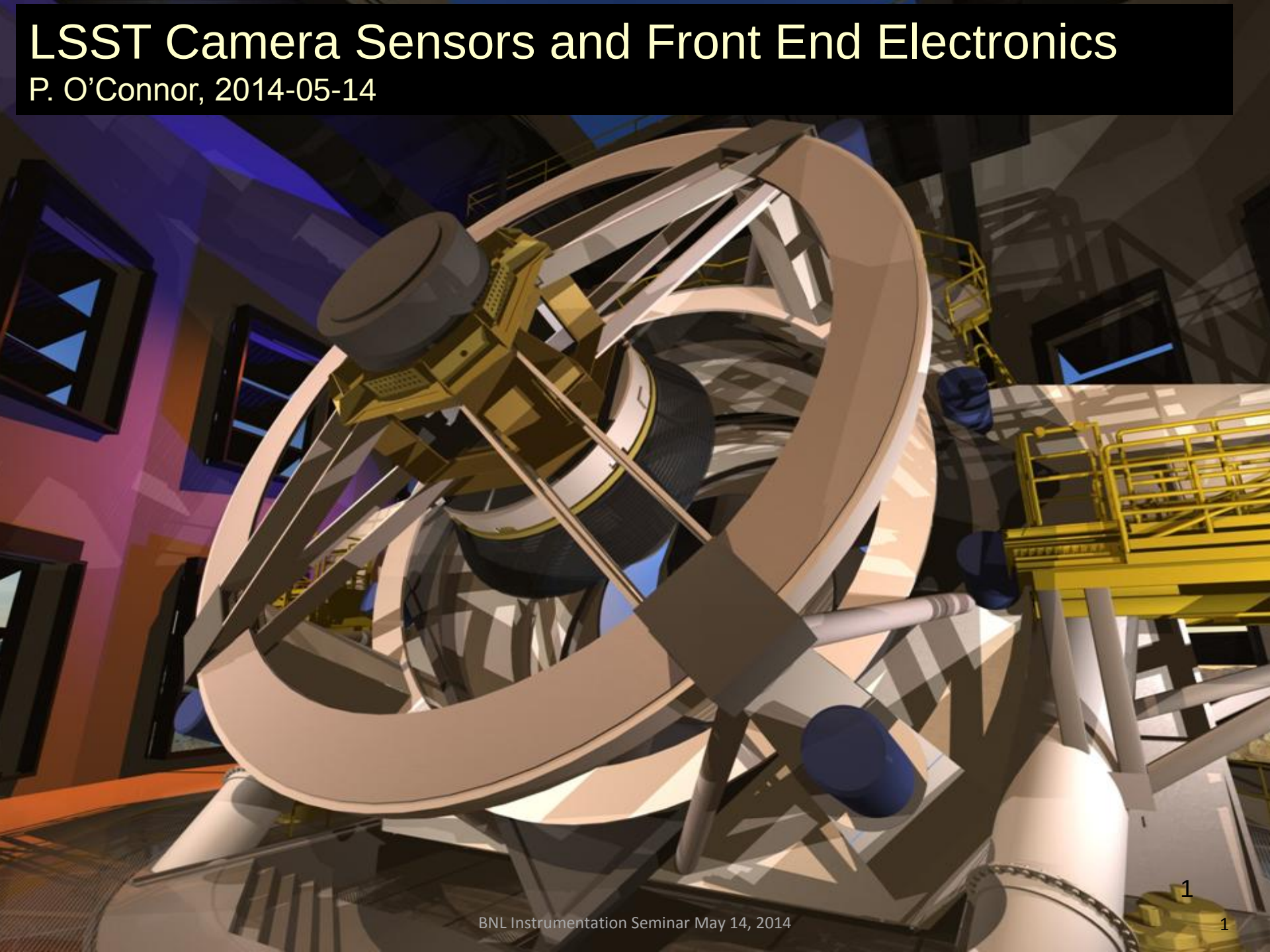
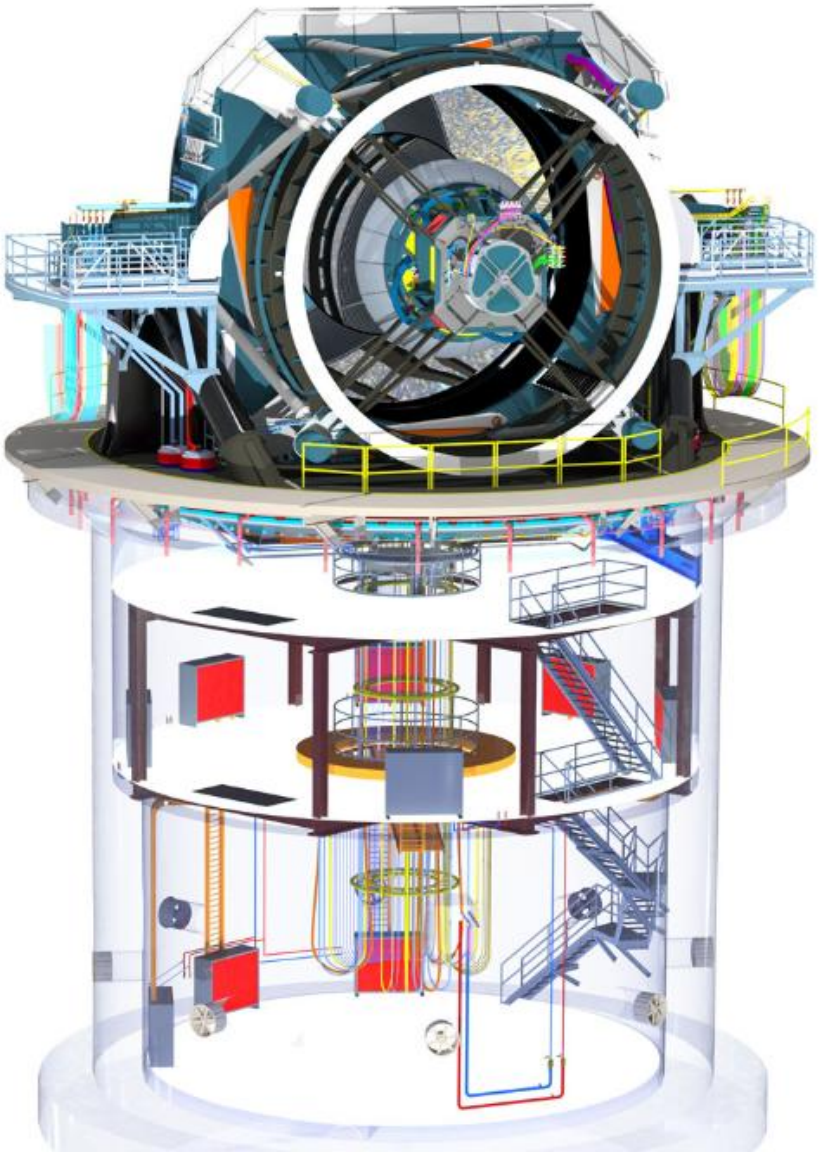
LSST Camera Sensors and Front End Electronics

P. O'Connor, 2014-05-14



LSST in a Nutshell

- LSST is designed to conduct a decade-long survey of the sky in the optical, using a novel 8-m class ground-based telescope and a 3.2Gpixel camera whose key focal plane components are being fabricated here at BNL.
- Data products will include:
  - A catalog of 37 billion sources
  - Real-time alerts to tens of billions of time domain events
- The LSST will enable a wide variety of complementary scientific investigations, including:
  - Mapping the dark matter distribution
  - Precision estimates of the dark energy equation of state parameters
  - Testing the ΛCDM paradigm of composition and expansion of the universe, search for new physics
  - Neutrino properties ($\Sigma_{m\nu}$, N_{eff})
- Cost and schedule:
  - Telescope, site, DM: $473M
  - Camera: $165M
  - Operations: $37M/yr
  - First light: 2019
  - Survey operations start: 2022



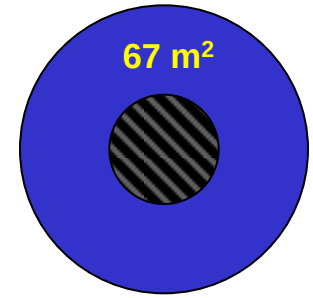
Summary of High Level Requirements

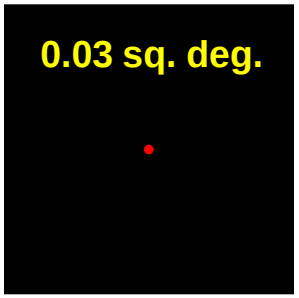
Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute, 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

Etendue is the figure of merit for astronomical survey instruments

Primary mirror effective area	X	Field of view	=	Étendue AΩ

Keck





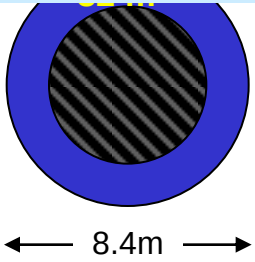
2 m²-deg²

Oschin Schmidt

Astron…nvestigations at the largest telescop…d on small sampl…mic sources or individual objects. T…e our largest telesc…ties typically had rather small fields …

20 m²-deg²

… and those with large fields of view could not detect very faint sources.

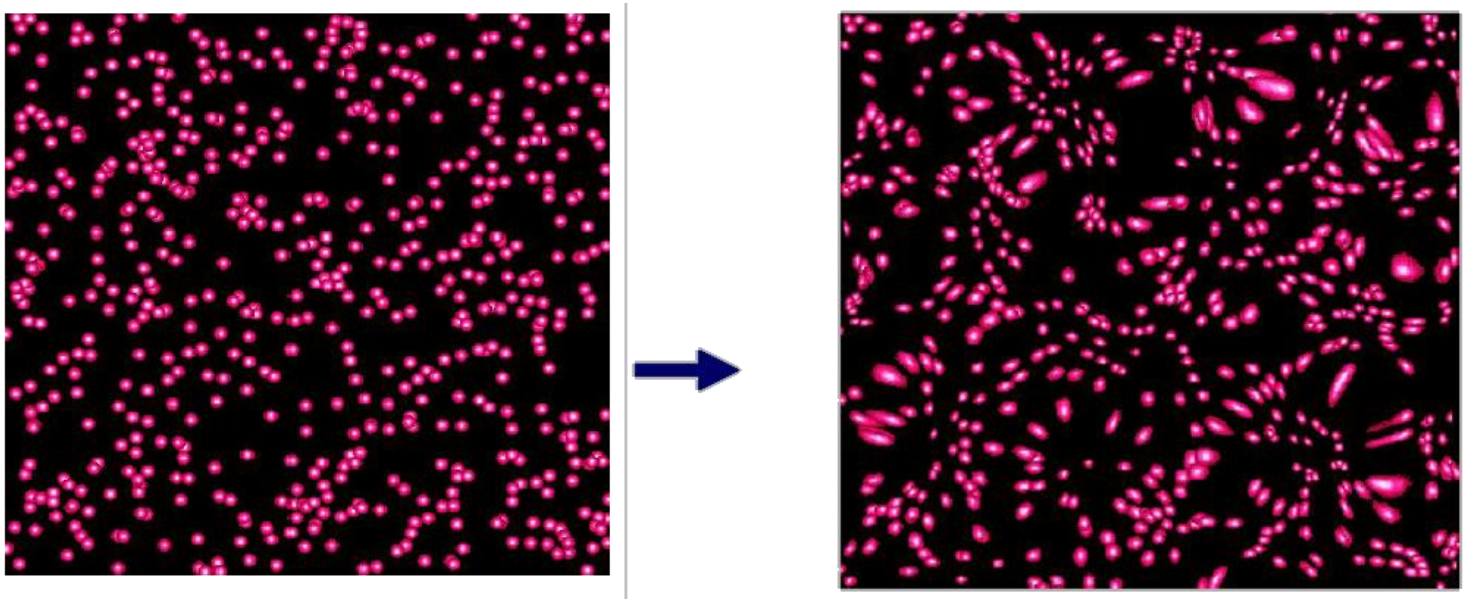


320 m²-deg²

LSST combines large aperture and field of view to go WIDE and DEEP.

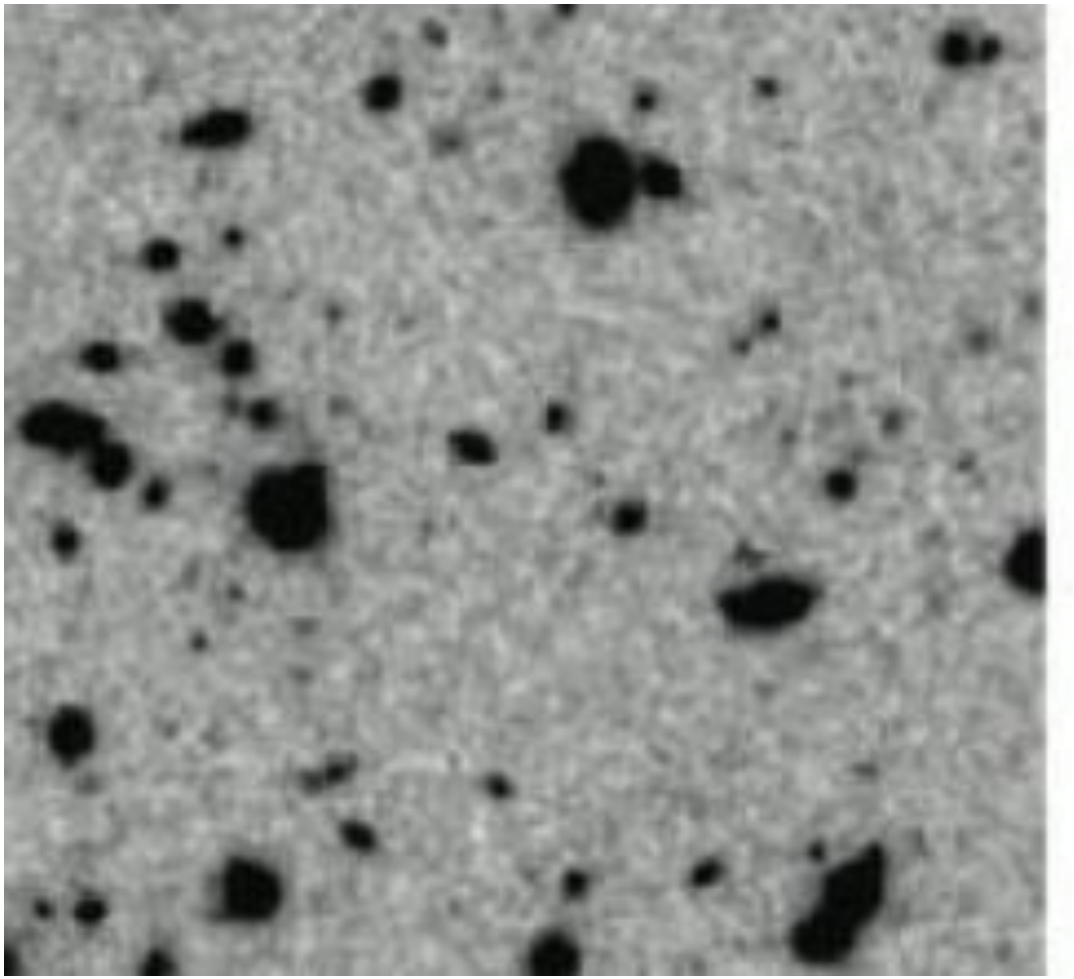
weak gravitational lensing

- is a small distortion (*< 1%*) of galaxy shapes
- is detected *statistically* by sampling many galaxies
  - ~ 40 detected galaxies per square arcminute
- the projected mass distribution can be obtained from properties of the shear field
- is unique in that it is *sensitive to mass*, not light
- sets the tightest constraints on LSST sensor properties, as it requires accurate *shape, flux, color, and position* of the *faintest, smallest* galaxies



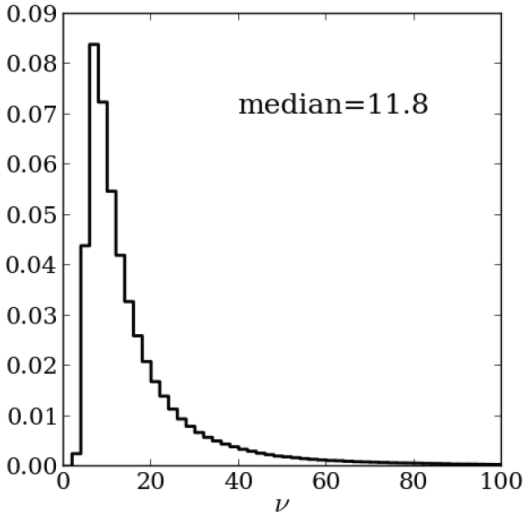
Typical galaxy field at LSST depth

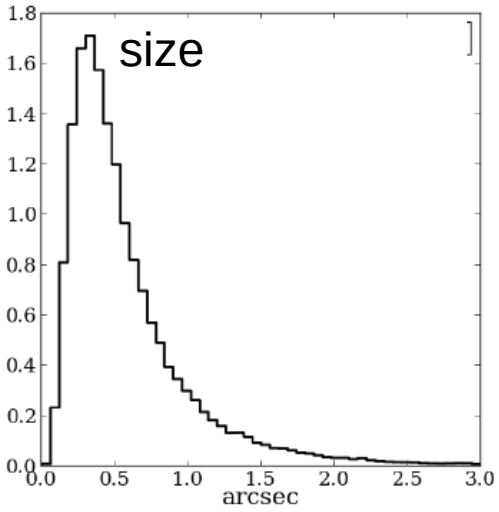
deep image from Subaru – another 8m telescope



Miyazaki et al. 2011

signal-to-noise

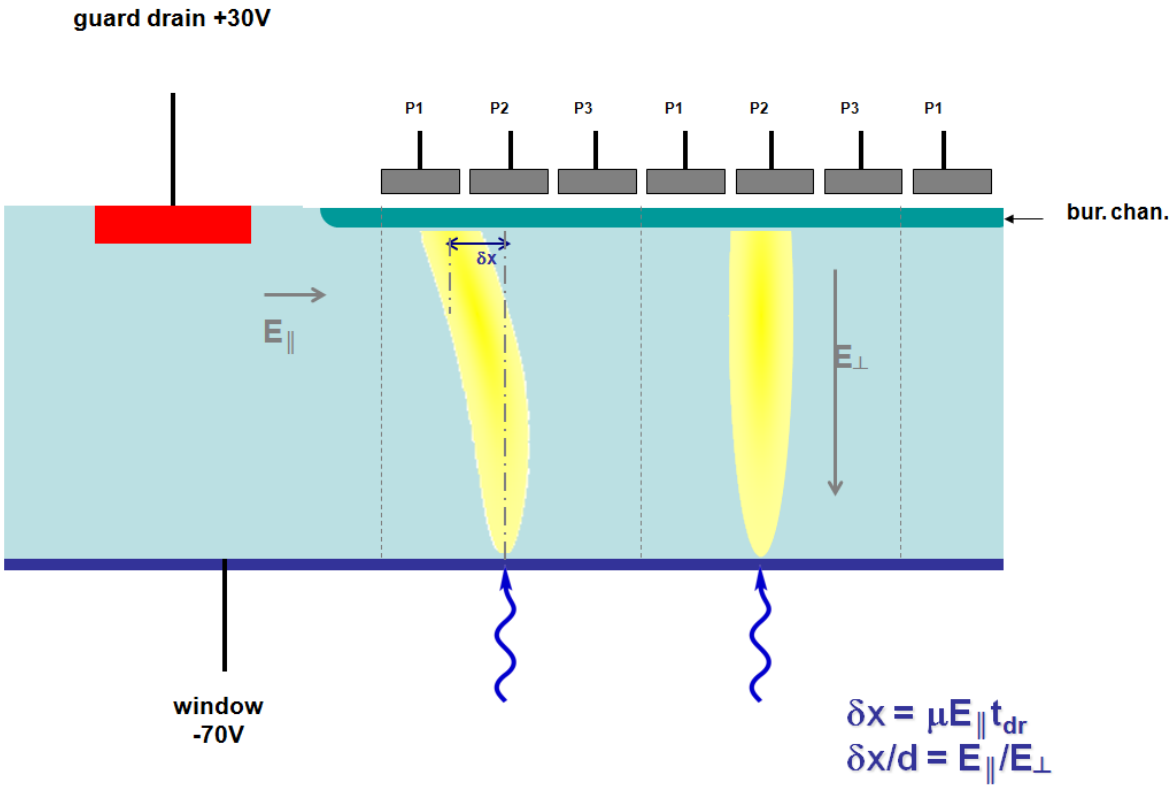


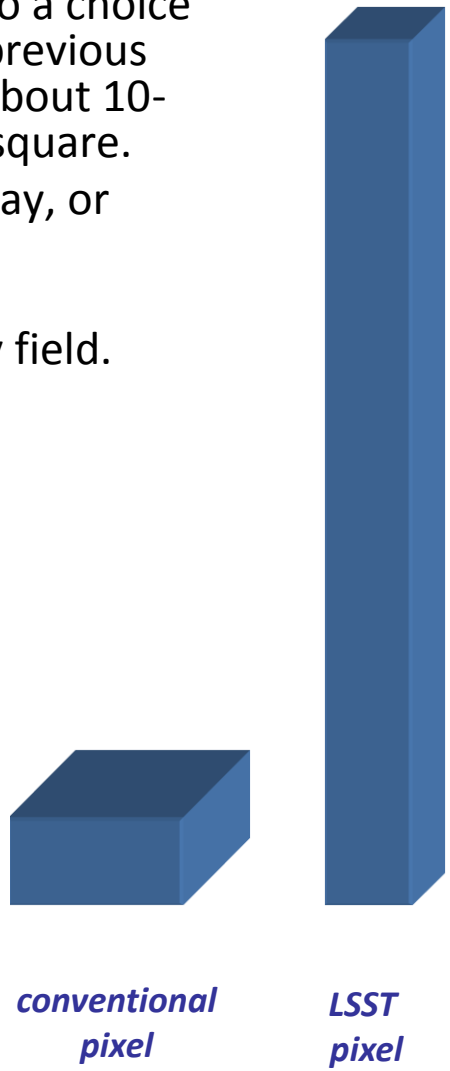


Chang et al. 2013

Electrostatics in thick, fully-depeleted CCDs

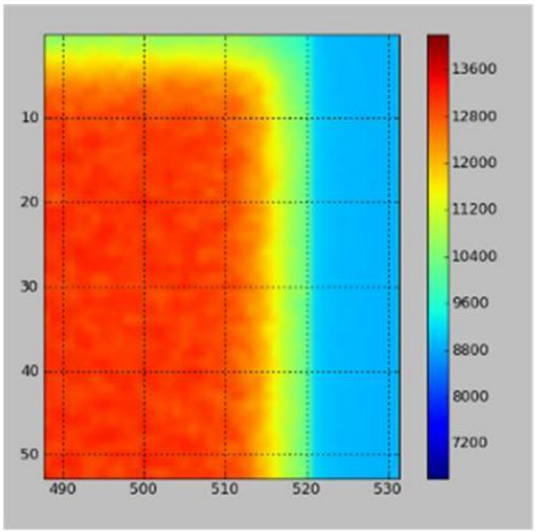
- LSST needs sensitivity to the near infrared and which leads to a choice to use back-illuminated, thick, fully-depleted sensors. Most previous cameras have used silicon CCDs made on epitaxial material about 10-20 microns thick, with pixels in the range of 15 - 25 microns square.
- Lateral electric fields (from broken symmetry at edges of array, or doping inhomogeneities in the silicon crystal) cause paths of photogenerated electrons in a thick sensor to bend.
- The collected charge may not reproduce the optical intensity field.



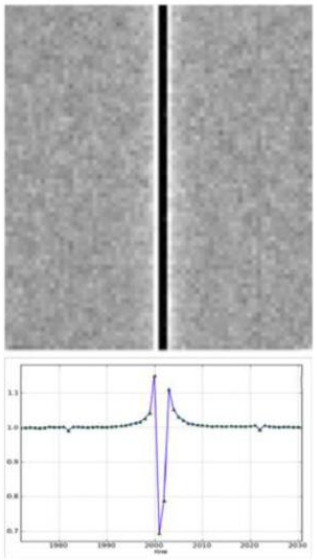


Effects of lateral fields

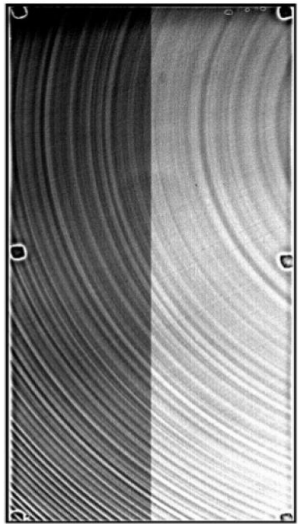
Flatfield illumination (laboratory)



(a) Edge rolloff



(b) Midline

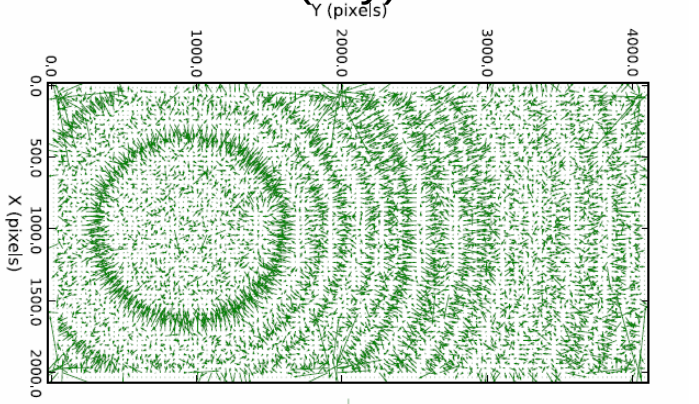


(c) Radial resistivity variation

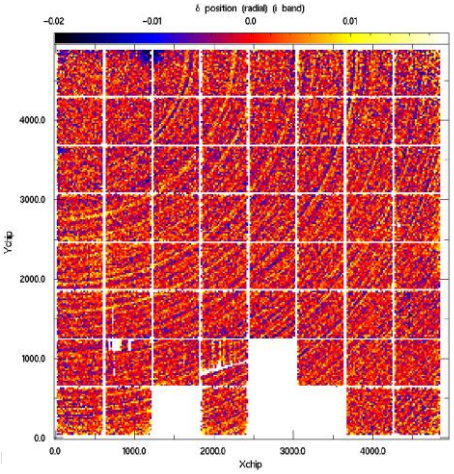
LSST prototype, 100um, n-channel

DECam, 200um, p-channel

Astrometric residuals (sky)

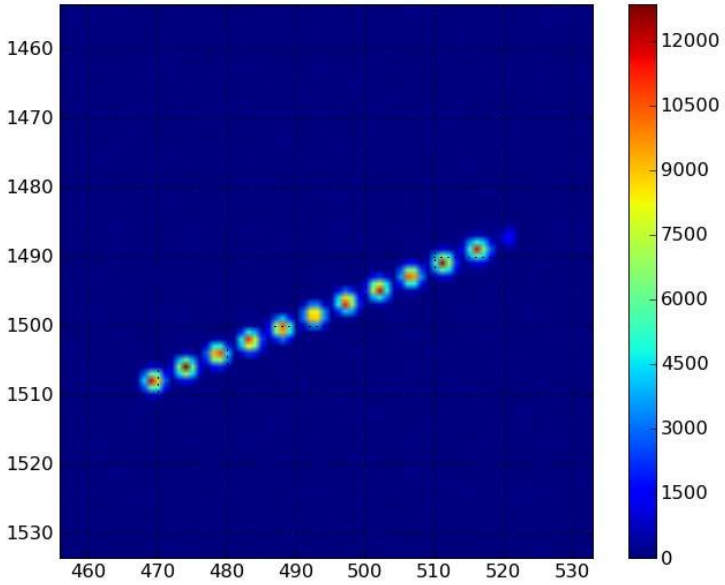


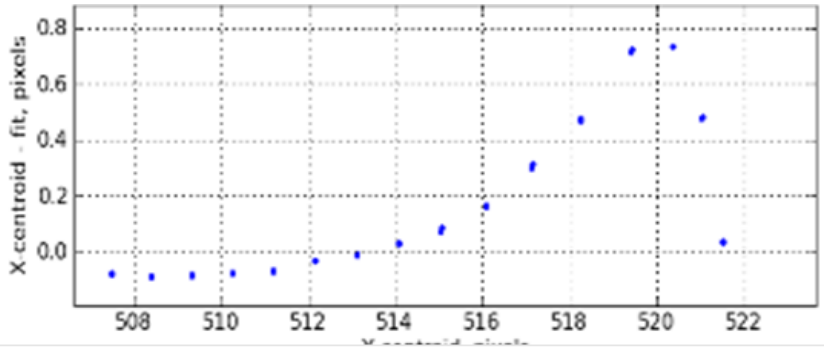
Dark Energy Survey (A. Plazas et al.)

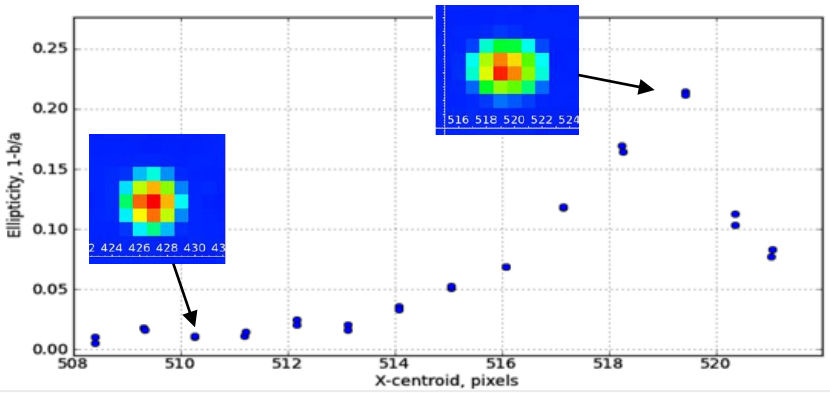


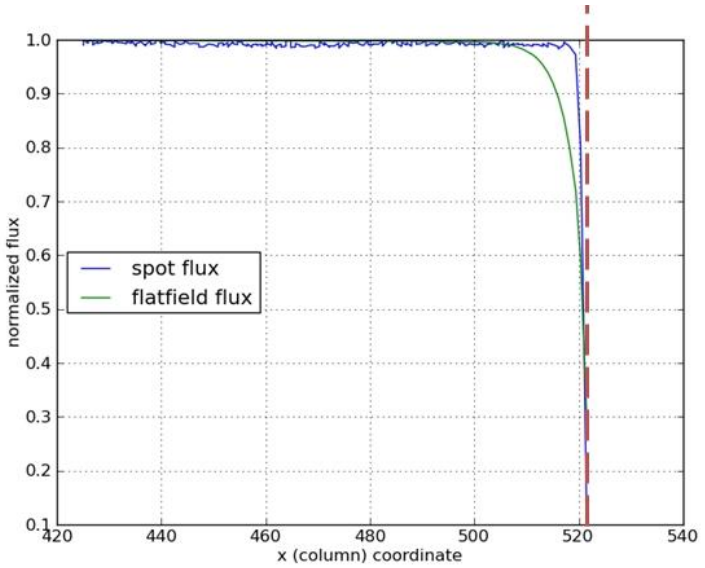
PanSTARRS (G. Magnier)

Edge response spot projector and flat field data



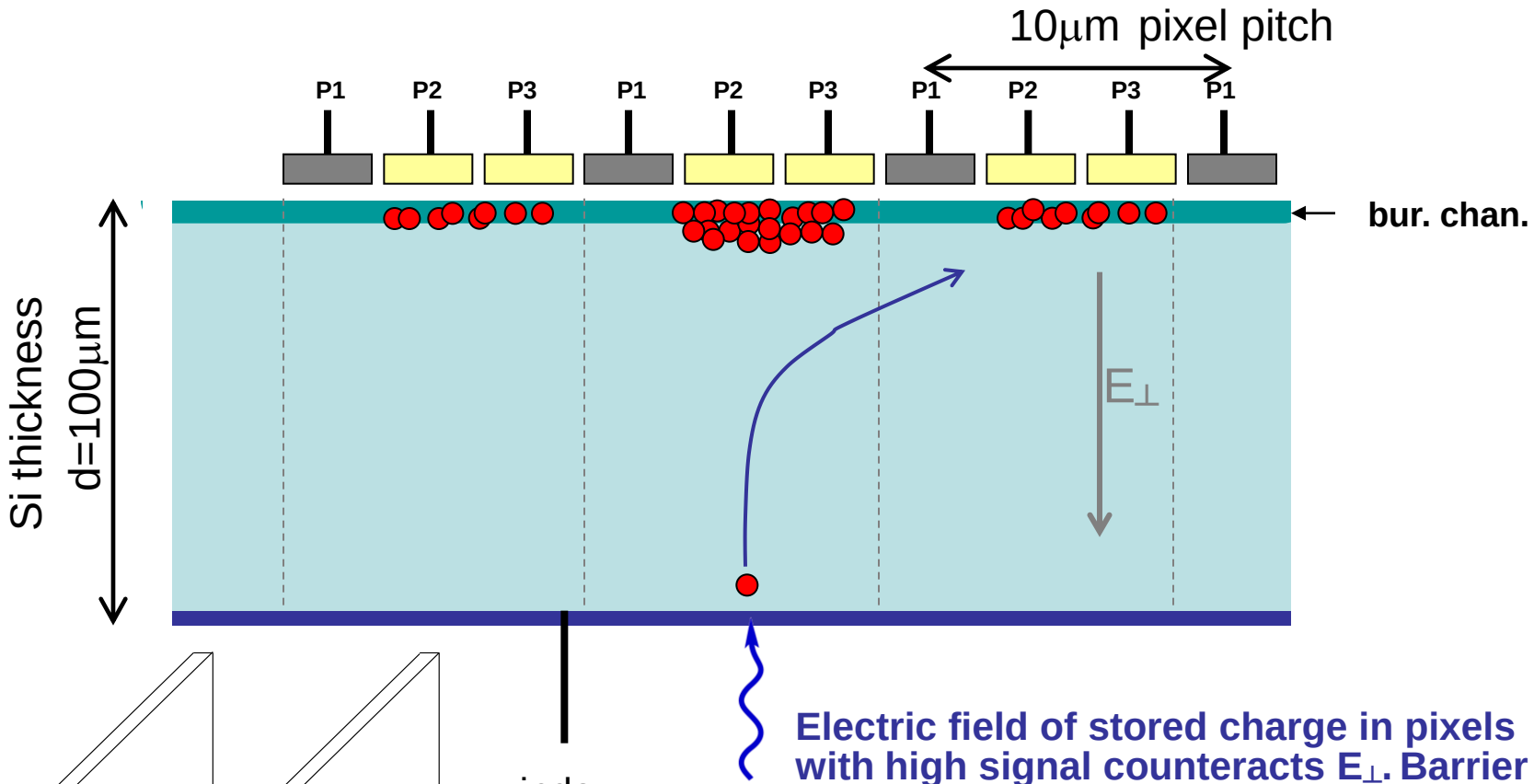


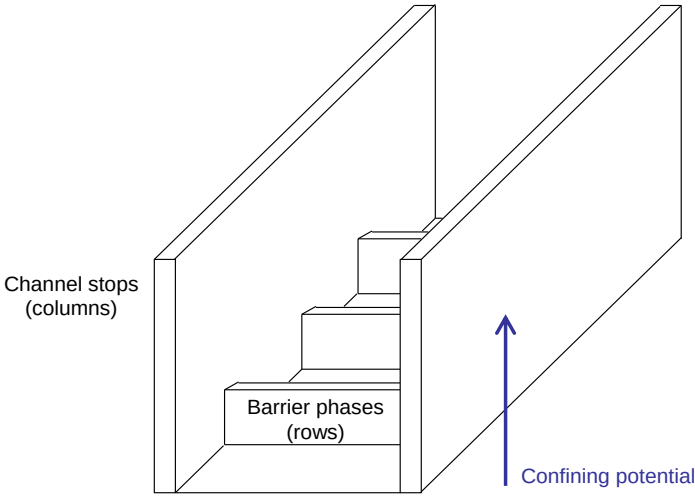




- scan a small spot of light through the edge rolloff region
- its intensity is unchanged (left)
- position and ellipticity are distorted (above)
- profile is stretched and position is shifted towards the attractive guard ring potential
- shape distortion significant for WL

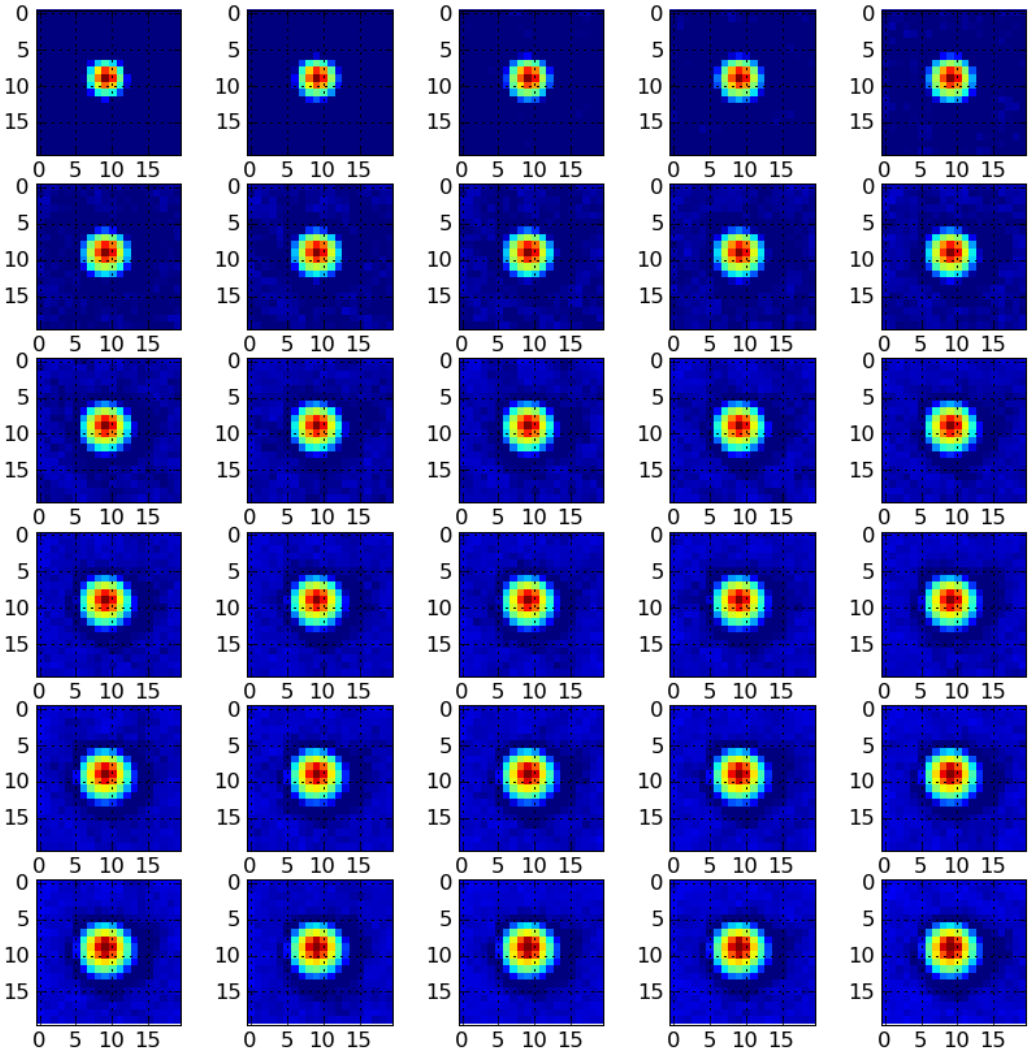
Charge correlation and intensity-induced PSF broadening

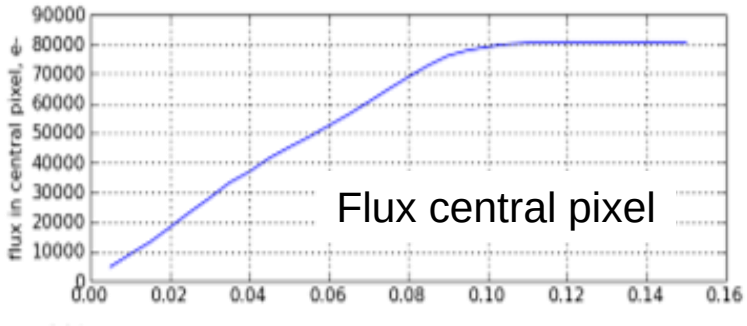


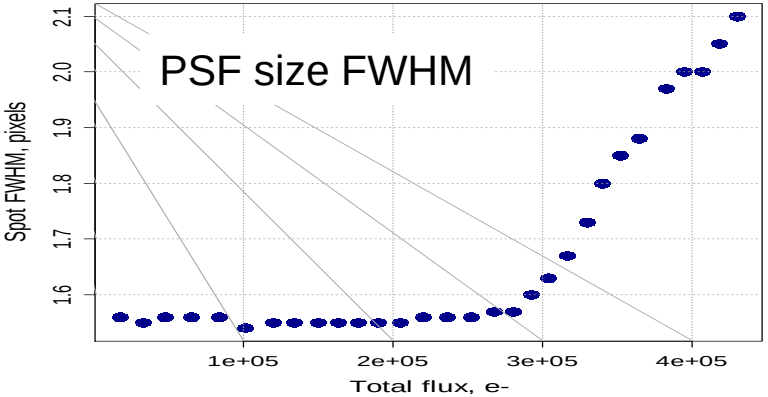


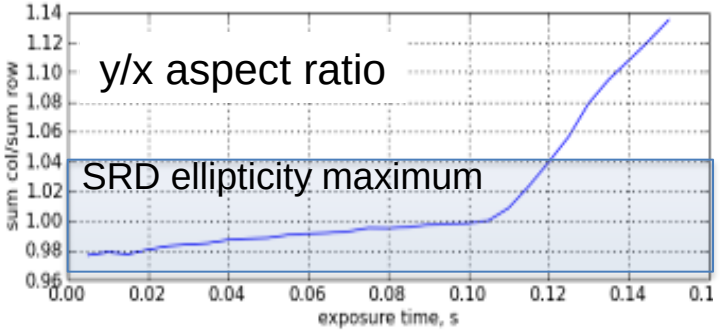
Electric field of stored charge in pixels with high signal counteracts $E_\perp$. Barrier between columns higher than between rows ➔ signal-dependent correlation along columns.

Spot profile vs. intensity: correlation-induced broadening



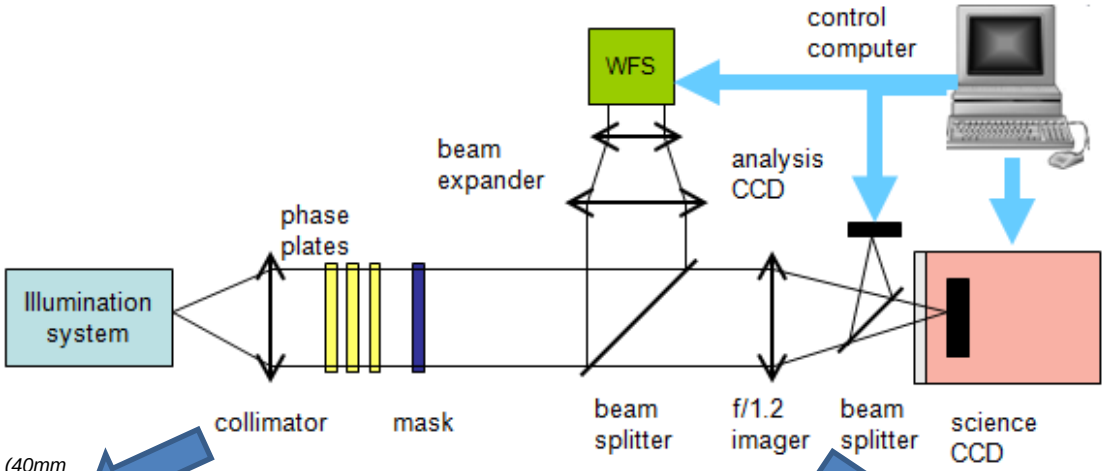


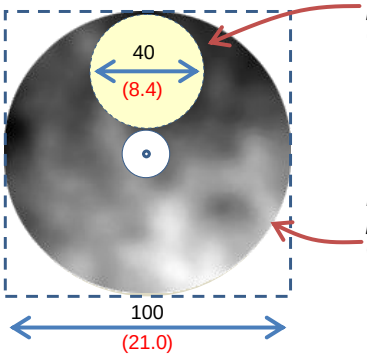




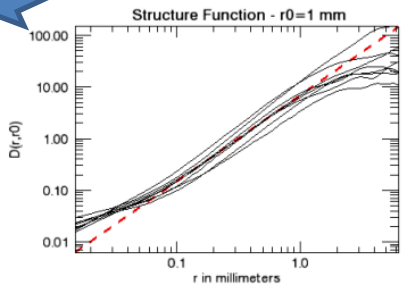
LSST DM might need to parameterize PSF by flux as well as position

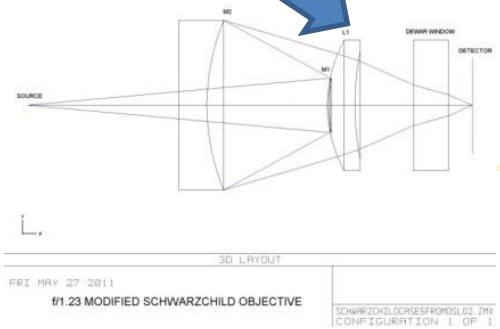
Telescope and atmosphere simulator





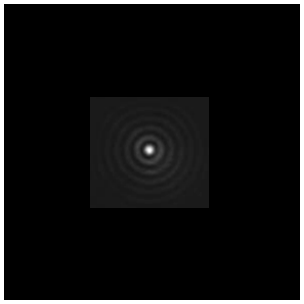
R. Rampy, UCSC



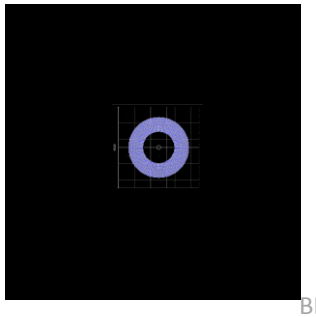


J. Haupt

Focussed – no atmosphere



Defocus – no atmosphere



Wavefront with atmosphere

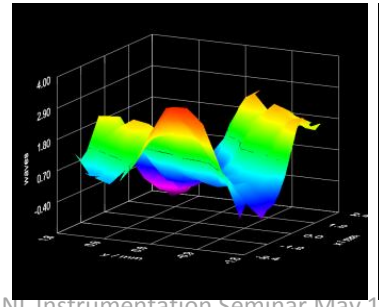
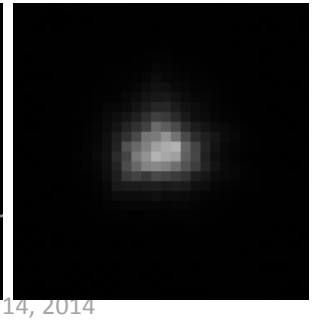
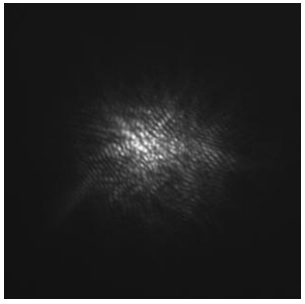


Image with atmosphere

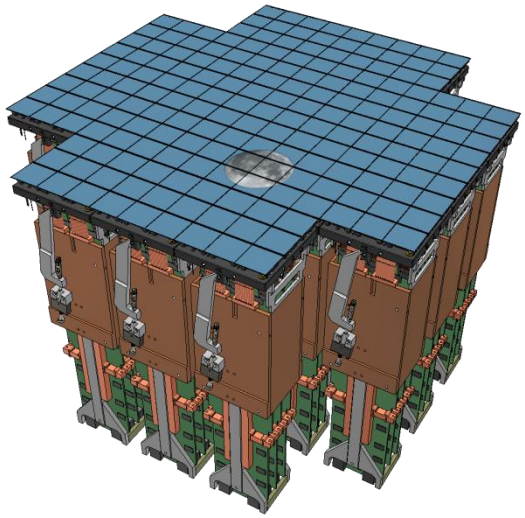


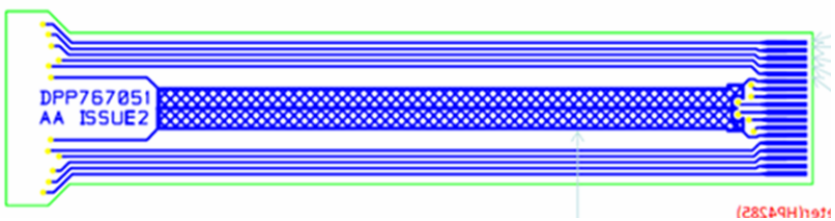
20X re-imaged

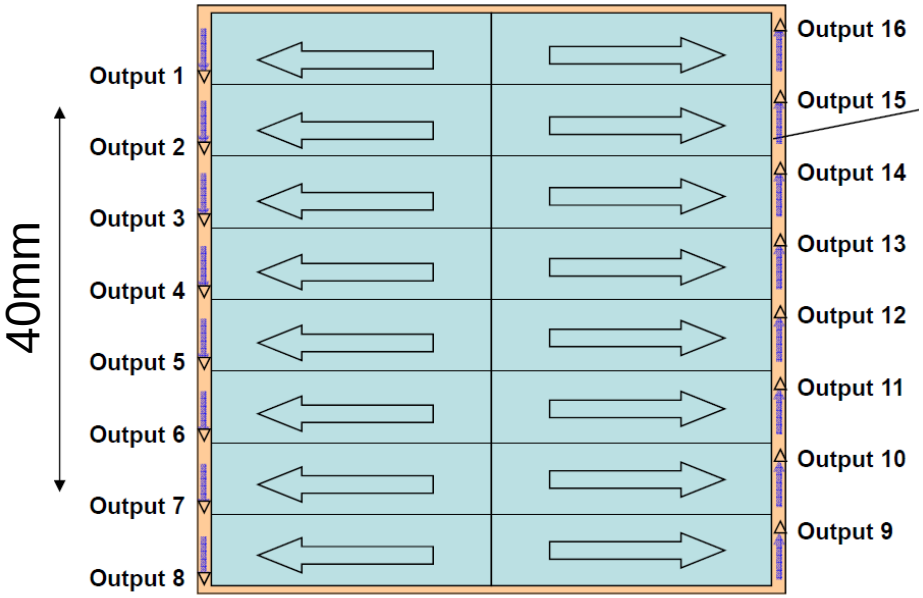


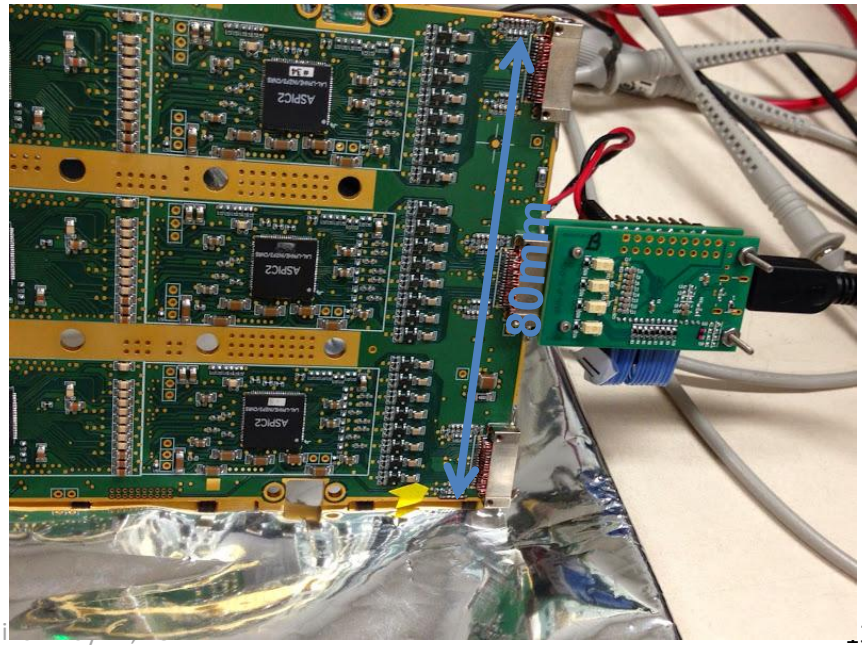
Electronic crosstalk sources

- LSST's 3.2Gpix camera uses fast, compact, and power-constrained readout electronics
  - 2s readout, 550kpix/s
  - Neighboring video signals separated by .25mm
  - 350mW/channel









How much crosstalk is too much?

Table 19.12. *Model* $\log N(l)$ *(stars per square degree) averaged over galactic longitude and over the whole sky.*

l	$b=0$	$b=5$	$b=10$	$b=20$	$b=30$	$b=60$	$b=90$	Sky
12.0	2.466	2.434	2.279	2.011	1.799	1.450	1.374	2.001
13.0	2.922	2.877	2.671	2.355	2.138	1.816	1.728	2.396
14.0	3.316	3.262	3.023	2.678	2.461	2.149	2.045	2.753
15.0	3.650	3.594	3.344	2.991	2.772	2.445	2.326	3.075
16.0	3.951	3.897	3.653	3.301	3.069	2.702	2.575	3.376
17.0	4.243	4.191	3.955	3.594	3.341	2.926	2.799	3.663
18.0	4.548	4.494	4.247	3.861	3.584	3.133	3.005	3.947
19.0	4.868	4.807	4.530	4.103	3.804	3.327	3.191	4.230
20.0	5.191	5.120	4.802	4.326	4.005	3.503	3.353	4.510
21.0	5.479	5.398	5.039	4.515	4.173	3.649	3.488	4.761
22.0	5.710	5.623	5.234	4.673	4.313	3.770	3.604	4.967
23.0	5.909	5.816	5.400	4.806	4.430	3.874	3.706	5.145
24.0	6.092	5.991	5.546	4.916	4.528	3.970	3.797	5.308
25.0	6.258	6.150	5.669	5.002	4.606	4.055	3.875	5.453

5σ limiting magnitude is r=24.2

If crosstalk spec is x

→r < (24.2+2.5log(x)) source will produce detectable crosstalk ghost

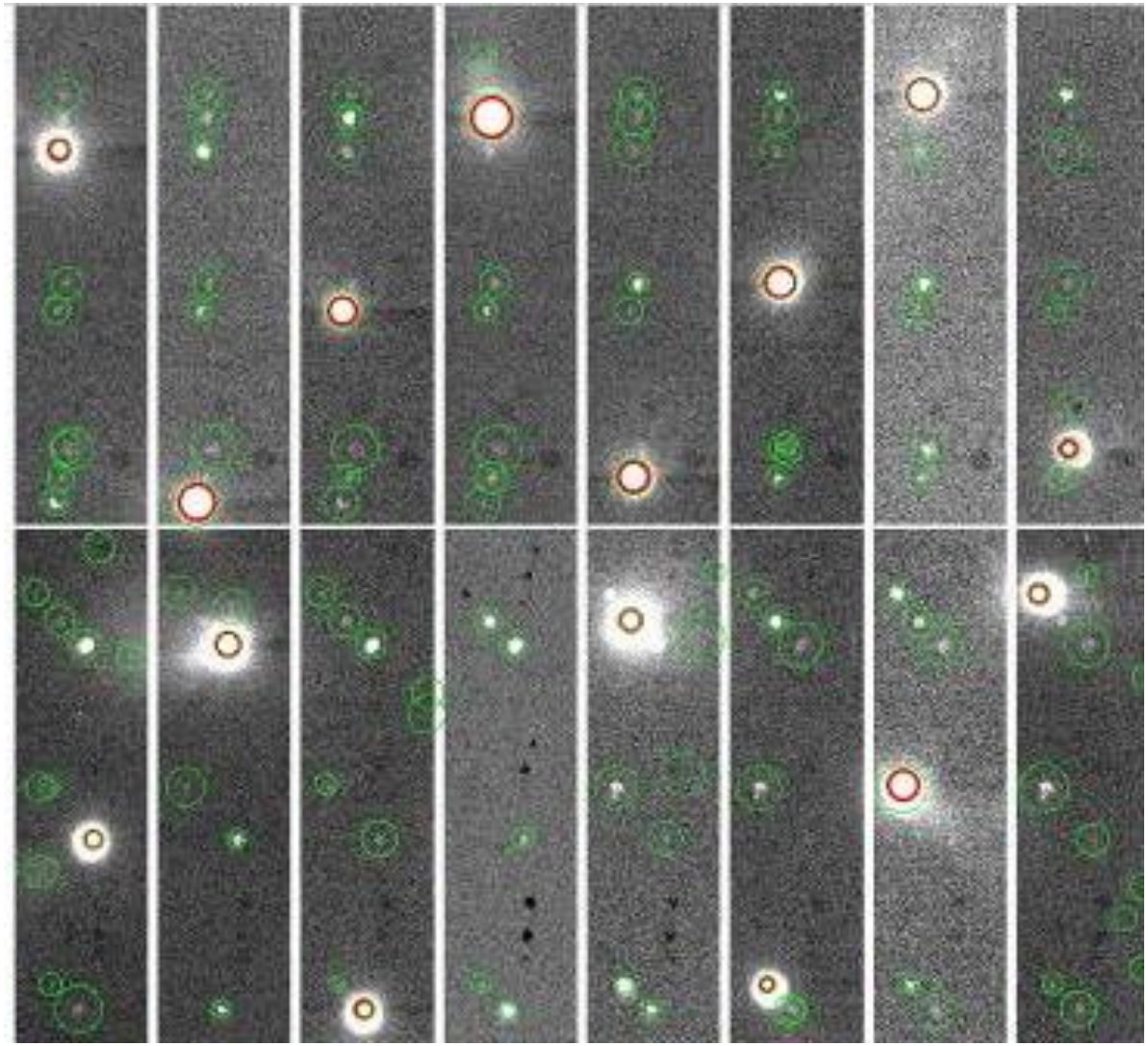
How many stars/CCD will produce detectable ghosts?

	crosstalk level			
	0.2%	0.07%	0.02%	0.004%
l	17.5	16.3	14.95	13.2
Log(N(l))	3.8	3.4	3.08	2.45
10^(N(l))*(14/60)^2	344	137	65	15

Crosstalk measurement using multi-aggressor mask

100 coadded images with identified aggressors (red) and victims (green)

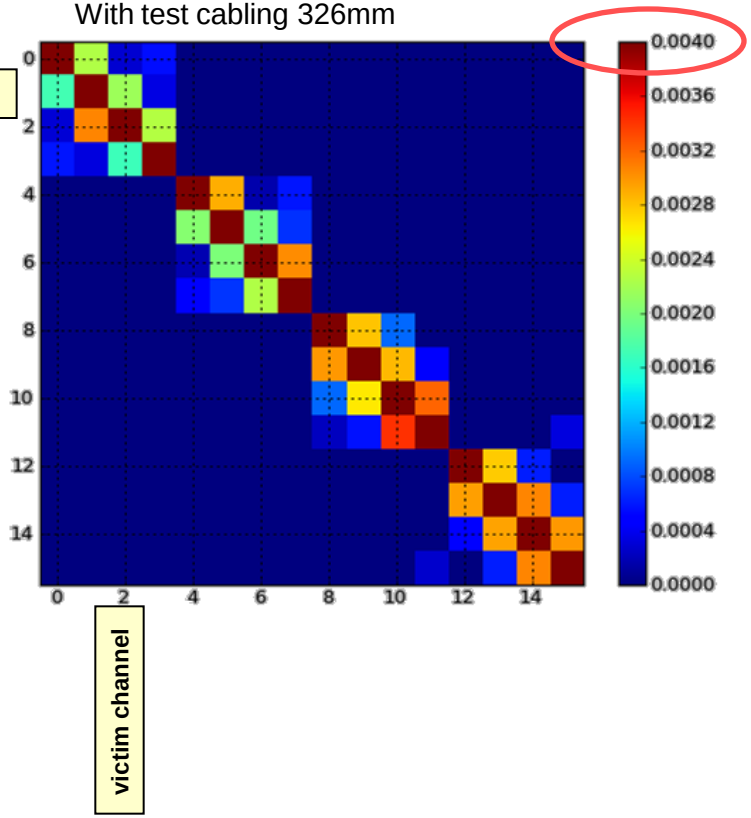
Aggressors peak amplitude ~ 35,000 e-. Background noise level ~ 1.2 e-



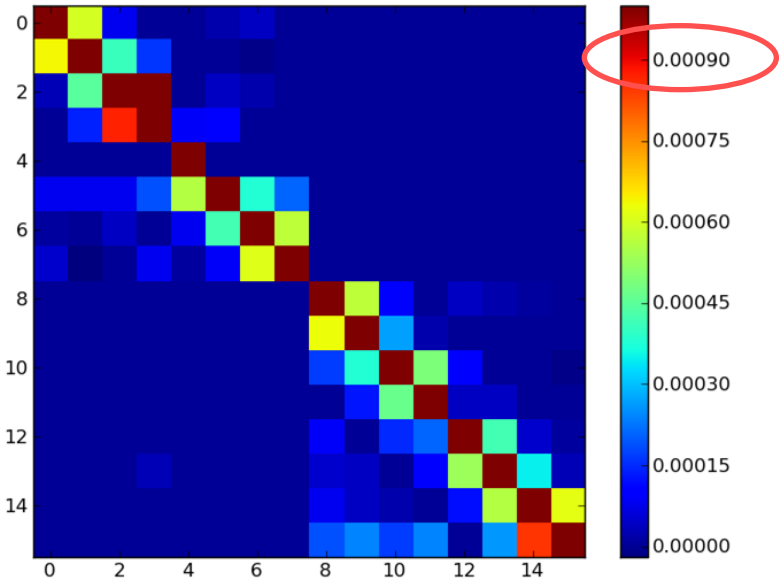
SExtractor finds over 100 "victims" down to 10^{-5}

16 x 16 crosstalk matrix

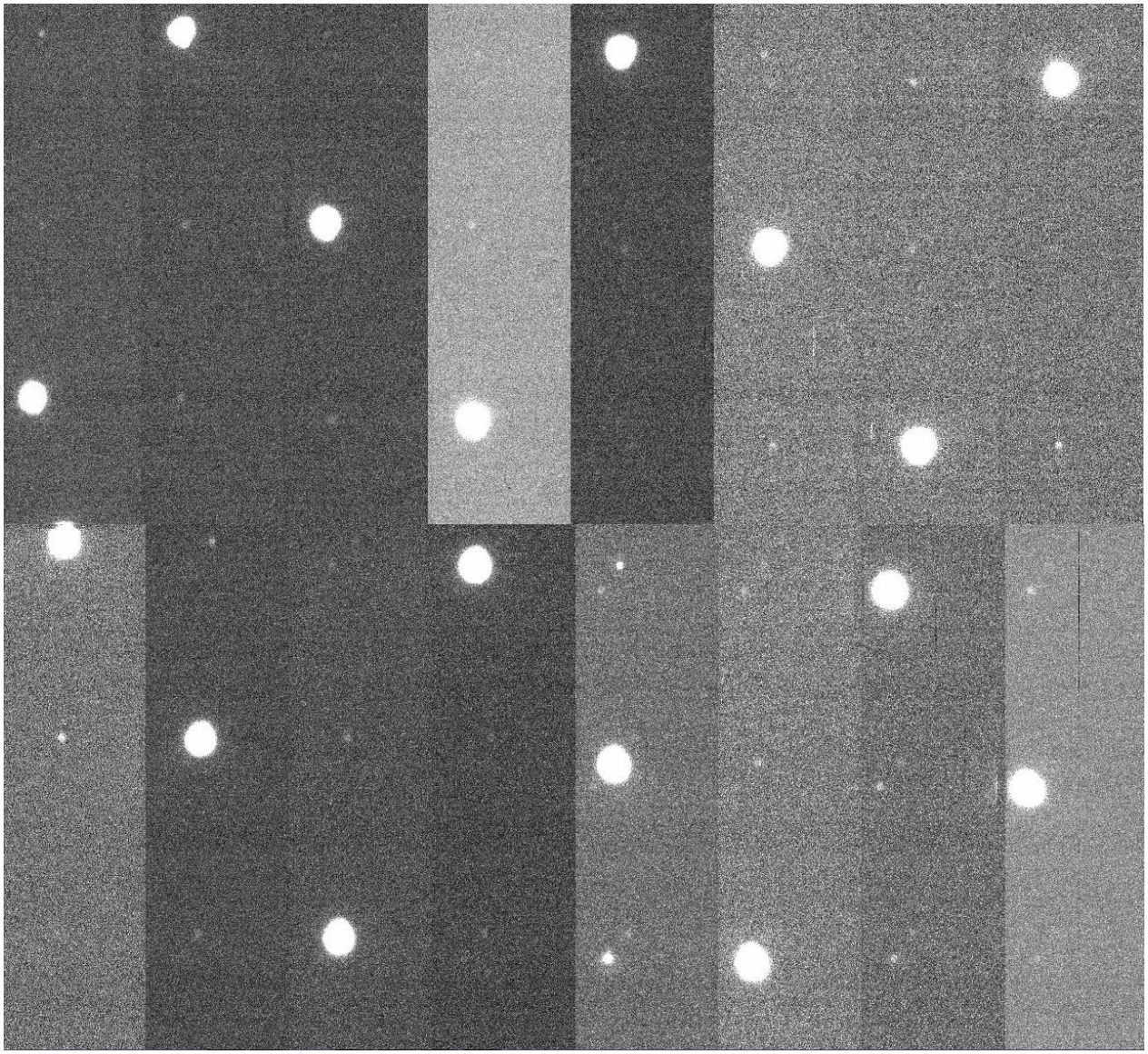
With test cabling 326mm



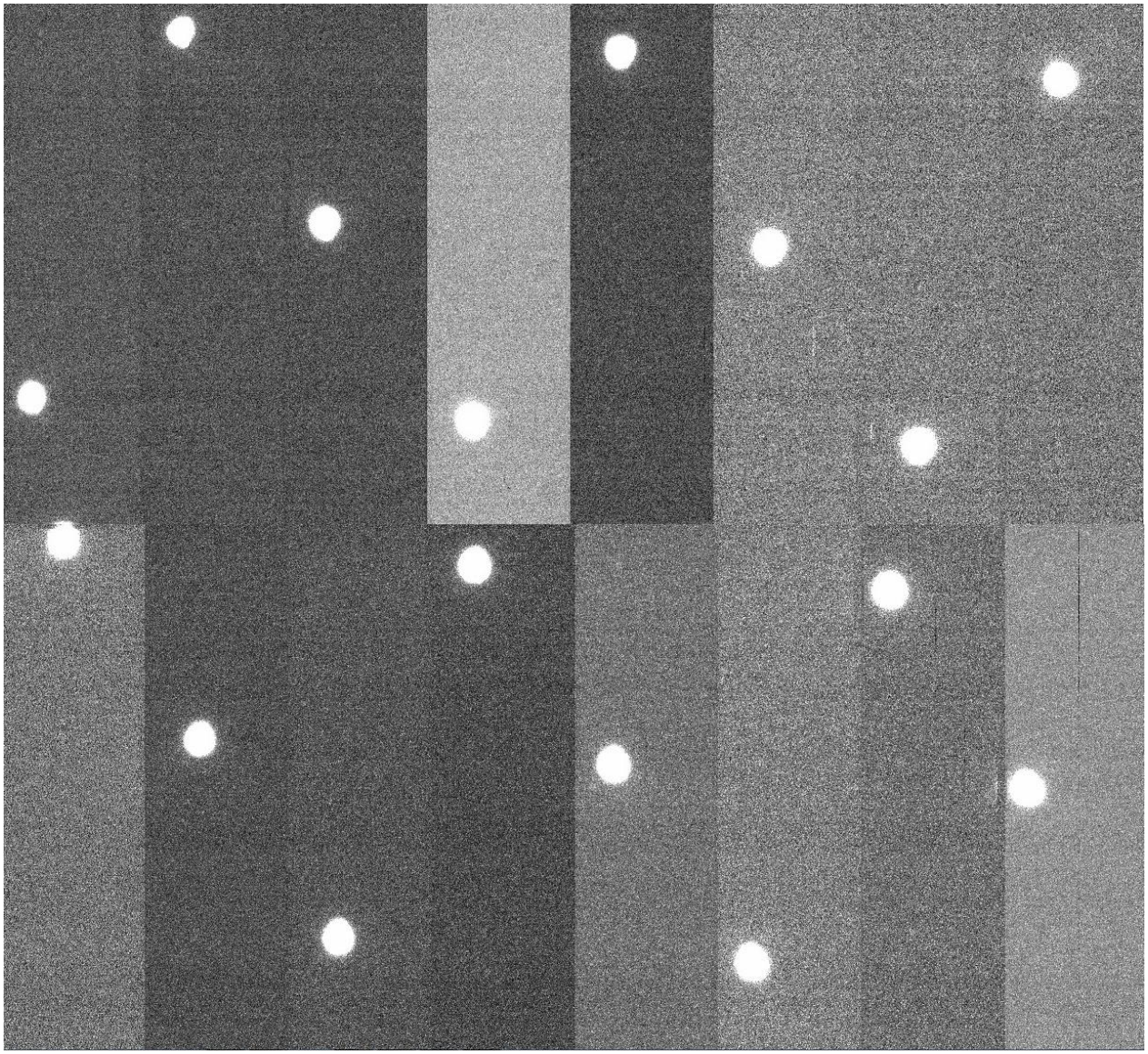
With system cabling 67mm



Crosstalk before correction (no coadd, ~ 11e- noise)

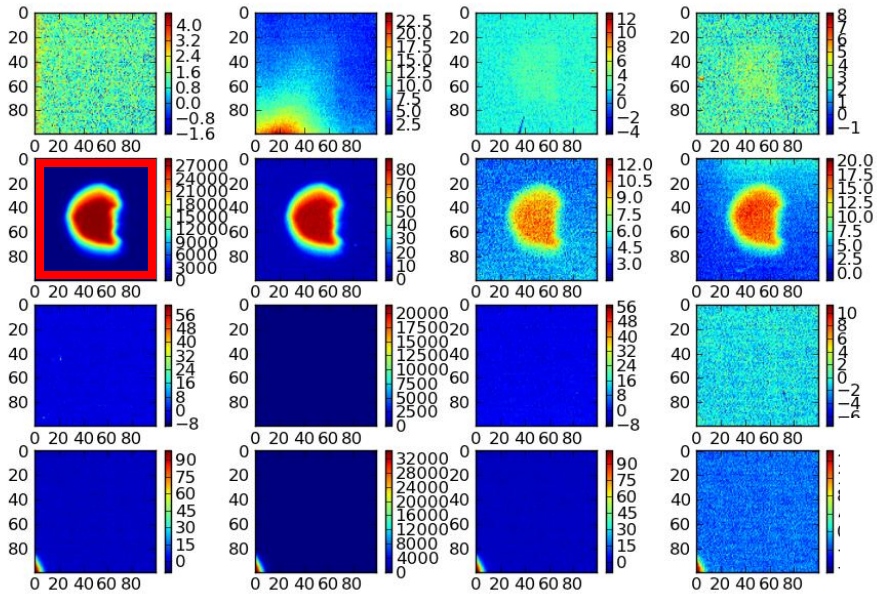


Crosstalk after correction (no coadd, ~ 11e- noise)

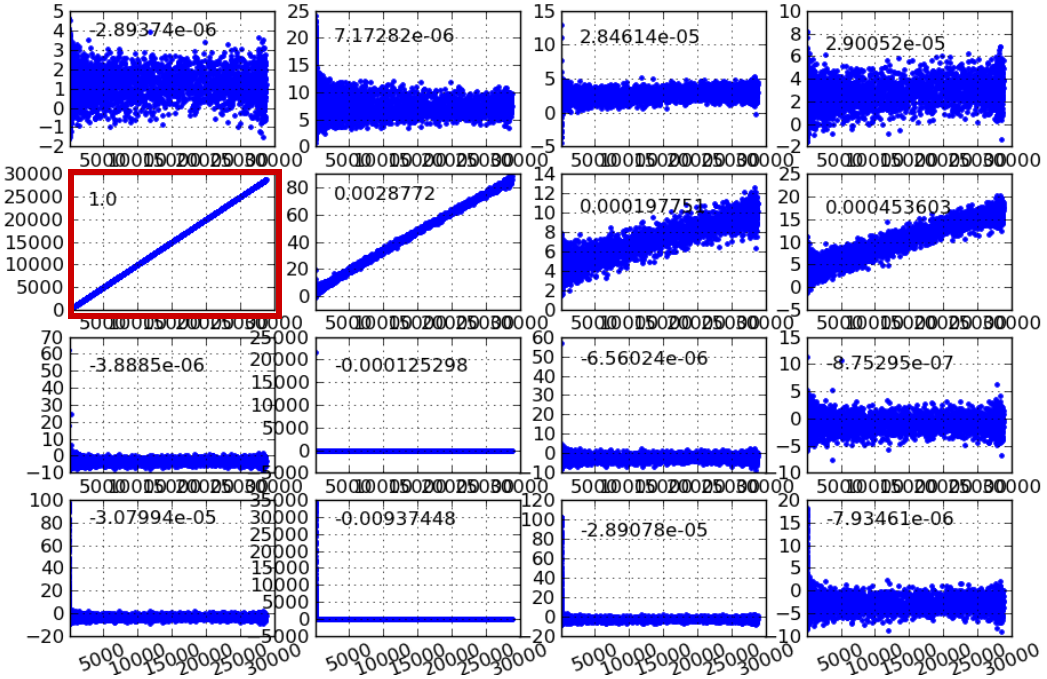


Crosstalk linearity check

aggressor in segment 5

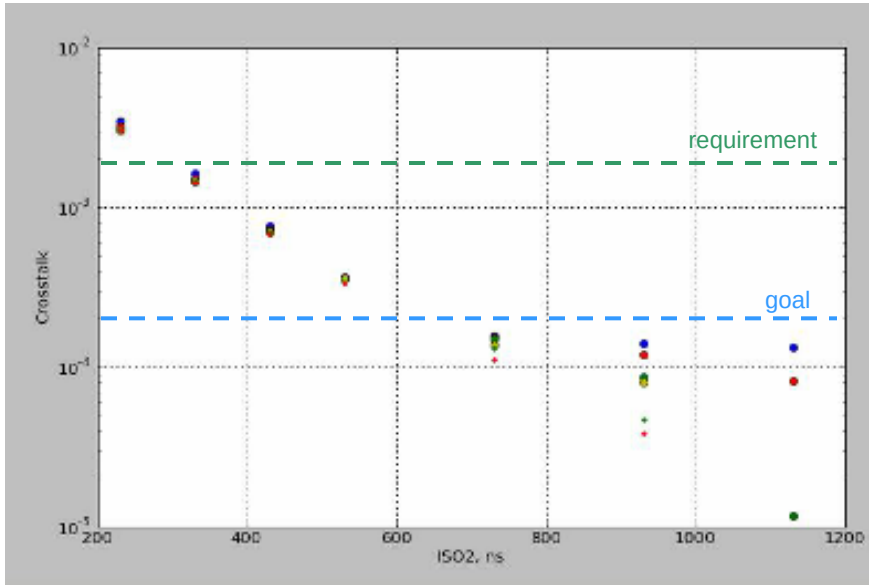


plot pixel-by-pixel counts in victim channels vs. corresponding aggressor pixel

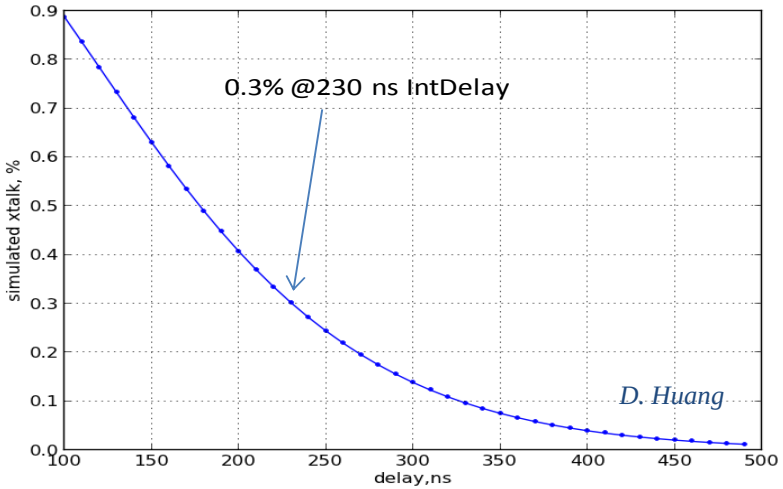


CCD250 crosstalk vs. pixel timing and drive current

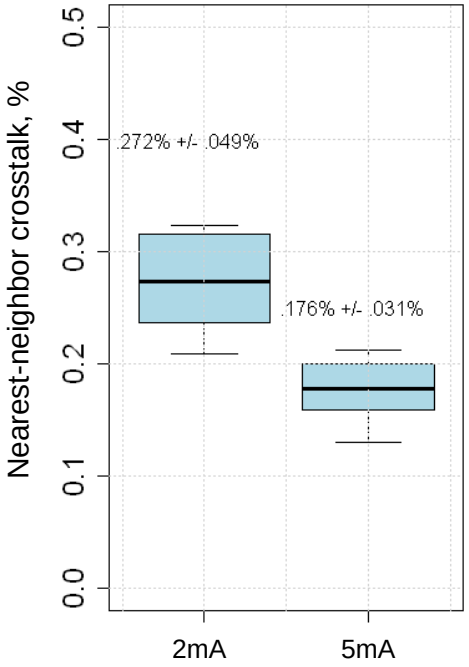
Crosstalk vs. video CDS window delay (with test cabling)



SPICE simulation



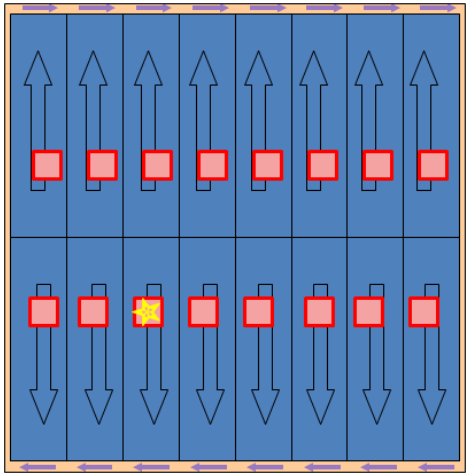
Crosstalk vs. output source follower bias current

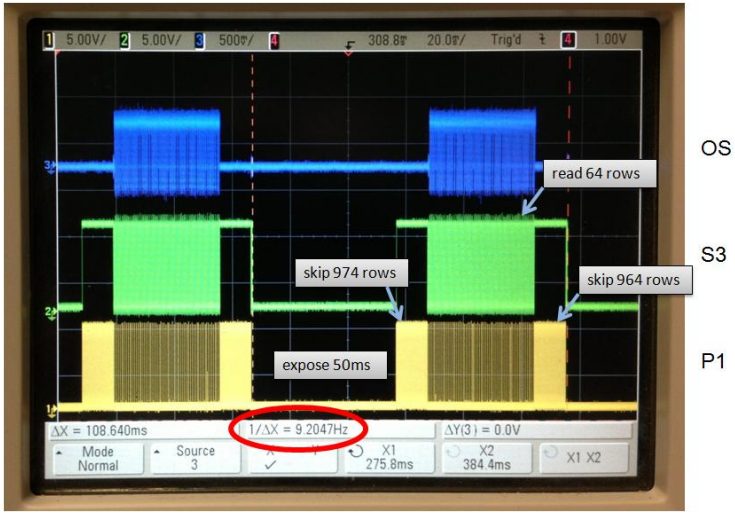


- **Increasing I_{bias} reduces output impedance and increases transconductance by ~ $1/\sqrt{I_{bias}}$**
- **Crosstalk and noise reductions seen are consistent (crosstalk 55% lower, noise 17% lower)**

Using the science CCD as a guider

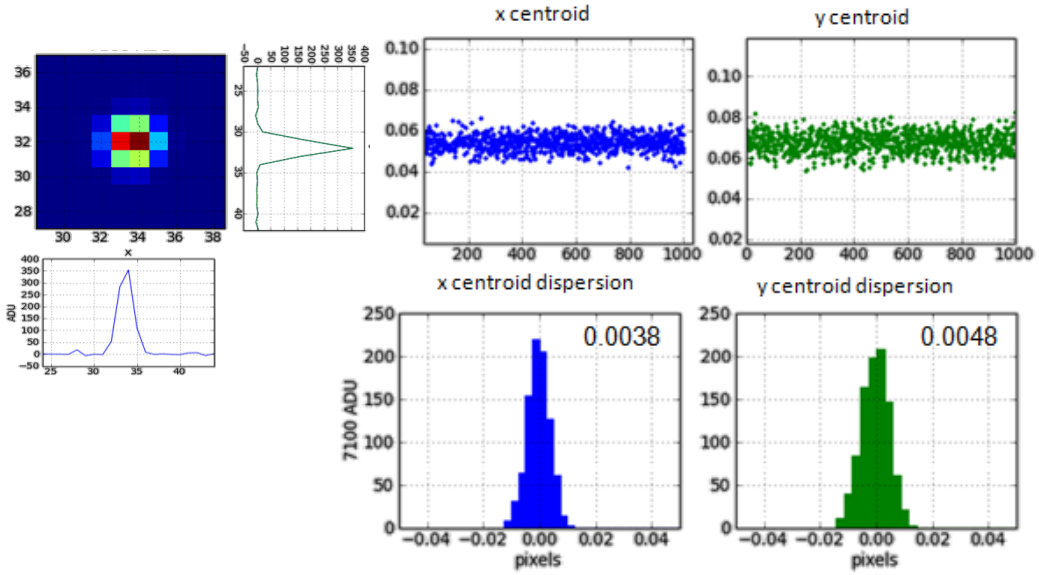
- 4 CCDs in corners of FP to be used for telescope guiding loop
- require 9Hz readout of 50x50 pixel ROI
- centroid noise < 0.2 pixels

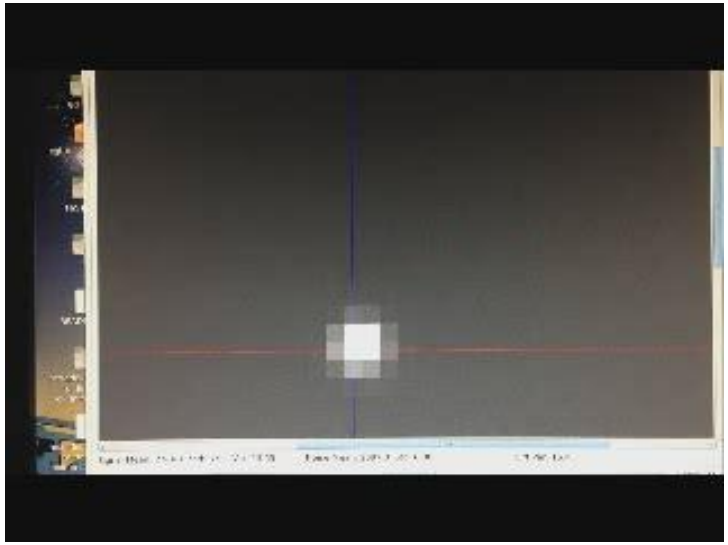




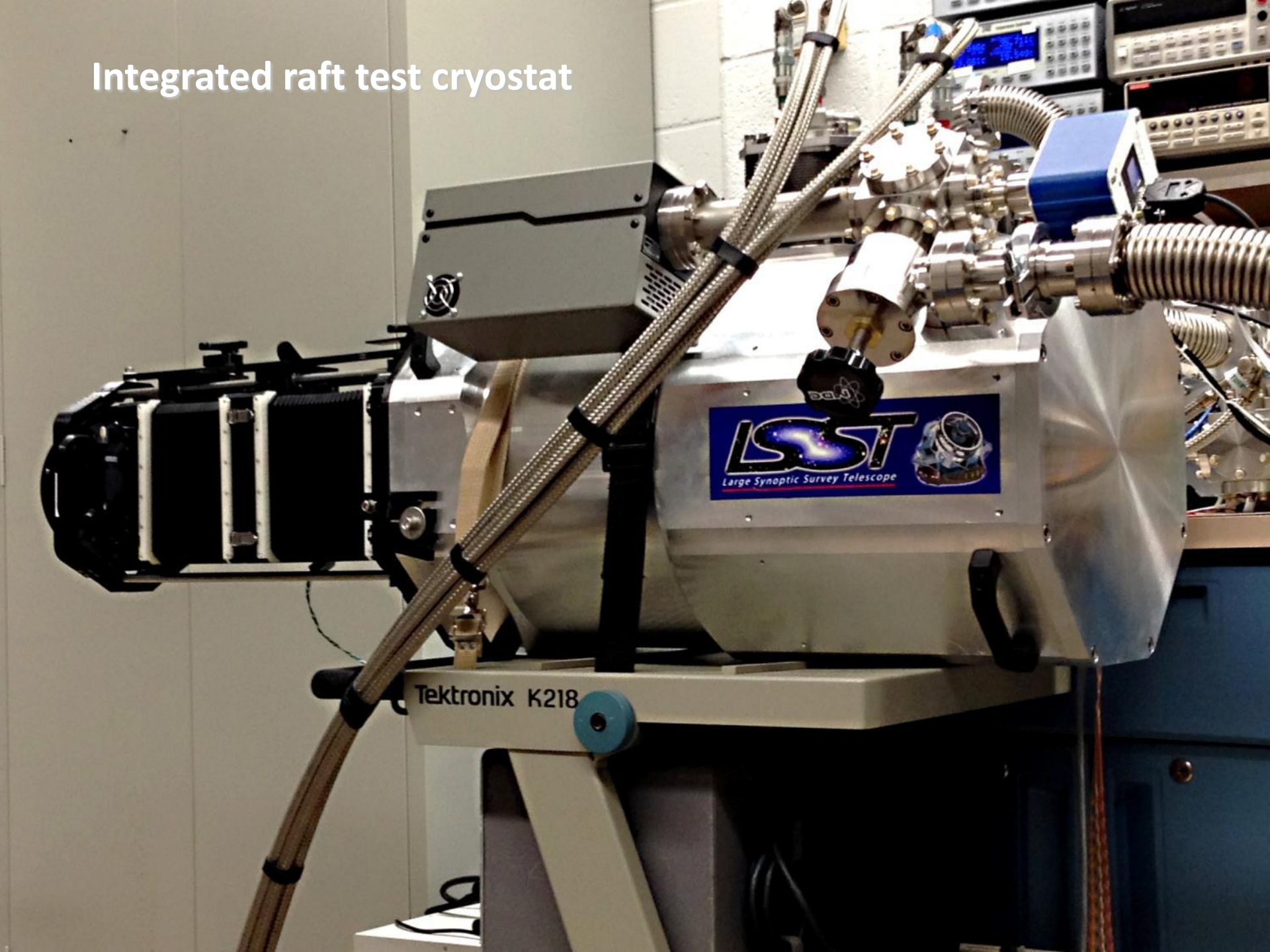
I. Kotov

test with focused spot, prototype CCD, Reflex controller

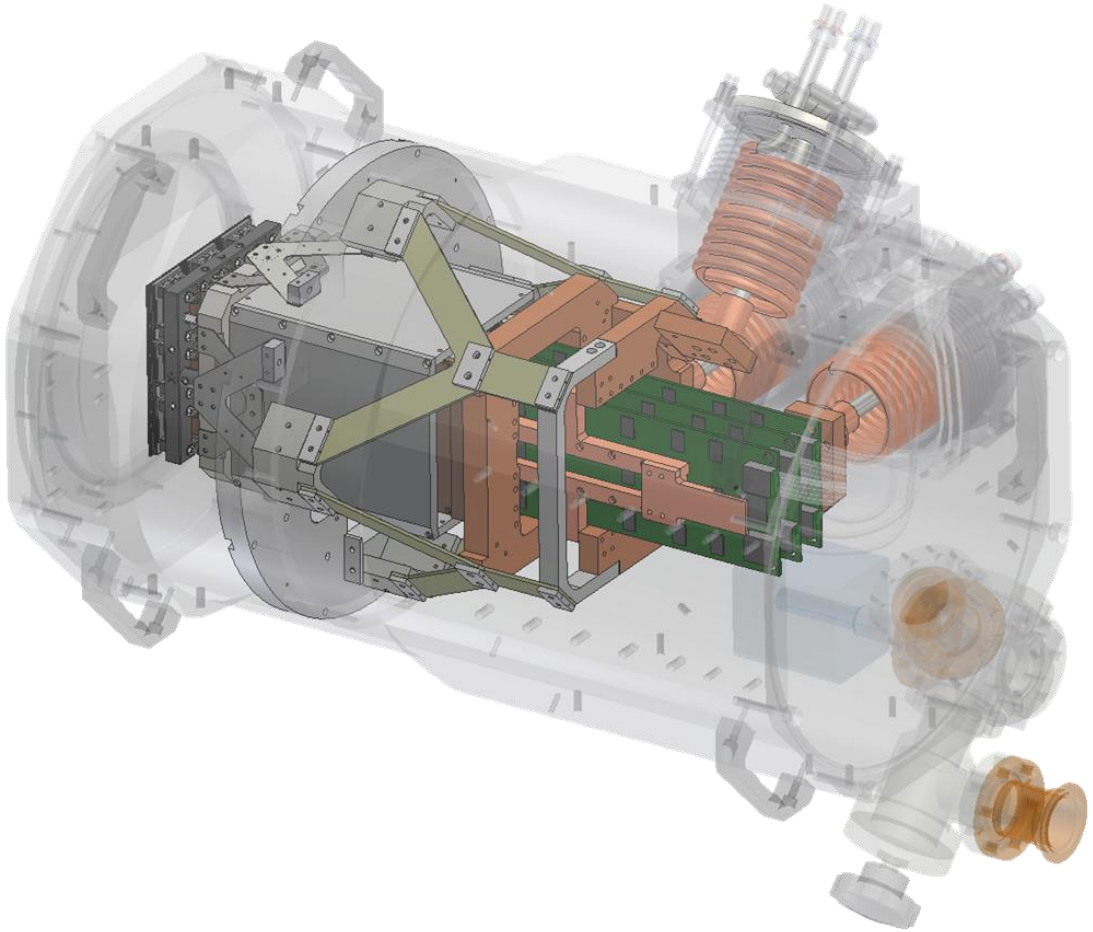


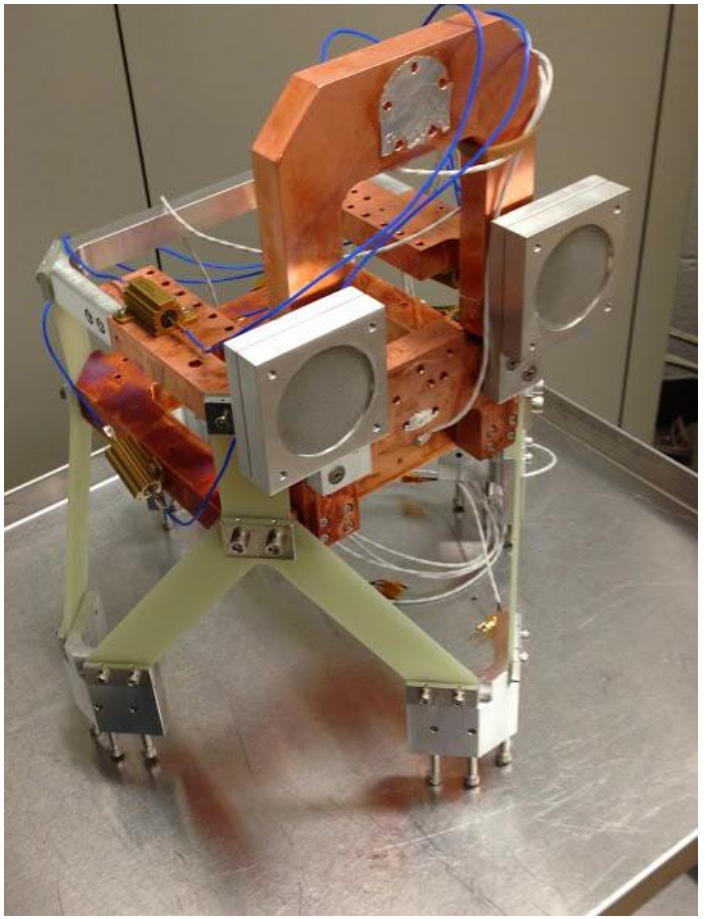


Integrated raft test cryostat



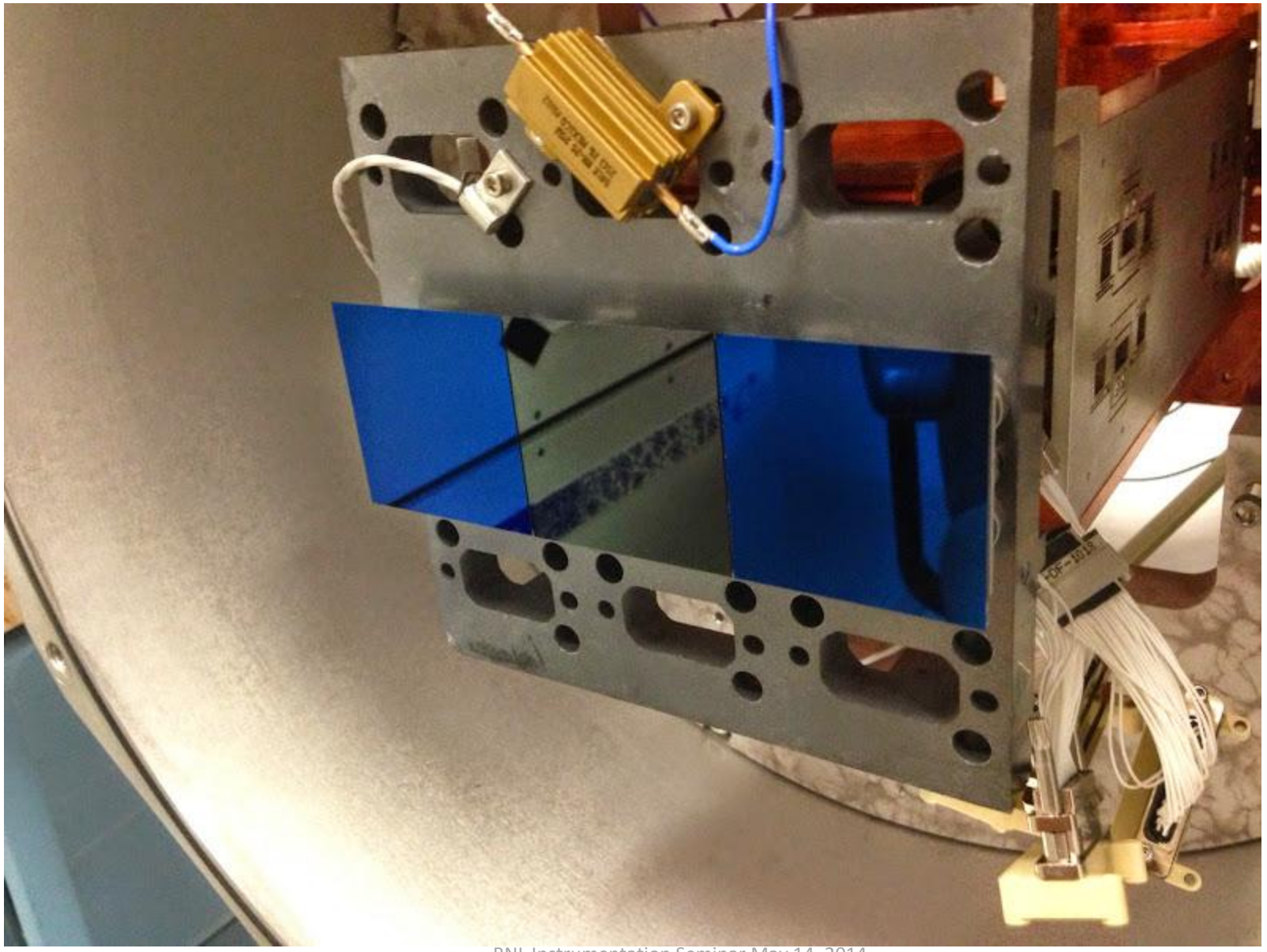
Camera details - internal



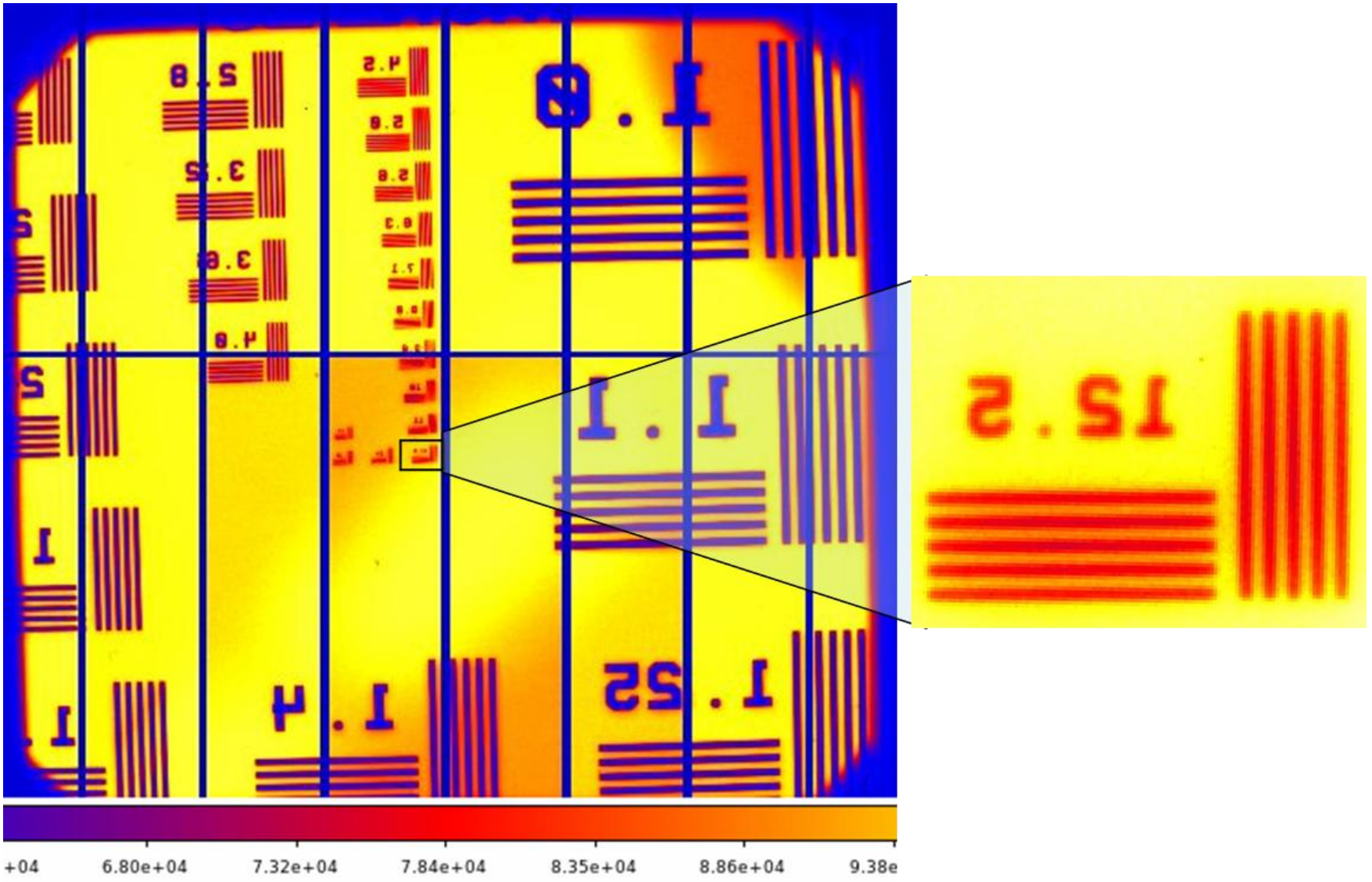


J. Haupt
G. Fraser

3 engineering-grade CCDs installed on SiC baseplate, in cryostat, connected to REB

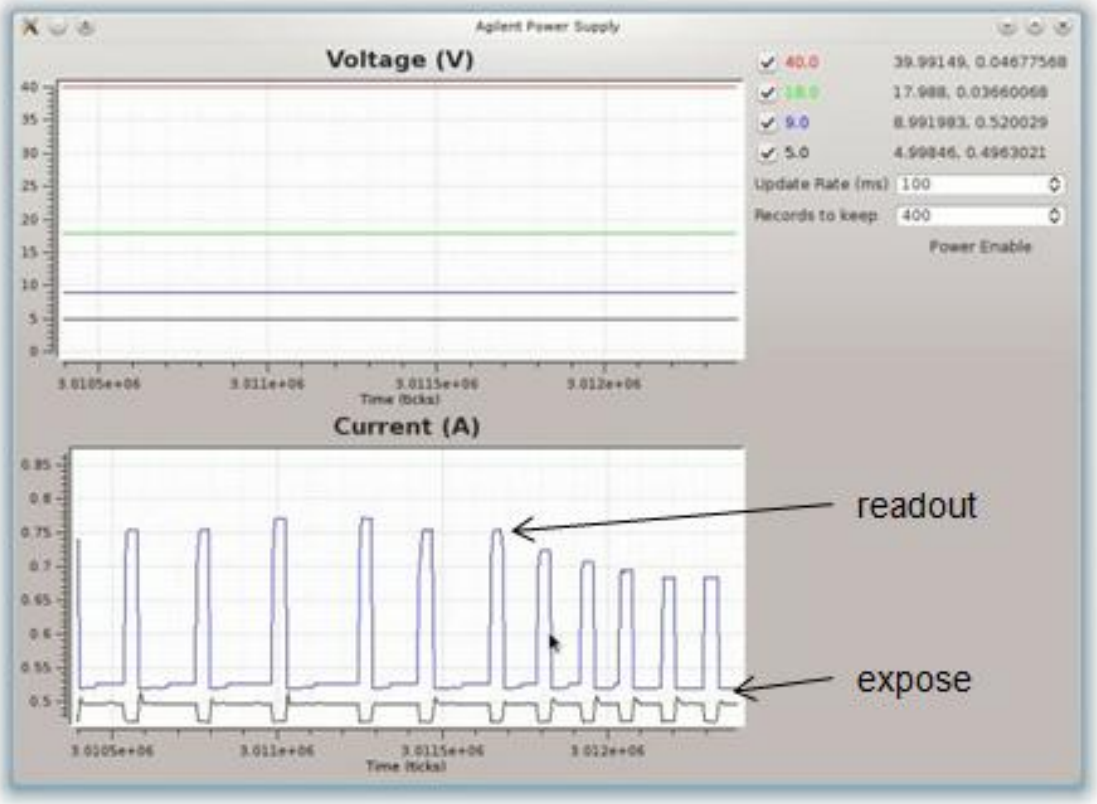


First light



Signal-dependent power consumption

Current vs. time reading flatfields

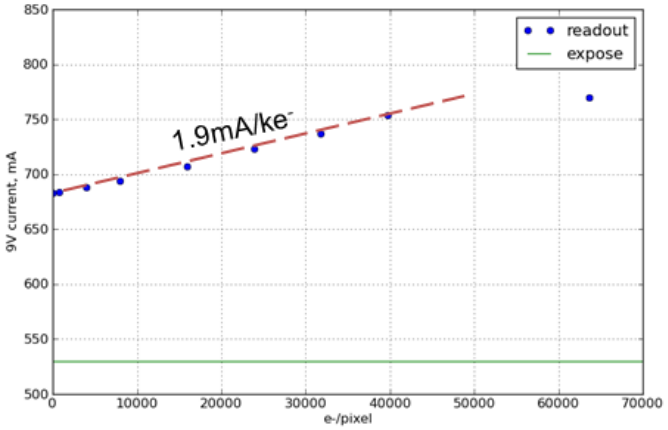


high signal

intermediate

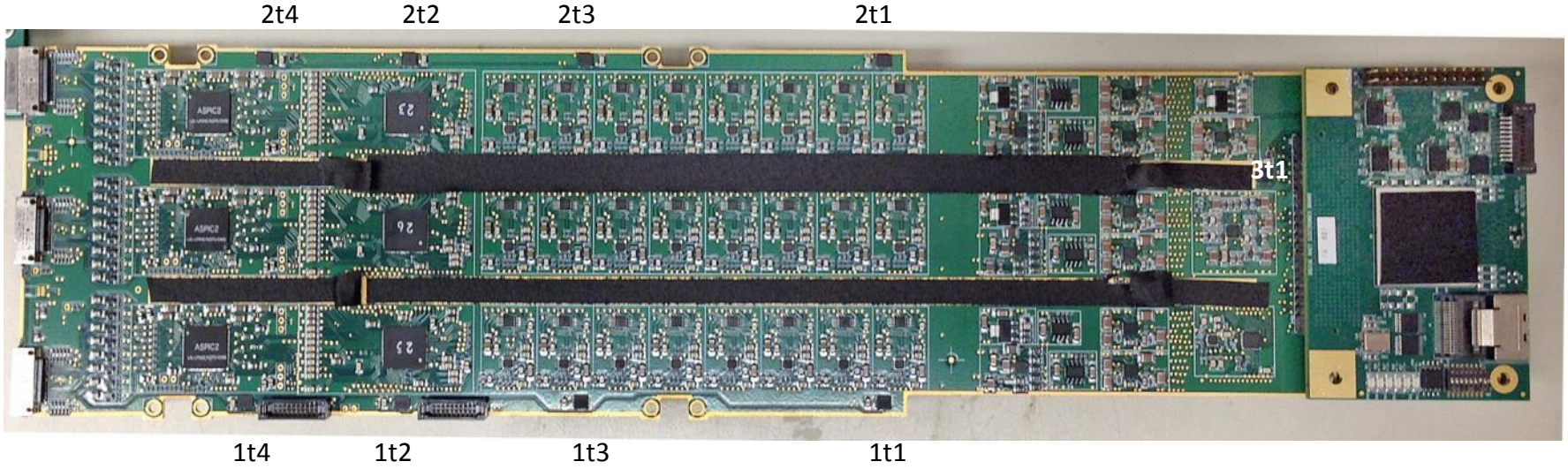
zero signal

J. Kuczewski



REB thermal profile

Location of temperature sensors on REB



Measurements on 1-stripe REB:

	A	B	C	E	G	H	
1		Temperatures			Temperature relative to Cold Plate		
2	Date	3-13 18:43	3-14 15:31		3-13 18:43	3-14 15:31	
3	CP	-20.64	-40		0	0	
4							
5	2t3	-14.69	-34.13		5.95	5.87	
6	2t2	-14.88	-34.32		5.76	5.68	
7	2t1	-13.75	-33		6.89	7	
8	2t4	-15.125	-34.44		5.515	5.56	
9	3t1	-7.438	-26.25		13.202	13.75	
10	1t1	-14.5	-33.19		6.14	6.81	
11	1t2	-15.19	-33.81		5.45	6.19	
12	1t3	-27.13	-42.81		-6.49	-2.81	bad?
13	1t4	-17.5	-35.56		3.14	4.44	
16							

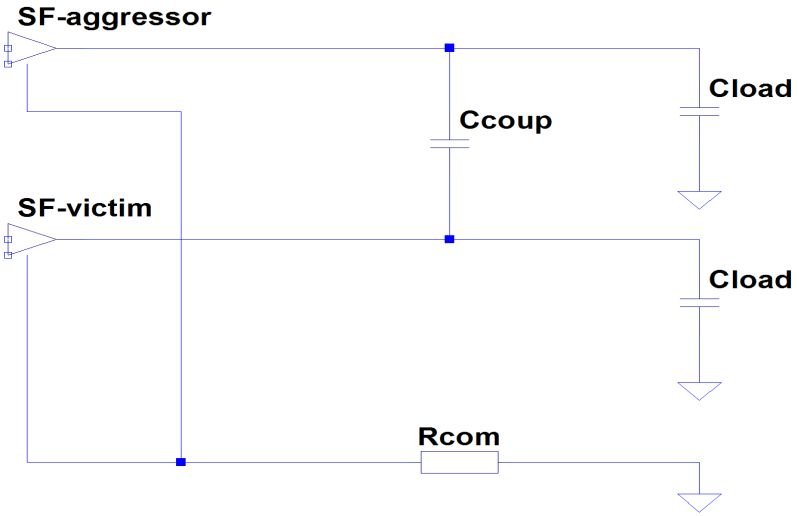
- *Video components within 4°C*
- *Back end of board 7°C warmer*
- *REB temperatures move with cold plate*
- *Thermal transients under study*

Summary

- LSST project is entering the construction phase after ~ 10 years of R&D
- BNL is responsible for delivering the critical components of the camera focal plane
- R&D investigations on thick, fully depleted CCDs link sensor behavior to science
- A flexible platform for system integration tests has been developed at BNL and is the prototype for production acceptance tests and the LSST commissioning camera

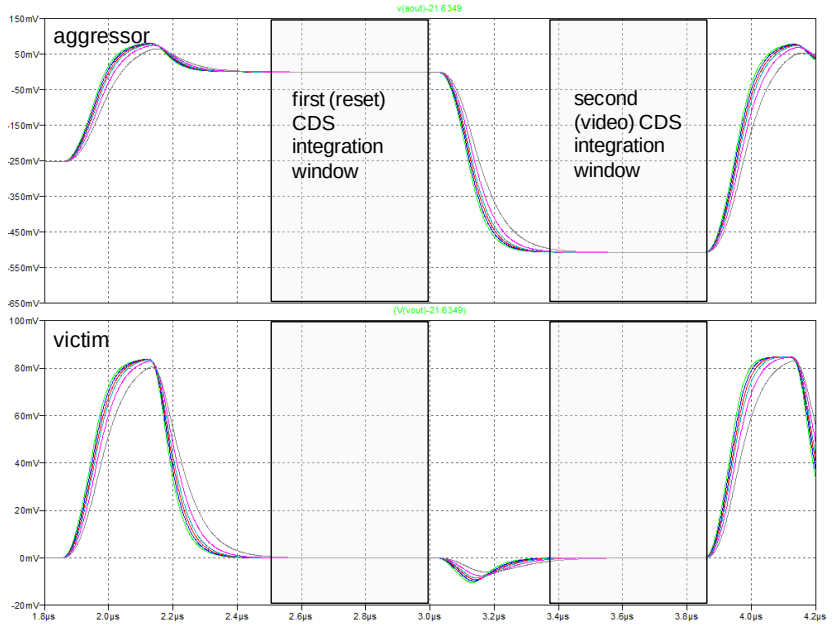
BACKUP

Simplified circuit model

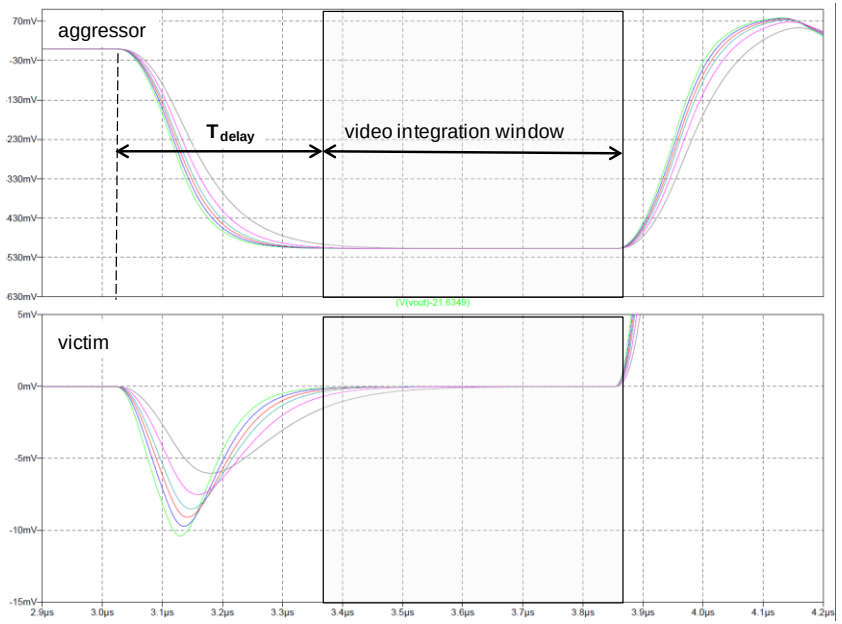


C_{coup} = 2.8pF
C_{load} = 5, 10, 15, 20, 30, 50 pF

(a)

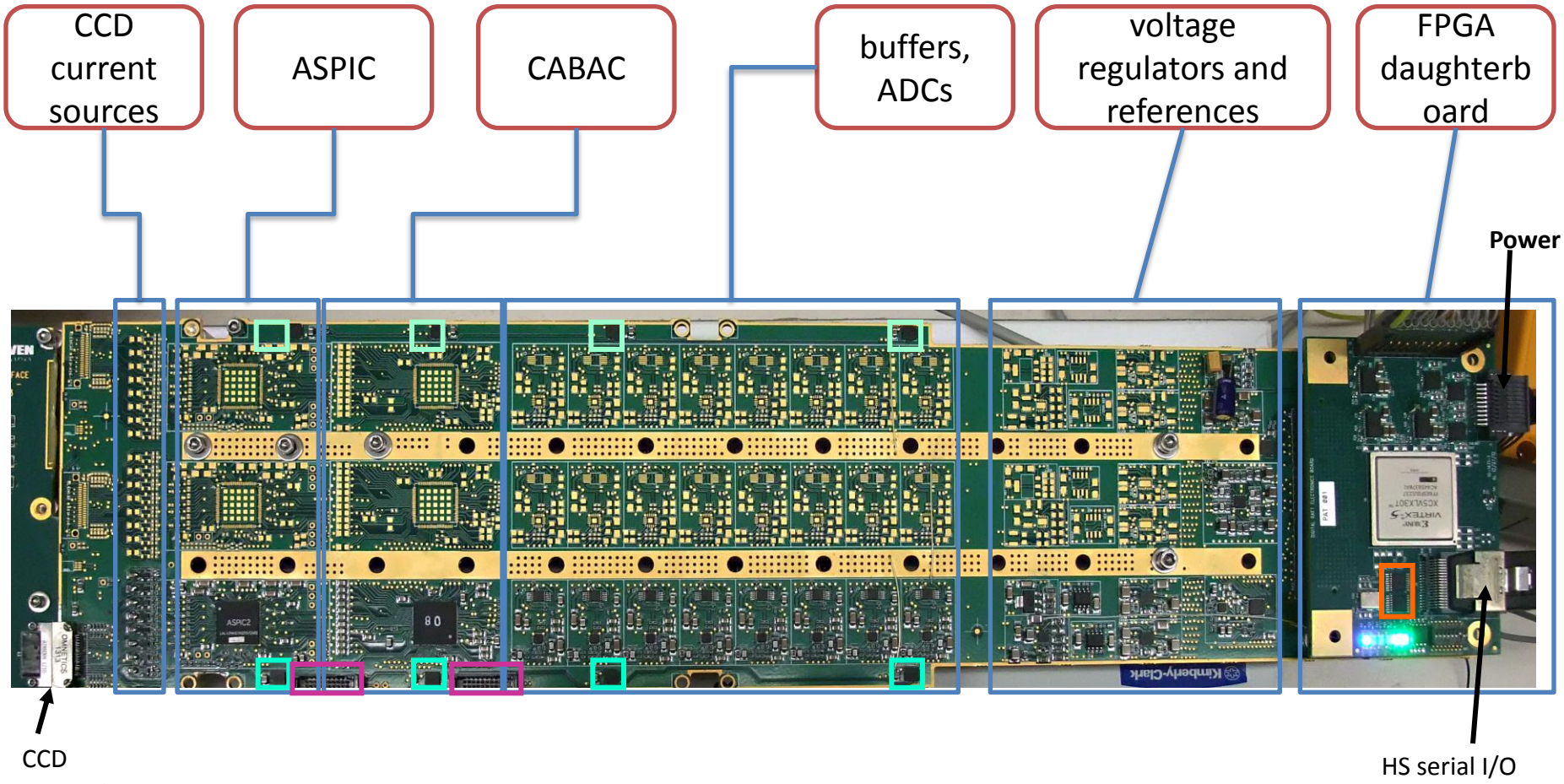


(b)

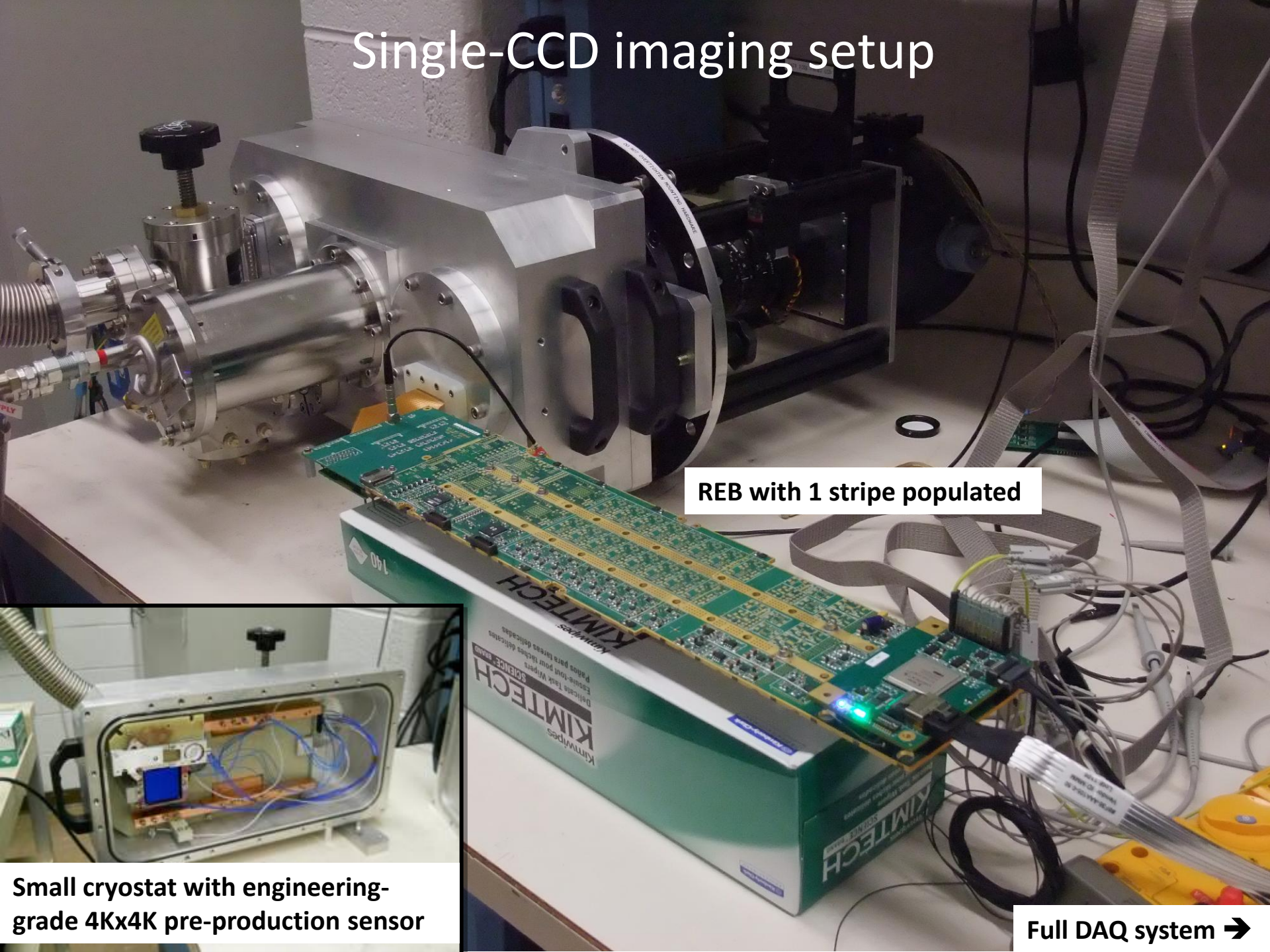


raft electronics board (REB)

STRIPE 1 POPULATED



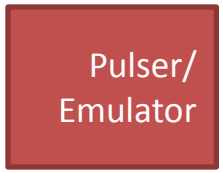
Single-CCD imaging setup

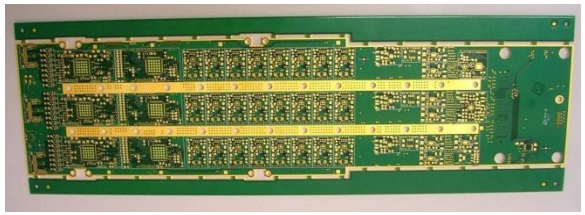


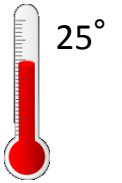
Small cryostat with engineering-grade 4Kx4K pre-production sensor

Next steps

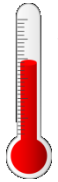
1 REB only

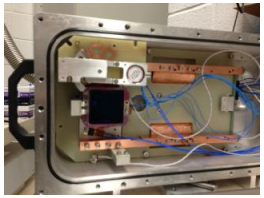


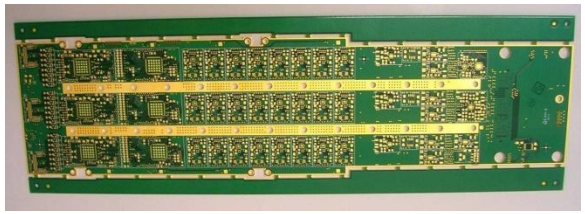




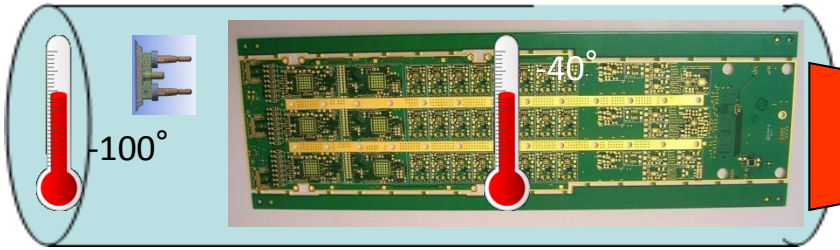
1 REB warm +
1 CCD



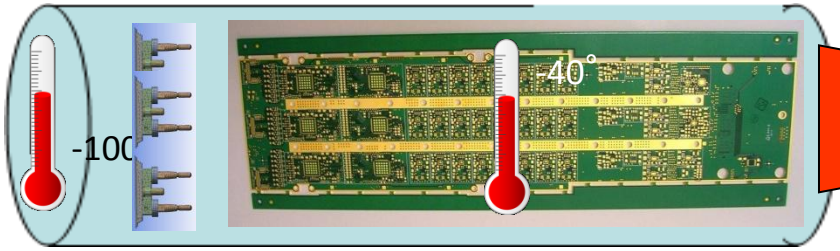




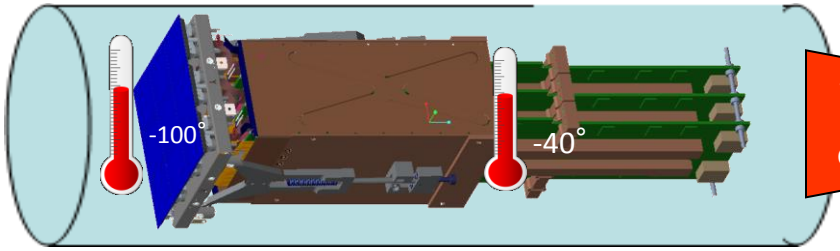
1 REB + 1 CCD in
cryostat



1 REB + 3 CCDs in
cryostat

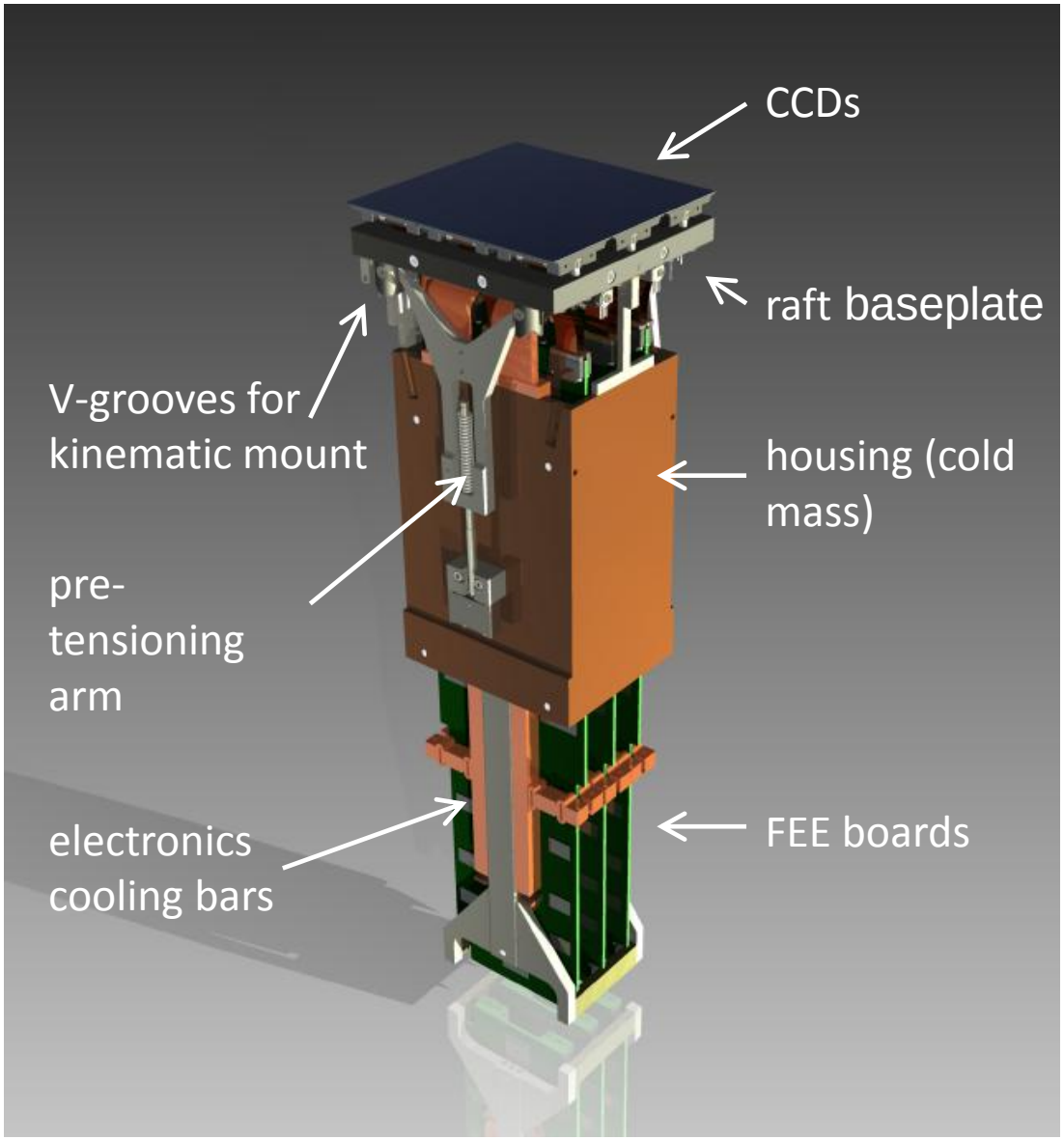


Full RTM: 9 CCDs, 3
REBs



TCM

Raft Tower Module



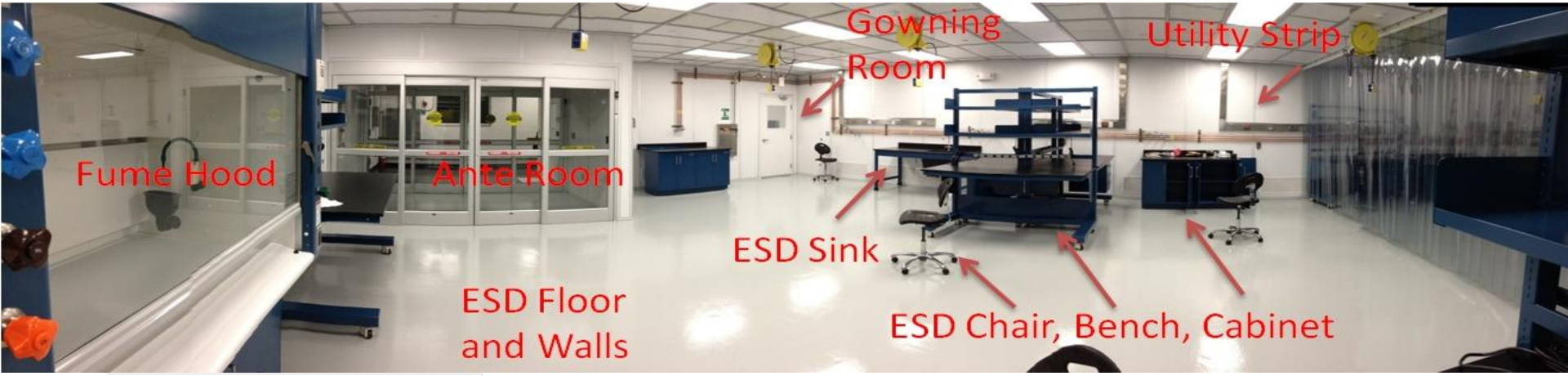
- Complete 144-Mpixel imager
- Support sensors mechanically to meet strict coplanarity and piston tolerances
- Thermal management of sensors and electronics
- Protect sensor surfaces from condensable contamination
- Provide bias, timing, and control signals for CCD operation
- Low noise analog signal processing
- Digitizing, multiplexing of pixel data
- Diagnostics and slow controls

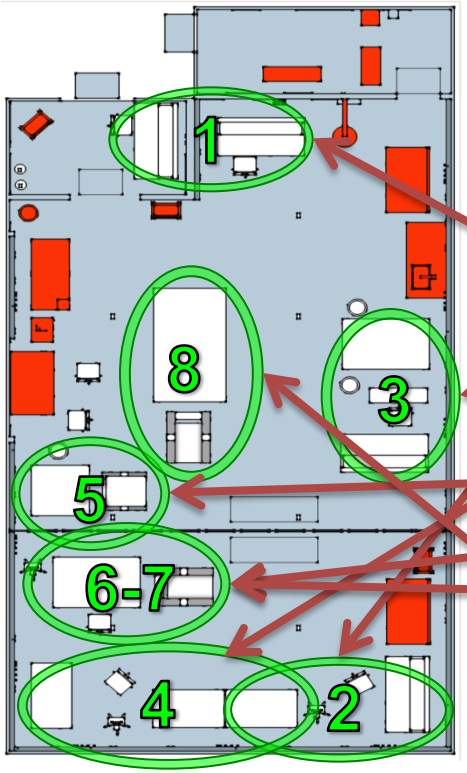
Optimized for

— *Compactness*

— *Low power*

System Description (2): Cleanroom, assembly and testing support



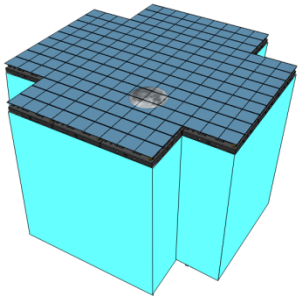


TS1 - Receiving & Inspection
TS2 - Initial Metrology
TS3 - Sensor EO Characterization
TS4 - Sensor Out of Jig Metrology/RSA Integration
TS5 - RSA/Science Raft Warm/Cold Metrology
TS6 - Science Raft Assembly
TS7 - Science Raft Dewar Integration
TS8 - Science Raft EO Testing

P. O'Connor – LSST integrated readout: design

The problem

- Electronics to ***control CCDs*** and ***process an aggregate of 1.5Gpixels/s*** must fit into 1/6m³ behind the focal plane
- Inclusive of thermal and mechanical FPA support
- ***Everything in cryostat***



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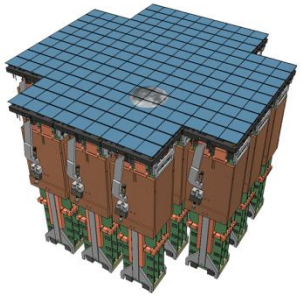
The solution

- A modular system of 21 "raft towers".
- Each is an autonomous, fully-testable 12K x 12K imager.
- Roughly the same size and power envelope as a 16-channel SDSU controller.
- Keys to compactness and low power:
  - *Shortest possible CCD-electronics interconnect length*
  - *Analog CDS*
  - *ASIC-based clock, bias, and video processing*



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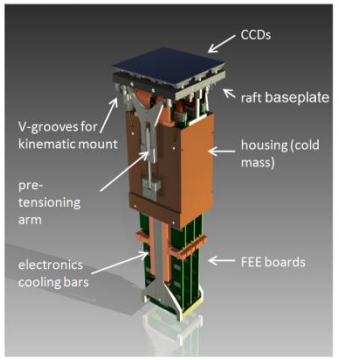
Raft Tower Module



- Complete 144-Mpixel imager
- Support sensors mechanically to meet strict coplanarity and piston tolerances
- Thermal management of sensors and electronics
- Protect sensor surfaces from condensable contamination
- Provide bias, timing, and control signals for CCD operation
- Low noise analog signal processing
- Digitizing, multiplexing of pixel data
- Diagnostics and slow controls

Optimized for
- *Compactness*
- *Low power*

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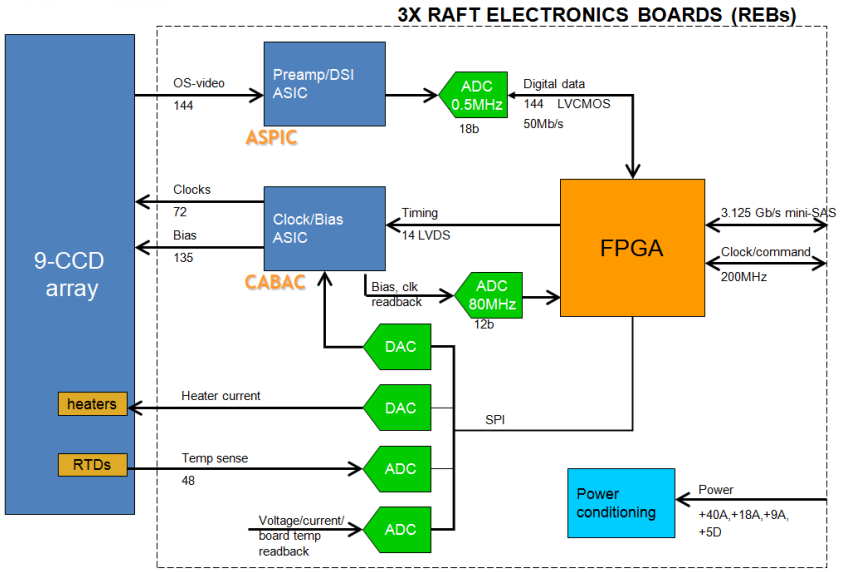
Raft tower electronics



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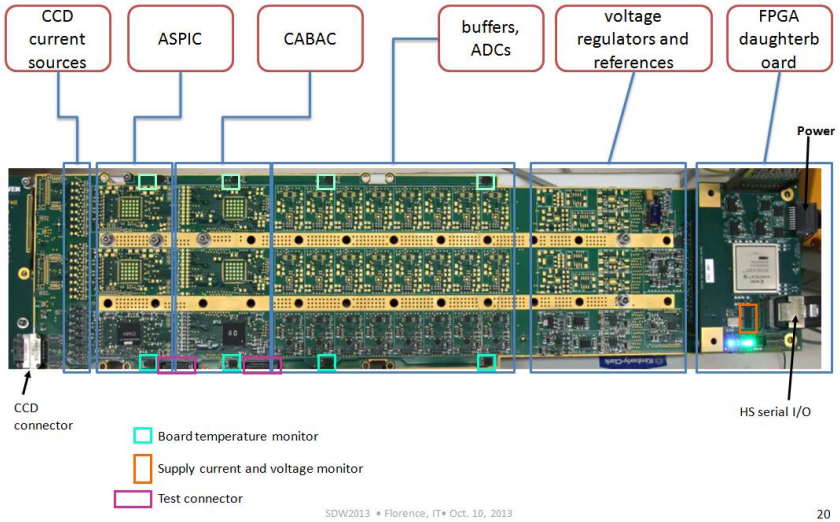
Raft electronics key requirements

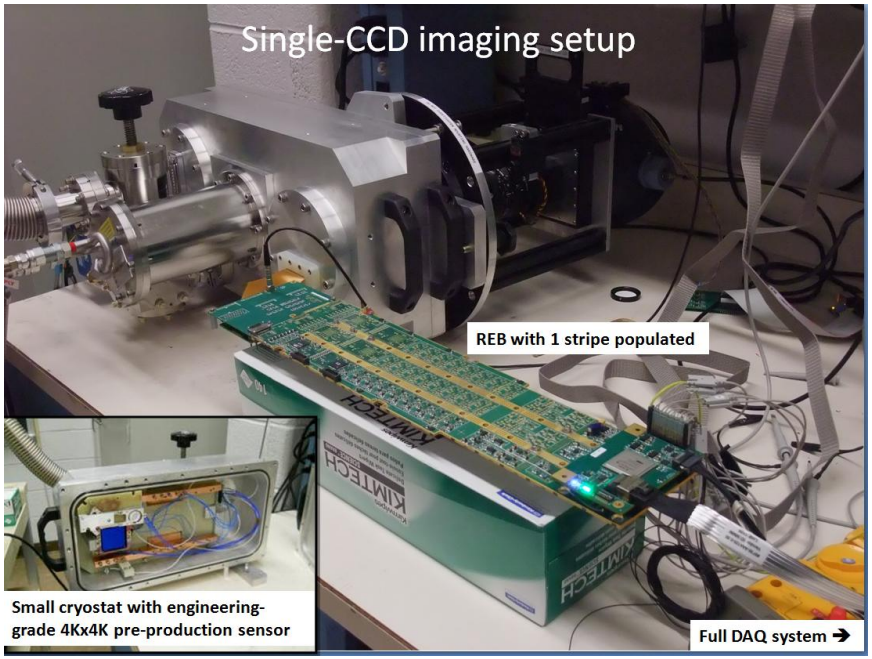
CCD bias	Provide programmable voltages for all CCD biases, except back depletion voltage
CCD clocking	Provide switches and programmable rail voltages/slew rate for all CCD clocks
Sequencer	Timing generator for CCD clocks, CDS switches, ADCs. ***Independent state machines for each CCD.***
Video processing	CDS by dual slope integration for 48 video channels Pixel rate ***545kpix/s*** ***Noise <9e-*** ***Crosstalk <0.2%*** Nonlinearity < 2%, 1 – 90ke- Max signal 175ke-
Data acquisition	***18b sampling***, 48 channels @545kpix/s Serialize with ECC. No frame buffer on REB 3.125Gbps Cu link to optical TX/RX
Slow controls and monitoring	Configure ASICs Monitor board and CCD temperatures, P/S current and voltage Read serial ID chip CCD protection
Special diagnostic port	Read back CCD bias voltages 80MSa/s ADC to monitor CCD clocks via mux on CABAC
Environmental	Vacuum operation; -40C coldsink.; low outgassing; ***power ≤ 350mW/chan***

P. O'Connor – LSST integrated readout: implementation

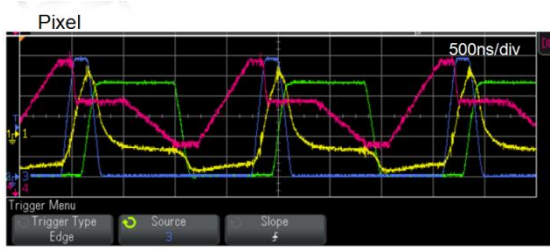
raft electronics board (REB)

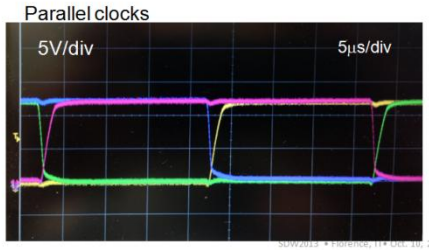
STRIPE 1 POPULATED

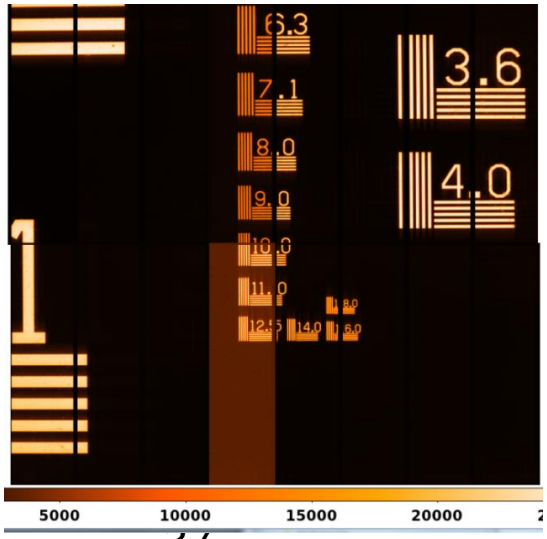




- Each REB serves 3 CCDs of 16 channels each.
- 12 ASICs for video processing, clock and bias generation
- T,V,I monitors
- 18b SAR ADCs (48)
- Virtex5 FPGA
- 3.125Gbps link



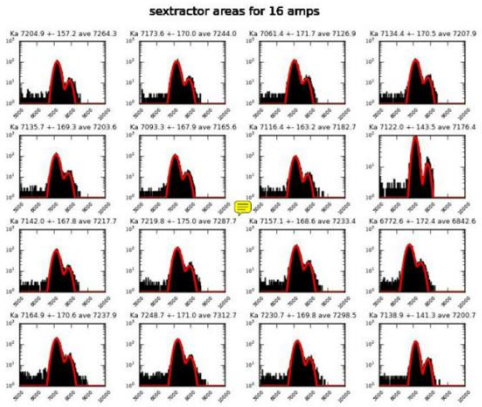




P. O'Connor – LSST integrated readout: results

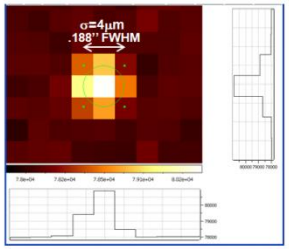
^{55}Fe xrays, -50V substrate bias

Spectra with Kα, Kβ peaks

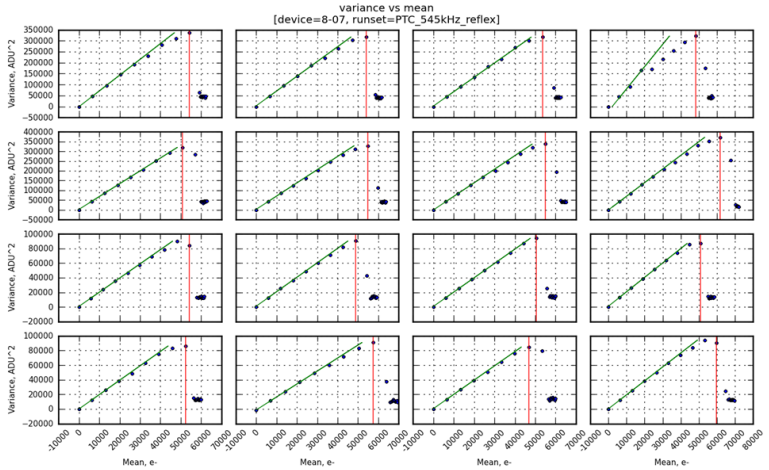


Gain dispersion 1.5%

Single cluster (zoom)



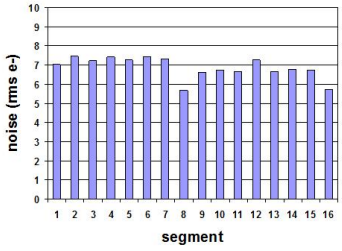
photon transfer



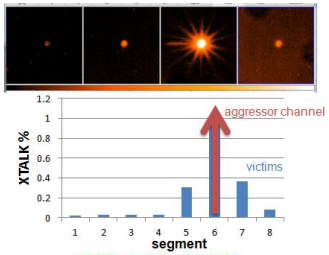
Full well capacity of CCD is ~140ke-; dynamic range of REB1 limited to ~ 60-80ke- withcurrent gain setup

Noise, crosstalk, nonlinearity

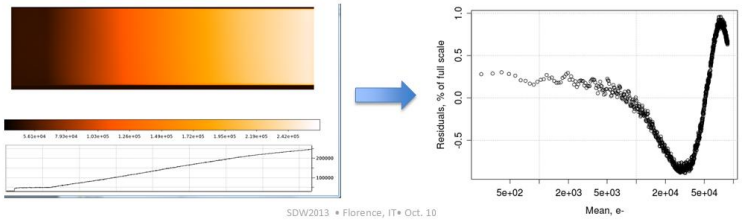
480kpix/s



** REB noise is 1.5 -2.2 e-*

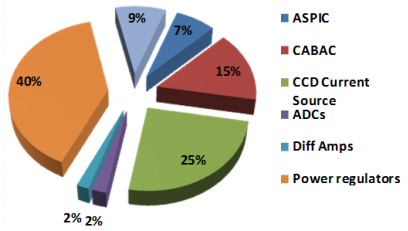


** REB xtalk is ≤ 0.04%*



Electronics power dissipation

Source	Peak power dissipation, W	
	Per REB	Per channel
CCD current source	4.21	.088
Video ASIC	1.20	.025
Clock/bias ASIC	2.52	.053
ADC differential buffer/driver	0.31	.0065
ADC	0.36	.0075
Power Regulators	6.63	.138
Control FPGA	1.50	.031
TOTAL Electronics Power	**16.73**	**0.349**

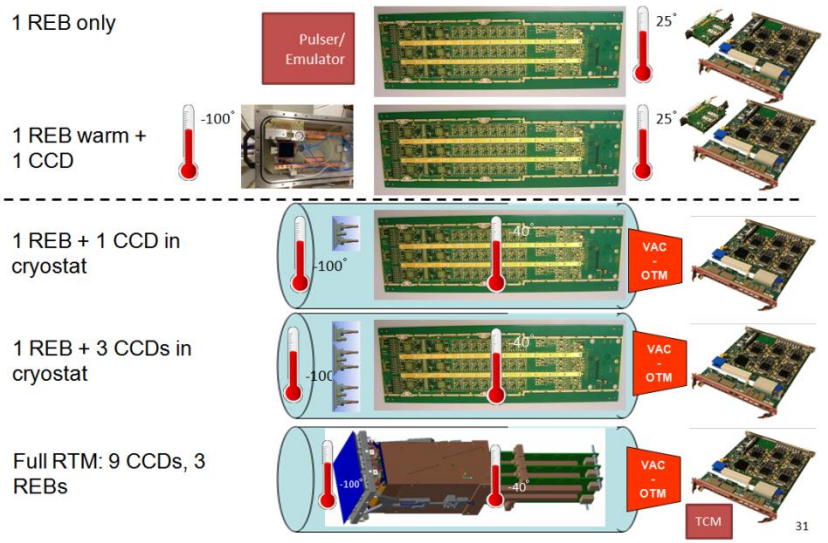


Measured (on single-stripe REB)	
Expose	6.98W
Readout	8.96W

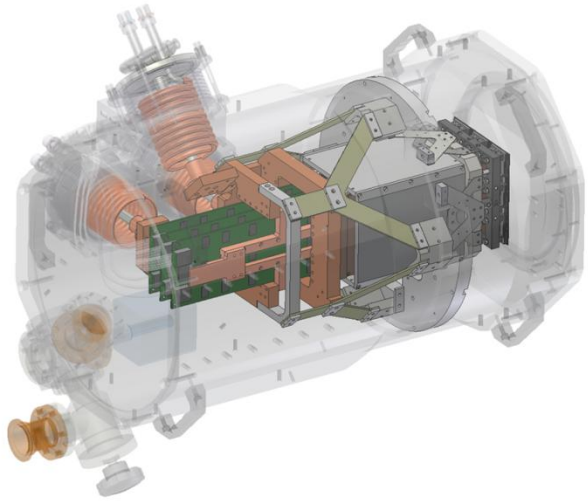
Ave(LSST cadence) ~ 7W
30% power common
≈.35W/chan for fully-populated REB ✓

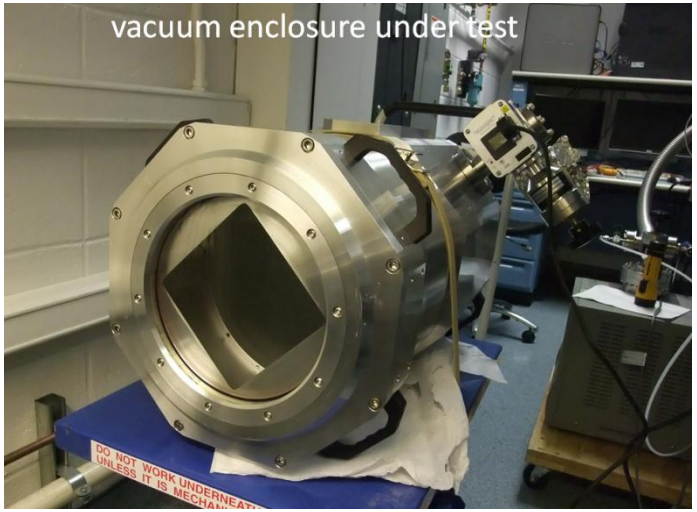
P. O'Connor – LSST integrated readout: plans

Next steps



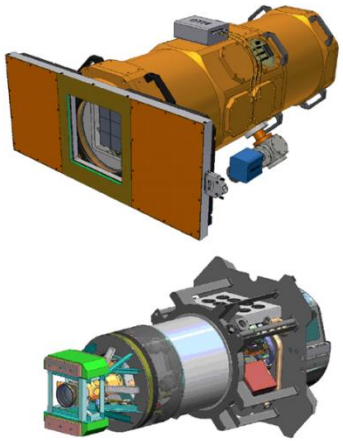
mechanics and thermal



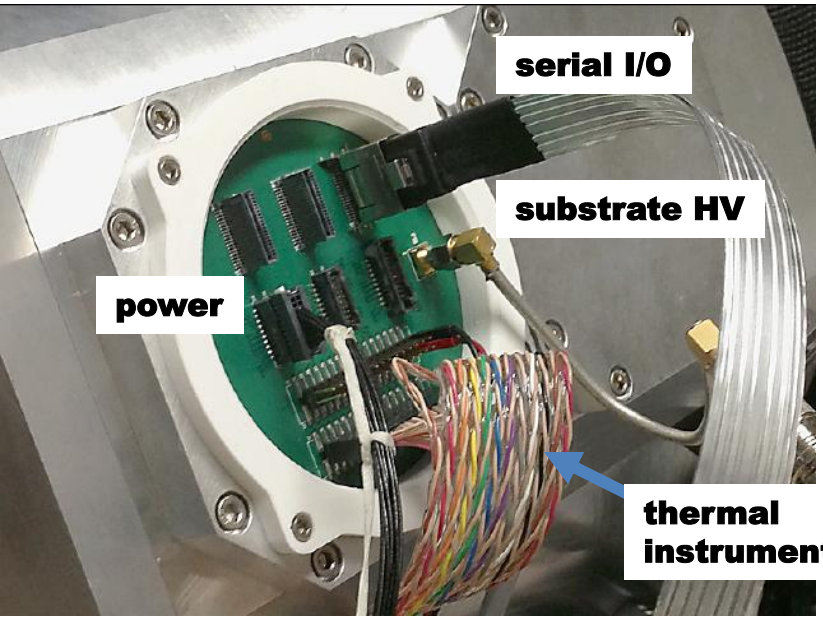


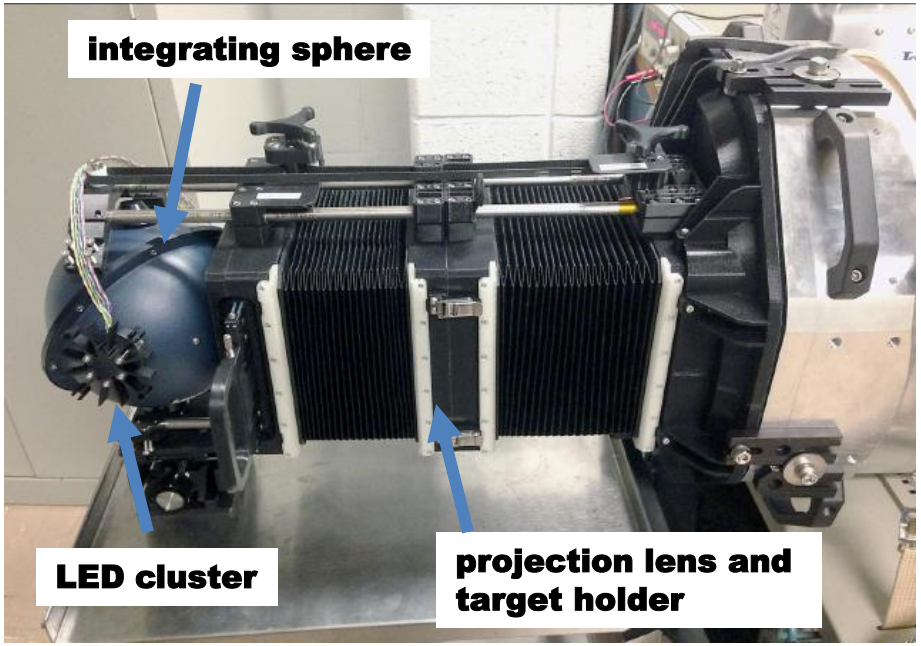
proposed LSST commissioning camera (ComCam)

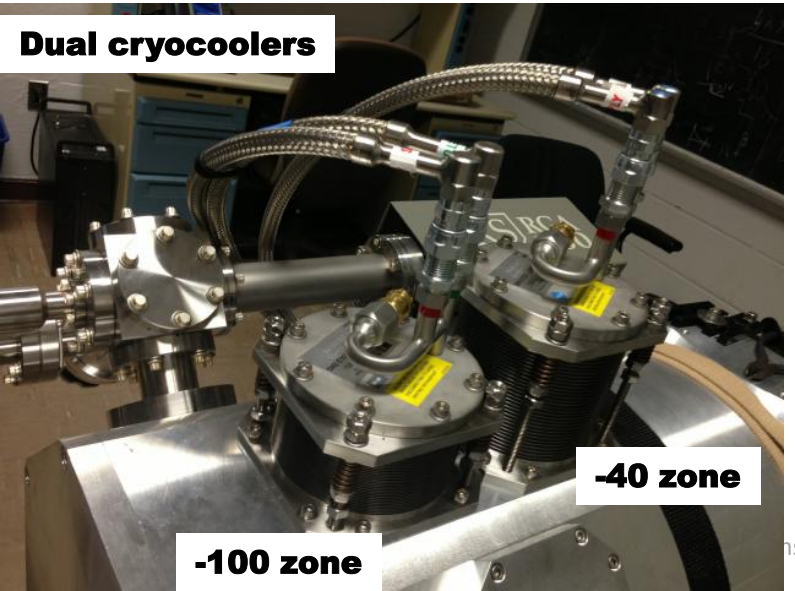
- Raft test cryostat with 9 engineering-grade CCDs, full electronics and DAQ, LN2 cooling, shutter, corrector + filters
- Installed on camera hexapod/rotator at LSST 3-mirror focus prior to full Camera readiness
- 30 arcmin field on-axis
- Early commissioning studies



Camera details - external

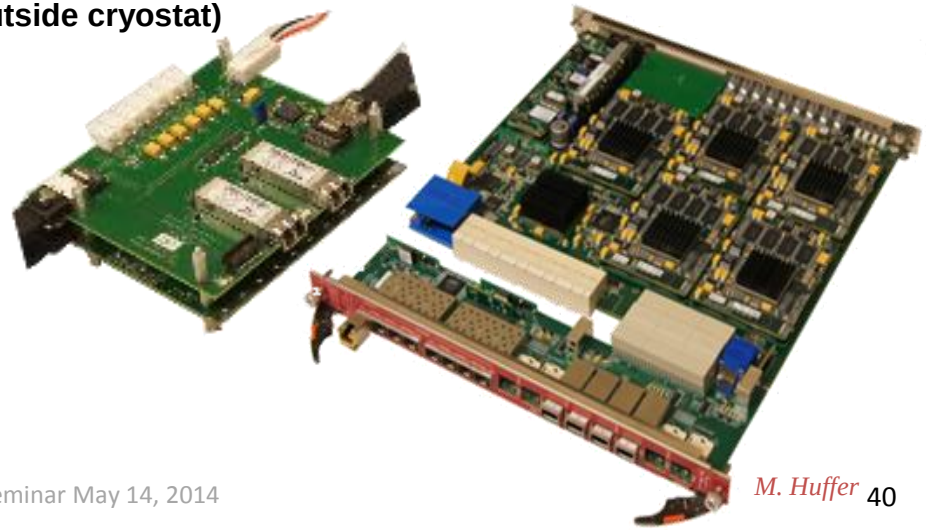






Optical transition module (outside cryostat)

ATCA-based DAQ server



proposed LSST commissioning camera (ComCam)

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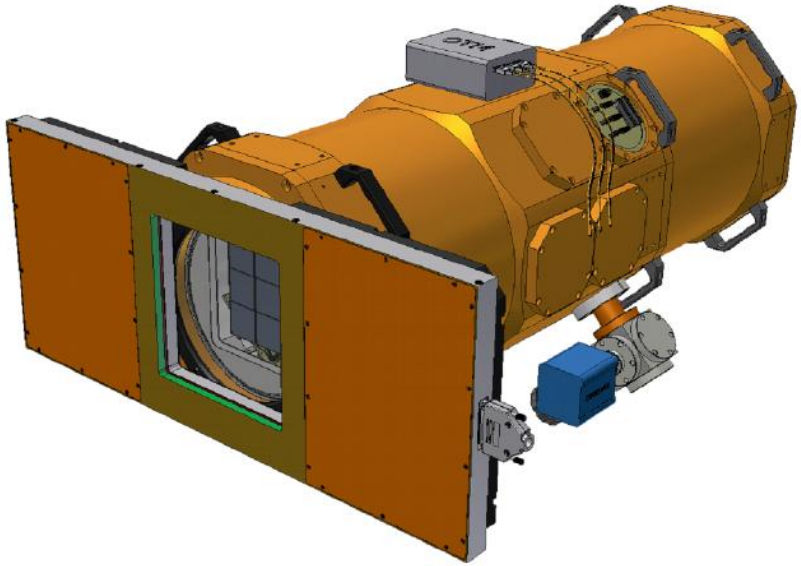
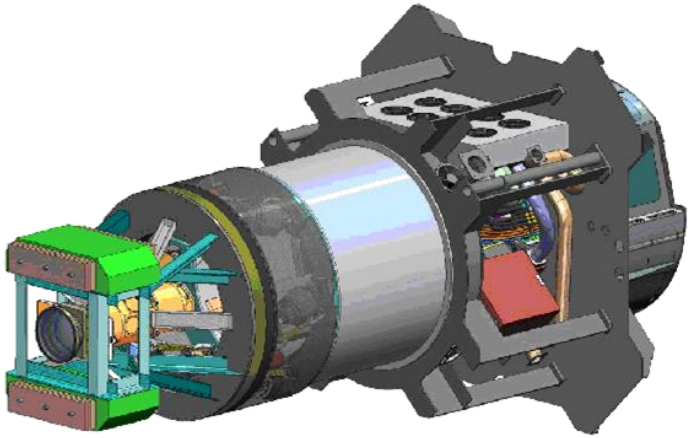
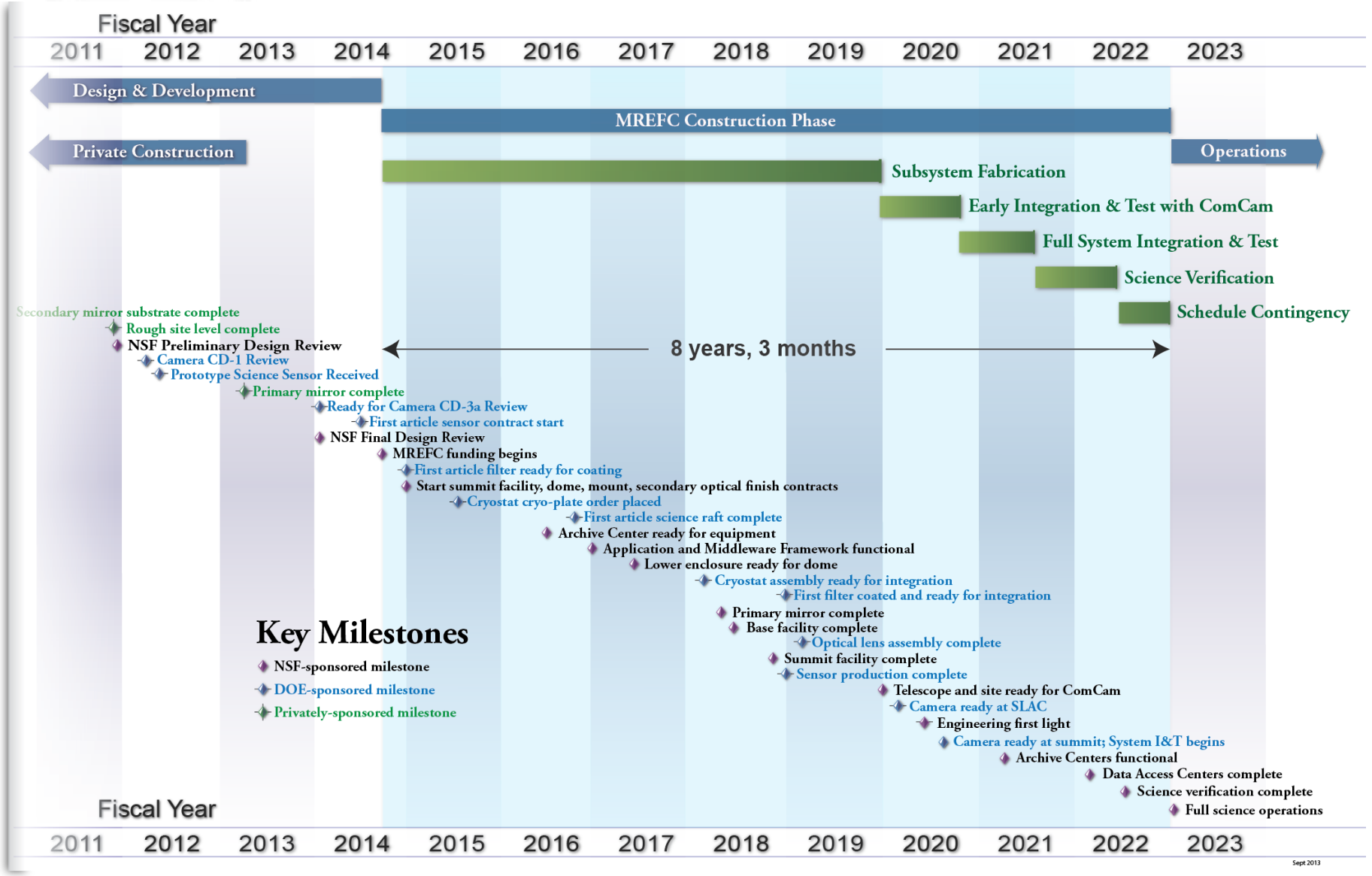
- **Early commissioning studies**

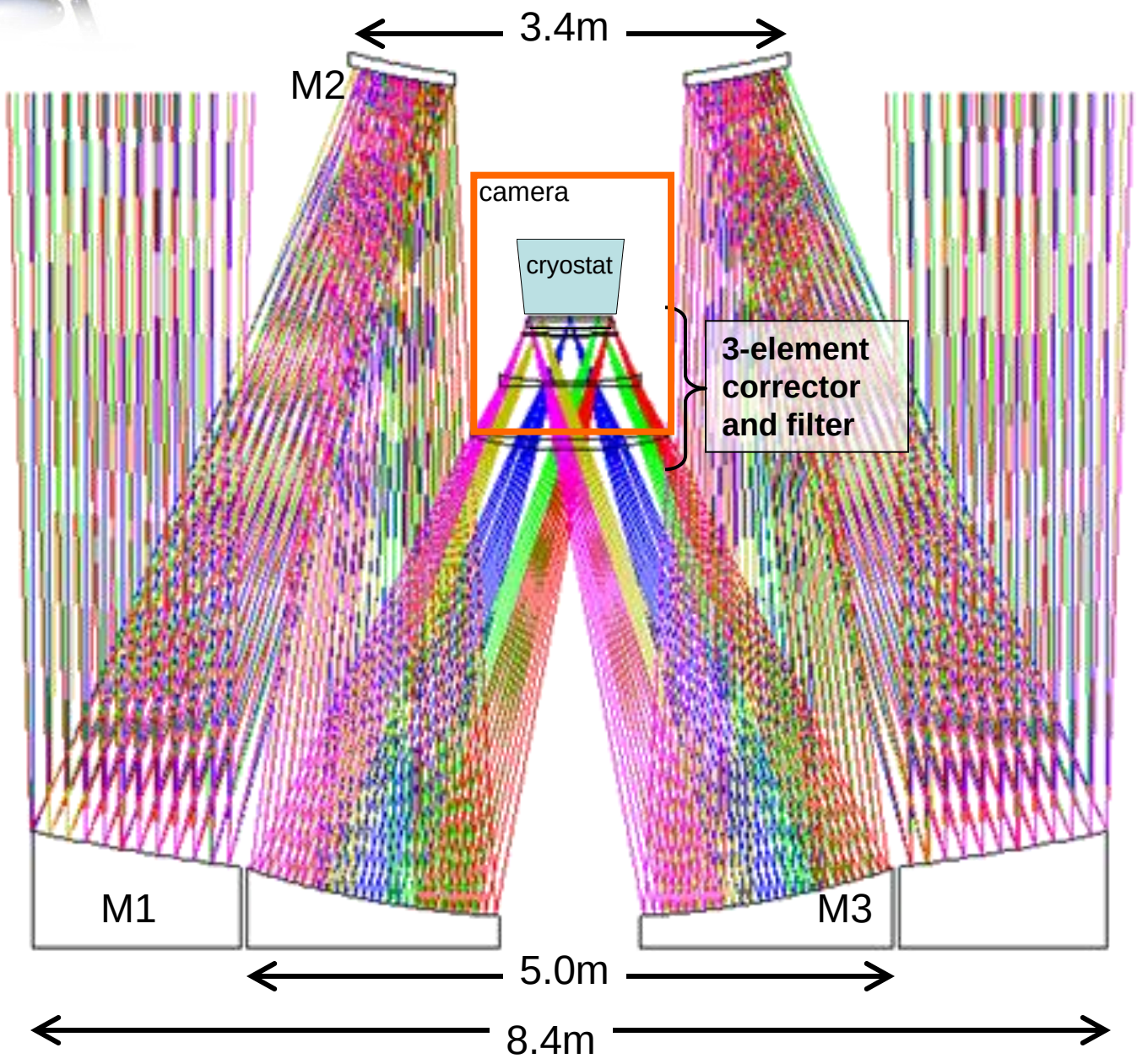




Integrated Project Schedule



Optical configuration



Major actions and approvals at the 436th meeting of the Board included the following (not in priority order):

1. The Board authorized the NSF Deputy Director, at her discretion, to make an award for the construction of the Large Synoptic Survey Telescope (LSST).