Development of a 3.2 Gpixel Camera for the Large Synoptic Survey Telescope (LSST)

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For the LSST Camera Electronics Team

15-Sept-2008

Large Synoptic Survey Telescope

Overview

- Major science drivers
- Critical specifications
- Telescope
- Camera
  - Sensors
  - Readout electronics

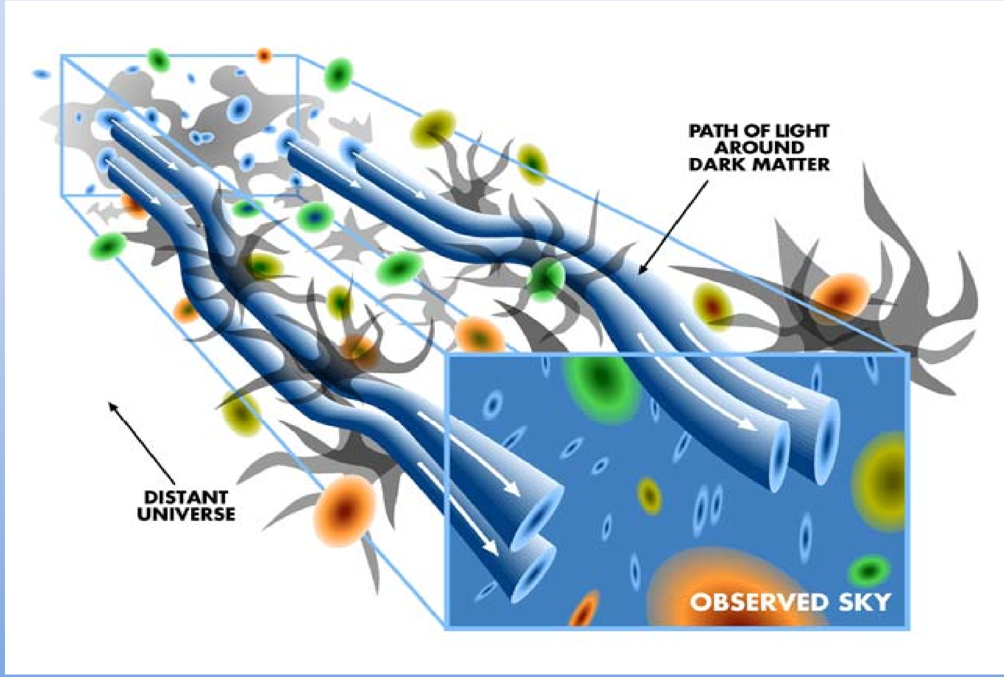
Major Science Drivers

- "Synoptic survey" : Comprehensive & multipurpose
- Survey entire visible sky (20,000 deg^2) in five filter bands (400 nm – 1,000 nm) every 3 nights
  - Dark matter survey → Weak gravitational lensing
  - Dark energy probe → Type 1a supernovae discovery > 10^3/night
- Galactic structure
- Near Earth Objects & Potentially Hazardous Asteroids
- Transient phenomena

Dark Matter Survey

- Weak lensing-

Apparent rotation of elipticities of faint galaxies
→ Cosmic Shear

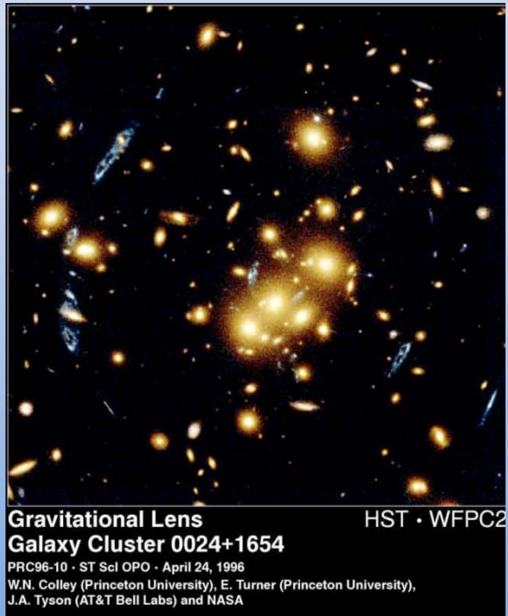


T. Tyson

Dark Matter Survey

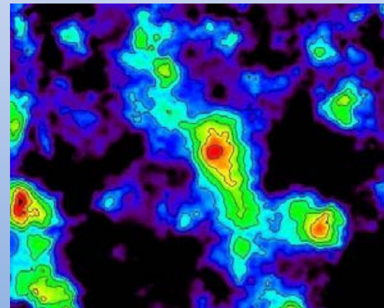
- Weak lensing -

Strongly lensed galaxy



- Weak lensing -
Measurements of elipticity correlations of large numbers of faint galaxies
→ "cosmic shear"

Tomographic reconstruction of dark matter density from shear data



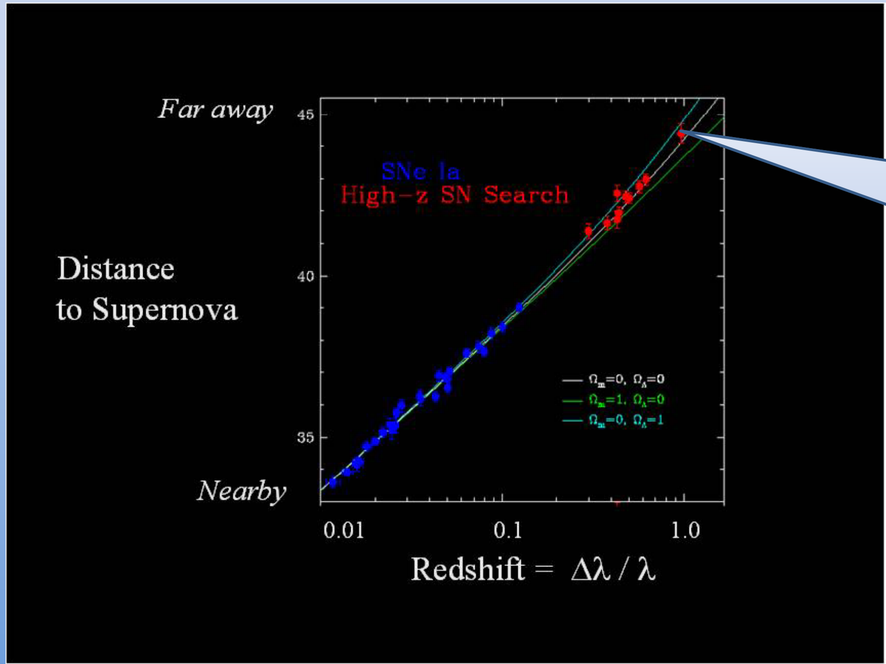
T. Tyson

http://www.nsf.gov/od/lpa/news/press/00/pr0029.htm

Dark Energy Measurement

- Type 1A Supernovae -

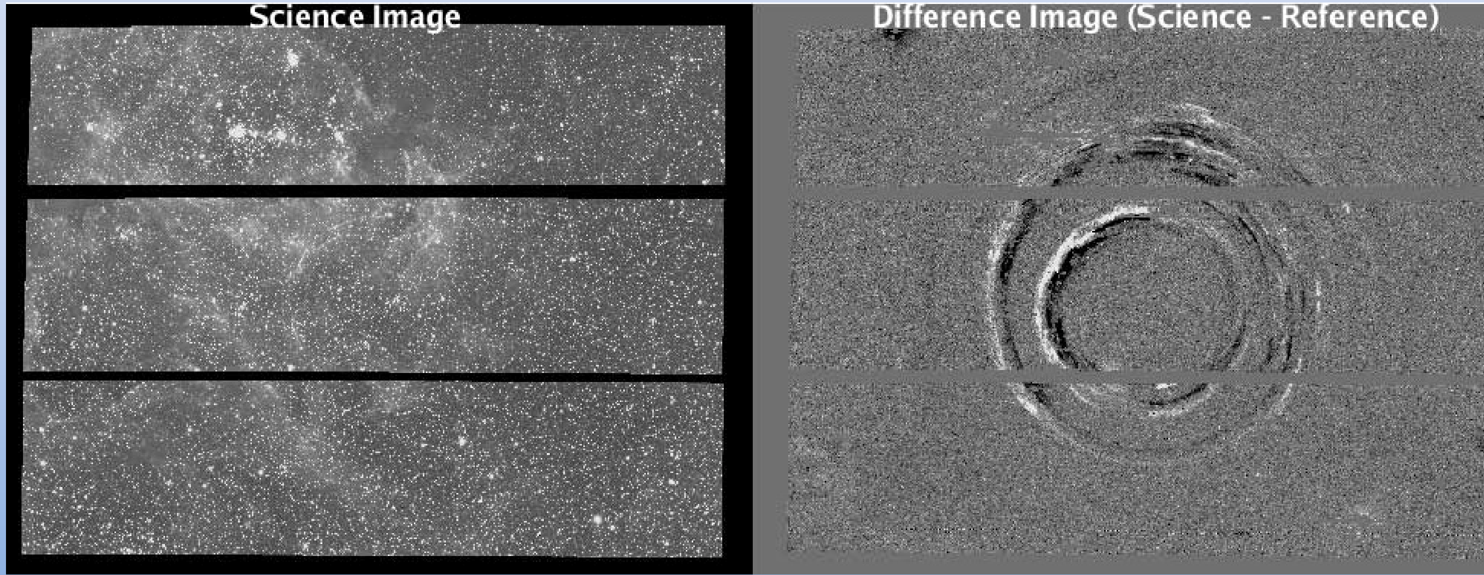
- High statistics measurements of Type 1A SN → > 10^3 per observing night
- Redshift & distance measurement
  - Fixed luminosity (standard candle) → distance
  - *Photometric* redshift measurements in five filter bands to Z = 1.2



Deviations from linearity
→ Acceleration
→ Dark Energy
→ Cosmological constant

- Transient phenomena -

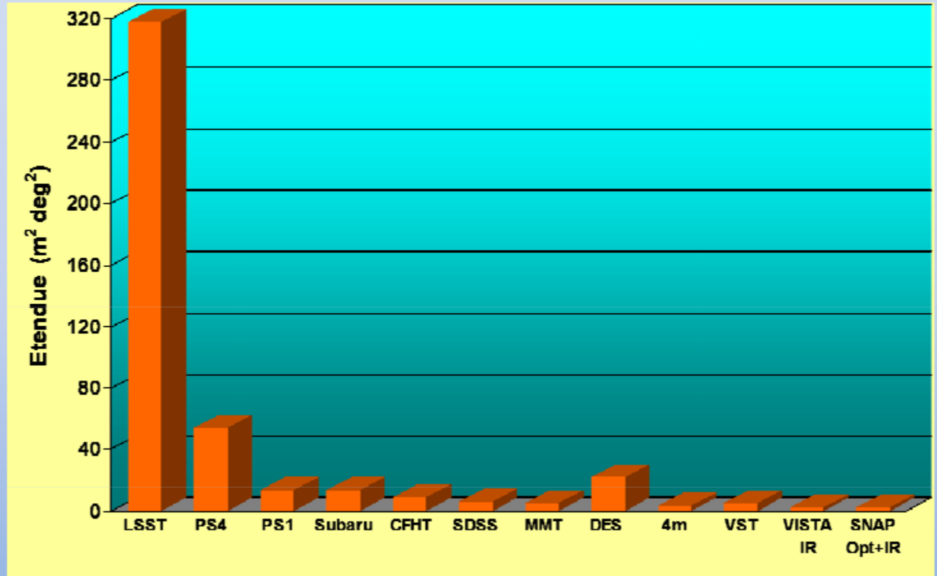
Differential images of SN 1987A



A. Becker, U. Washington (SDSS)

Critical Specifications
- Telescope -

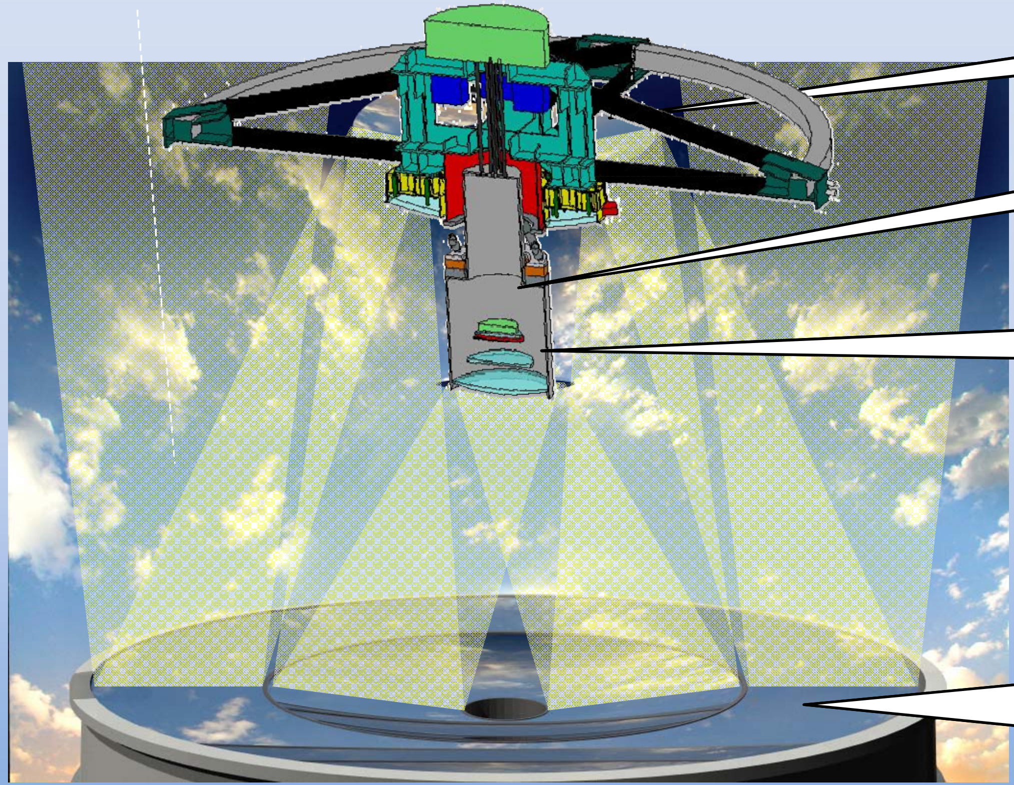
- Survey telescope figure of merit “Etendue” {$(Dia)^2$ x (FoV solid angle) }



- Large aperture ~ 8.4 m, (6.7 m equivalent clear aperture)
- Large FoV ~ 3.5 deg
- Large focal plane ~ 64 cm diameter
- LSST Etendue ~ 320 $(deg^2)(m^2)$
- High “throughput”

Large Synoptic Survey Telescope

Optics



[*] Corrects gravitational sag due to mirror inclination

Large Synoptic Survey Telescope

Spin casting at the Steward Mirror Lab U. Arizona

Lid is lifted from the primary/tertiary mirror blank 23-July-08
Made possible by grant from Bill Gates, Charles Simonyi – Microsoft Corp.

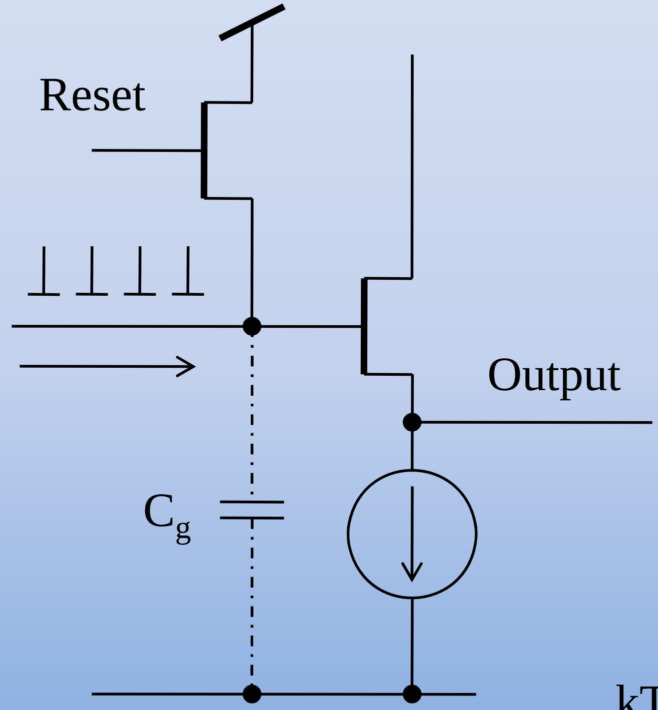
LSST Large Synoptic Survey Telescope

Critical Specifications
- Camera & Sensors-

- Image sensors
  - Large focal plane → ~ 64 cm dia
  - ~ 200x 16-Mpixel CCD image sensors, 10µ pixels (0.2”) → 3.2 Gpixels
  - Back side illuminated
  - Small “Point spread function” – PSF (minimum spot size) < 7.5 µ (10 µ max)
  - Low f-number = 1.2 → must be flat to 10µ (peak-valley) across focal plane
  - High quantum efficiency 400 nm – 1,000 nm (40%, 80%, 40%)
  - Low leakage < ~ 1 e/s per pixel → T~ -100 C
  - High “full well” capacity ~ 100,000 e/pixel
- Back-to-back 15 second exposures on each piece of sky →Cosmic ray rejection
- 2 second readout → low dead time, high throughput
- Sky shot noise limited images → CCD *read noise* ~ 5 e rms
- Focal plane contained in a *contamination free* evacuated cryostat to prevent fogging of sensor surfaces

Note: Last three requirements highly constrain the readout topology

Critical Specifications
- Implications for readout & sensors -



CCD output “amplifier”

Typical sensitivity S = 5 μV/e
→ Cg ~ 32 ff

Dominant noise source → “kTC noise”

$$\sigma_{kTC} = \sqrt{k \cdot T \cdot C_g} \rightarrow \sqrt{\frac{V_T}{S}} \approx 50e\ (cold)$$

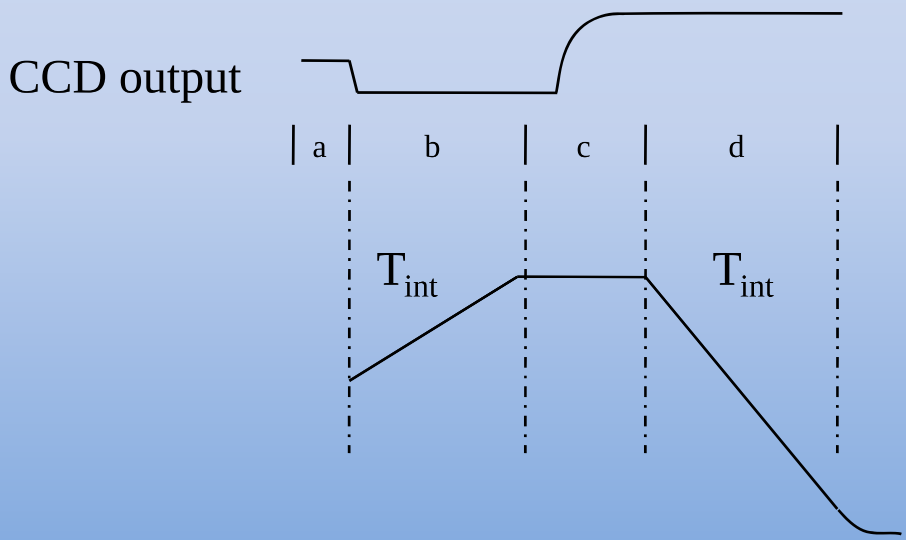
kTC noise easily removed by

- Correlated Double Sampling (Clamp & Sample)
- Dual Slope Integration (optimal)

Dual Slope Integration sequence

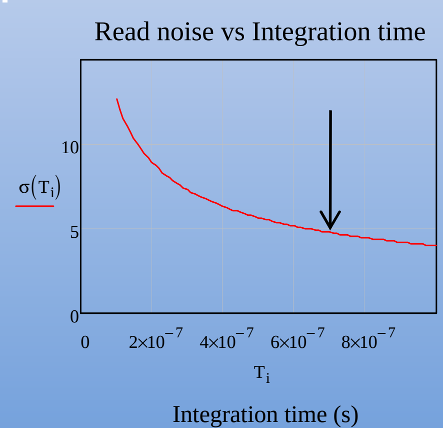
a) Reset
b) Integrate baseline up
c) Move charge to output fet
d) Integrate signal down

$$\sigma = \frac{e_n}{S} \cdot \frac{1}{\sqrt{T_{\mathrm{int}}}}$$



For typical “science grade” CCD

$$e_n \approx 10 \; to \; 20 \frac{nV}{\sqrt{Hz}}$$



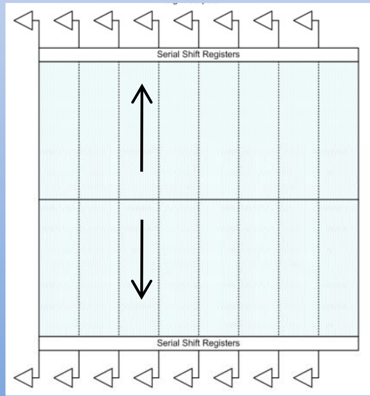
→ T_{read} > ~ 2 µs/pixel

Critical Specifications

- Implications for Sensors -

• At $f_{pixel\text{-}read}$ = 500 kpixels/sec → 32 sec Read Time (with one output amplifier)

→*Each CCD must have 16 parallel outputs & electronic readout channels*
→ *~200 sensors* →*3,200 parallel readout channels*



• 16x segments, gap-less
• ½ k x 2k each
• ~ 40 mm x 40 mm

Critical Specifications
- Implications for Sensor Thickness -

Conflicting requirements →

- Small PSF
  - Blue light has very *small* absorption length

    →favors *thin* sensor to minimize diffusion

    →favors *full depletion* in *high resistivity silicon*

- High QE in red
  - Red light has very *long* absorption length
  - *Thin* sensor would be transparent in red & near IR → favors thick sensor

- Optimization : "Study of Silicon Sensor Thickness Optimization for LSST" [1]
  - Calculations
  - Simulations

[1] http://www.inst.bnl.gov/~poc/LSST/Study%20of%20sensor%20thickness.doc

LSST Sensor Working Group D. Figer, J. Geary, K. Gilmore, S. Marshall, **P. O'Connor**, J. Oliver, **V. Radeka**, C. Stubbs, **P. Takacs**, T. Tyson

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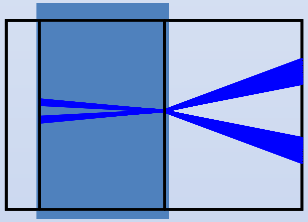
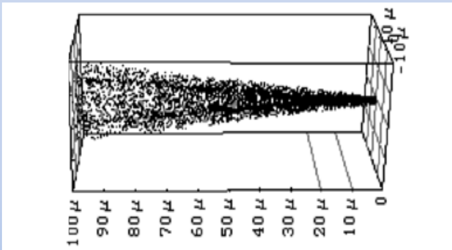
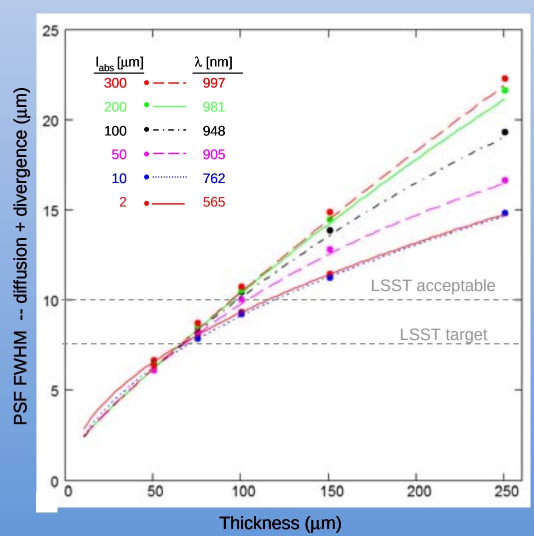
Effect of sensor thickness on PSF



Beam divergence : f1.2 beam →46 deg max



Beam divergence in red, (simulation)

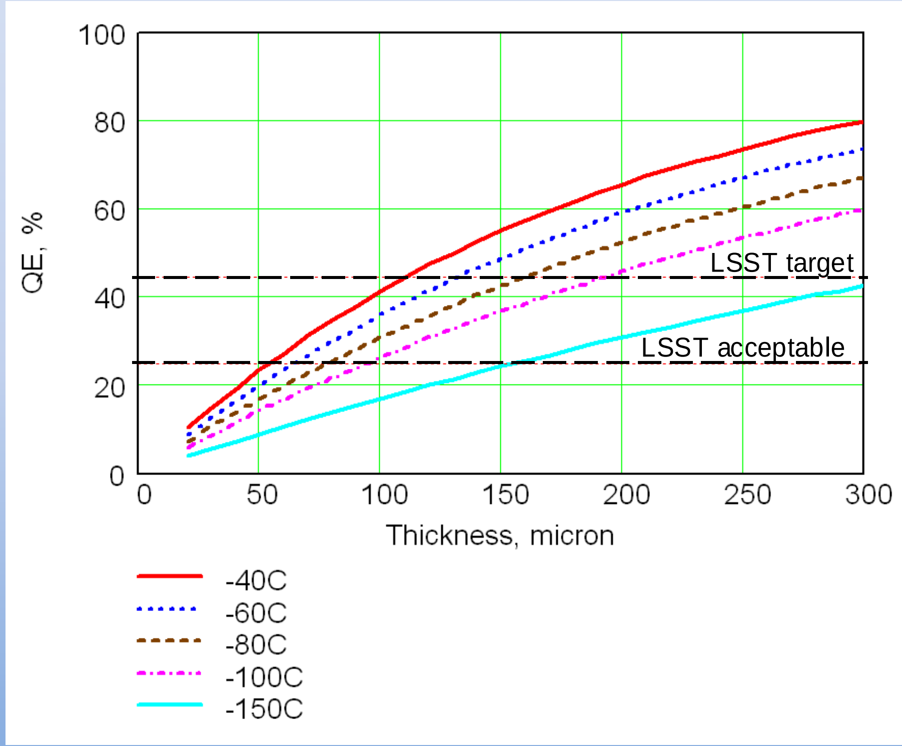


PSF vs Thickness : Divergence + diffusion

→Sets thickness limit $t \leq 100\mu$

Effect of sensor thickness on QE

Silicon QE @ 1000 nm vs Thickness



To get > 25% QE @ - 100C → $t \geq 100\mu$

Optimal sensor thickness = 100 μ

Sensor Requirements cont'

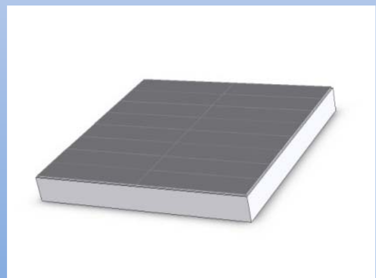
- Temperature Stability -

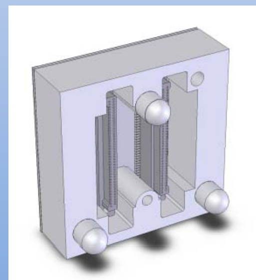
- Sensor QE is very temperature dependent near ~ 1,000 nm
- For accurate photometry, temperature stability ~ +/- 0.1C
- Sources of heat
  - CCD gates (*small*)
  - CCD output amplifiers (*medium*)
  - Heat radiation through lens (*large* ~ ½ W per sensor)
- Heat removal by thermal straps to a cryogenic plate
- Thermal control loop
  - High stability temp sensors close to CCD package
  - Heaters → 0 to ~ ¼ W per sensor on sensor package or cold straps

Sensor Status

An array of "study" sensors has been produced by
- e2v
- STA/ITL
  - 100μ to 150μ thickness
  - All fully depleted between 10V – 25V "back window bias"
  - Sizes 1 MPixels to 16 Mpixels
  - Multiple output ports
  - Tested @ BNL
  - Not final package

"Pre-Production" sensors
  - E2v
  - STA/ITL
  - 100μ thickness
  - Final packaging
    - → 4 side buttable
    - → flat to 6 μ (p-v)
  - Expected →Fall 2010

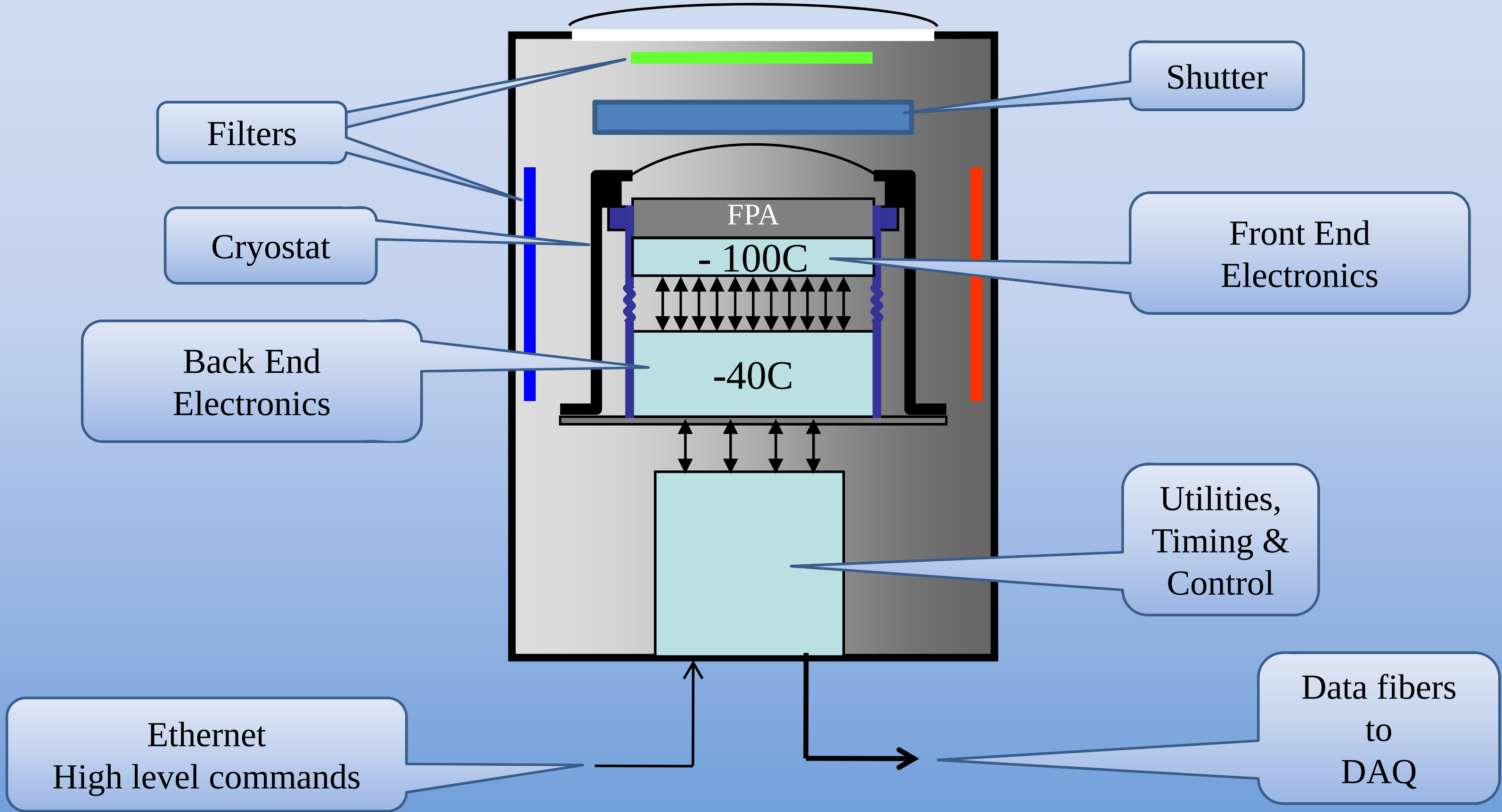




Focal Plane Construction

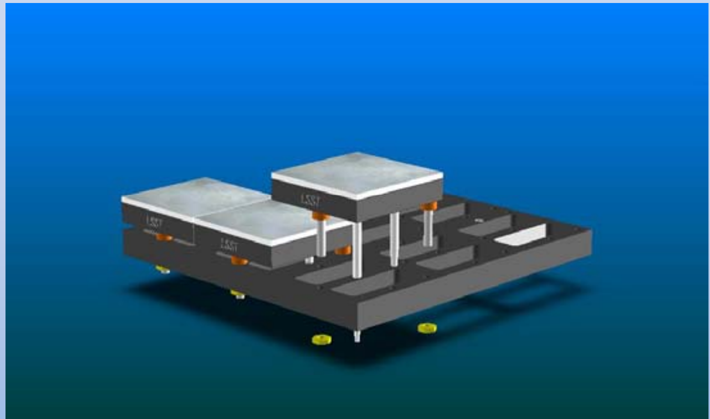
- 3 x 3 arrays of CCDs are mounted into a precision “Raft”
- 144 Mpixels per Raft
- 21 Rafts are mounted onto a rigid (SiC) “Grid”
- Major issues
  - Each sensor has ~ 150 bond pads
  - Total of ~ 30,000 bond pads
  - Sensors reside in high-vacuum cryostat
  - To avoid 30,000 cryostat feedthroughs, all readout electronics is placed within cryostat.
  - Each Raft is modular. All its readout electronics must reside in the shadow of the Raft.
- Raft electronics is divided into two sections
  - Analog, front end, in cryo-zone (-100C)
  - ADC/digital in warmer zone (- 40C)

Camera Overview

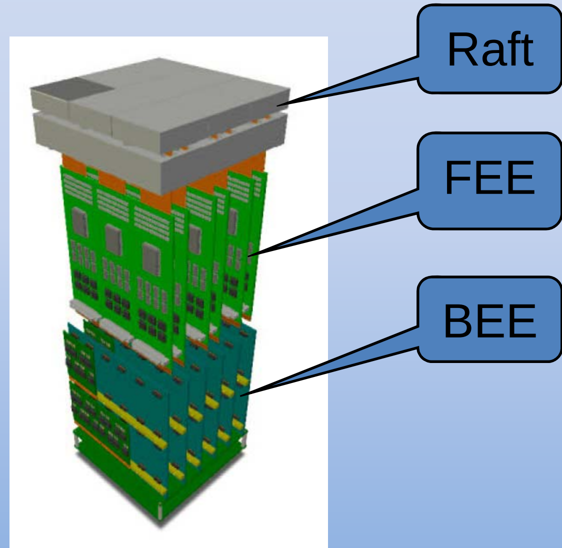


Focal Plane Construction

9 Sensor Raft



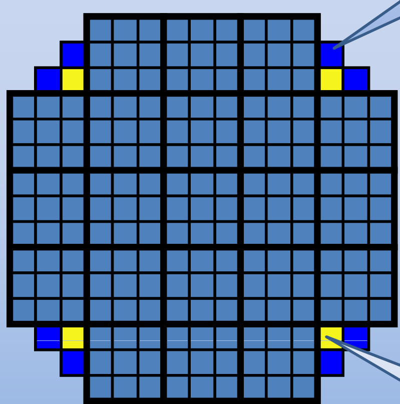
Raft Tower Assembly



- Trimmed for flatness requirement during assembly
- Very high image “fill factor” > ~ 90%

21 “Science Rafts”
4 special purpose
“corner Rafts”

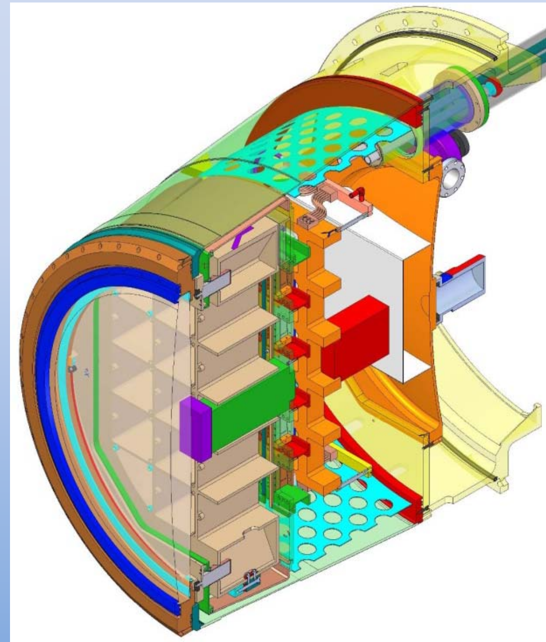
“Guide” sensors for telescope fine steering



~ 64 cm dia

“Wavefront” sensors determine mirror distortions for active mirror adjustments

Cryostat Assembly



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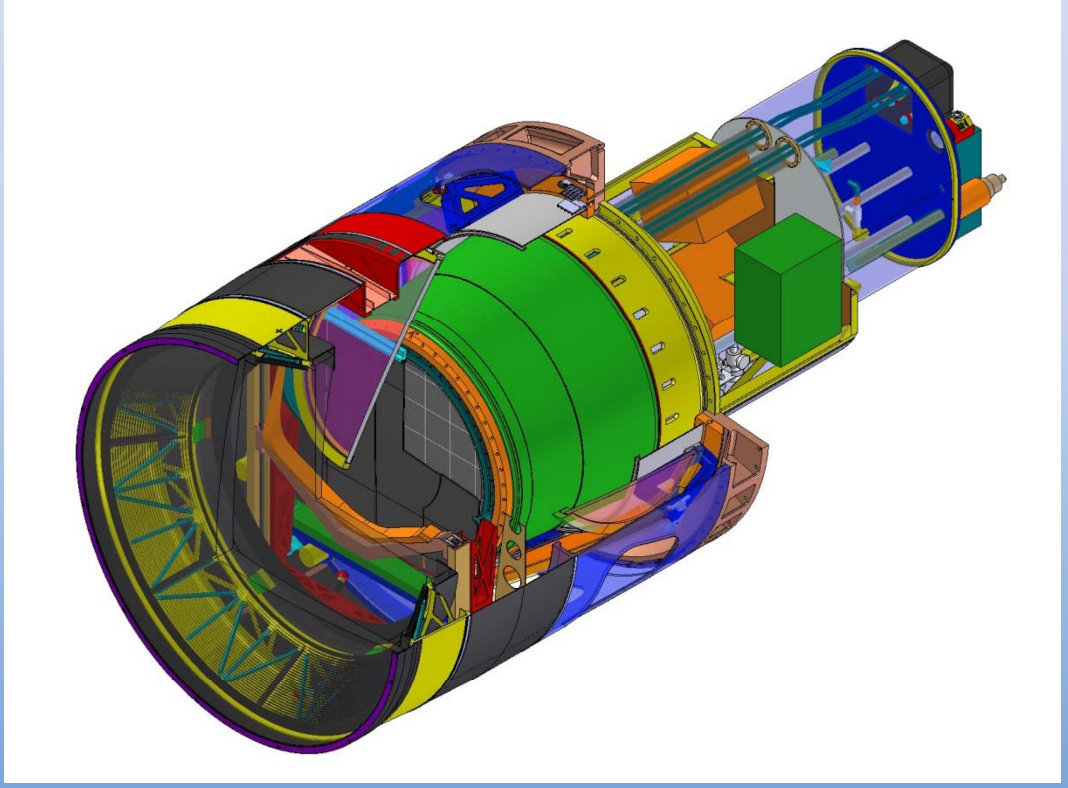
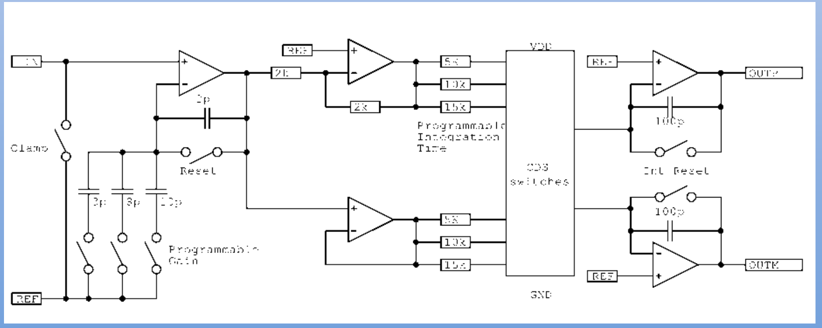
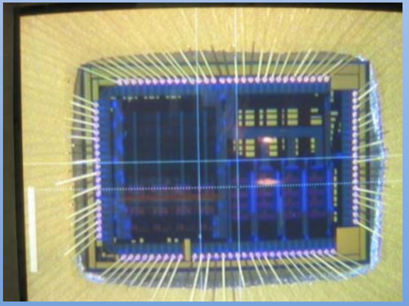
Camera with filters



Front End Electronics

- Located within "grid" : Operates at – 100C to – 120C
- Each "FEB"services 24 CCD segments – 6 FEBs per Raft
- Analog functionality in 2 ASICs
  - Analog Signal Processing ASIC (ASPIC)
  - LPNHE/IN2P3 collaboration[1] - France
  - Dual Slope Integrator : Programmable gain
  - Specs:
    - e_n < ~ 5 nV/rt(Hz)
    - x-talk < ~ 10^{-3} (achieved in 1st version)
  - Differential output to Back End Boards (ADCs) via shielded flex cable
  - 8 channel ASIC, AMS 0.35µ CMOS @ 5V, ~ 25mW/ch



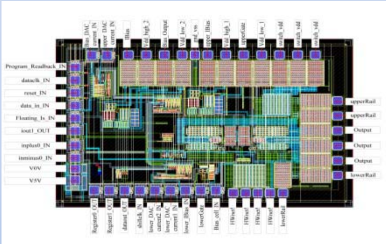


[1] V. Tocut, H. Lebbolo, C. De La Taille, P. Antilogus, S. Bailey, M. Moniez, F. Wicek, R. Sefri

Front End Electronics – cont

Sensor Control Chip (SCC)

- ORNL – U. Tennessee [1]
- Receives LVDS signals from BEBs → Converts to Clock levels to CCDs
- Parallel gates (4), Serial gates(3), Reset(1)
- Clock Hi/Lo levels in range 0V to ~ 25V, programmable on BEB
- 4 channels per chip, 2 chips per CCD.
- CCD bias level buffers in range up to ~ 30V
- ATMEL BCD-SOI process. HV to 45V
- Status
  - 1st submission tested & fully functional
  - Some pulse shape "wrinkles" (fully understood in simulation)
  - 2nd submission → Fall '08



Additional FEB functionality

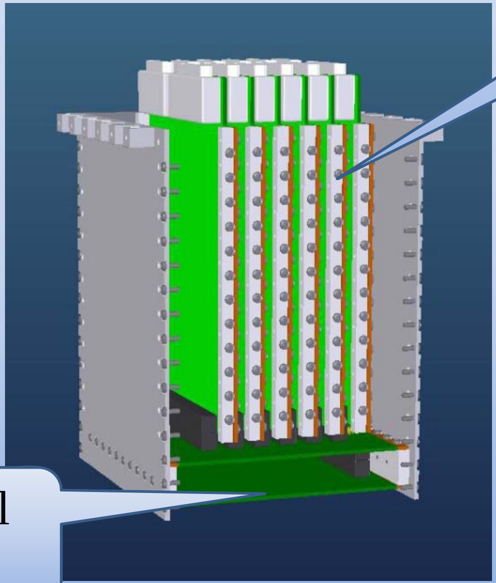
- Temp sensing & other usual monitoring
- Raft heaters → Part of focal plane thermal control loop

[1] P. Stankus, C. Britton, Z. Ning, N. Ericson

Back End Electronics

Back End Boards

Raft Control Crate



Raft Control Module

- 6x Back End Boards (BEBs)
- 24 channels ea, 18 bit 1 MHz ADCs (COTS)
- Temp sensor processing
- Programmable bias & clock levels for FEBs
- Sensor heater control
- Misc slow controls

- FPGA (Xilinx) based programmable “Readout State Machine”
- Collects all ADC data @ 100 MHz
- All control loops stored locally
- Responds to high level commands from Timing & Control Module (TCM)
- All Rafts in fully synchronous operation
- “Rocket i/o” data output to drive data fiber to DAQ (~1.6 Gb/s)
- Power PC for non-time critical operations

Back End Electronics

- Data Volume -

- Per image: 3.2 Gpixels → ~ 7 GB
- Per minute : 4 images → ~28 GB
- Per night : ~ 600 min → ~ 16 TB
- Per year : → ~ 5 PB

- All fibers received by “Science Data System” – (SLAC)
- Public data set

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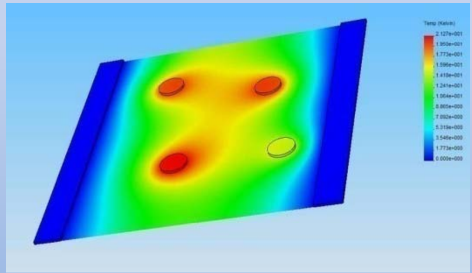
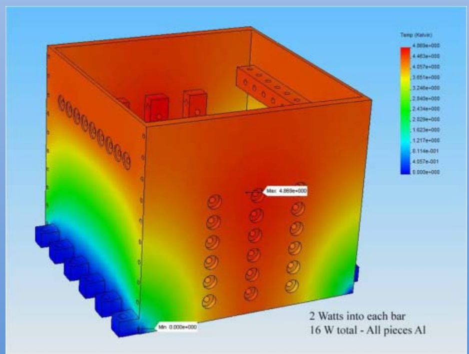
Additional Electronics Issues
Thermal management

- Thermal paths & modeling
  - → ICs and components to ground/thermal planes
  - → "Chip scale" packaging
  - → Conduction bars
  - → Crates/housing
  - → Cold plates / cryoplates



Board level R_t ~ 20C/W across 2 oz copper plane

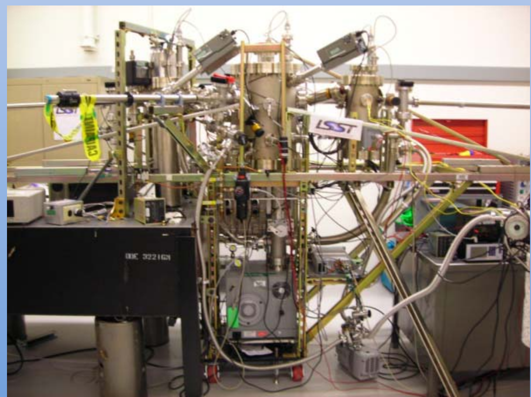


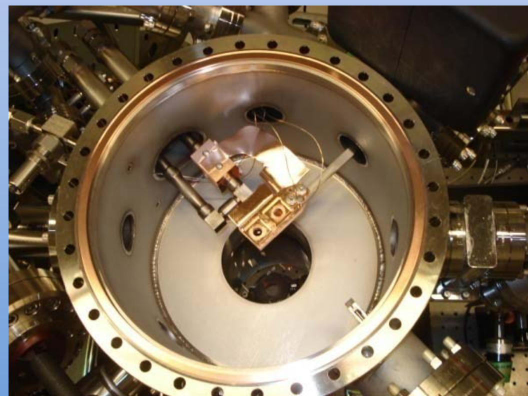
Crate level R_t < ~ 0.5C/W

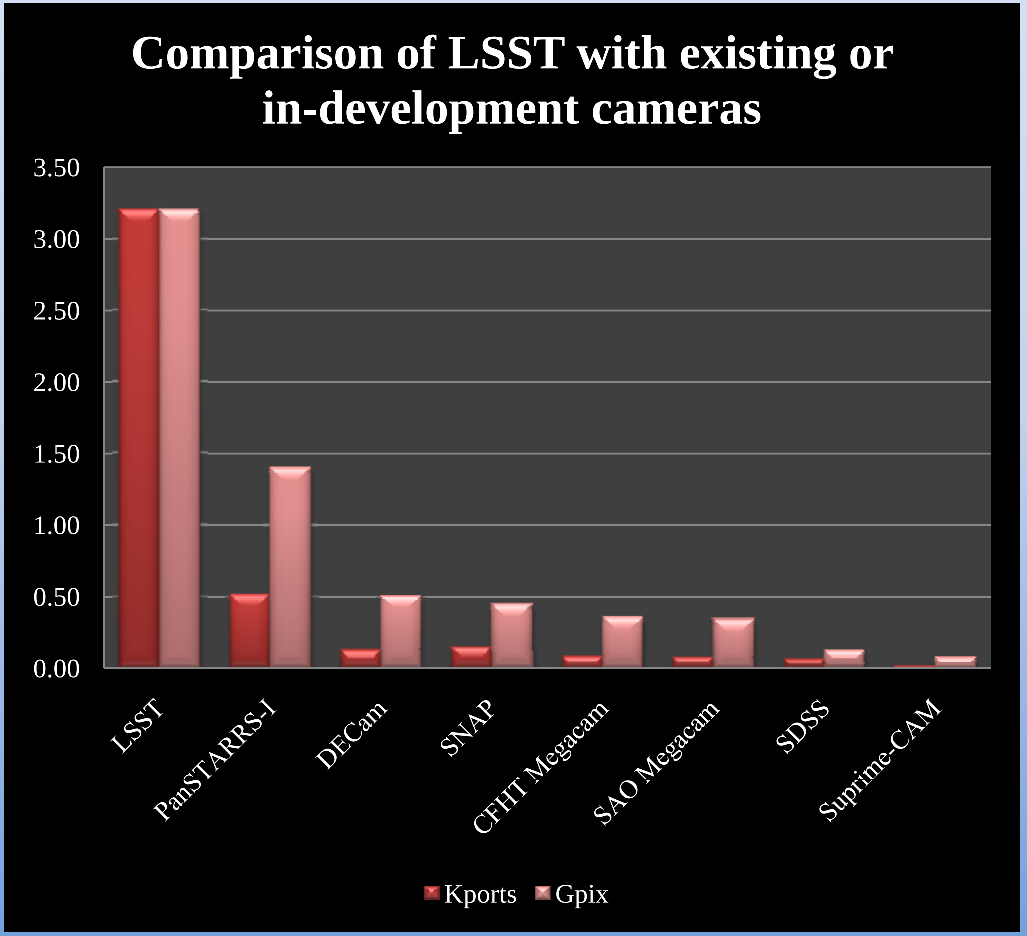
Additional Electronics Issues

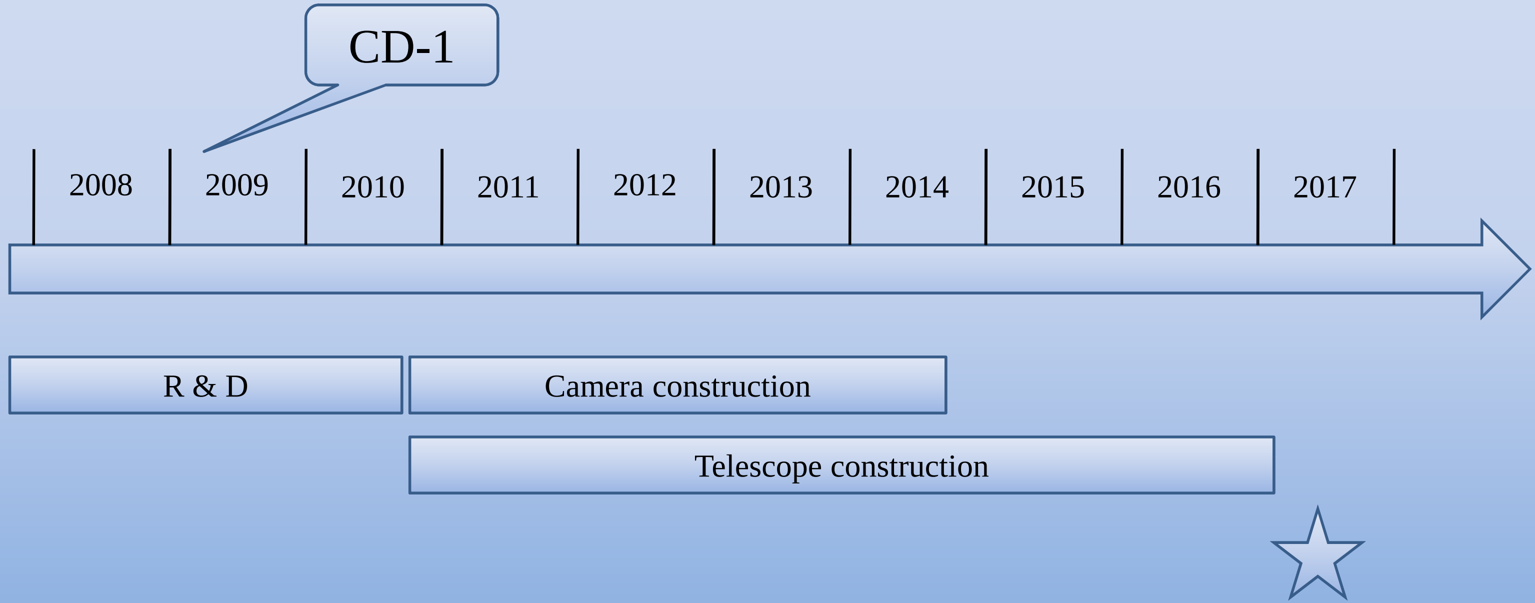
Contamination & outgassing

- Outgassing materials may condense on sensor surface
- ~ 2 m^2 of pcb materials in cryostat
- Polyimide pcb construction (if necessary)
- Parylene (vapor deposition) or similar coatings
- Electronics separated from focal plane by molecular barriers (tortuous paths) and separate vacuum pumping
- All in-cryostat materials tested / certified in test “Materials Test Facility” @ SLAC
- Optical loss measurement over LSST pass band & residual gas analyzer (RGA)






Comparison of LSST with existing or in-development cameras
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
LSST
PanSTARRS-I
DECam
SNAP
CFHT Megacam
SAO Megacam
SDSS
Suprime-CAM
Kports
Gpix


CD-1
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
R & D
Camera construction
Telescope construction

Telescope and site : Cerro Pachon, Chile