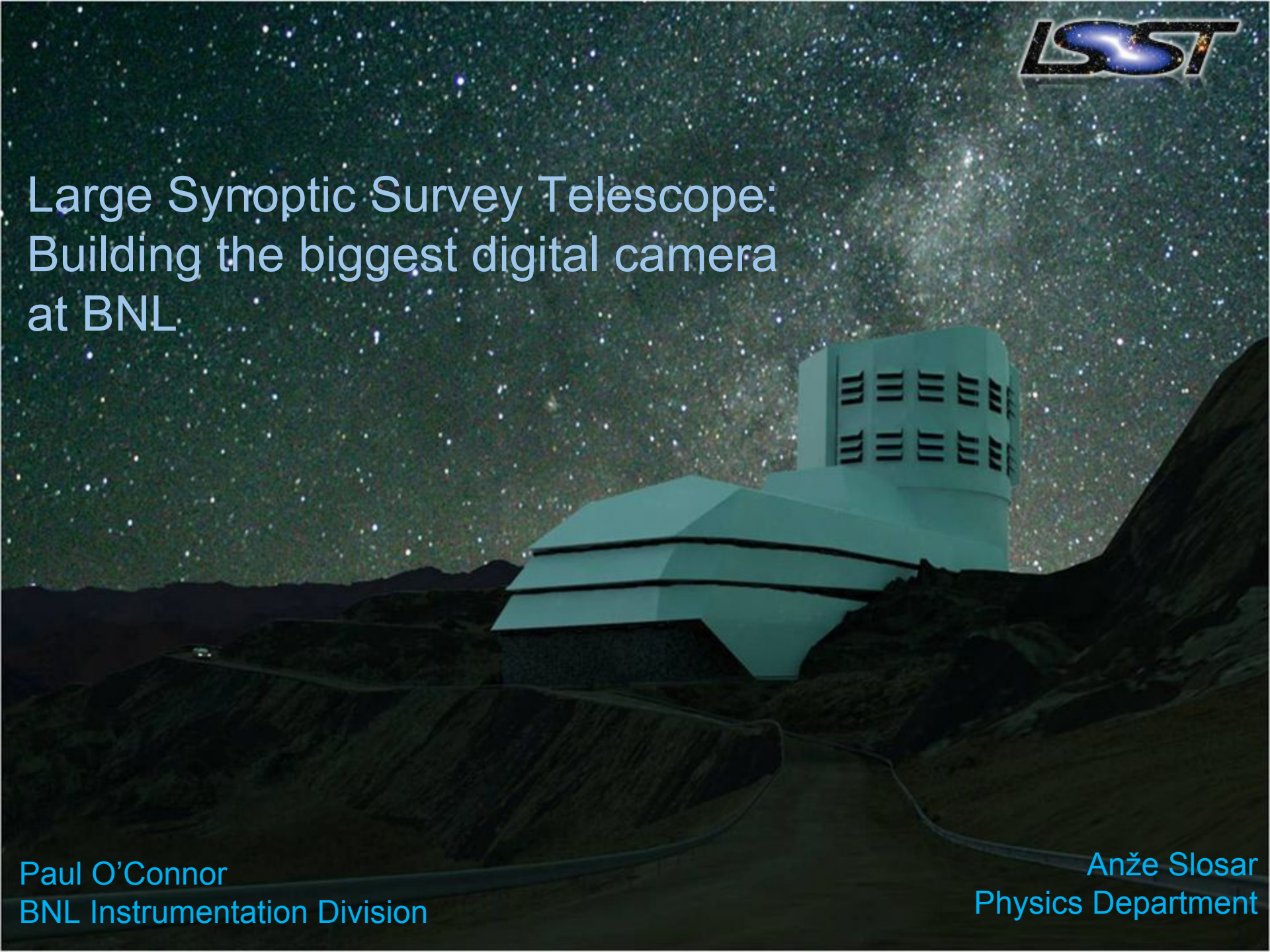


Large Synoptic Survey Telescope: Building the biggest digital camera at BNL

Paul O'Connor
BNL Instrumentation Division

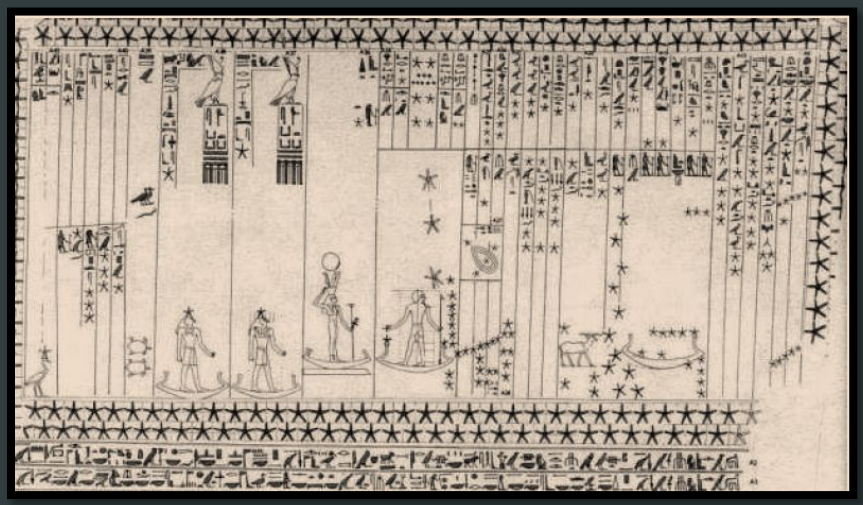
Anže Slosar
Physics Department

- Taking pictures of the night sky
- Discovering Dark Energy
- Building the largest digital camera

Capturing the night sky

N. Europe
1600BC

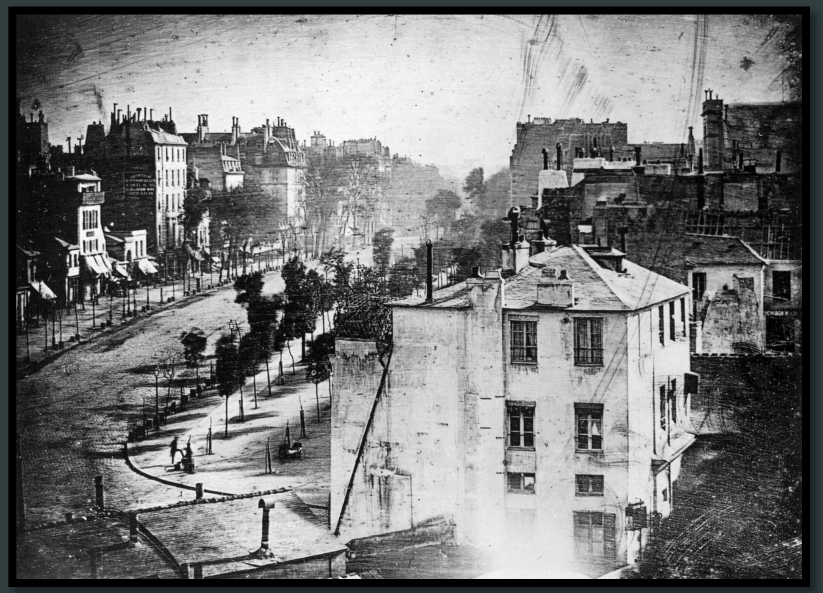
Egypt
1460BC



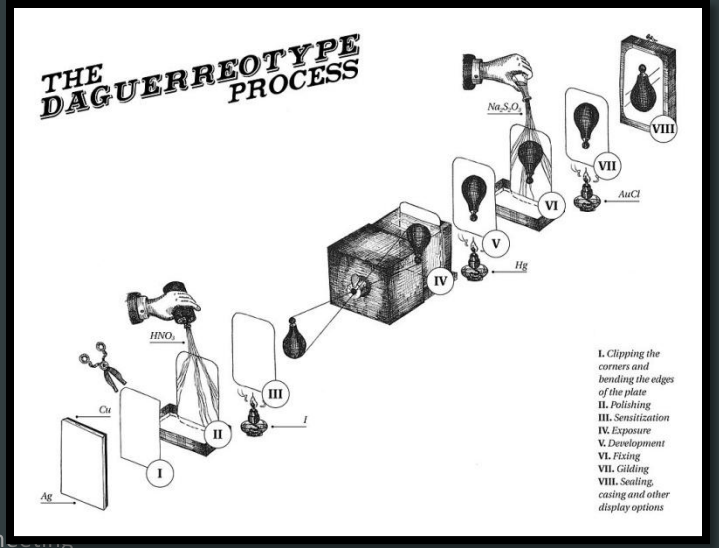
Mesoamerica
1050AD

China
185BC

Photochemical imaging: the Daguerreotype



Louis Daguerre
1839



First astrophotograph

Moon
Draper 1840

Bond
1852

Early astrophotography

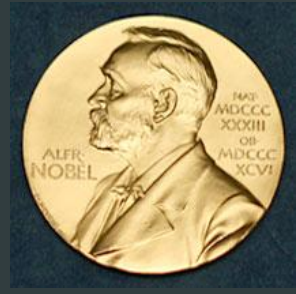
Vega
Bond 1850

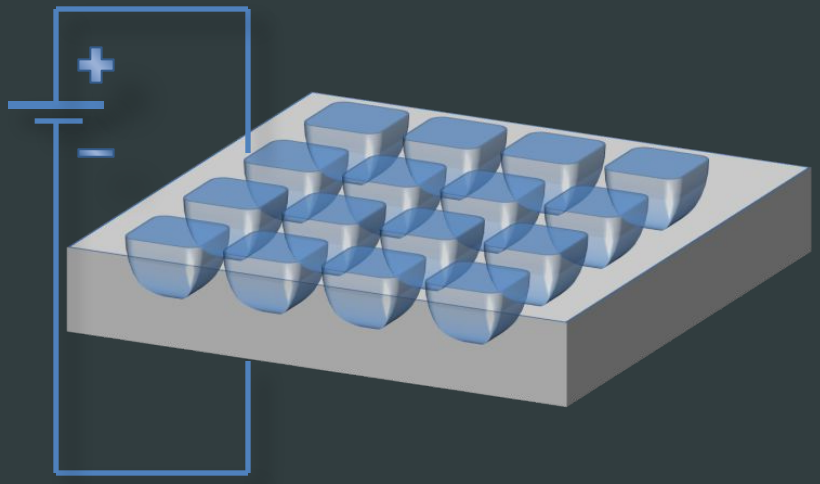
Orion nebula
Draper 1880

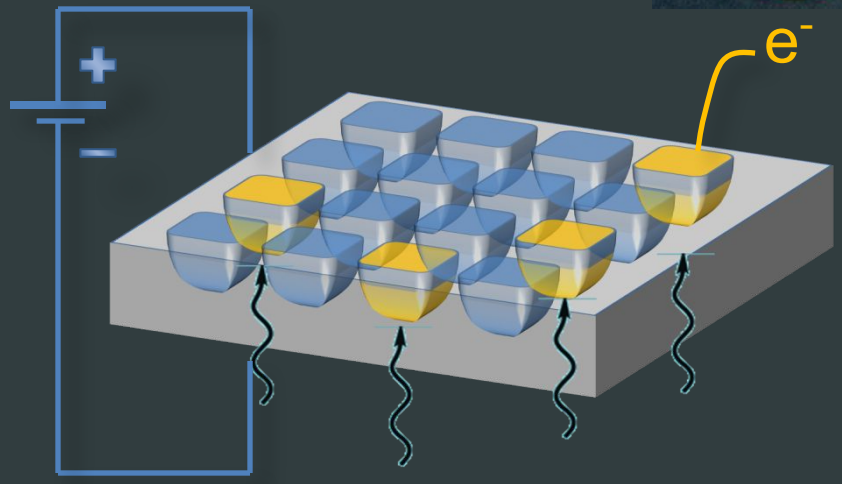
M31
Roberts 1887

Transit of Venus
Janssen 1874

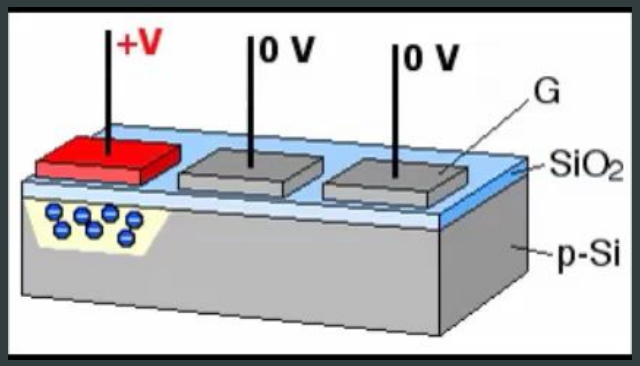
Electronic imaging: the Charge Coupled Device

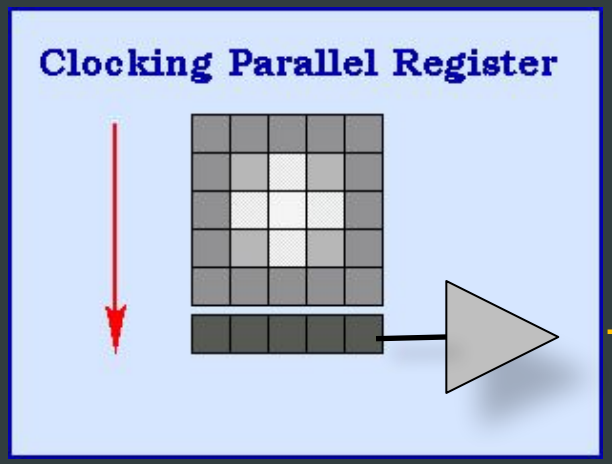




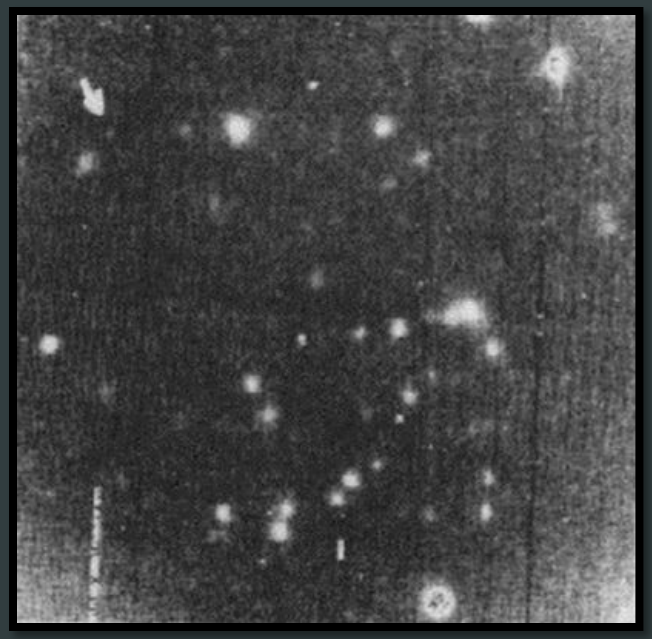


William Boyle and George Smith received 2006 Nobel prize for invention of CCDs





CCD astrophotography



Cl 13Kpα
Gunn 1981
500x500

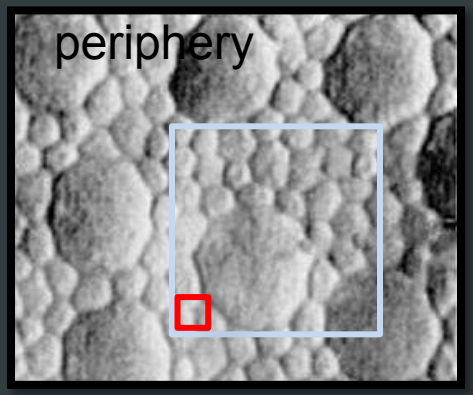
M16
2014

NASA/ESA/Hubble Heritage Team
(STScI/AURA)/J. Hester, P. Scowen
(Arizona State U.)

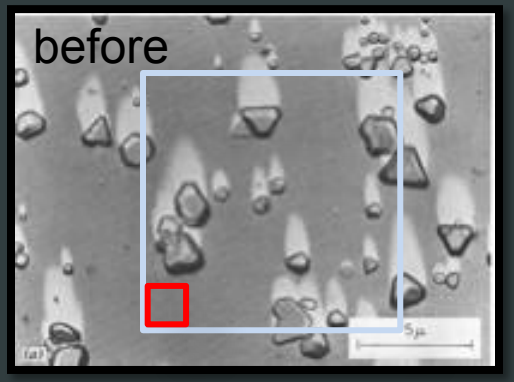
"The CCD is a nearly perfect device, with problems that appear only because the device performance is so high compared to other detectors…"

Three types of photosensor compared

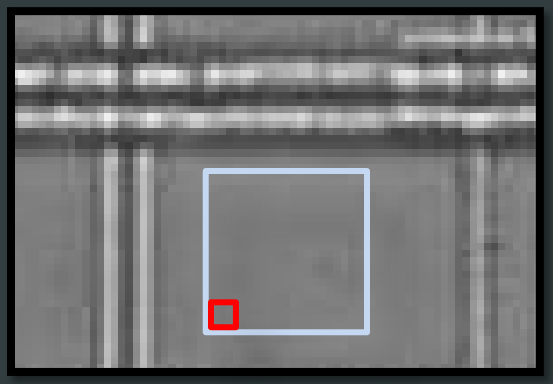
retina

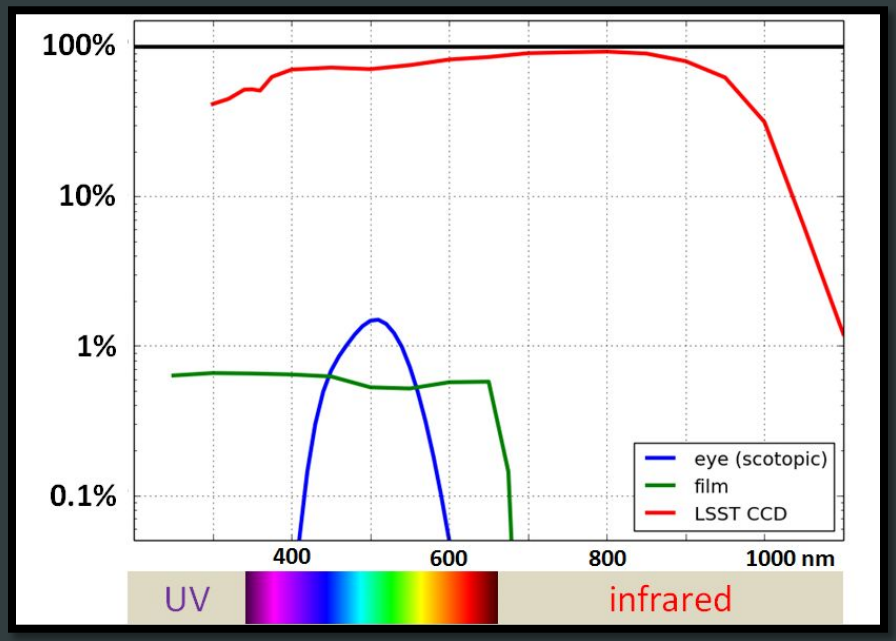


film



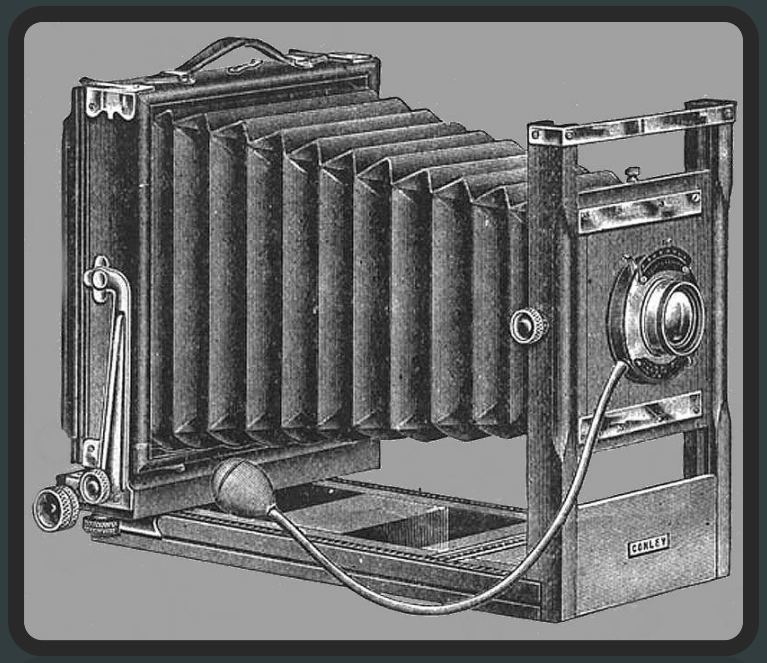
CCD



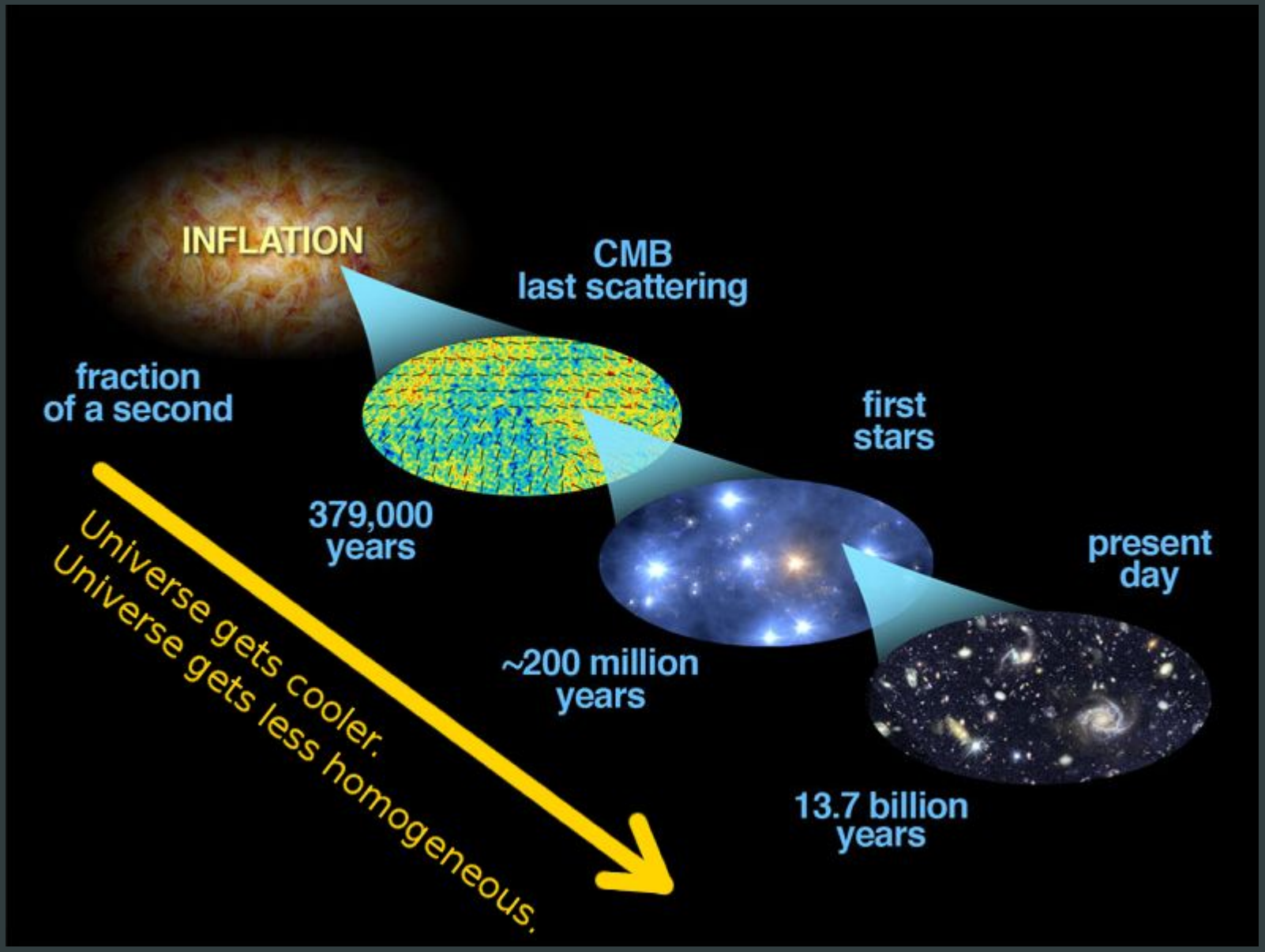


	Dynamic range	Retention time
Retina	5000	30ms
Film	16000	100ms
CCD	60000	∞

- Taking pictures of the night sky
- Discovering Dark Energy
- Building the largest digital camera



Cosmic History

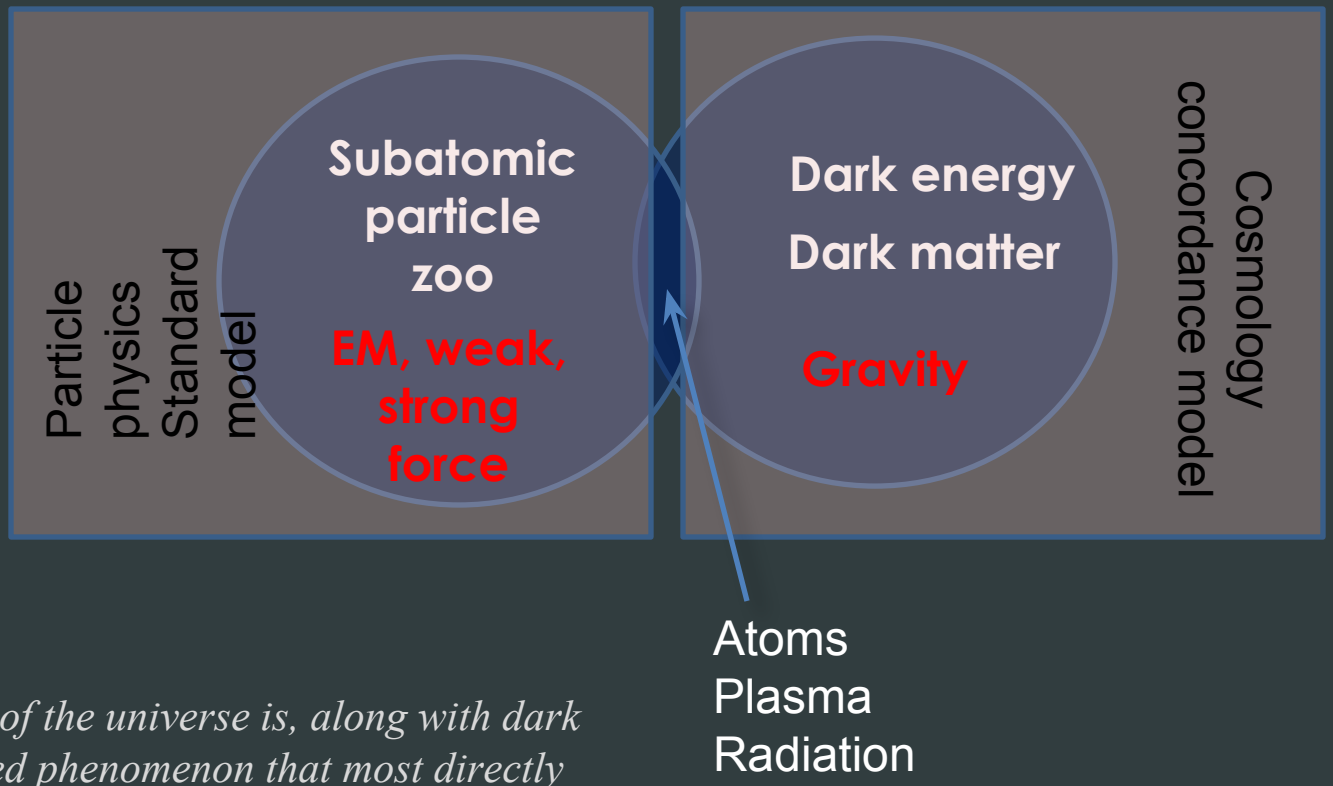


Cosmic Pizza

- 95% of the Universe made of stuff we don't know
- dark components well understood macroscopically, but their physics remains a mystery
- **Dark Matter** is cold, non-interacting "stuff" collapsing under its own gravity

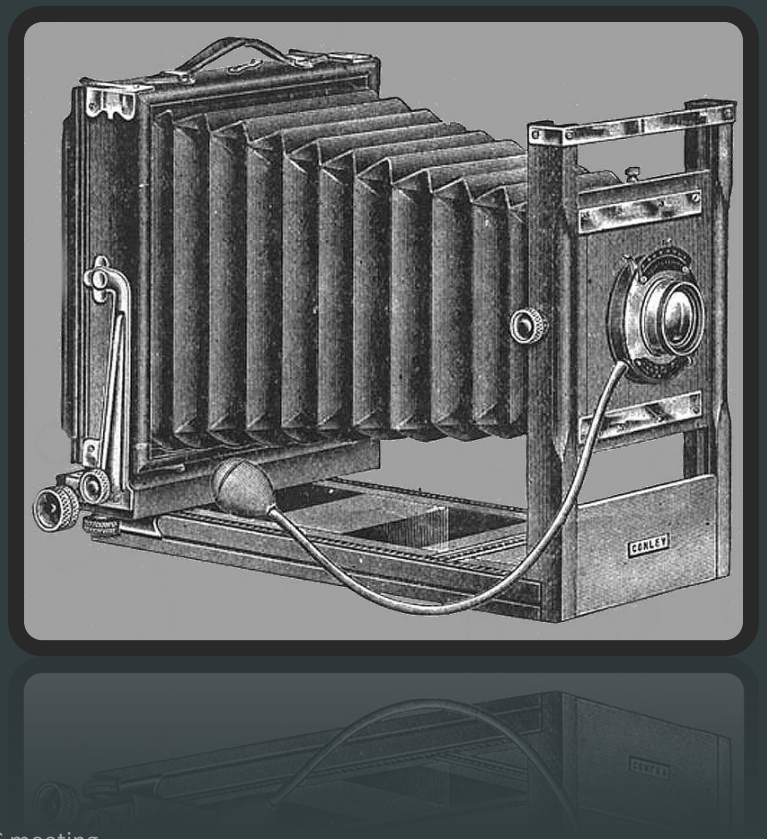
- **Dark Energy** drives an accelerate expansion of the Universe - on of the most unexpected turns of late 20th century

Clash of the "standard models"



"The acceleration of the universe is, along with dark matter, the observed phenomenon that most directly demonstrates that our theories of fundamental particles and gravity are either incomplete or incorrect".
Albrecht et al., Dark Energy Task Force report

- Taking pictures of the night sky
- Discovering Dark Energy
- Building the largest digital camera



The ideal survey for cosmology

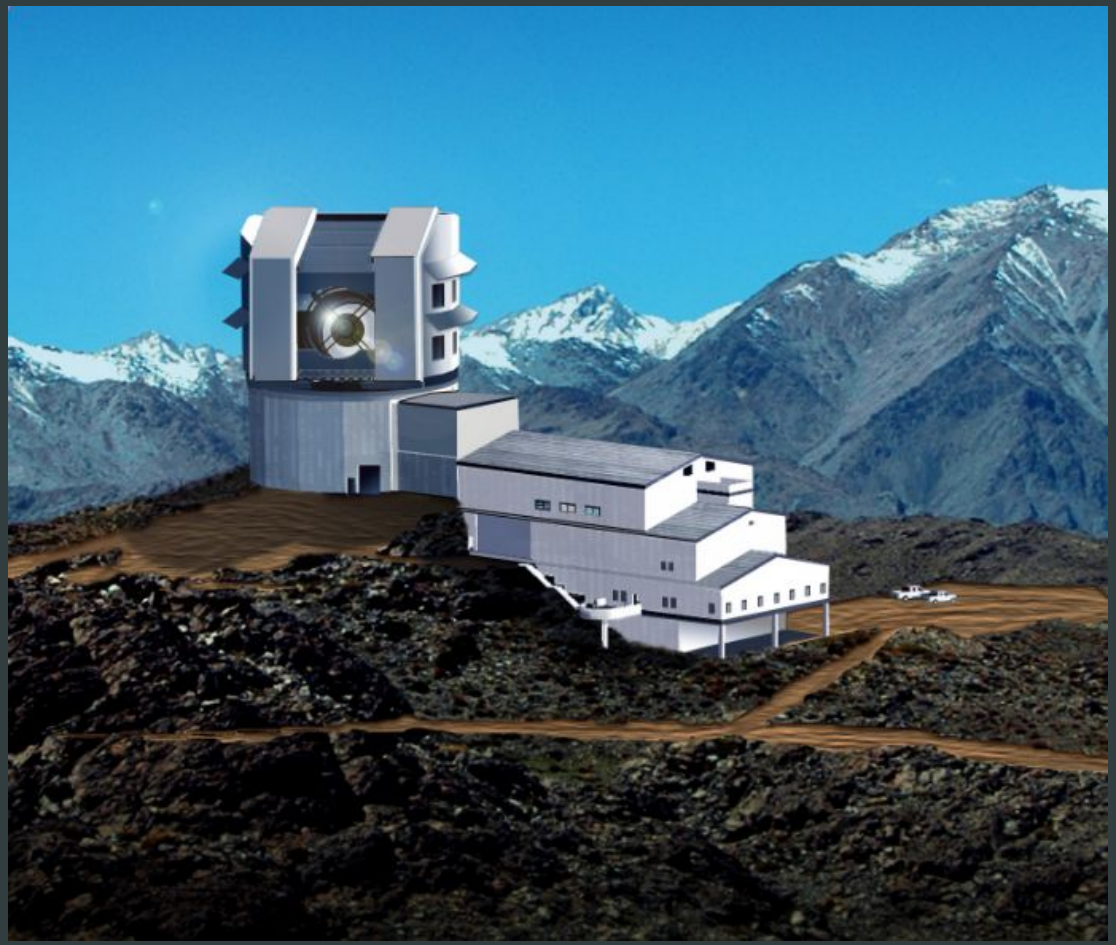
- Detect as many galaxies as possible
- Over as wide an area of sky as possible
- Measure their positions, brightness, colors, and shapes as accurately as possible

Miyazaki et al. 2011

Microscope vs Telescope

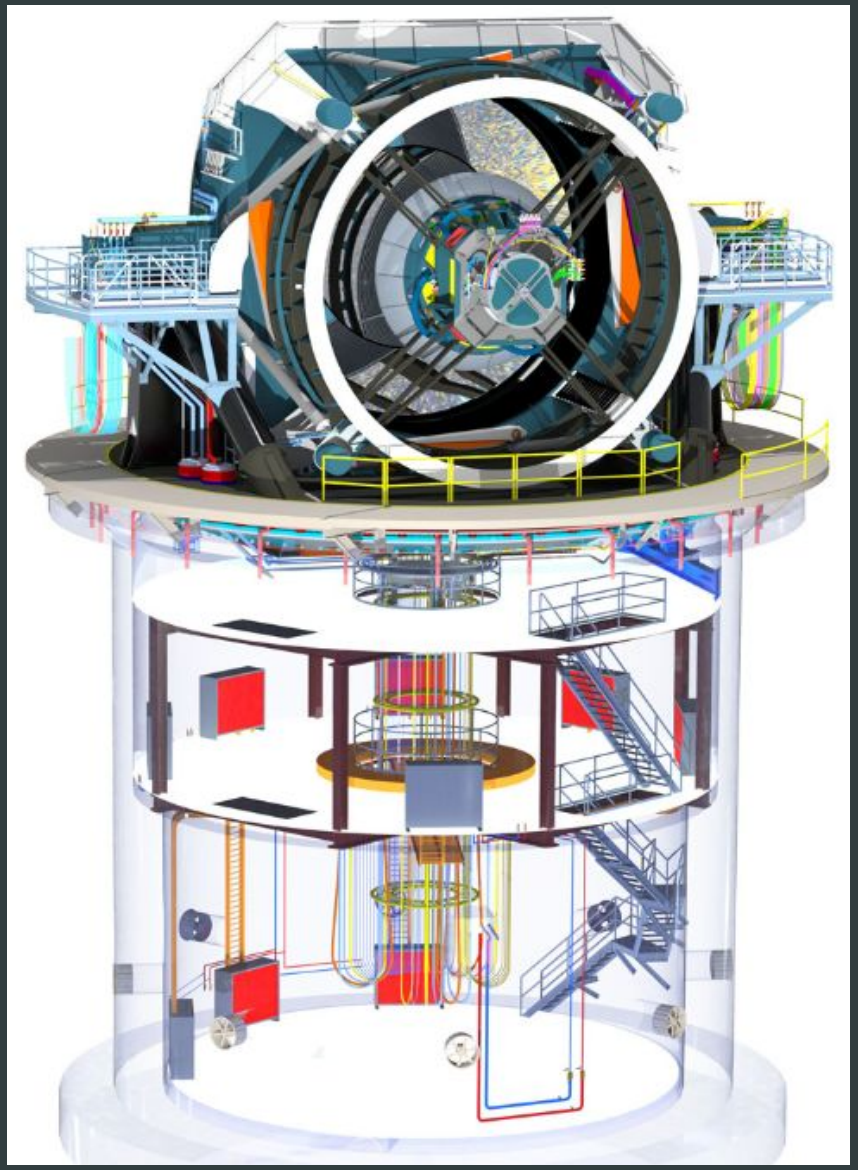
Large Synoptic Survey Telescope

- Leadership survey telescope
- Collaboration between NSF and DOE
- Will do all kinds of science: from asteroid searches to the largest observable structures in the universe
- We are in the game for cosmology

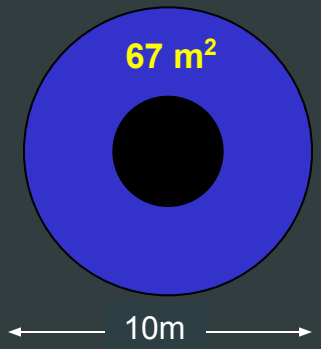
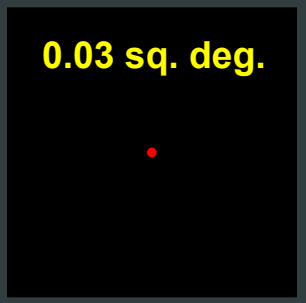
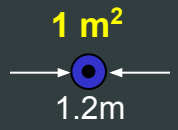


LSST in a Nutshell

- Decade long survey 2022-2032
- 8m mirror, 3200 megapixel camera
- takes a picture every 15s - movie of the sky
- it will detect 37 billion sources
- Cost and schedule:
  - Telescope, site, DM: $473M
  - Camera: $165M
  - Operations: $37M/yr
  - First light: 2019
  - Survey operations start: 2022
- BNL responsible for detectors and analysis

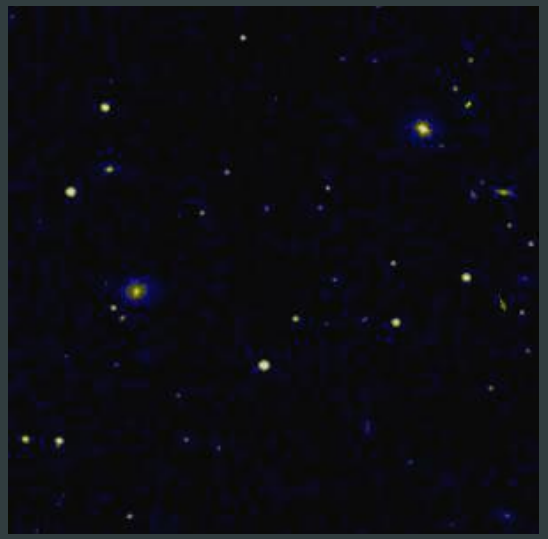


Collecting area × Field of View = Survey Power

	Primary mirror effective area	Field of view	Product
Keck 			2 m²-deg²
Oschin Schmidt 			20 m²-deg²
LSST 			320 m²-deg²

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

LSST's survey will be DEEP



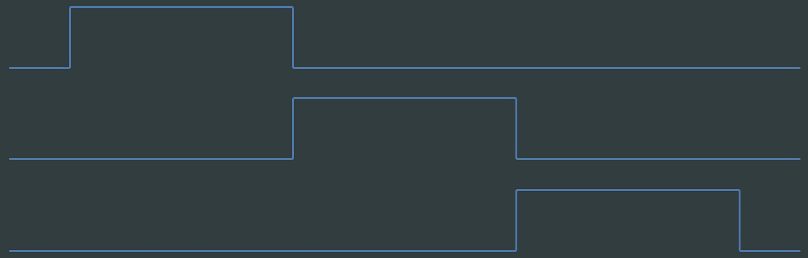
Largest all-sky survey before LSST (photographic)

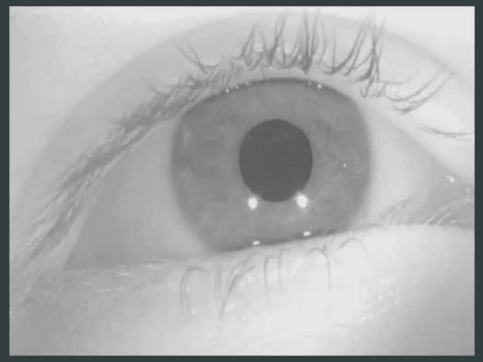
Sloan digital sky survey (CCD)

LSST (simulated)

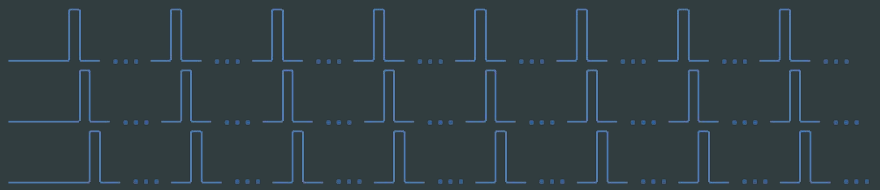
LSST's survey will be FAST

Field1
Field2
Field3
...

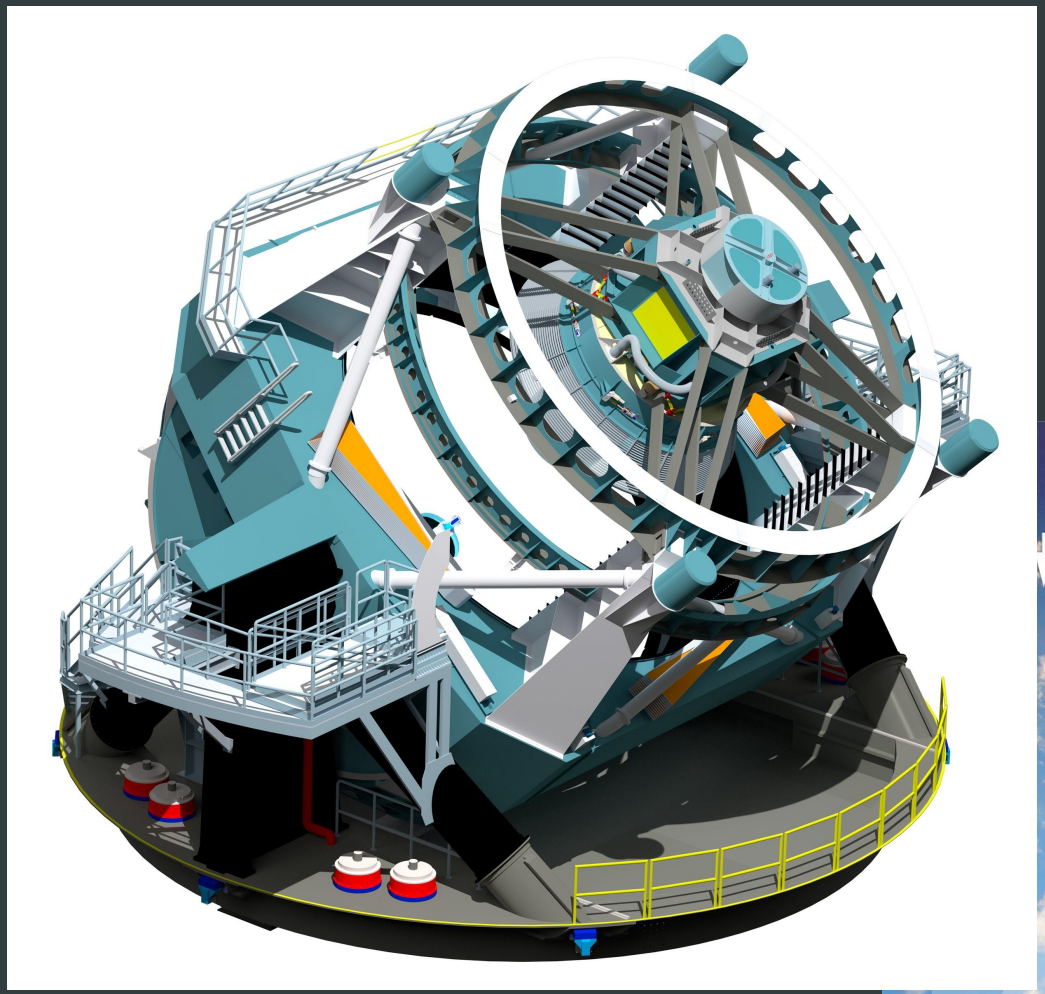




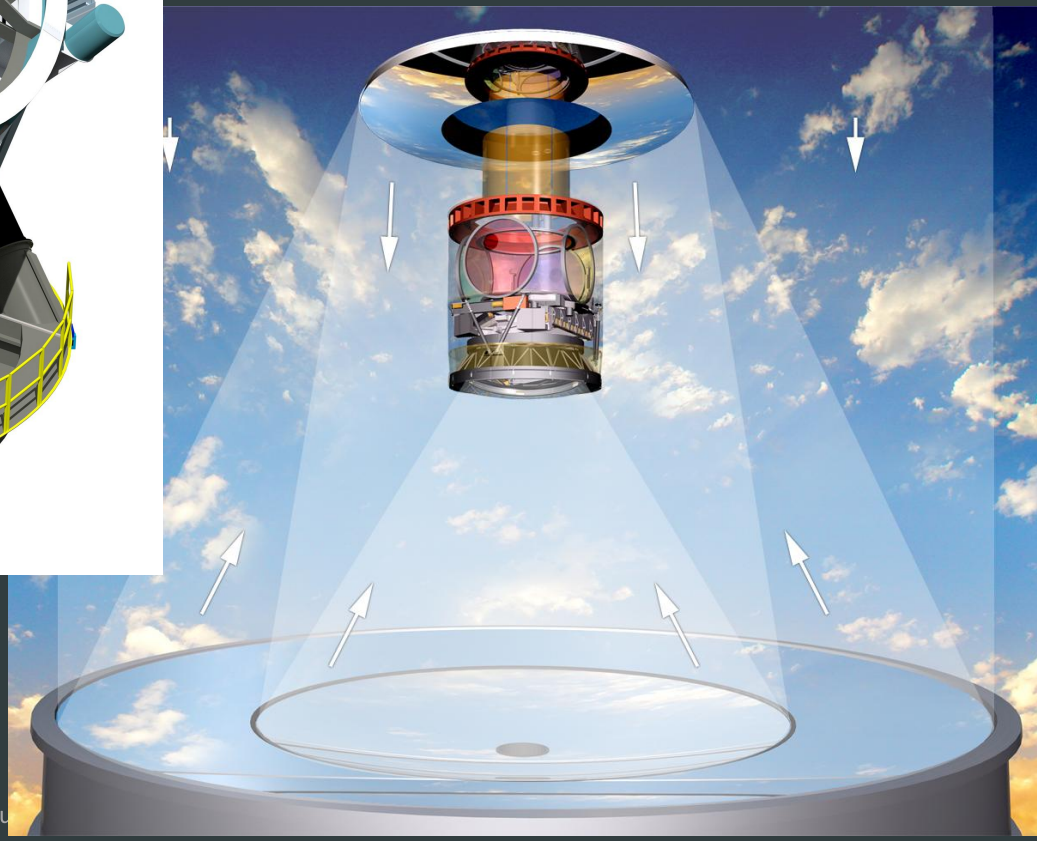
Field1
Field2
Field3
...

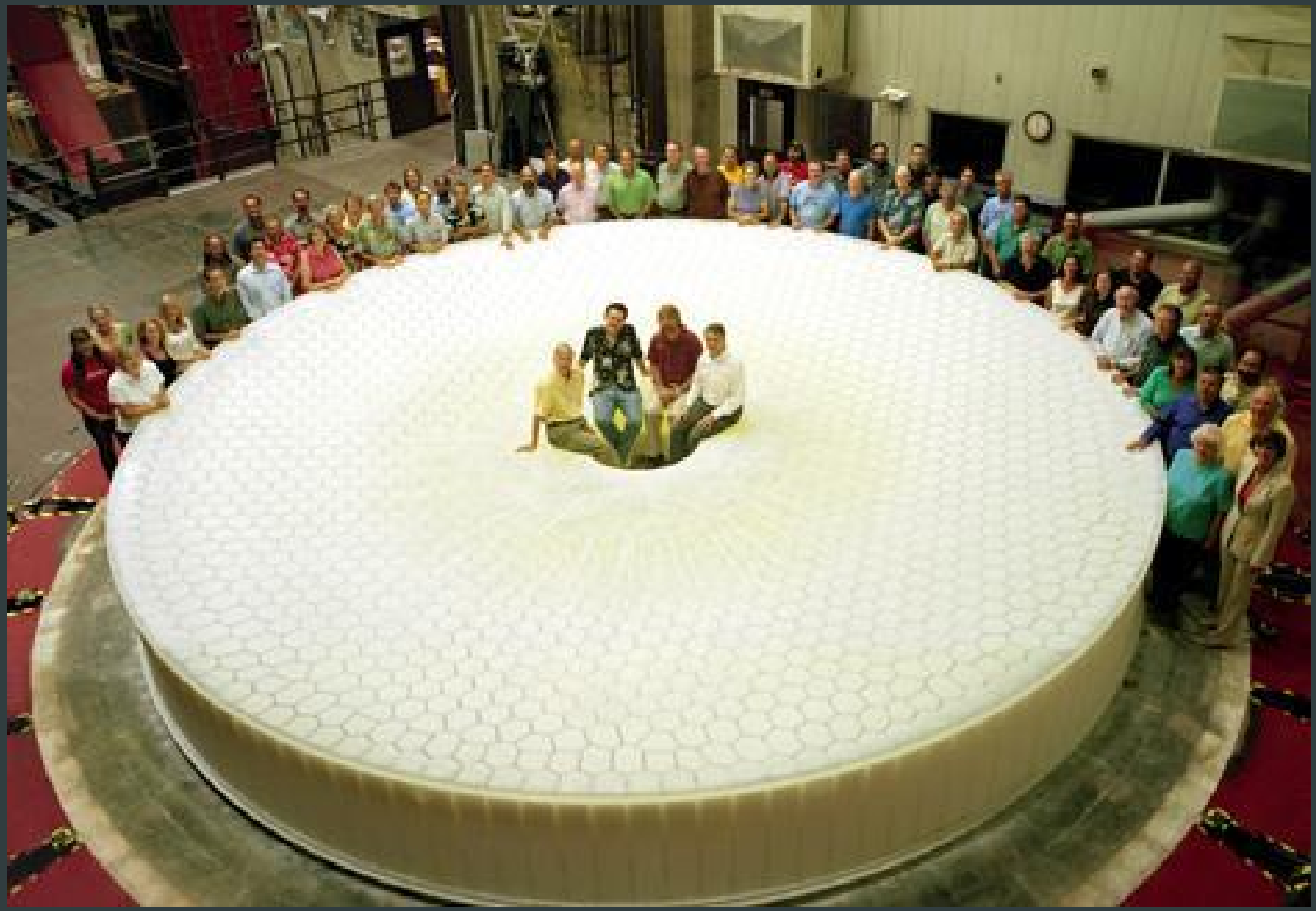


Telescope



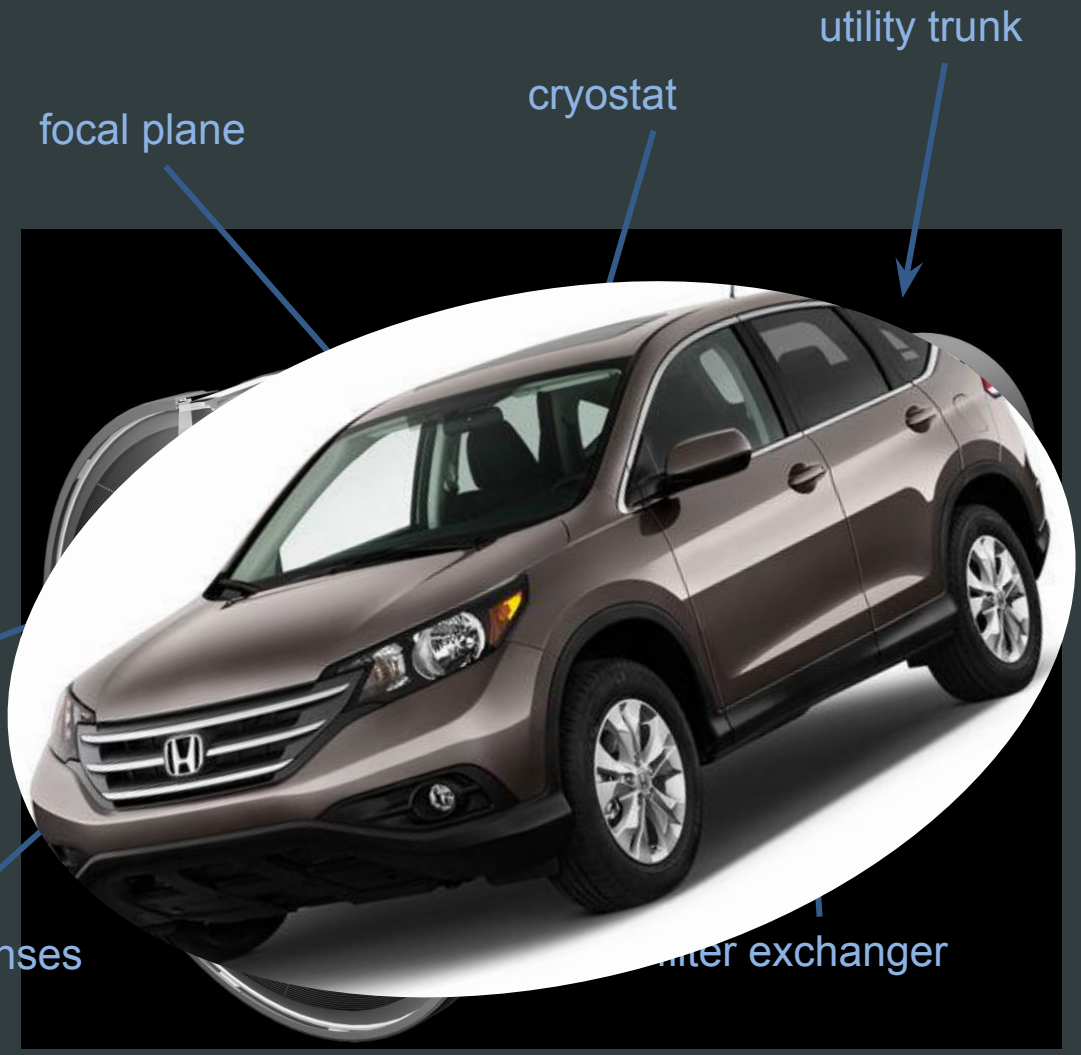
- 3-mirror design
- Fast f/1.2 beam
- Moving structure 350t
- 5s slew-and-settle time to 0.25’’





LSST camera – a different kind of pixel detector

- size of a small car
- 6200 lbs, 3 tons
- 3200 megapixels



LSST's new generation CCD sensors

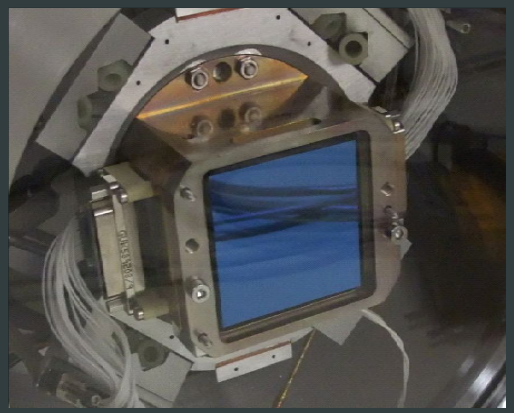
Thick, fully depleted, high resistivity silicon substrate
4K x 4K, 10µm pixels
16 independent amplifier segments
Plug-compatible prototypes obtained from 2 vendors, fully operational

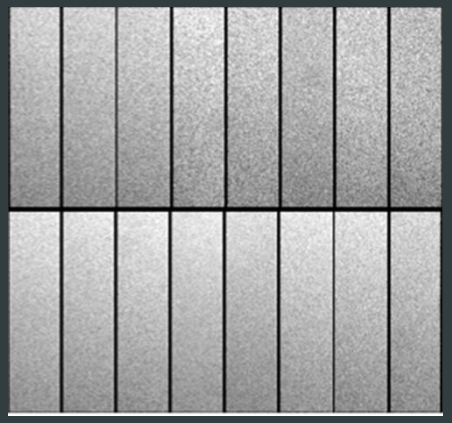
Packaged CCD

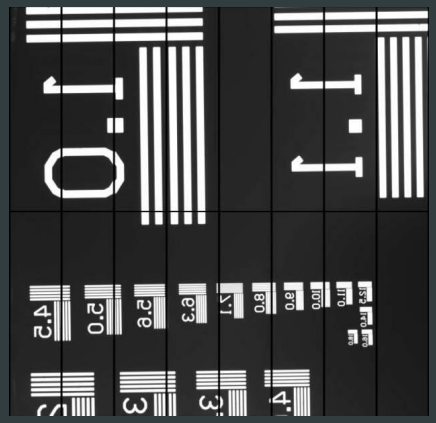
Uniform illumination

Test target image

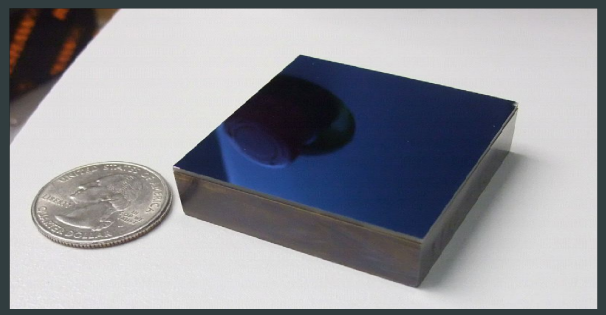
E2v CCD250

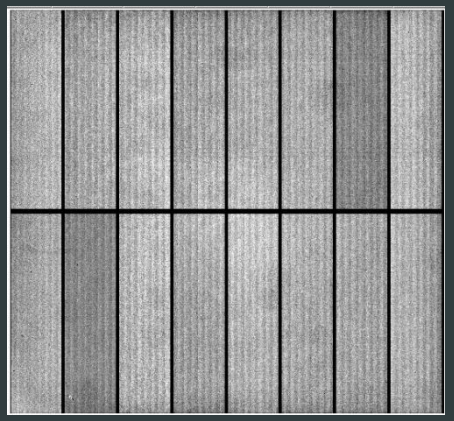


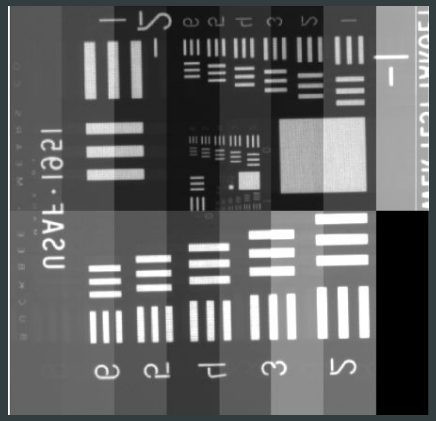




ITL STA3800B

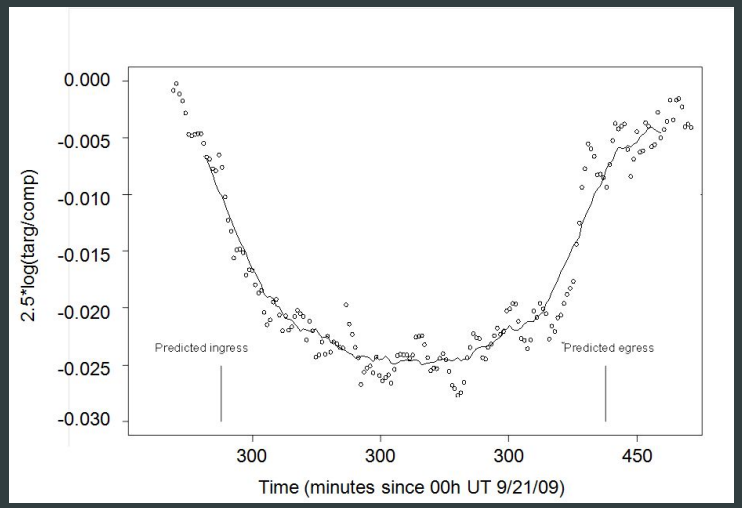




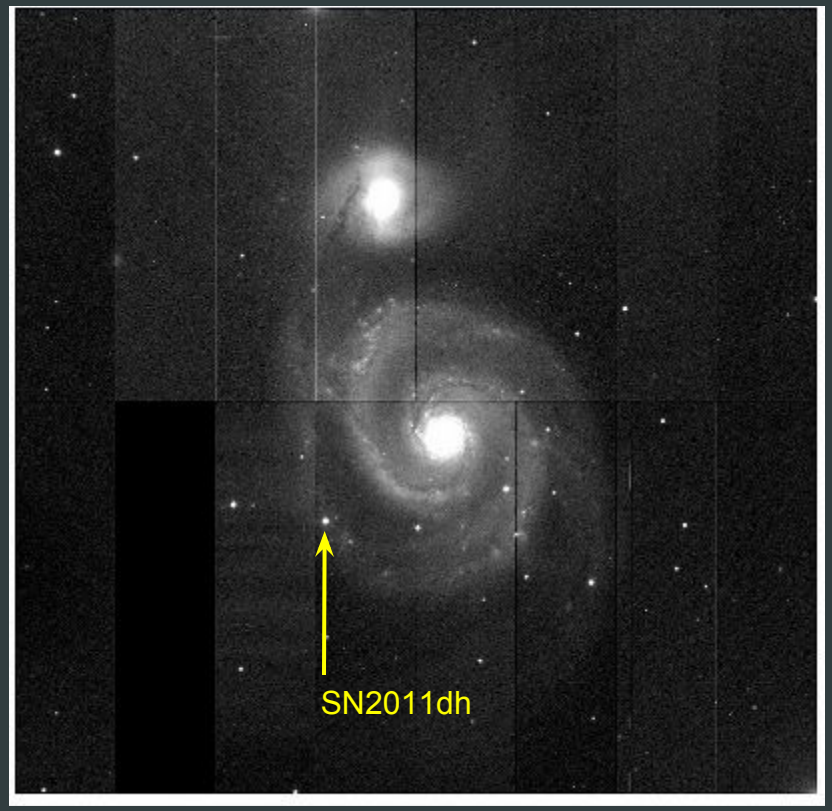


LSST CCD telescope test

Interfacing to 2.4m McGraw-Hill



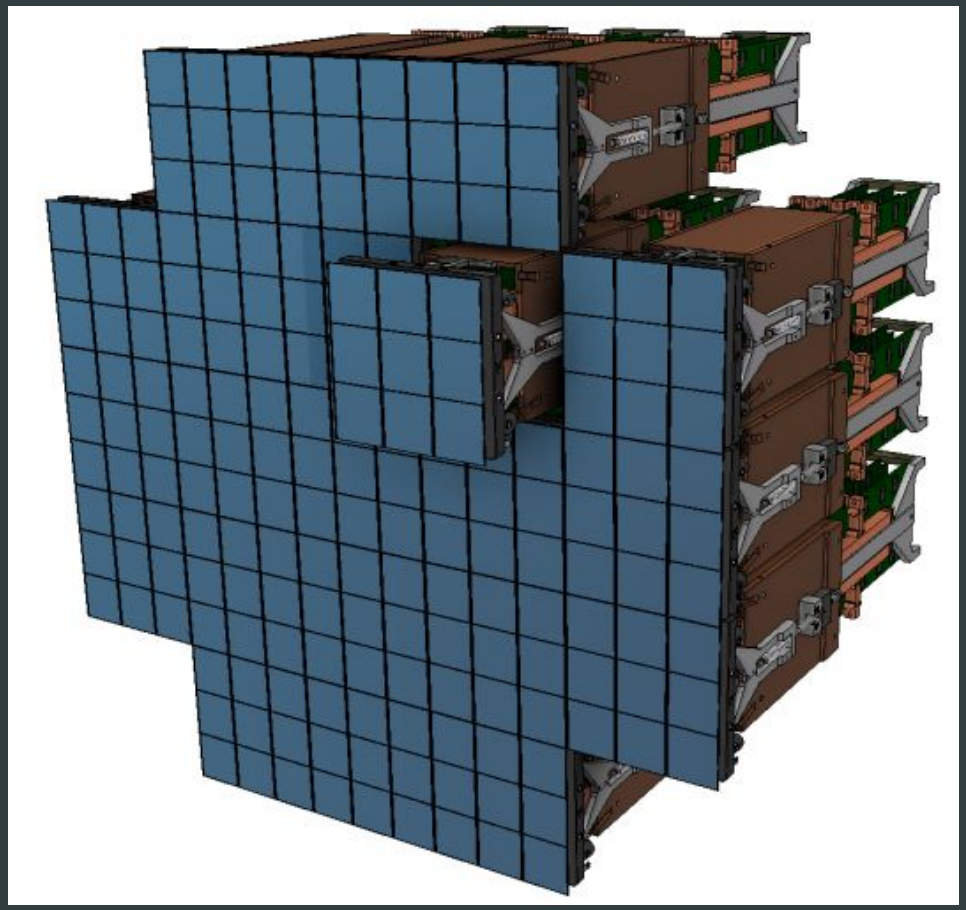
Exoplanet transit of TRES-1B



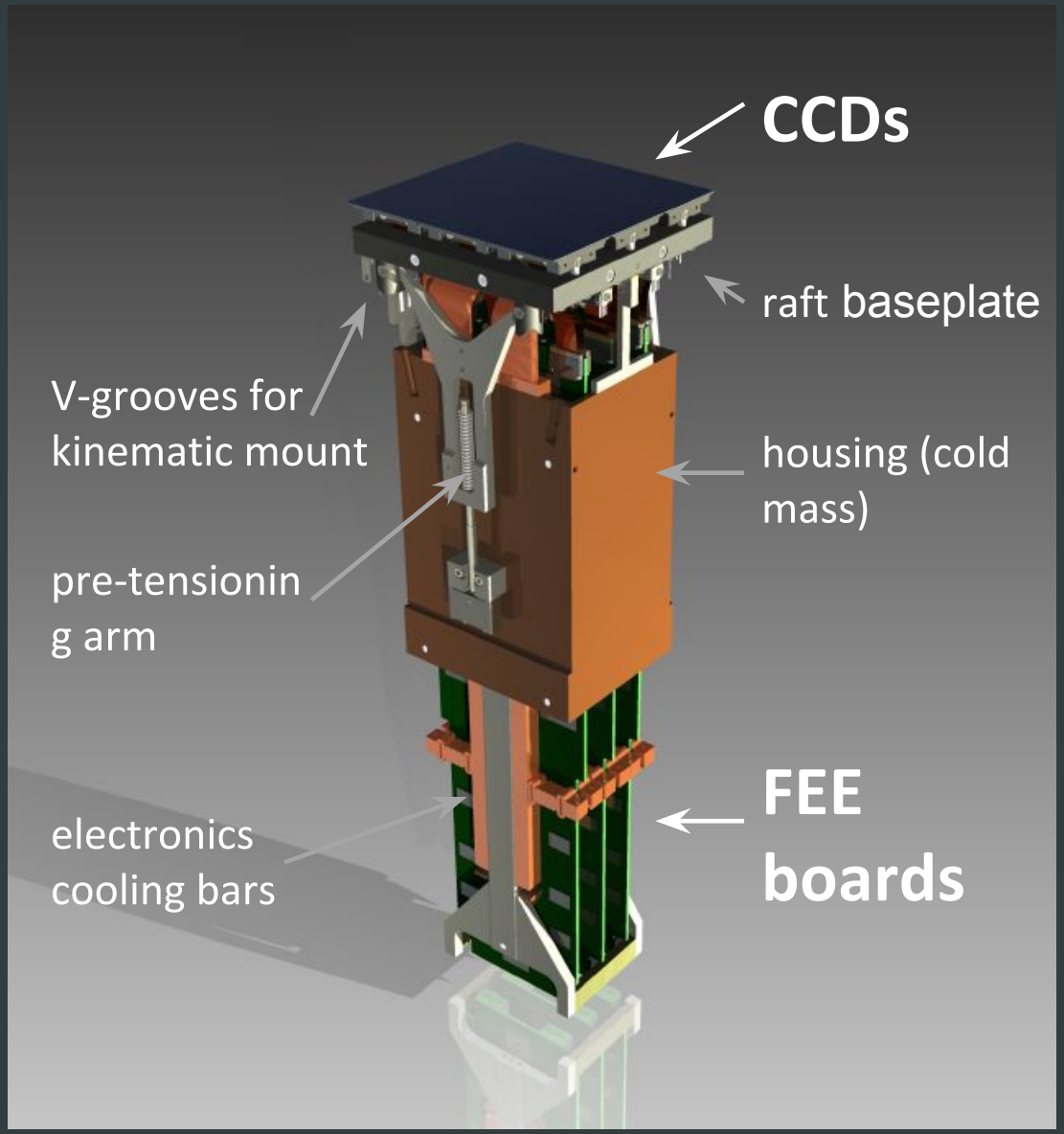
M51

LSST science focal plane

- 21 "rafts"
- 9 CCDs each
- Integrated readout electronics
- Inside vacuum cryostat
  - CCD temperature -100°C
  - Electronics -20°C



Raft Tower Module



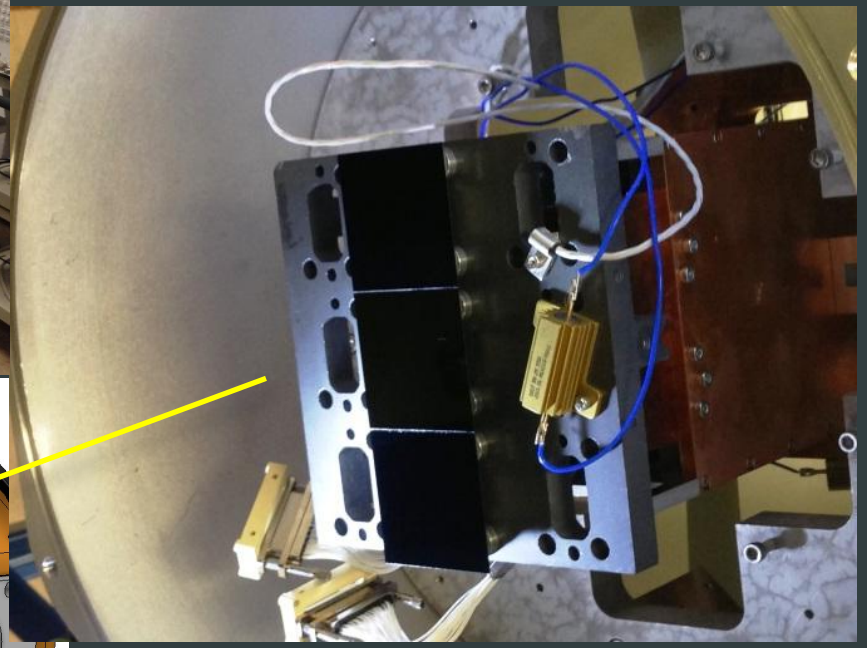
- Complete 144-Mpixel imager
- Provide bias, timing, and control signals for CCD operation
- Low noise analog signal processing
- Digitizing, multiplexing of pixel data
- Diagnostics
- Support sensors mechanically to meet strict coplanarity
- Thermal management of sensors and electronics
- 12.7 x 12.7 x 42cm^3; 12kg

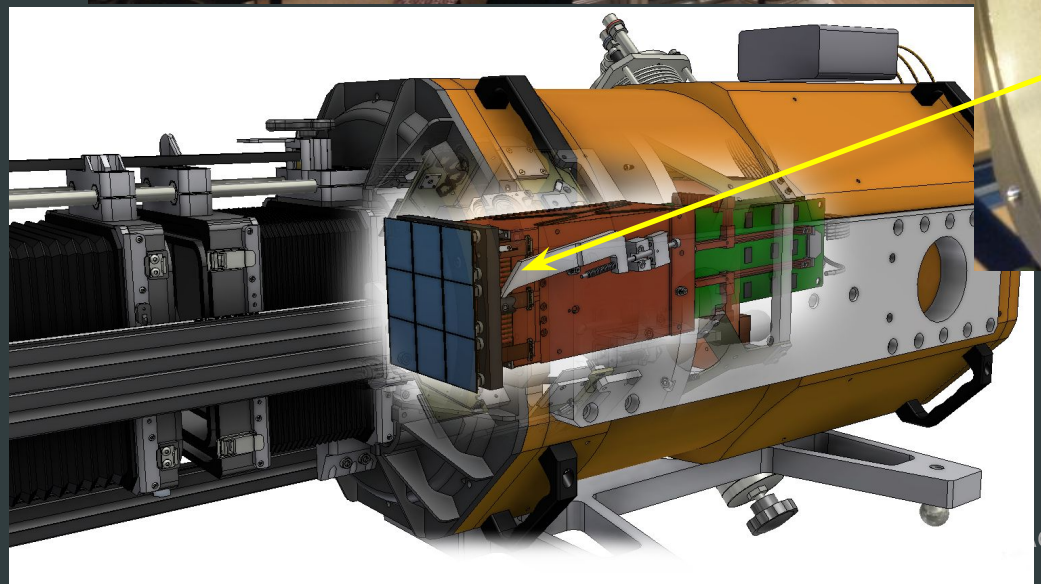
Photons in – bits out

BNL's deliverable

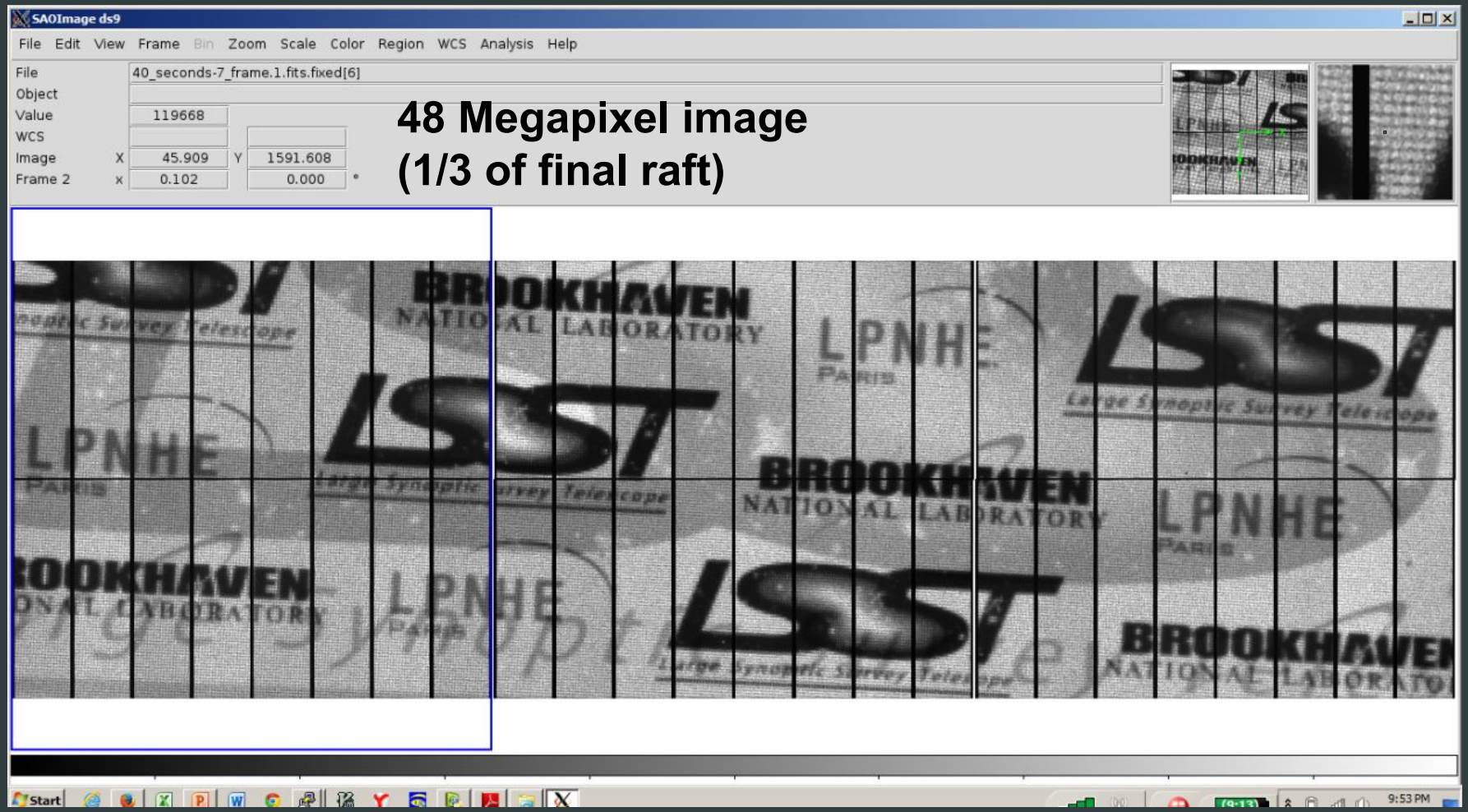
Raft tower module under construction

Testing in lab cryostat

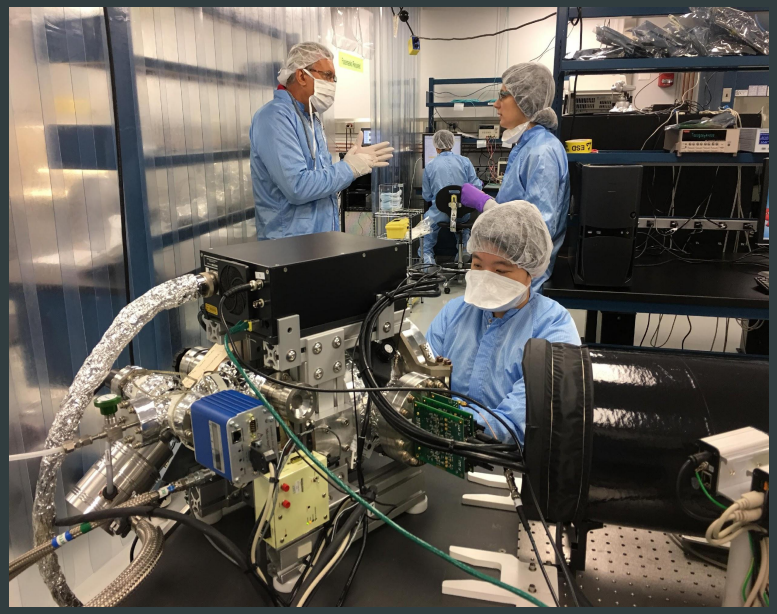




Performance: photons in to images out



Production of rafts commenced this summer...



CCD Specifications for each sensor

Status	Spec. ID	Description	Specification	Measurement
x	CCD-007	Read Noise	$< 8\,e^-$ rms	7.79–8.78 e^- rms
✓	CCD-008	Blooming Full Well	$< 175000\,e^-$	161498–170522 e^-
x	CCD-009	Nonlinearity	< 2%	max. fractional deviation from linearity: 3.5×10^{-2}
✓	CCD-010	Serial CTE	$> 1 - 5 \times 10^{-6}$	$1 - 2.53 \times 10^{-6} \pm 1.20 \times 10^{-5}$ (min. value)
x	CCD-011	Parallel CTE	$> 1 - 3 \times 10^{-6}$	$1 - 5.44 \times 10^{-4} \pm 3.53 \times 10^{-6}$ (min. value)
x	CCD-012	Active Imaging Area and Cosmetic Quality	< 0.5% defective pixels	defective pixels: 306336 (1.8993%)
...	CCD-012a	Bright Pixels	...	1640
...	CCD-012b	Dark Pixels	...	3753
...	CCD-012c	Bright Columns	...	151
...	CCD-012d	Dark Columns	...	0
...	CCD-012e	Traps	...	0
...	CCD-013	Crosstalk	< 0.19%	...
✓	CCD-014	Dark Current 95th Percentile	$< 0.2\,e^-\,s^{-1}$	$1.80 \times 10^{-1} e^-\,s^{-1}$
✓	CCD-021	u Band QE	> 41%	62.4%
✓	CCD-022	g Band QE	> 78%	88.6%
✓	CCD-023	r Band QE	> 83%	90.6%
✓	CCD-024	i Band QE	> 82%	94.9%
✓	CCD-025	z Band QE	> 75%	88.3%
✓	CCD-026	y Band QE	> 21%	31.3%
✓	CCD-027	PRNU	< 5%	max. variation = 4.06% at 350 nm
✓	CCD-028	Point Spread Function	$\sigma < 5\mu$	$4.84\,\mu$

Conclusions

- LSST will be the premier astronomical project of the 21st century
- BNL is taking a big part