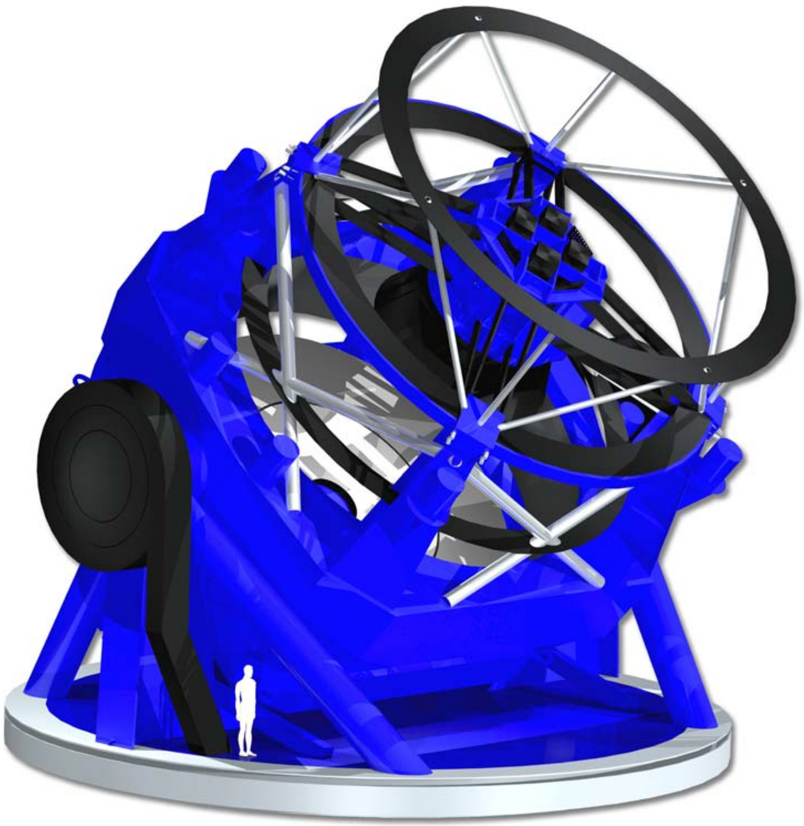


The Large Synoptic Survey Telescope Project

Steven M. Kahn

SLAC Summer Institute

August 4, 2005

Large Synoptic Survey Telescope

What is the LSST?

* The LSST will be a large, wide-field ground-based telescope designed to provide time-lapse digital imaging of faint astronomical objects across the entire visible sky every few nights.

* LSST will enable a wide variety of complementary scientific investigations, utilizing a common database. These range from searches for small bodies in the solar system to precision astrometry of the outer regions of the galaxy to systematic monitoring for transient phenomena in the optical sky.

* Of particular interest for cosmology, LSST will provide strong constraints on models of dark matter and dark energy through weak lensing.

The LSST Consortium

SLAC

RESEARCH CORPORATION

THE UNIVERSITY OF ARIZONA
TUCSON ARIZONA

NOAO

BROOKHAVEN NATIONAL LABORATORY

JOHNS HOPKINS UNIVERSITY

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UCDAVIS
University of California, Davis

VE RI TAS

UNIVERSITY OF WASHINGTON

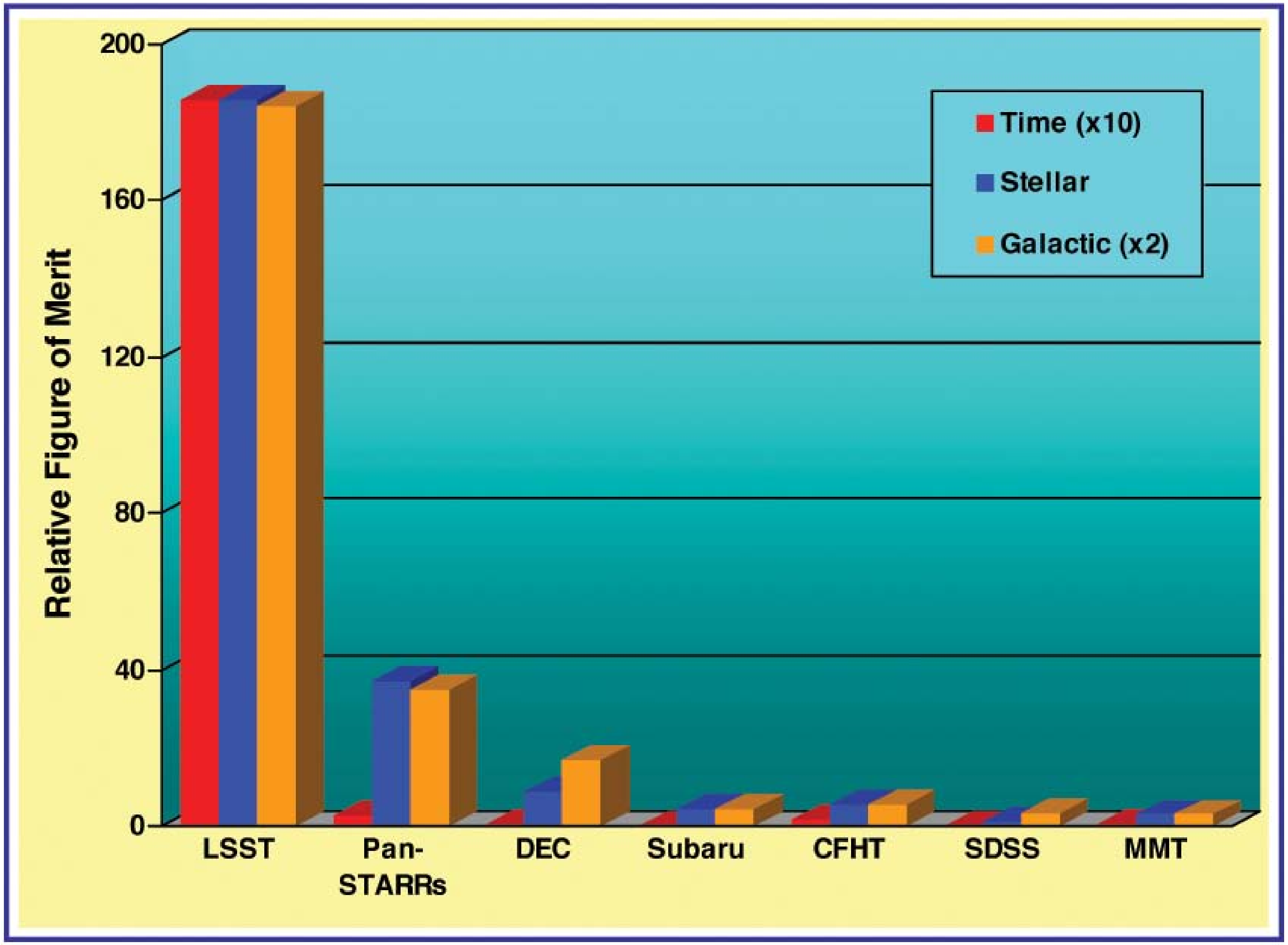
LELAND STANFORD JUNIOR UNIVERSITY
DIE LUFT DER FREIHEIT WEHT
1891

LSST
Large Synoptic Survey Telescope

The Essence of LSST is Deep, Wide, Fast!

* Dark matter/dark energy via weak lensing
* Dark matter/dark energy via supernovae
* Dark energy via baryon acoustic oscillations
* Galactic Structure encompassing local group
* Dense astrometry over 20,000 sq.deg: rare moving objects
* Gamma Ray Bursts and transients to high redshift
* Gravitational micro-lensing
* Strong galaxy & cluster lensing: physics of dark matter
* Multi-image lensed SN time delays: separate test of cosmology
* Variable stars/galaxies: black hole accretion
* QSO time delays vs z: independent test of dark energy
* Optical bursters to 25 mag: the unknown
* 5-band 27 mag photometric survey: unprecedented volume
* Solar System Probes: Earth-crossing asteroids, Comets, TNOs

Relative Survey Power



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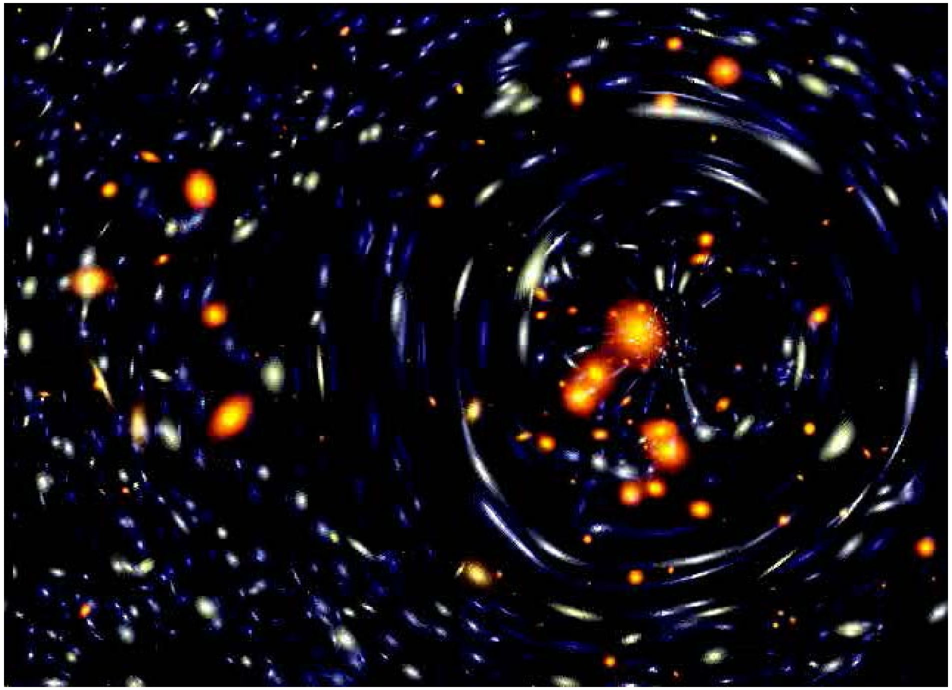
LSST and Dark Energy

* LSST will measure 250,000 resolved high-redshift galaxies per square degree! The full survey will cover 18,000 square degrees.

* Each galaxy will be moved on the sky and slightly distorted due to lensing by intervening dark matter. Using photometric redshifts, we can determine the shear as a function of z.

* Measurements of weak lensing shear over a sufficient volume can determine DE parameters through constraints on the expansion history of the universe and the growth of structure with cosmic time.



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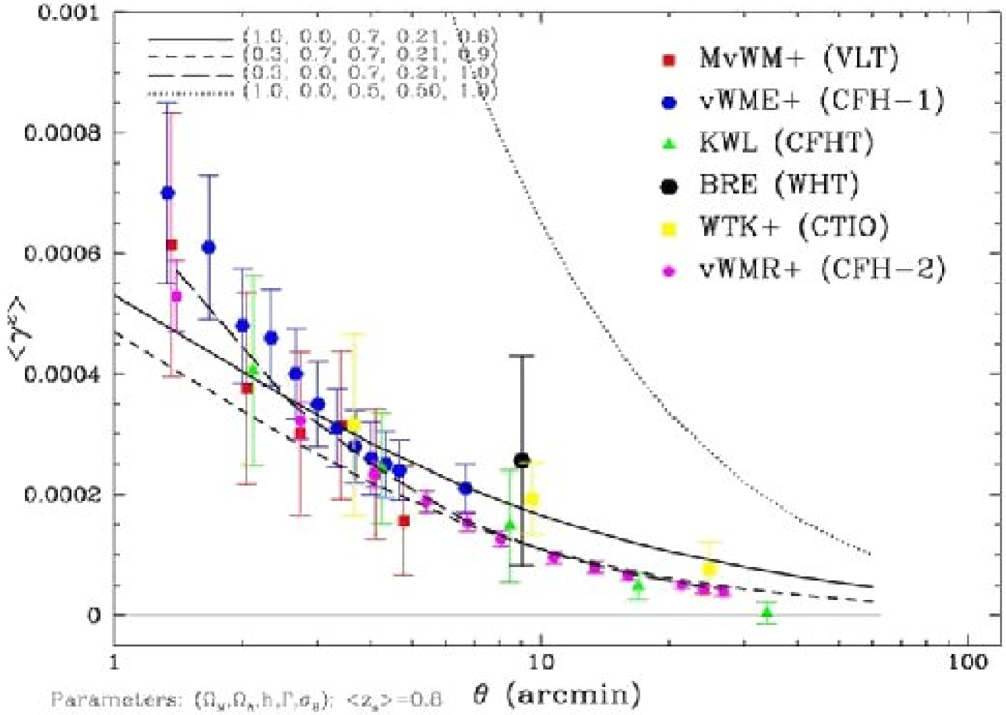
Results from completed surveys

Since the first detections reported in spring 2000, many cosmic shear measurements have been published.

Results in 2001



In general there is good agreement between surveys!

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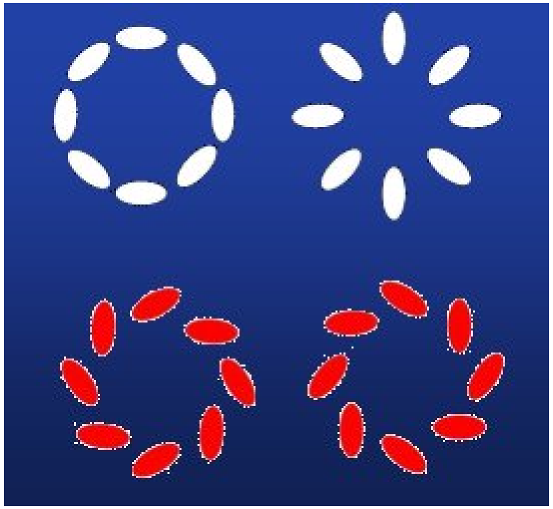
Dealing with systematics

The shear is a spin-2 field and consequently we can measure two independent ellipticity correlation functions. The lensing signal is caused by a gravitational potential and therefore should be curl-free. We can project the correlation functions into one that measures the divergence and one that measures the curl: E-B mode decomposition.

E-mode (curl-free)

B-mode (curl)



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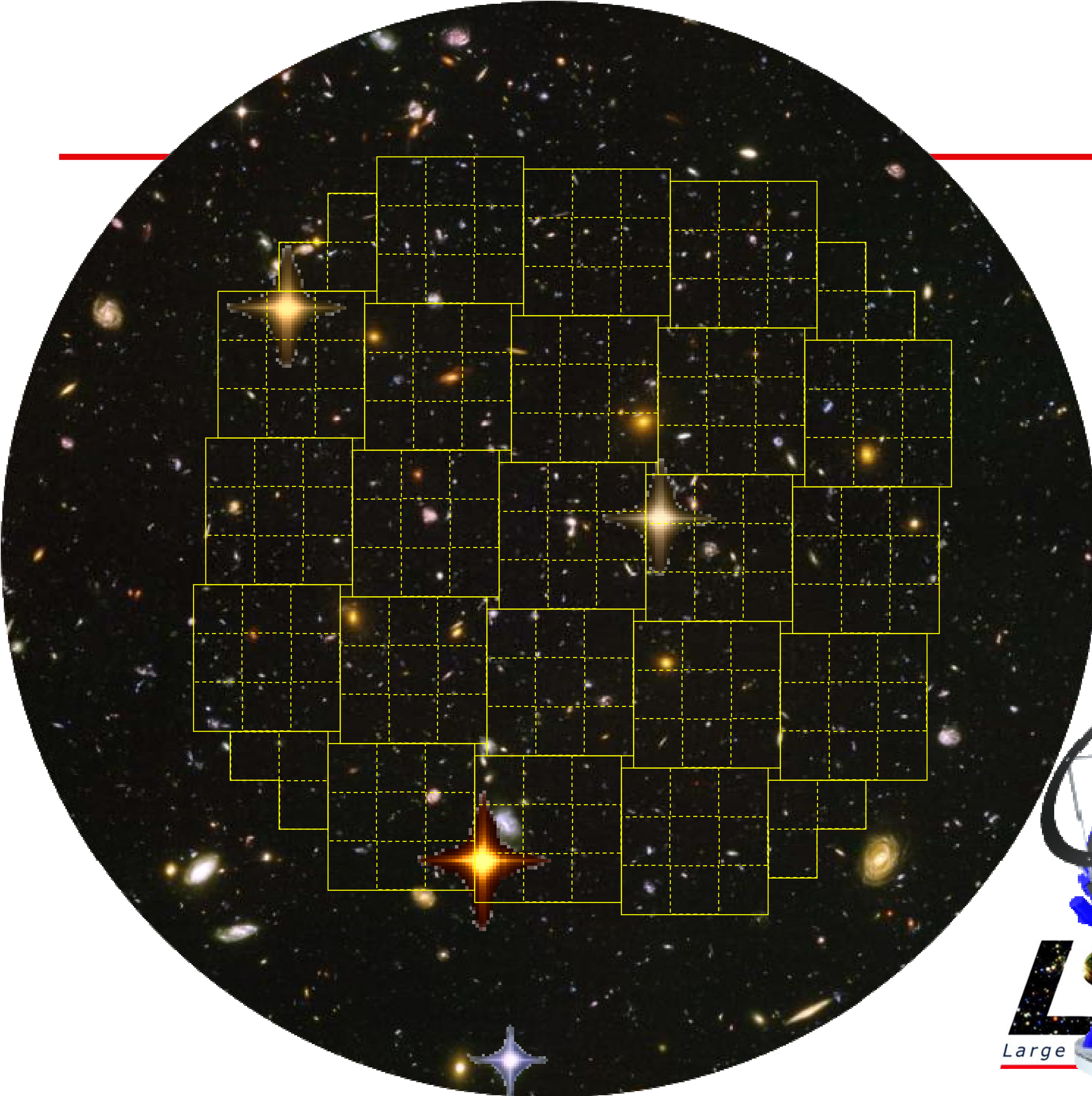

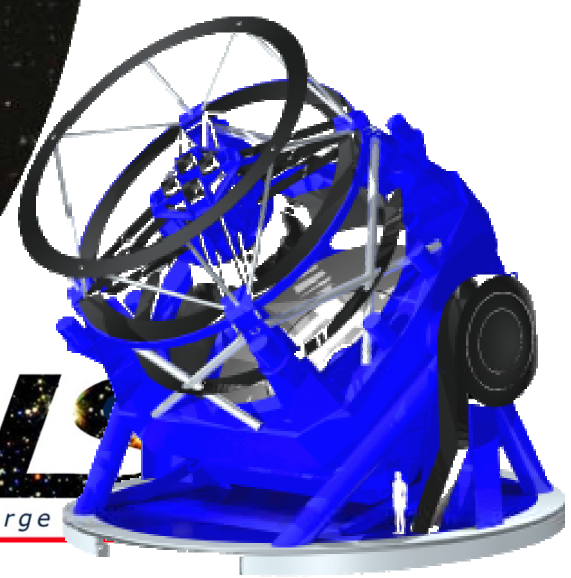

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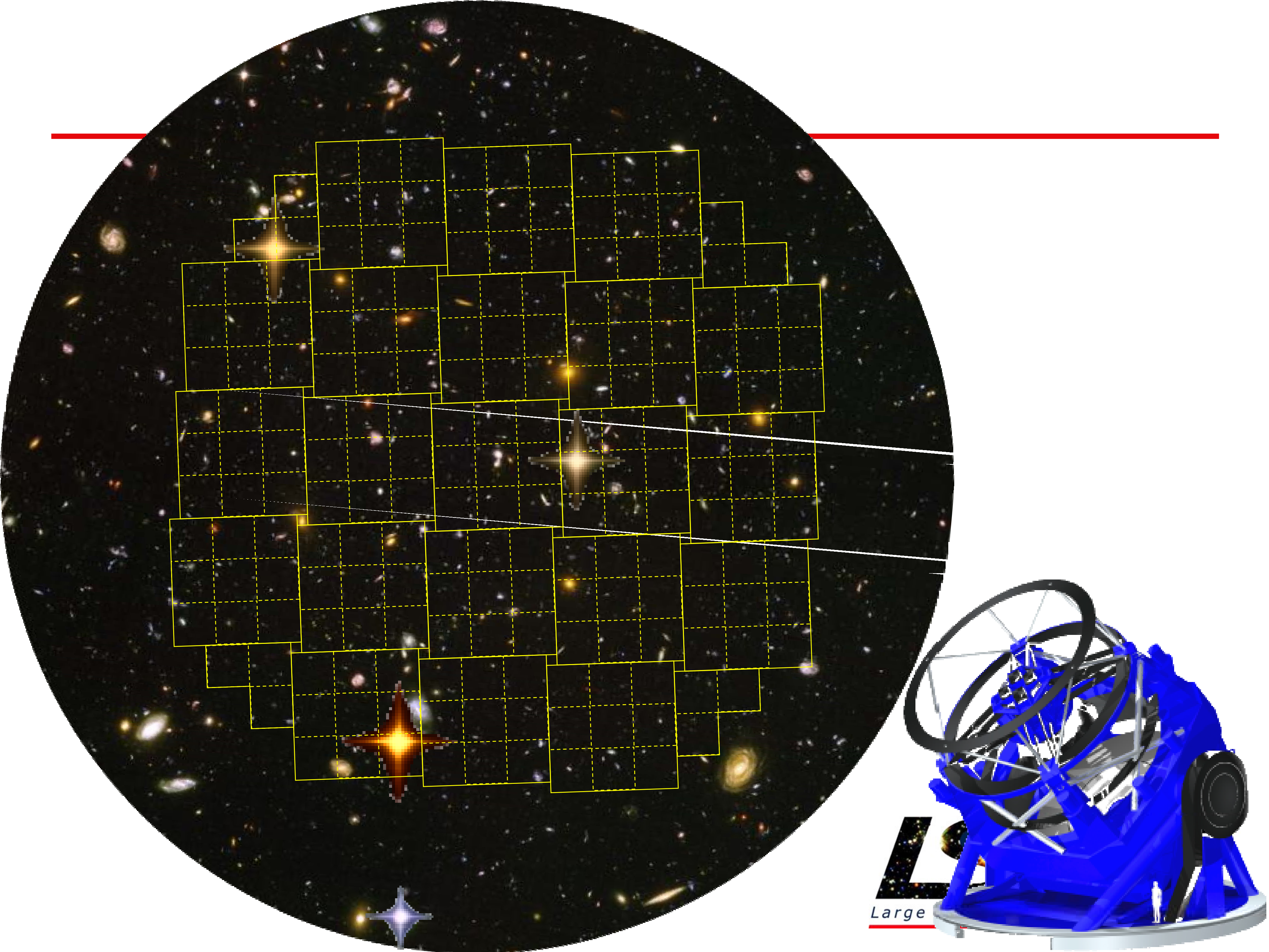
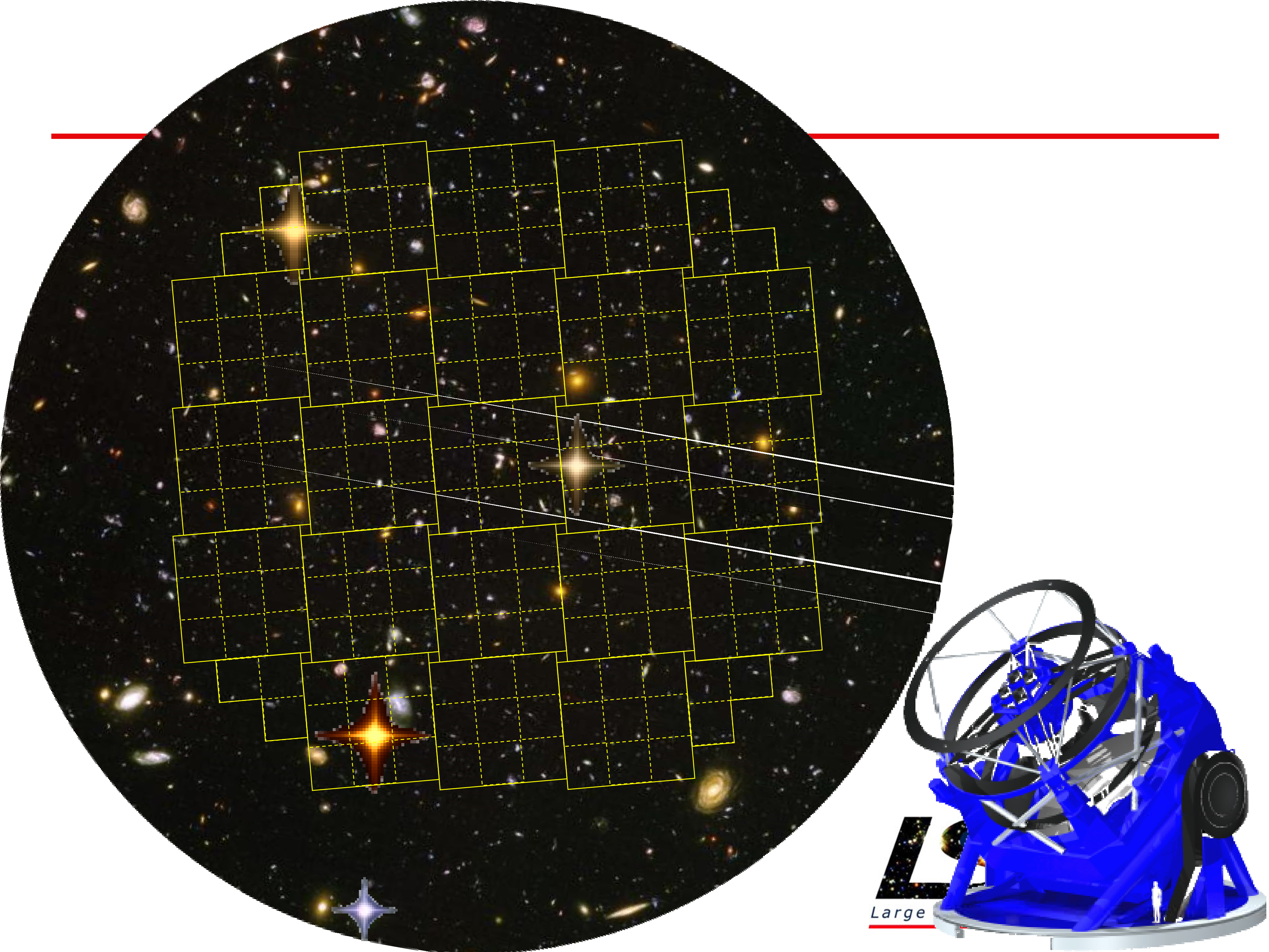
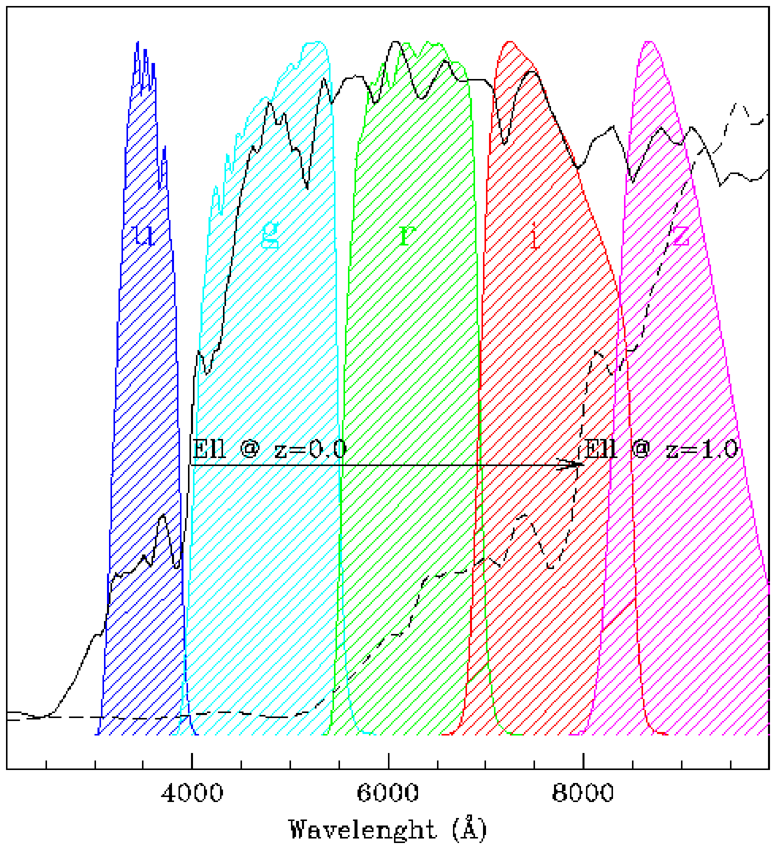

Large



Color-redshift



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LSST and Dark Energy

* The LSST Weak Lensing Survey will constrain DE via a variety of related, but different techniques:

  – *Shear Tomography:* The measurement of the large-angle shear power spectrum and higher moment correlations. With photo-z's, these can be measured as a function of cosmic time. Combining the shear power spectrum with the CMB fluctuation spectrum places constraints on w and w_a.

  – *Cluster Counts Versus Redshift:* The measurement of the number density of clusters as a function of mass and redshift - $dN/dMdz$.

* These techniques have different dependences and different systematics. Probing the Concordance Cosmological Model in multiple ways is probably the best means we have of discovering new underlying physics.

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Cosmological Constraints from Weak Lensing Shear

Underlying physics is extremely simple General Relativity: FRW Universe plus the deflection formula. Any uncertainty in predictions arises from (in)ability to predict the mass distribution of the Universe

Method 1: Operate on large scales in (nearly) linear regime. Predictions are as good as for CMB. Only "messy astrophysics" is to know redshift distribution of sources, which is measurable using photo-z's.

Method 2: Operate in non-linear, non-Gaussian regime. Applies to shear correlations at small angle. Predictions require N-body calculations, but to ~1% level are dark-matter dominated and hence purely gravitational and calculable with foreseeable resources.

Hybrids: Combine CMB and weak lens shear vs redshift data. Cross correlations on all scales.

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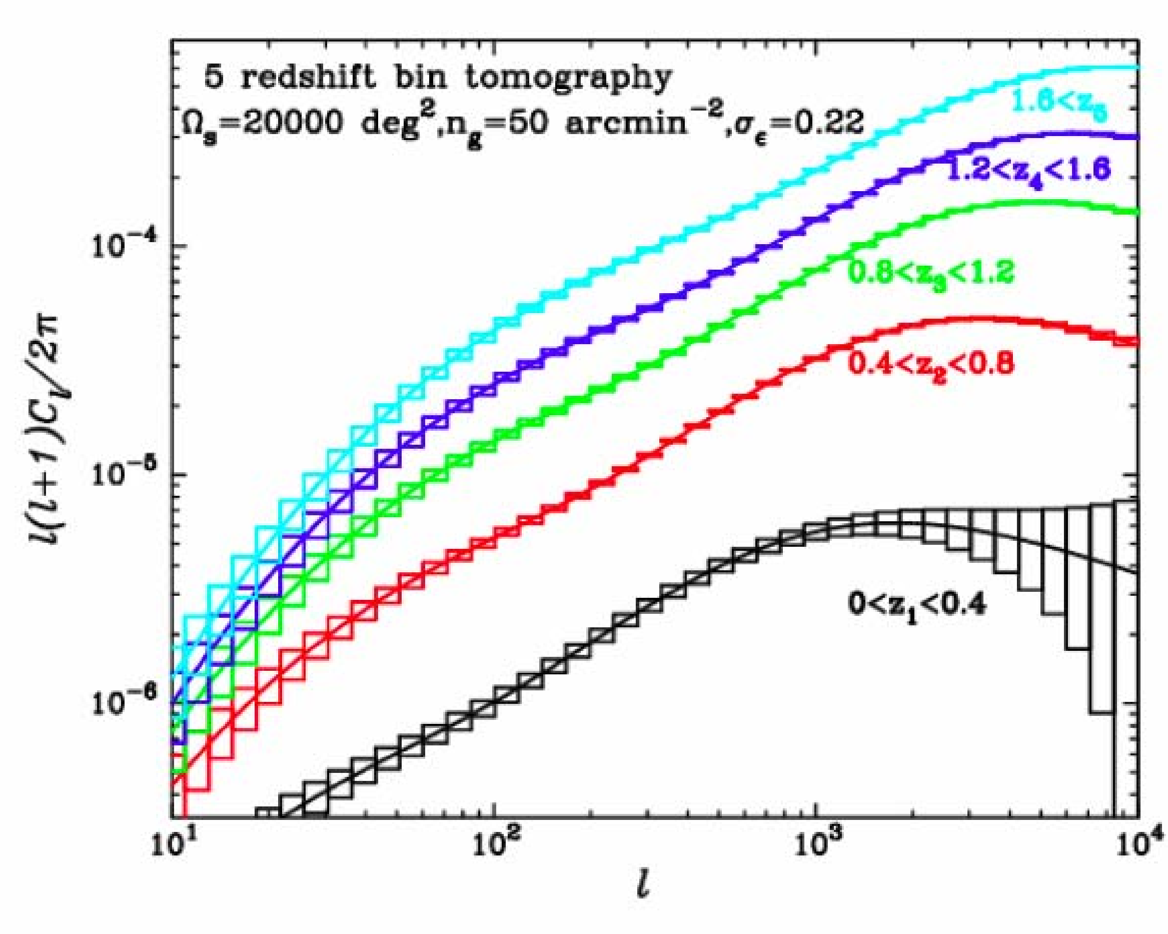
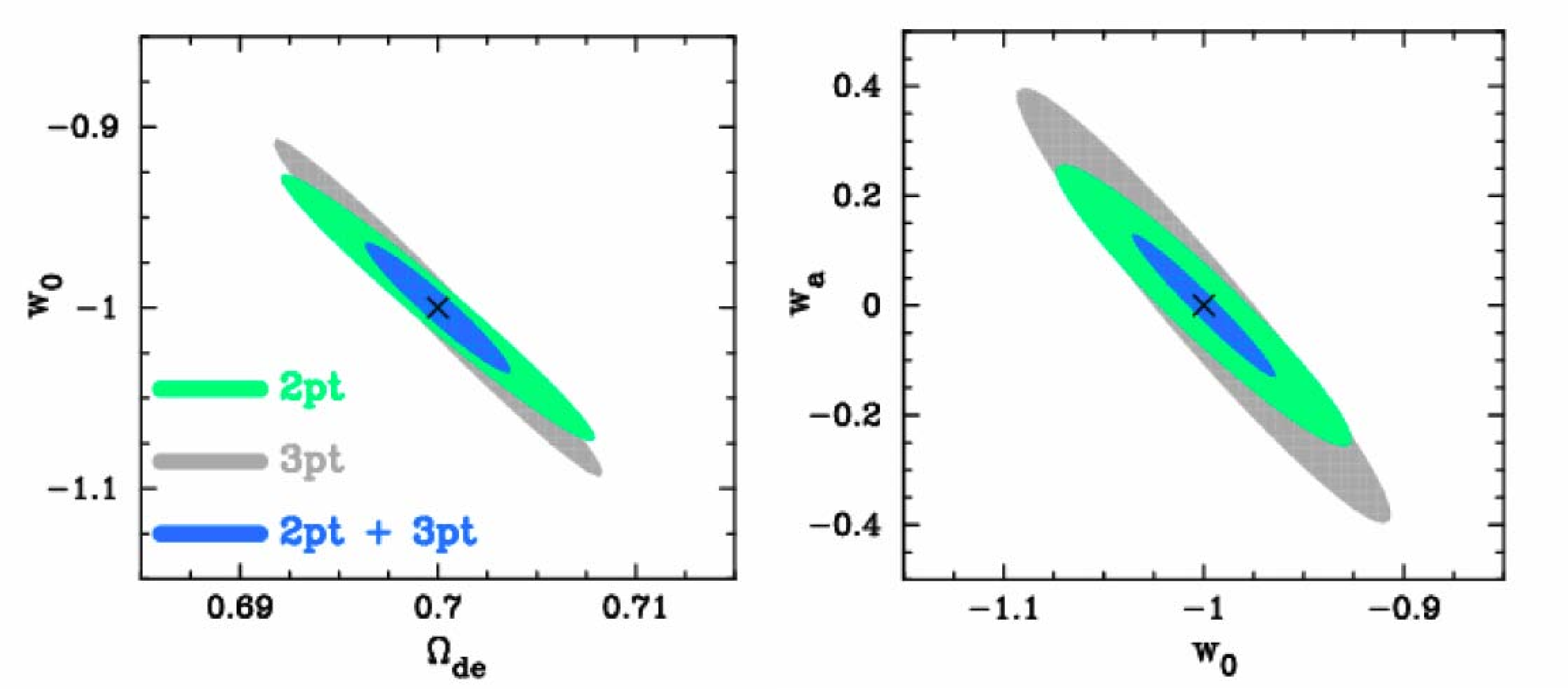
LSST Measurements of Cosmic Shear



From Takada et al. (2005)

Constraints on DE Parameters



From Takada et al. (2005)

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Cluster Counting

$$\frac{dN}{d\Omega dz}(w) = \frac{dV}{d\Omega dz} \int_{M_{\text{limit}}(z)}^{\infty} C(M,z) \frac{dn}{dM}(M,z \mid w)\, dM$$

* The mass function is steep and exponentially sensitive to errors in $M_{\text{limit}}(z)$ and uncertainty in $M(\text{observables},z)$.

* Measure mass function, determine $M_{\text{limit}}(z)$ from LSST cluster survey, devise a test that is insensitive to the limiting mass.

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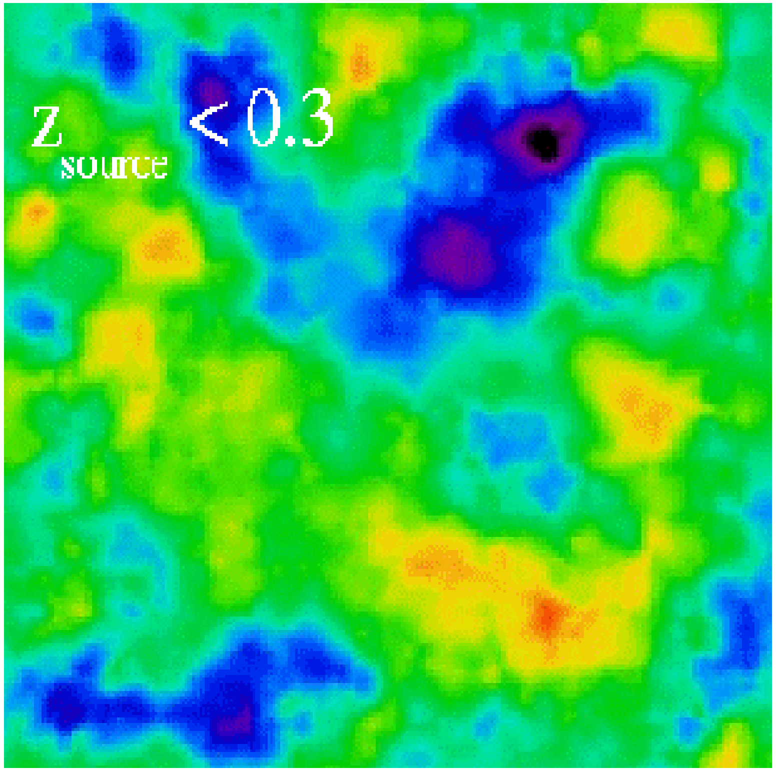
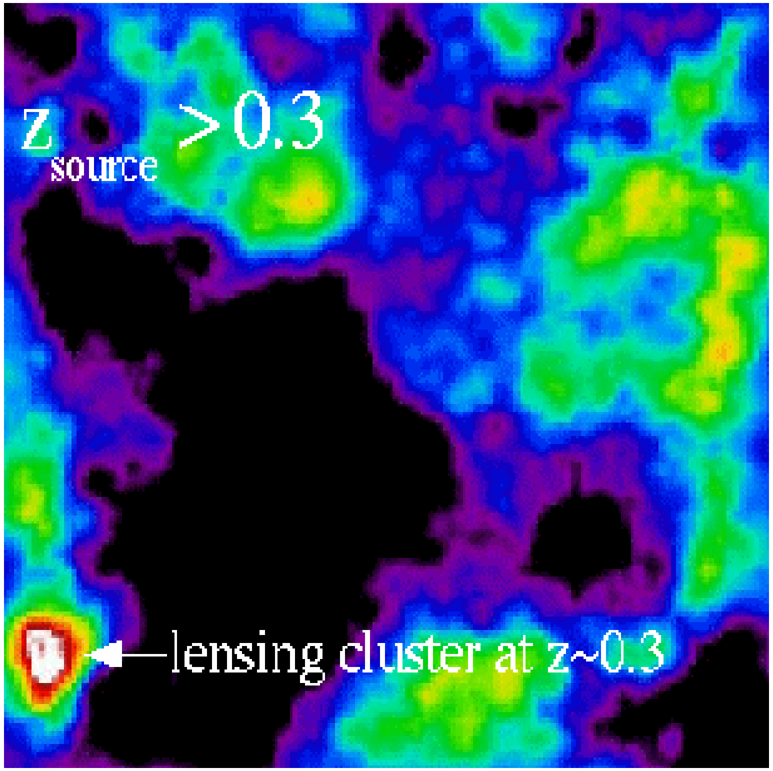
3D Mass Tomography





From Wittman et al. 2003.

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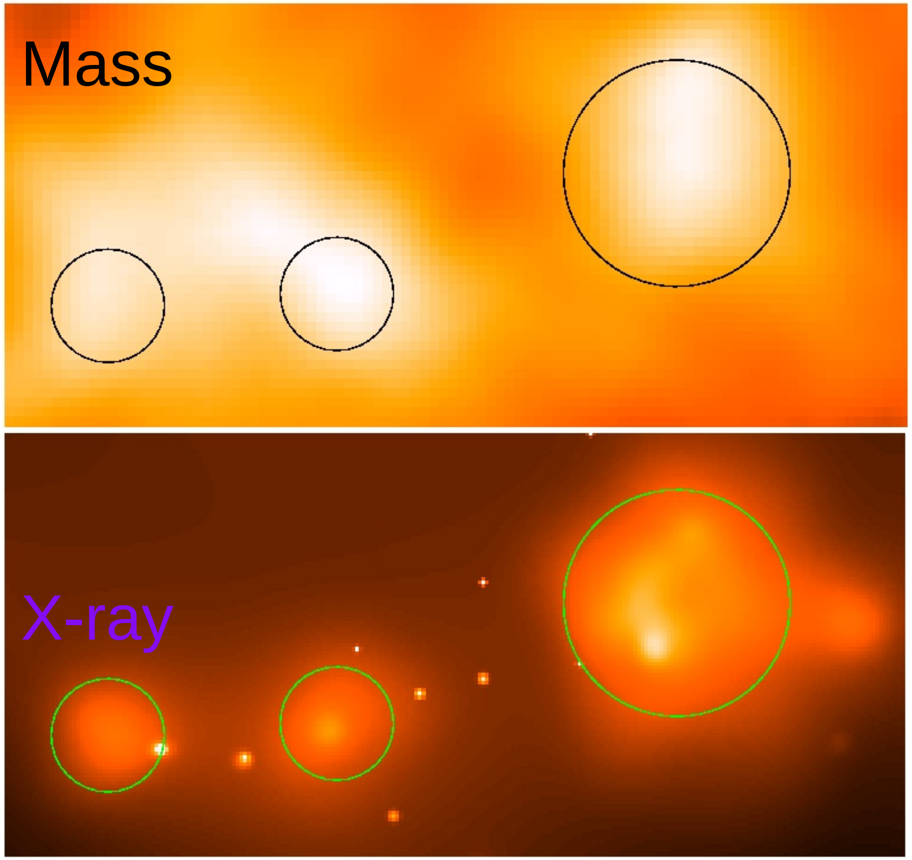
X-ray follow-up



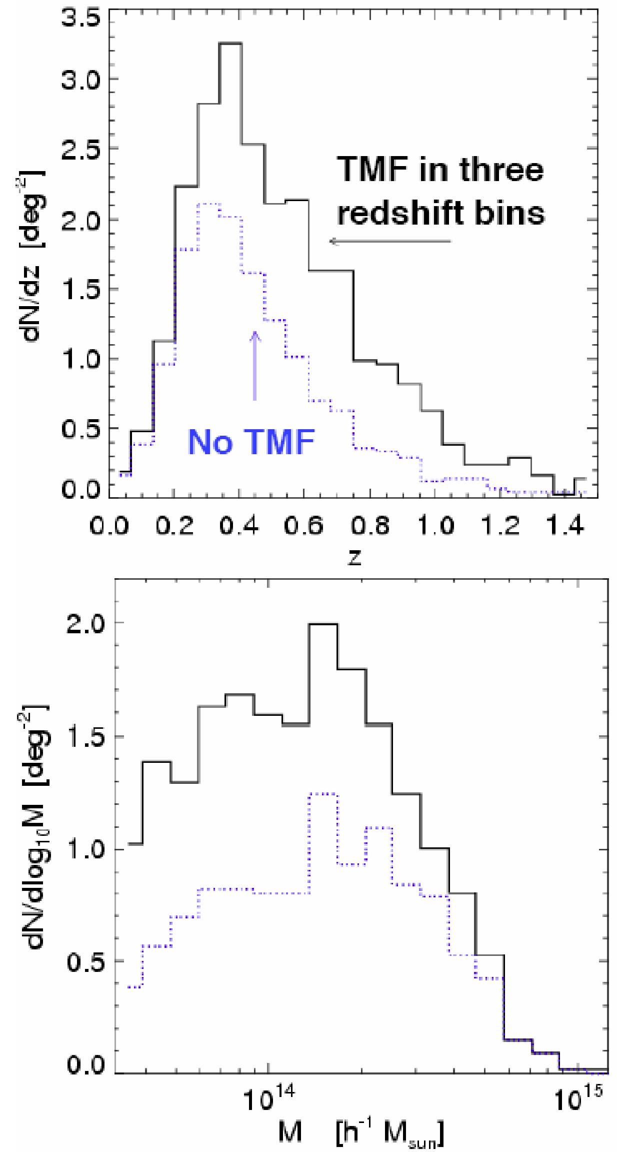
Courtesy Tony Tyson and the DLS Project Team

Cluster Counting Via WL Tomograhpy

* *dN/dMdz* constrains DE models via the dependences on the co-moving volume element, *dV/dΩdz,* and on the exponential growth of structure, *δ(z)*.

* Since WL measures DM mass directly, it does not suffer by the various forms of baryon bias and uncertainties in gas dynamical processes.

* With a sky coverage of 18,000 square degrees, LSST will find 200,000 clusters. A sample this size will yield a measurement of *w* to 2-3%.

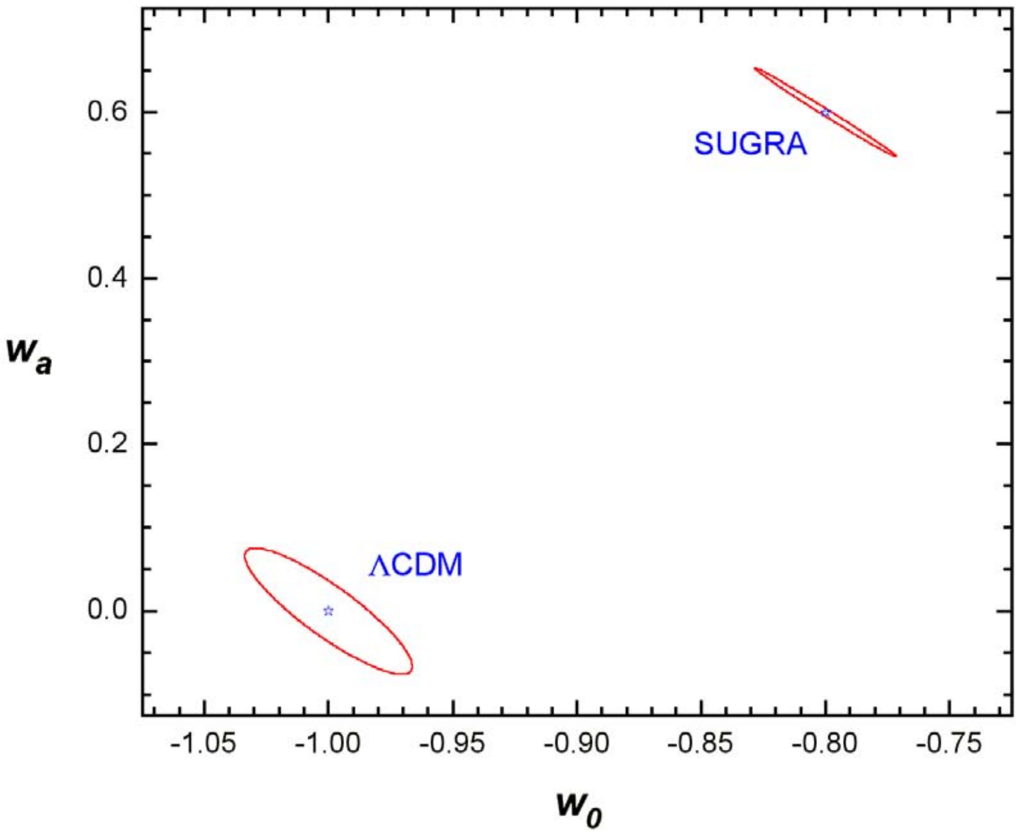


From Haiman et al. (2005)

LSST Dark Energy Constraints from Cluster Analysis

$p/\rho = w_0 + w_a (1\text{-}a)$

$a = (1+z)^{-1}$



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LSST SNe: Std Observations

* SNe from standard survey observations
  - ~250,000 Type Ia SNe found per year
  - Redshift range $0.1 < z < 0.8$
  - All followed with ~5 day cadence in one band (r), with 3 additional bands providing important color information for reddening, etc.
  - Use host photo-z's of both the parent galaxies and the SNe themselves

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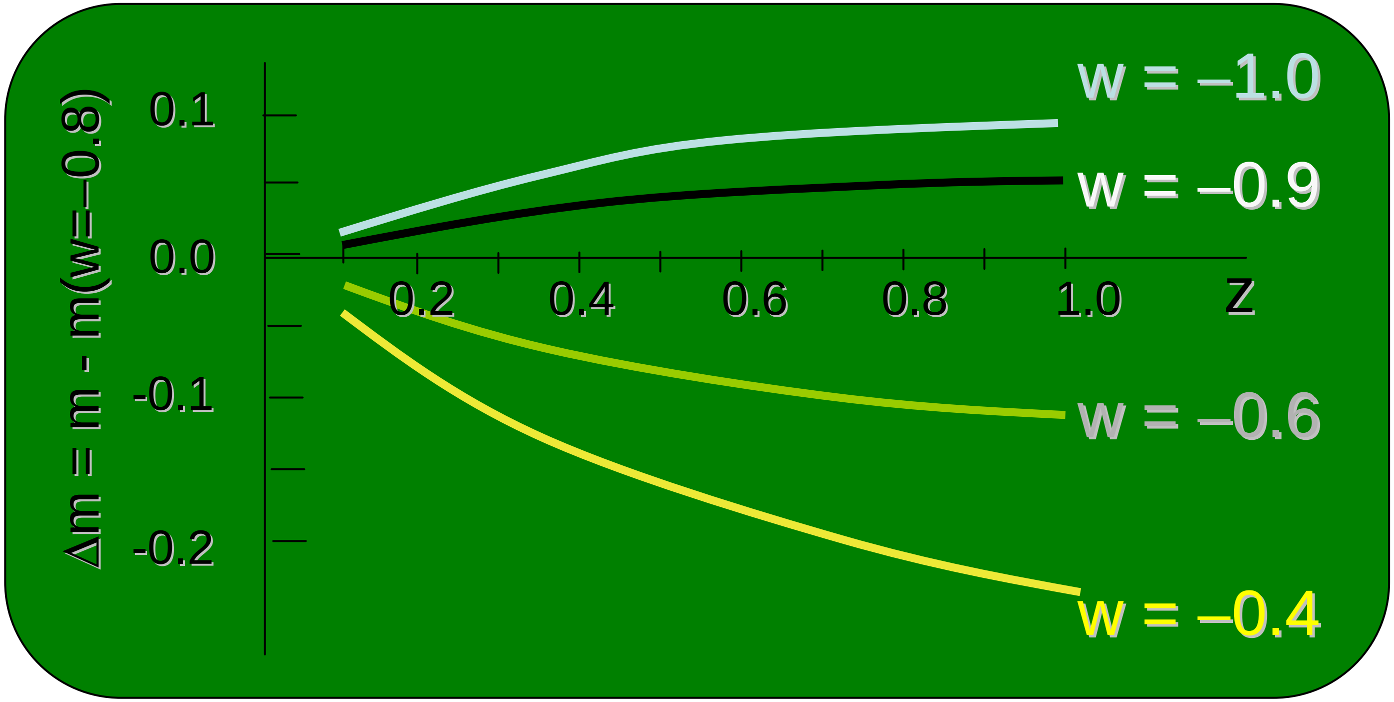
Equation of State Dependence



Difference in apparent SN brightness vs. z

Ω_Λ=0.73*, flat cosmology

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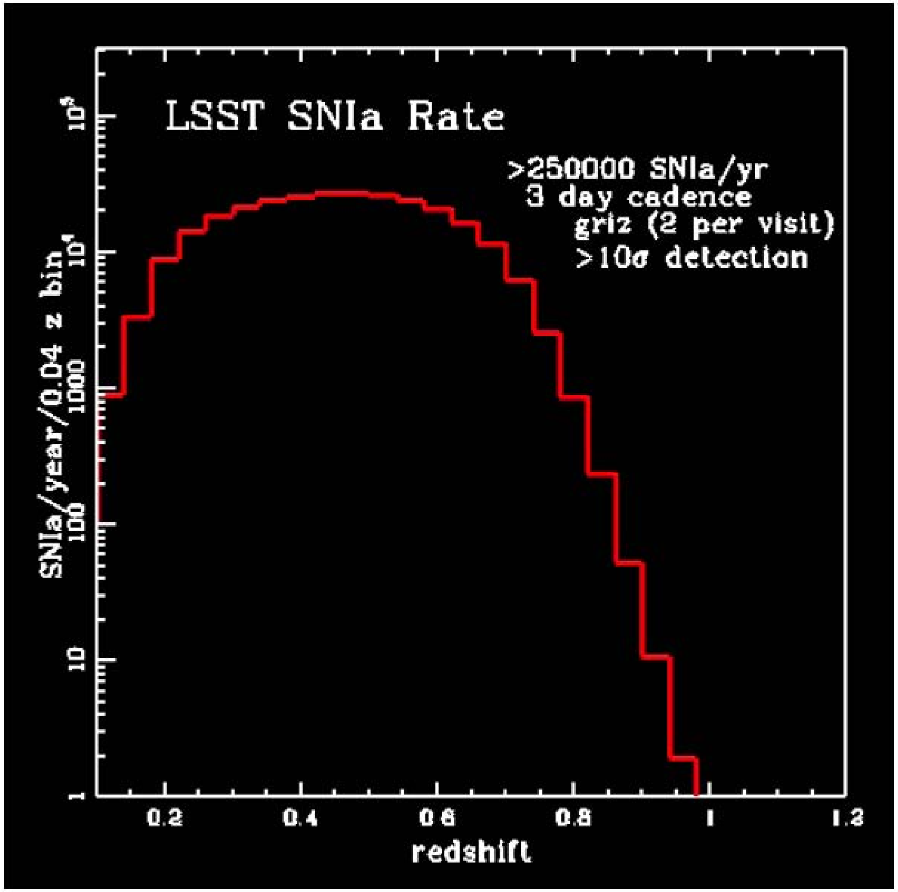
LSST SN Ia Redshift Distribution



From Garnavich et al. (2005)

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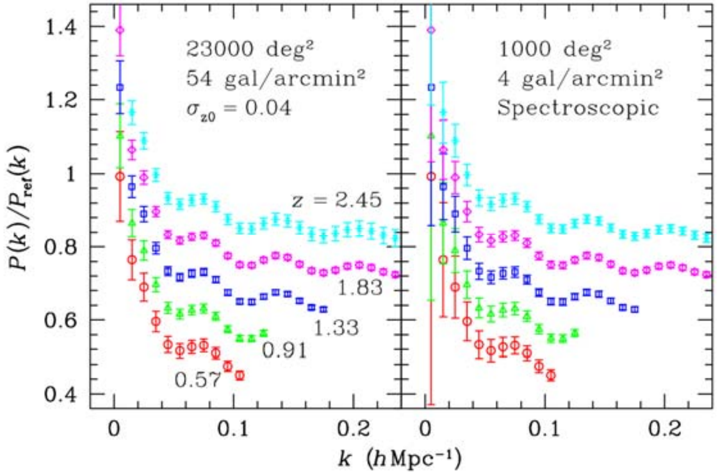
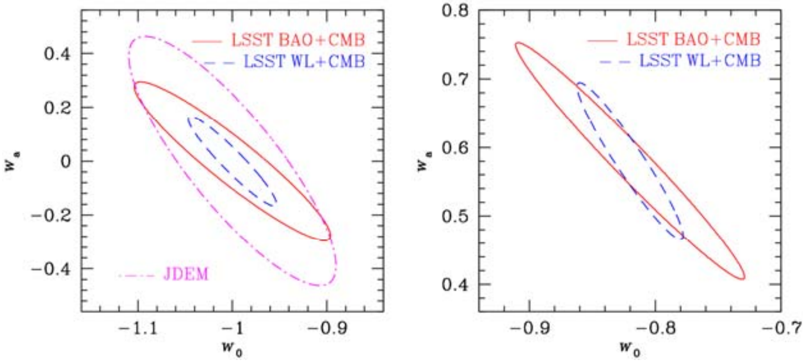
Baryon Acoustic Oscillations

* Baryon acoustic oscillations in the early universe leave a signature in the matter power spectrum.
* This has been detected at low redshift with SDSS.
* At higher redshift, more peaks are discernible.
* BAO's constrain DE via an angular diameter redshift relation.
* LSST is competitive with true redshift surveys because of the huge number of galaxies surveyed.





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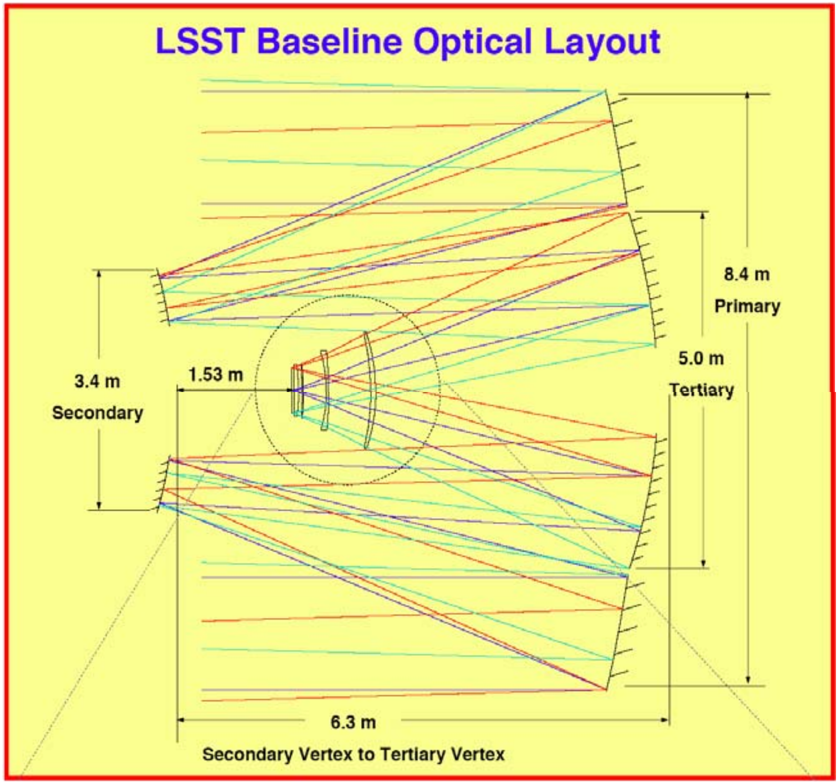
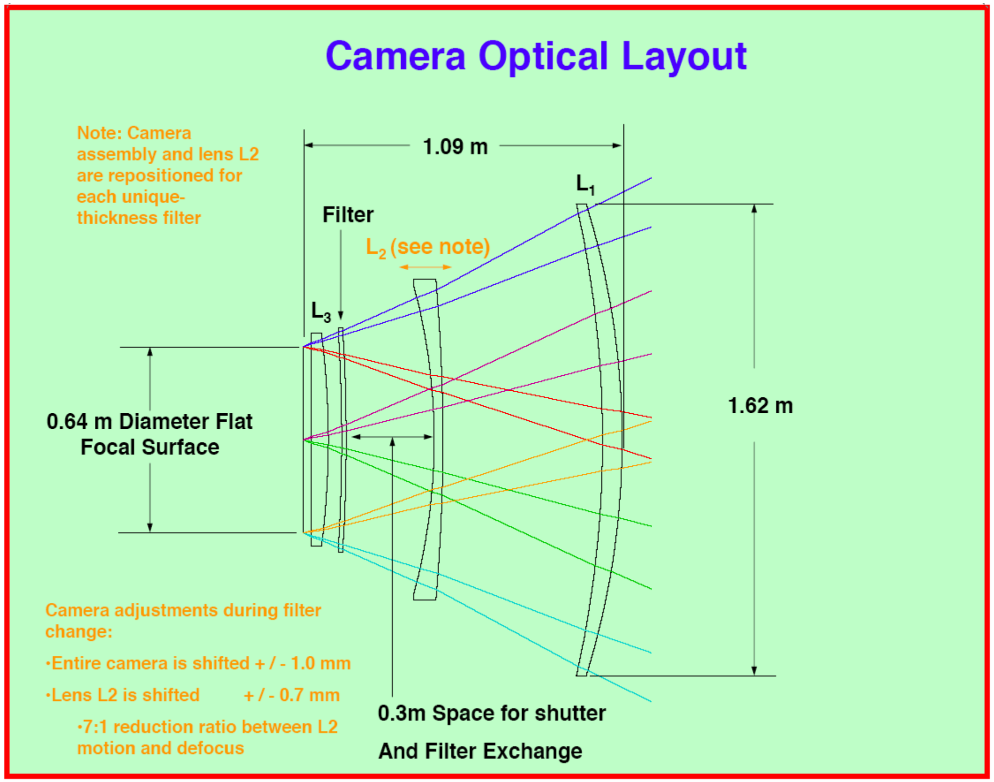
LSST Optical Design





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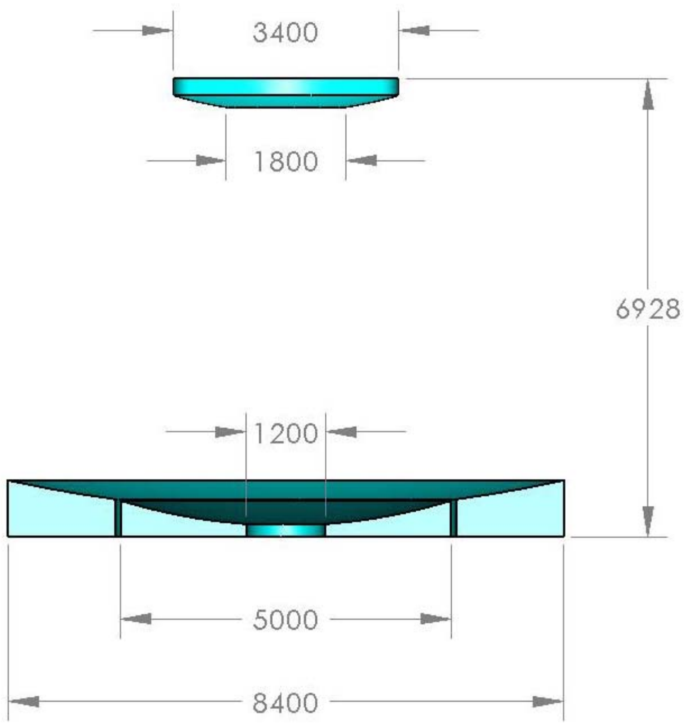
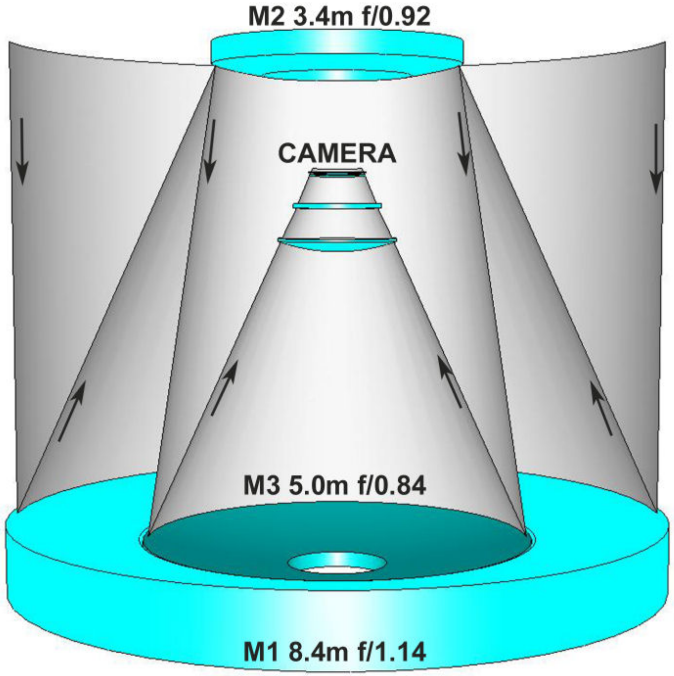
Optics Configuration

* LSST Adopted Baseline Optical Design
* M1 and M3 Surfaces Are “Continuous” at Edge





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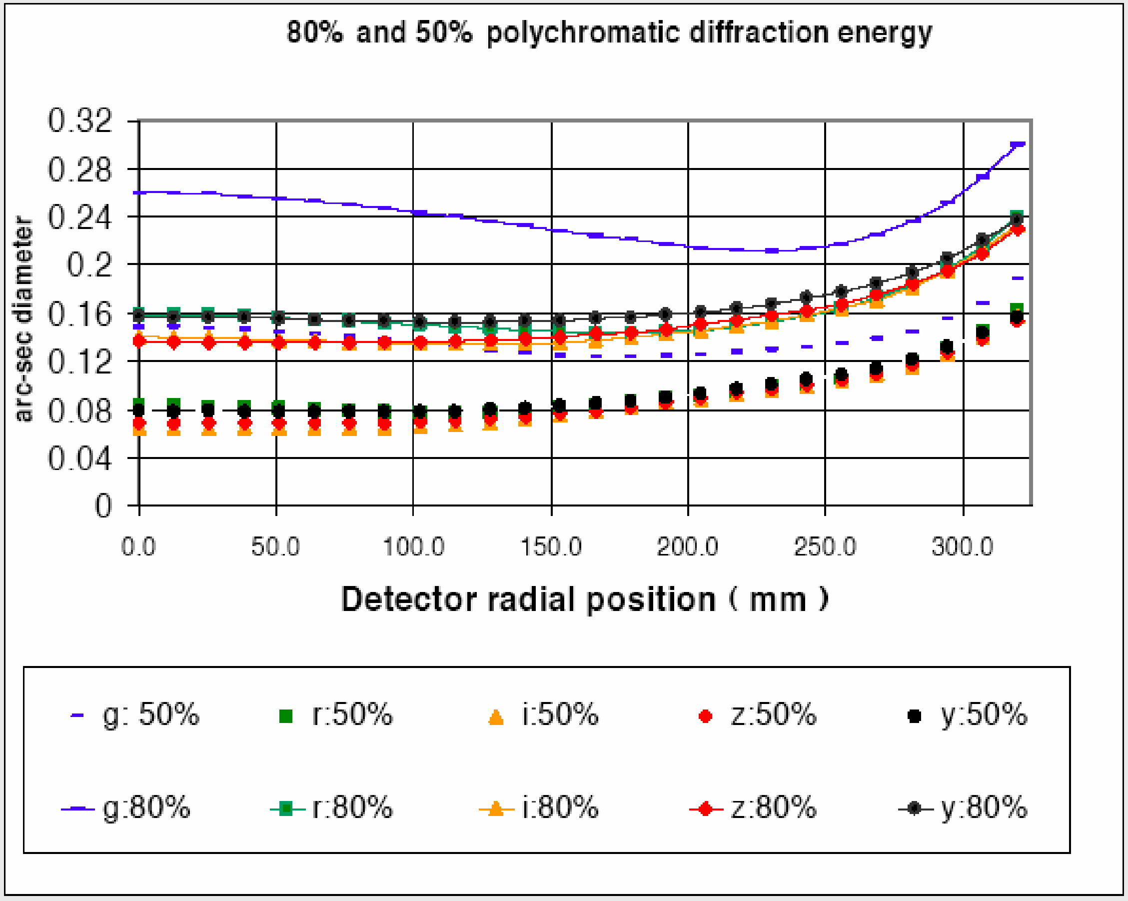
Crisp Images Over Entire Field

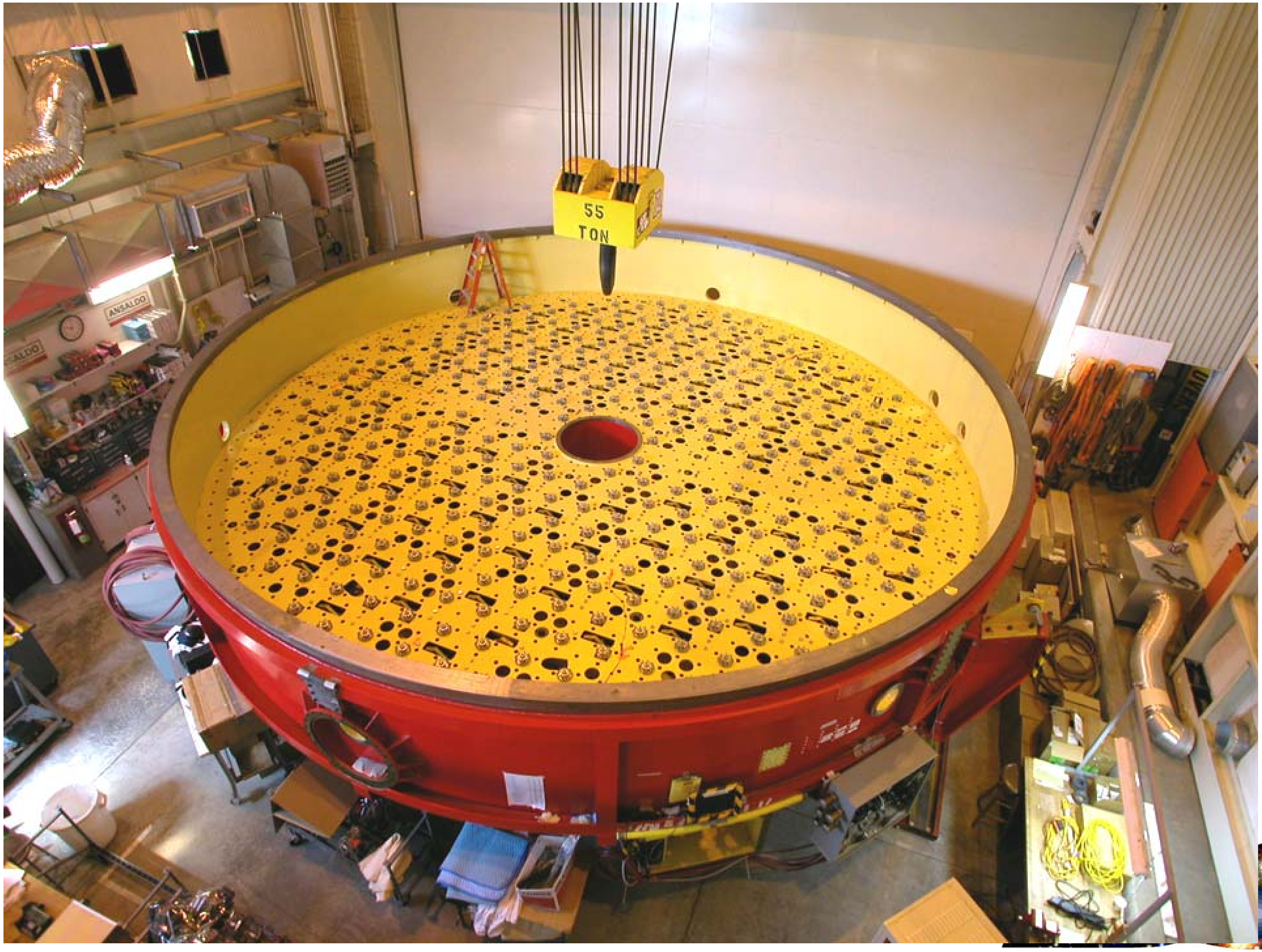


L. Seppala, LLNL

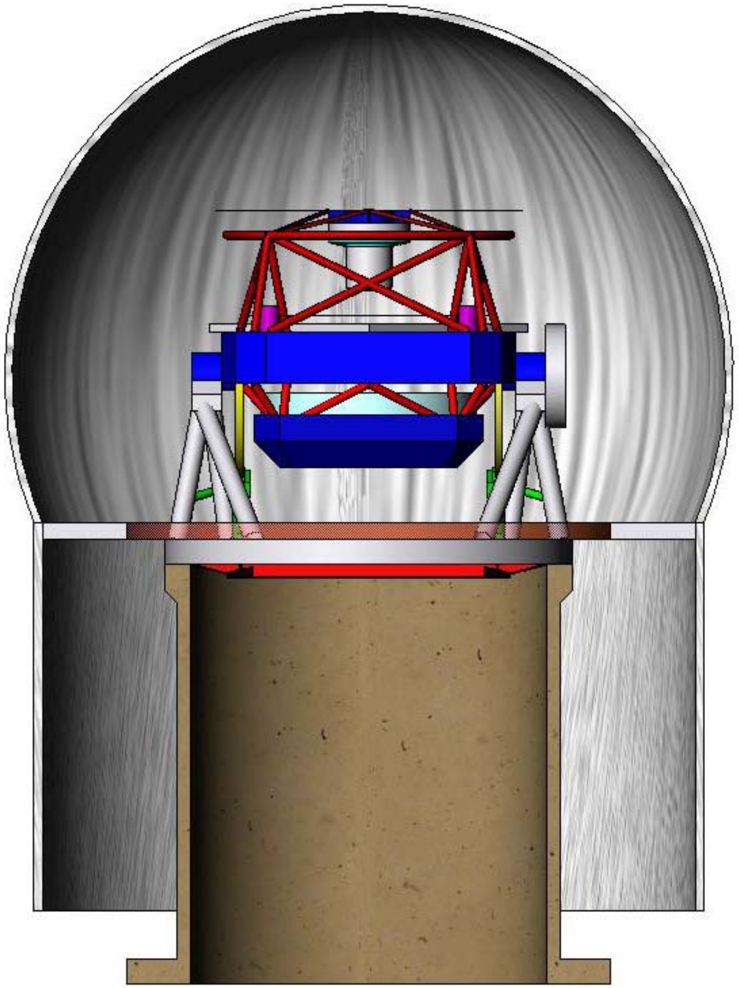
Large Synoptic Survey Telescope

Spin Casting of large optics at the U of A

The LBT 8.4m mirror cell with active optics



LSST Telescope Mount and Dome Concept



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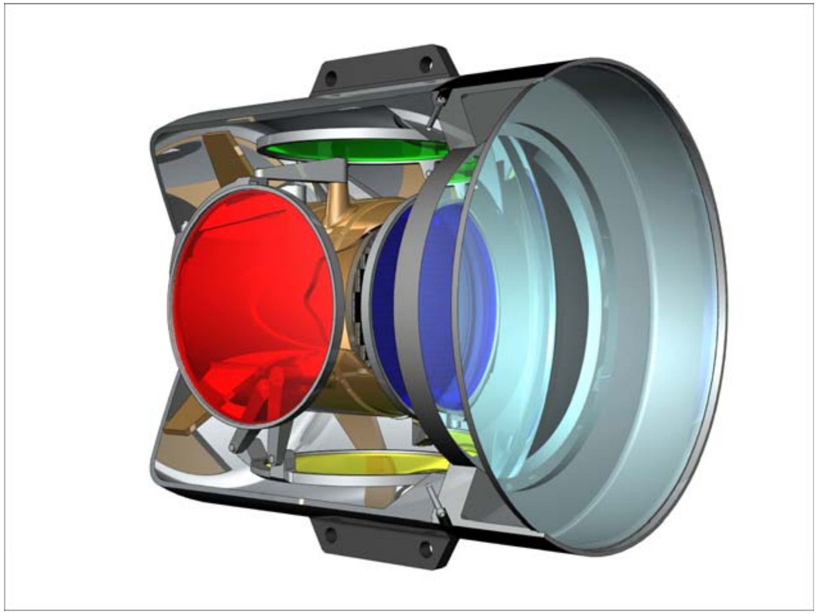
LSST Camera



Large Synoptic Survey Telescope

Camera Challenges

* Detector requirements:
  – 10 μm pixel size
  – Pixel full-well > 90,000 e^-
  – Low noise (< 5 e^- rms), fast (< 2 sec) readout (→ < –30 C)
  – High QE 400 – 1000 nm
  – All of above exist, but not simultaneously in one detector
* Focal plane position precision of order 3 μm
* Package large number of detectors, with integrated readout electronics, with high fill factor and serviceable design
* Large diameter filter coatings
* Constrained volume (camera in beam)
  – Makes shutter, filter exchange mechanisms challenging
* Constrained power dissipation to ambient
  – To limit thermal gradients in optical beam
  – Requires conductive cooling with low vibration

Science goals drive sensor requirements

* High QE out to 1000nm	➔	thick silicon (> 75 µm)
* PSF << 0.7”	➔	high internal field in the sensor
	➔	high resistivity substrate (> 5 kohm·cm)
	➔	high applied voltages (> 50 V)
* Fast f/1.2 focal ratio	➔	sensor flatness < 5µm
	➔	package with piston, tip, tilt adjustable to ~1µm
* Wide FOV	➔	3200 cm^2 focal plane
	➔	> 200-CCD mosaic (~16 cm^2 each)
	➔	industrialized production process required
* High throughput	➔	> 90% fill factor
	➔	4-side buttable package, sub-mm gaps
* Fast readout	➔	highly-segmented sensors (~6400 output ports)
	➔	> 150 I/O connections per package

Large Synoptic Survey Telescope

Advances in State-of-the-Art needed for LSST Detector

* The focal plane array will have about an order of magnitude larger number of pixels (~3 gigapixels) than the largest arrays realized so far.

* The effective pixel readout speed will have to be about two orders of magnitude higher than in previous telescopes in order to achieve a readout time for the telescope of ~1 - 2 seconds.

* The CCDs will have to have an active region ~100 µm thick to provide sufficiently high quantum efficiency at ~1000 nm, and they will have to be fully depleted (with no field free region) so that the signal charge is collected with minimum diffusion as needed to achieve a narrow point spread function.

* Packaging ensuring sensor flatness and alignment in focal plane to <5µm (not achieved with presently delivered devices by industry).

* Extensive use of ASICs to make the readout of a large number of output ports practical, and to reduce the number of output links and penetrations of the dewar.

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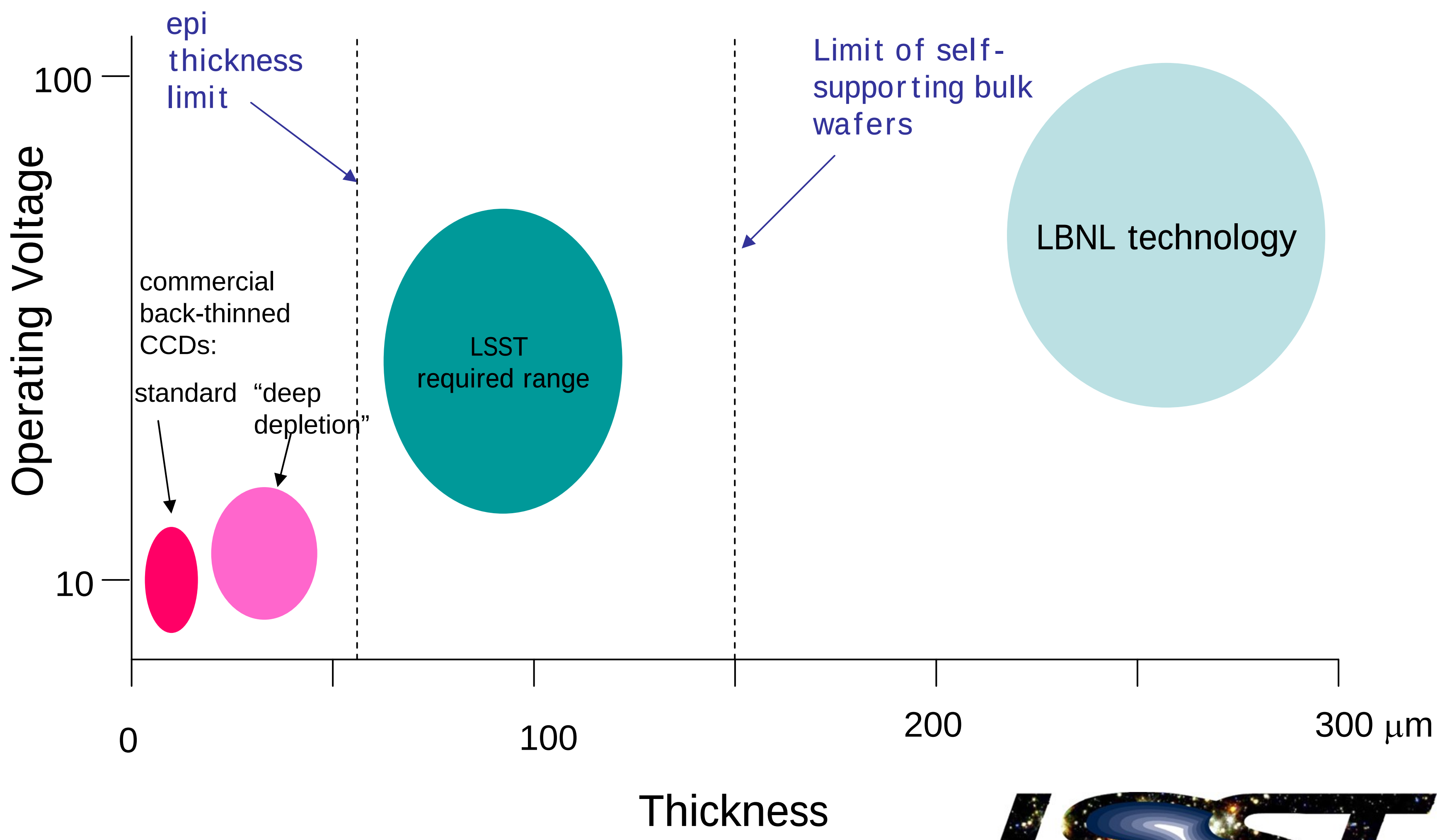
LSST requires sensors in a new thickness range



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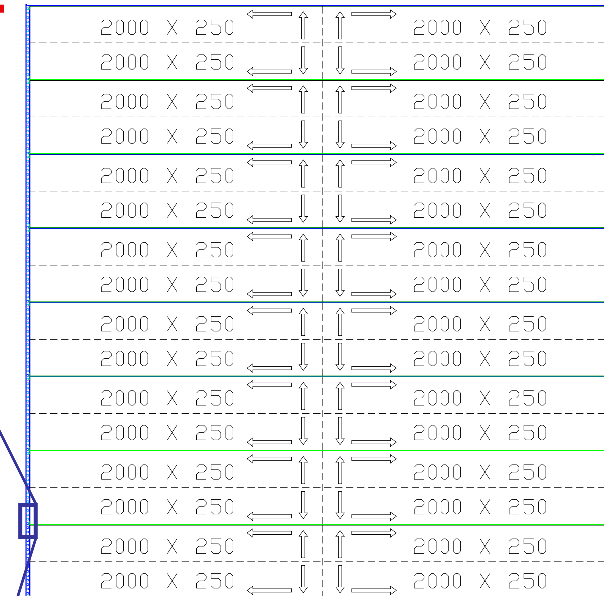
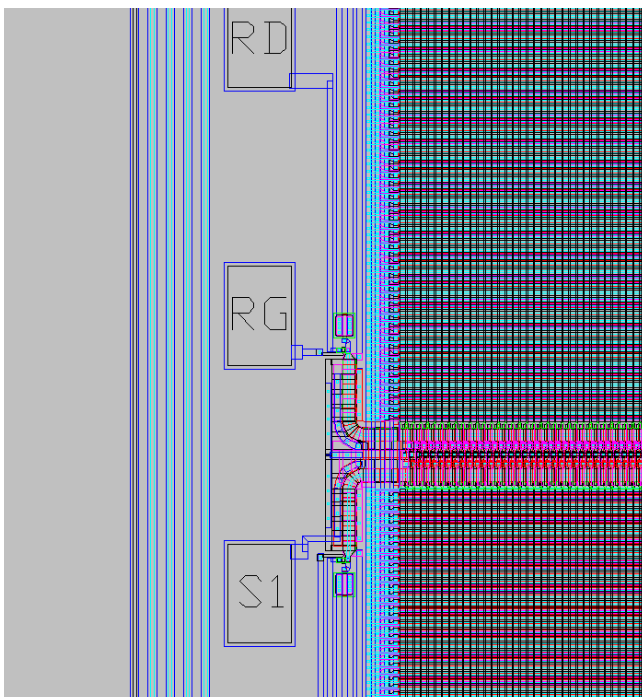
Multi-port 4K x 4K = 16M CCD strawman

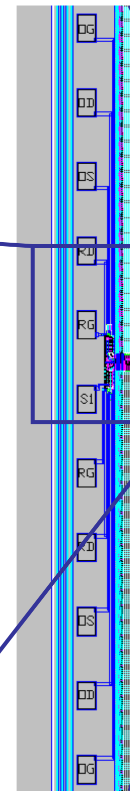
32 segments/ports



Full CCD showing segmentation. Note pads on left and right edges only

Detail of output port





Detail of one edge

Strawman has 208 bonding pads total

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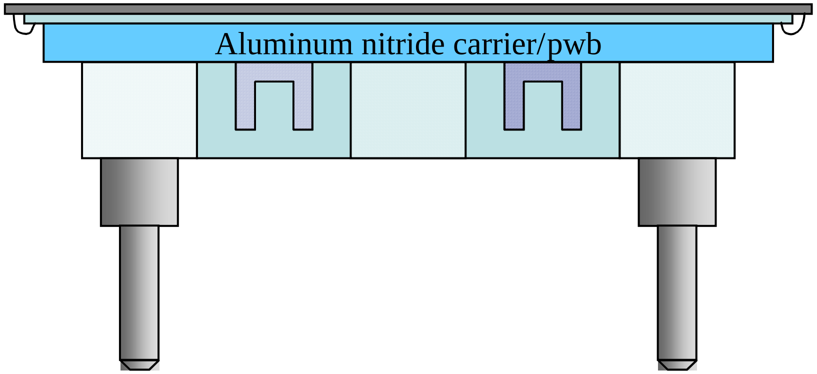
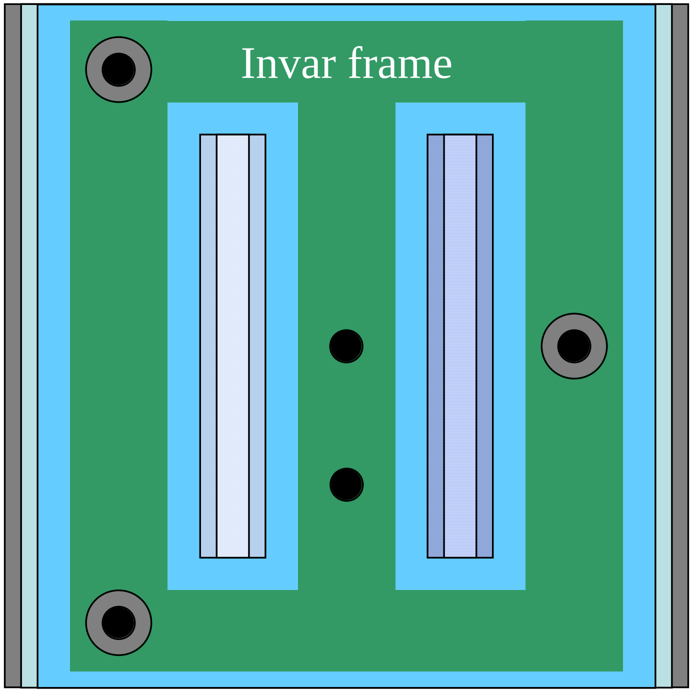
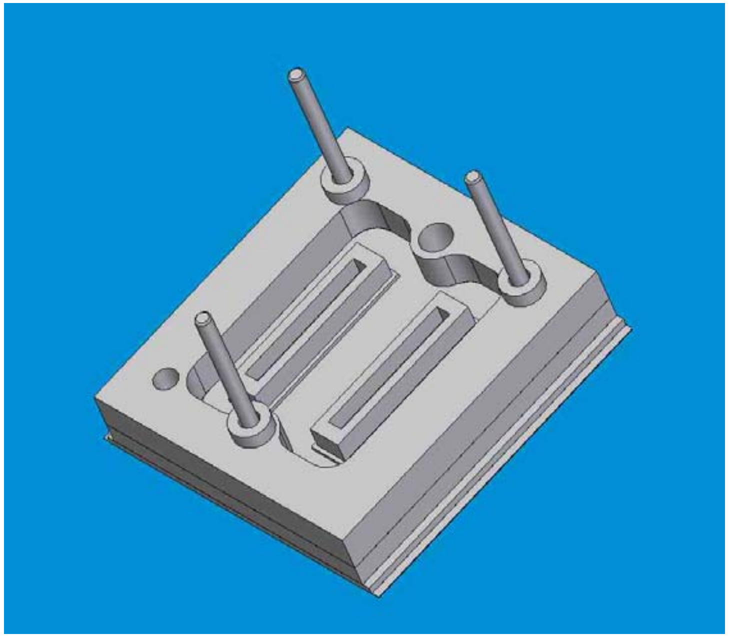
J. Geary, "LSST Strawman CCD Design", Dec. 2004

CCD Module Assembly







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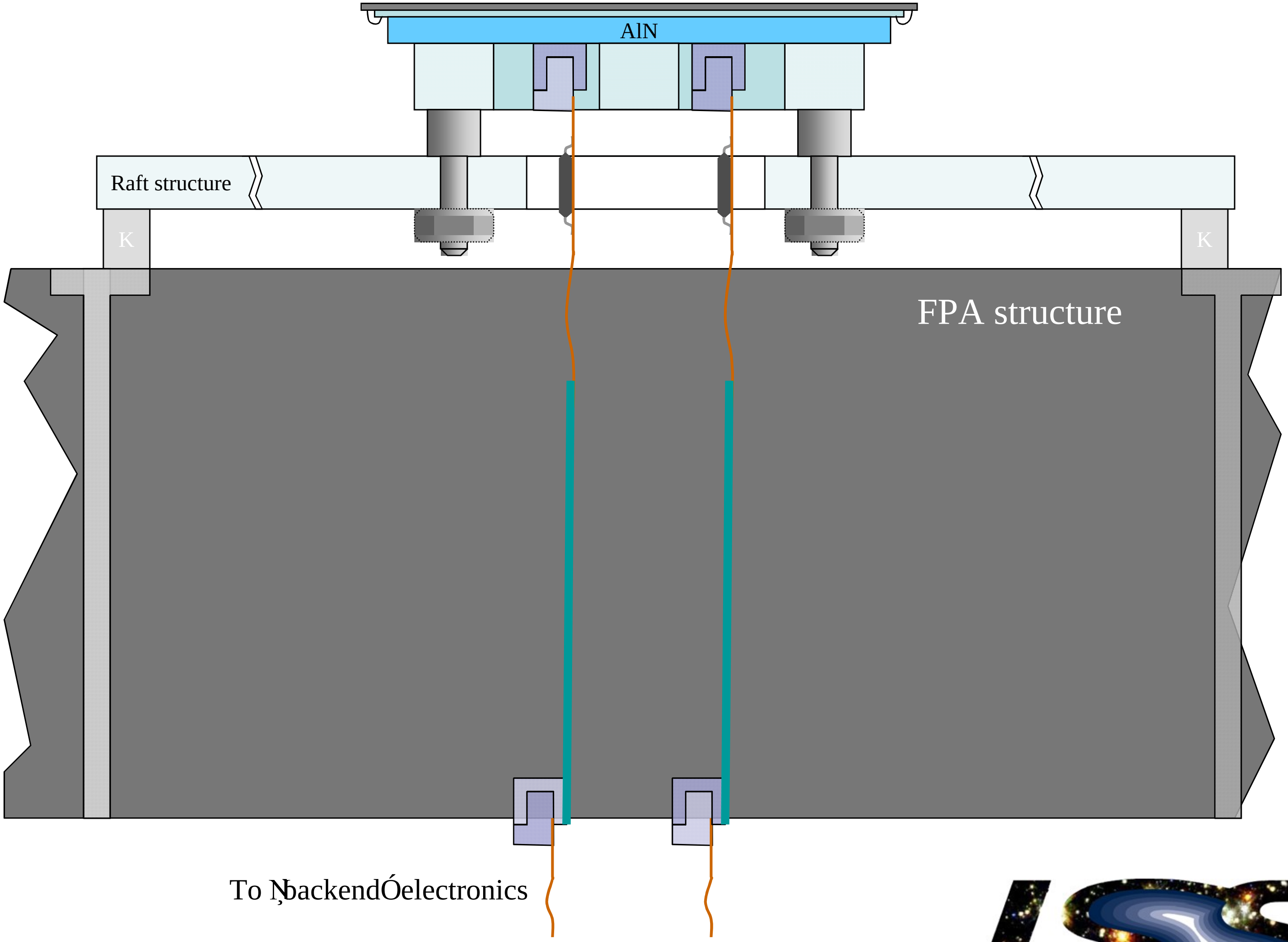
CCD Assembly



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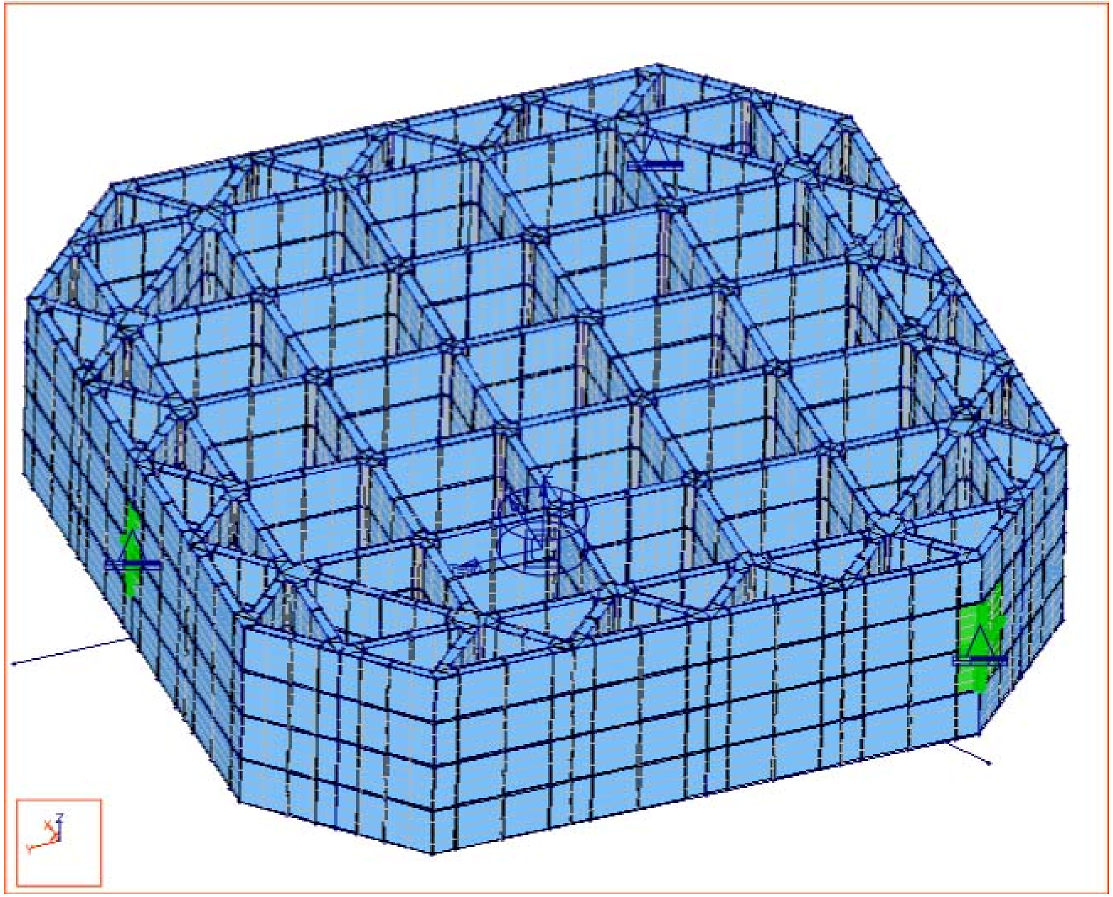
FPA Structure



Modeling
- Deflections, gravity
- Normal modes
- Thermal
- x-y motions

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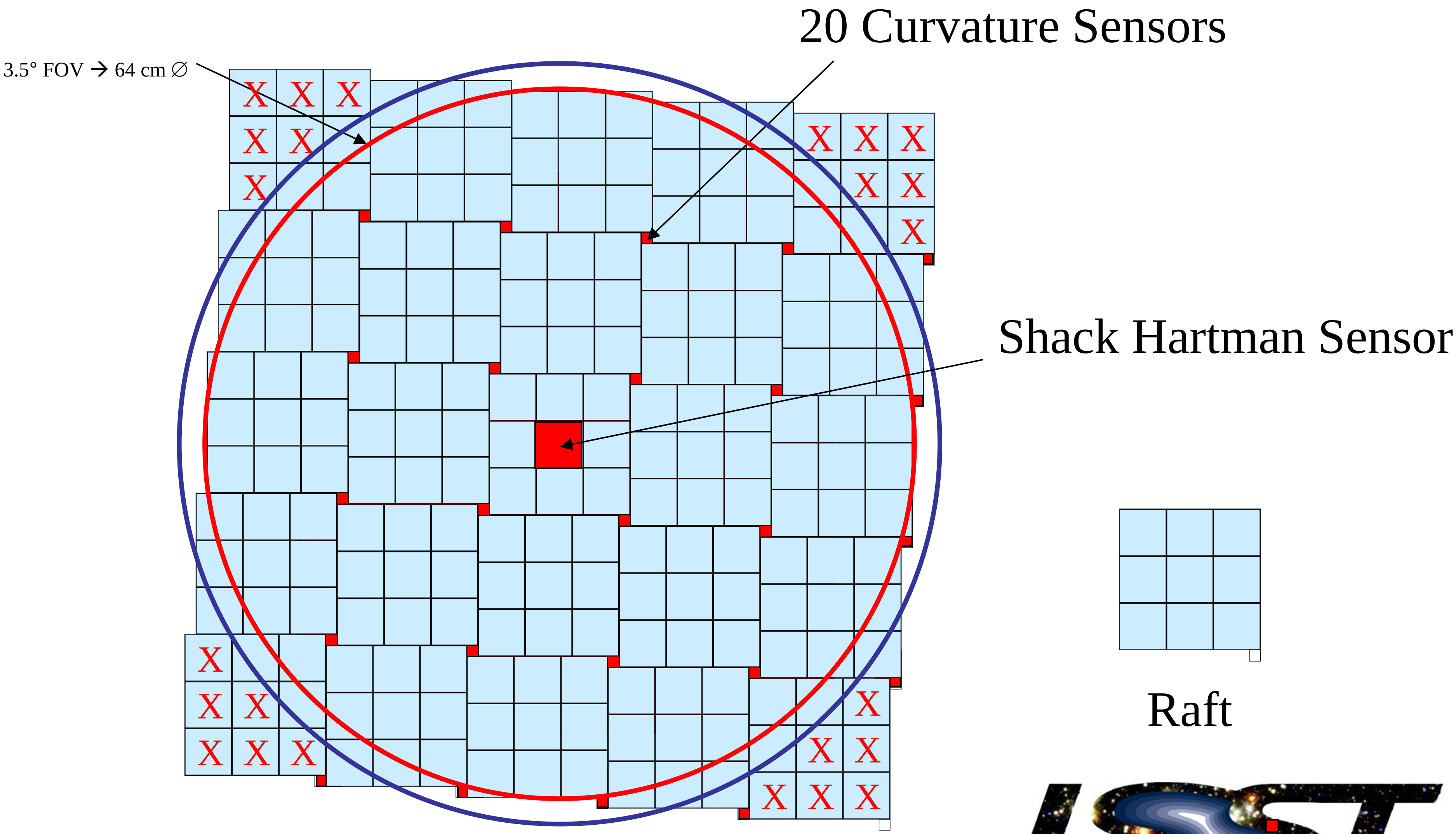
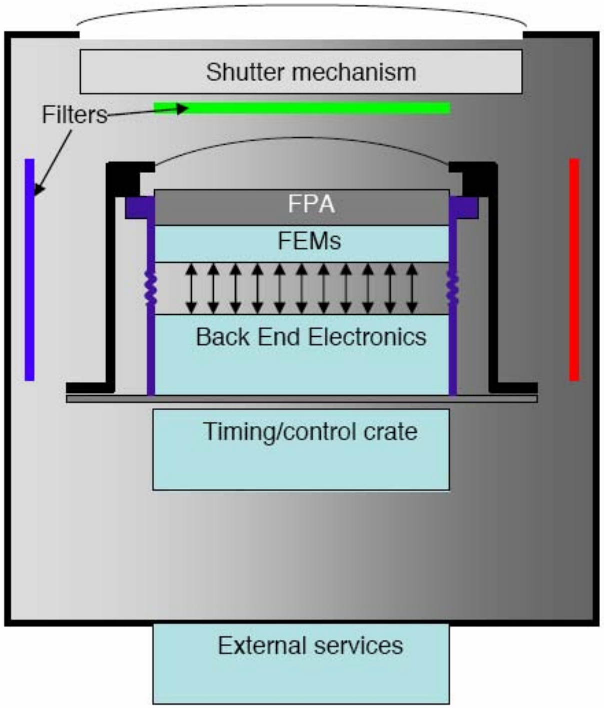
Current baseline WFS Layout

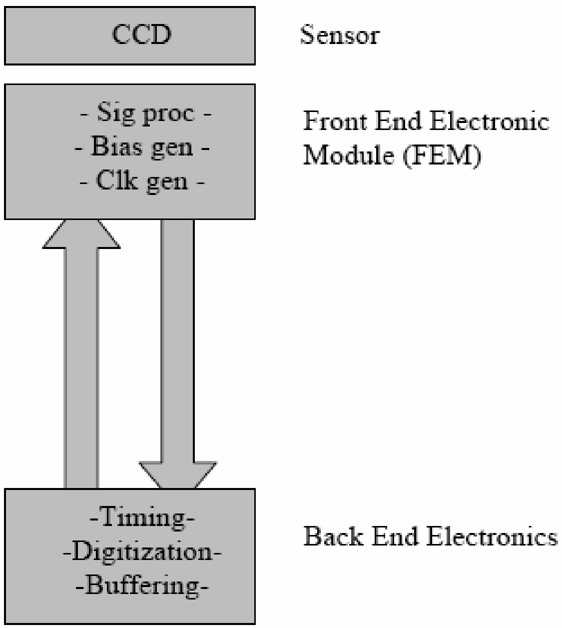


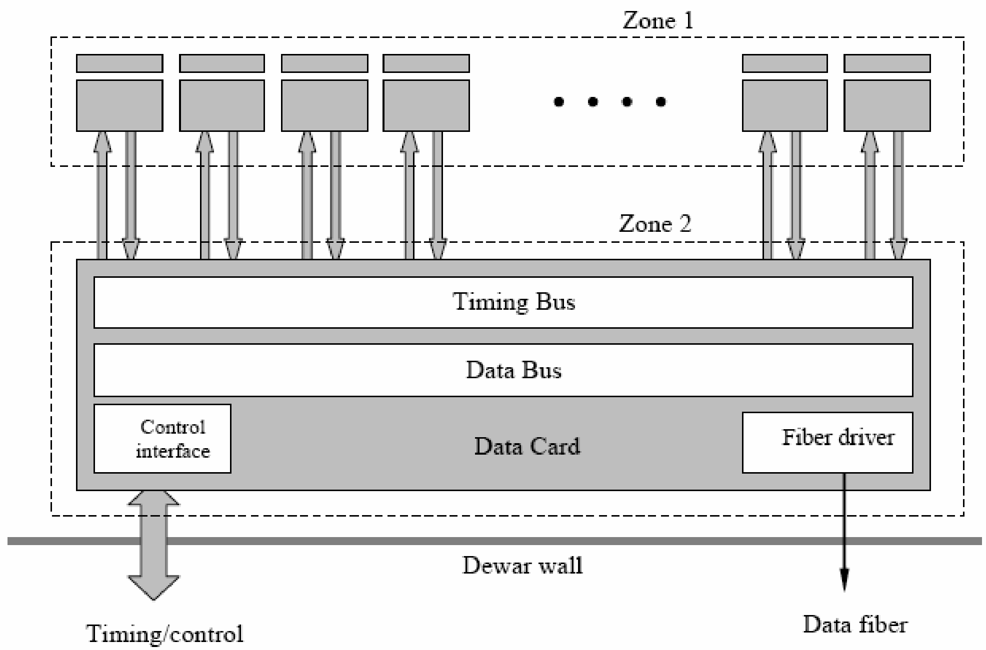
Camera Electronics Architecture

* Electronics is distributed over three “thermal zones”
  – A front end zone, located closely behind the focal plane (analog).
  – A back end zone, located further away, but inside the dewar (ADC, timing and control).
  – External services located outside the inner dewar.



Camera Readout Architecture





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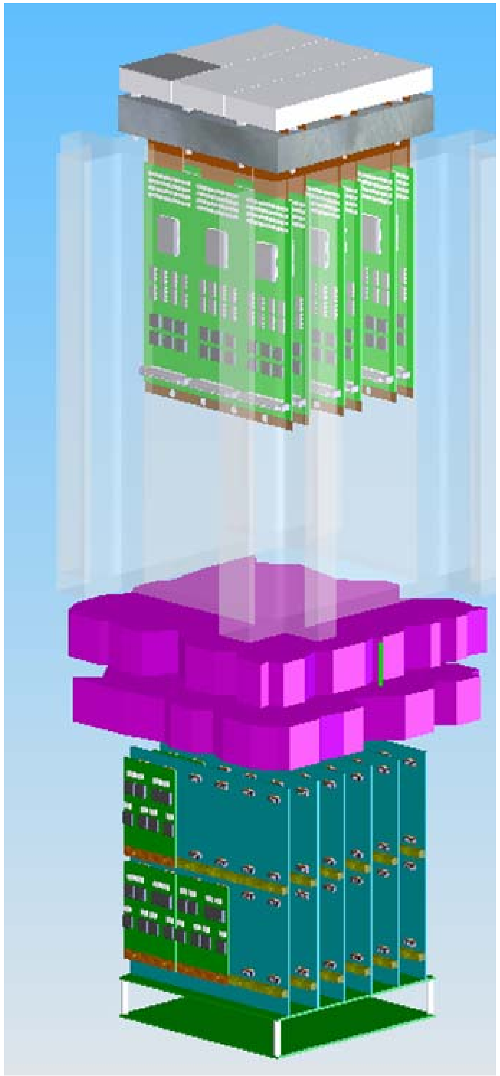
Raft Structure



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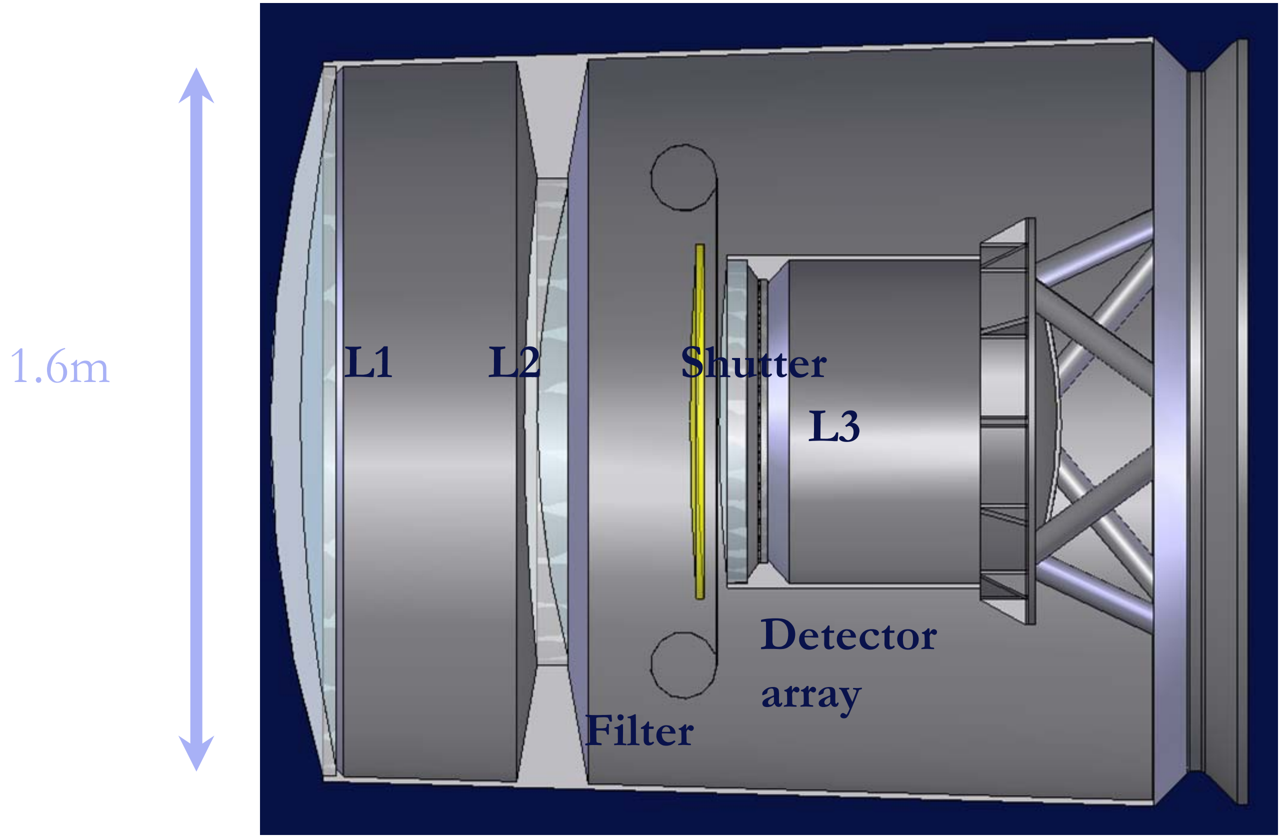
Camera Mechanical Layout



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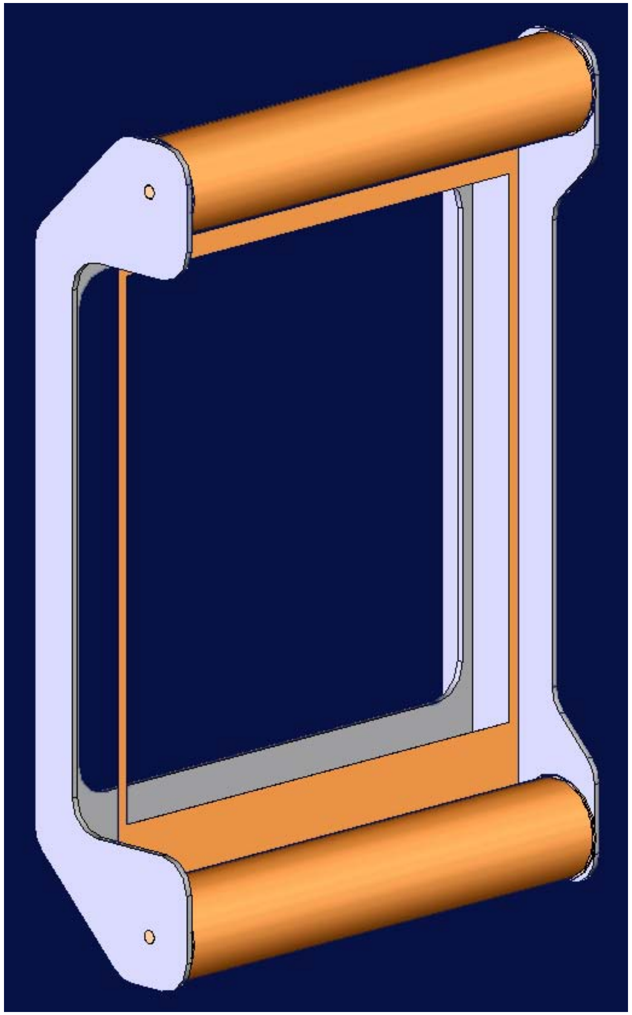
Shutter Design



One sheet design

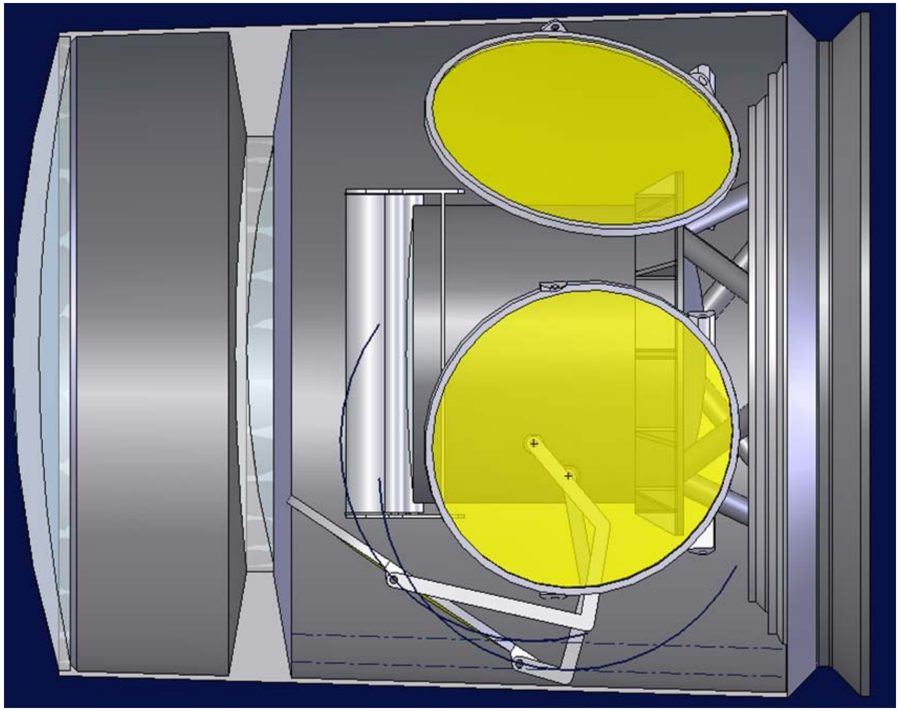
- Simplest design, fewest moving parts, fits the limited space most easily

Sheet Materials

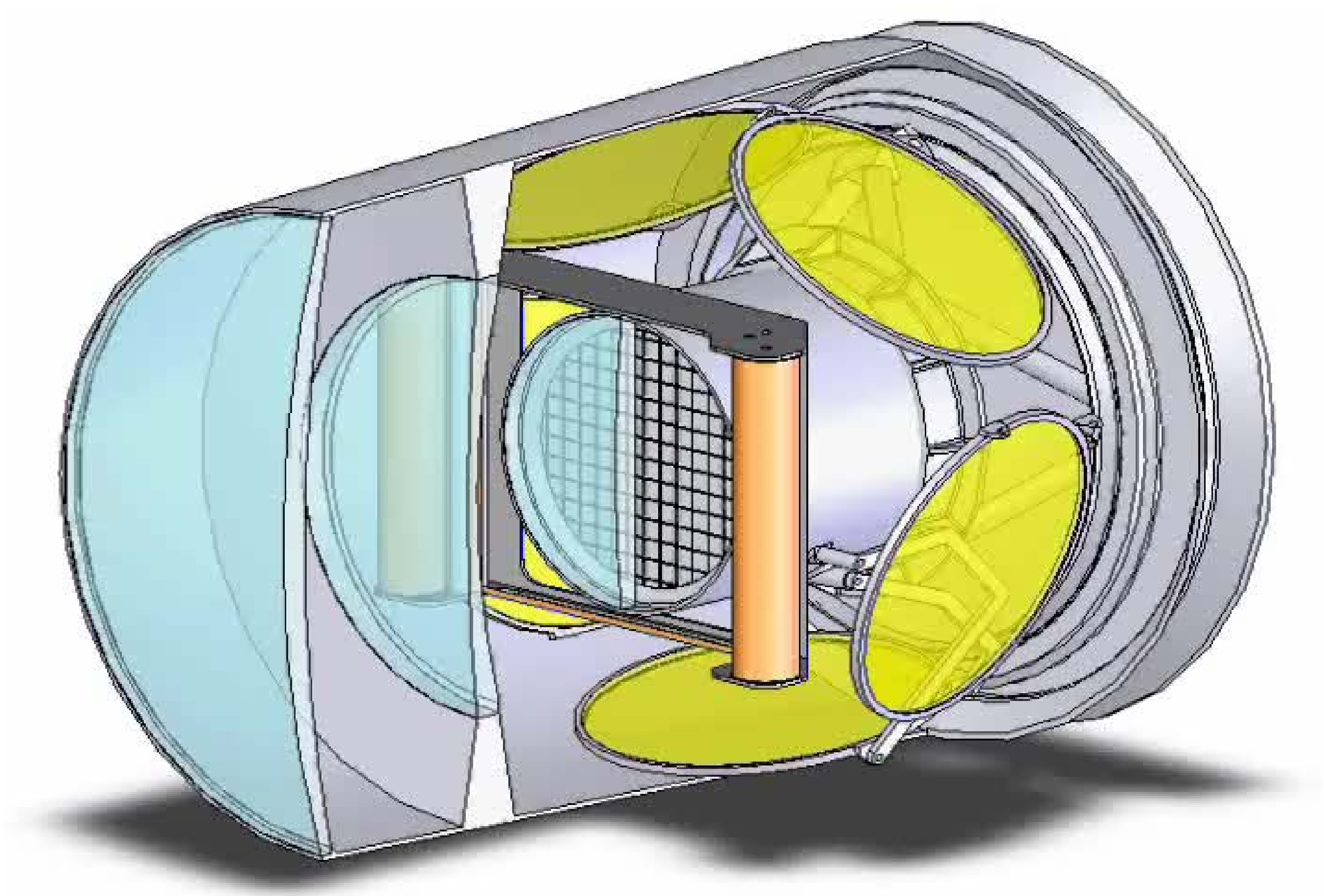
- titanium or beryllium copper (good tradeoffs between modulus and yield strength)

Filter exchange mechanism

4-bar linkage allows filter to move past shutter and fit inside the outer camera Dewar



Filter exchange mechanism



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LSST Data Rates

* 3.2 billion pixels read out in less than 2 sec, every 12 sec
* 1 pixel = 2 Bytes (raw)
* Over 3 GBytes/sec peak raw data from camera
* Real-time processing and transient detection: < 10 sec
* Dynamic range: 4 Bytes / pixel
* > 0.6 GB/sec average in pipeline
* 5000 floating point operations per pixel
* 2 TFlop/s average, 9 TFlop/s peak
* ~ 18 Tbytes/night

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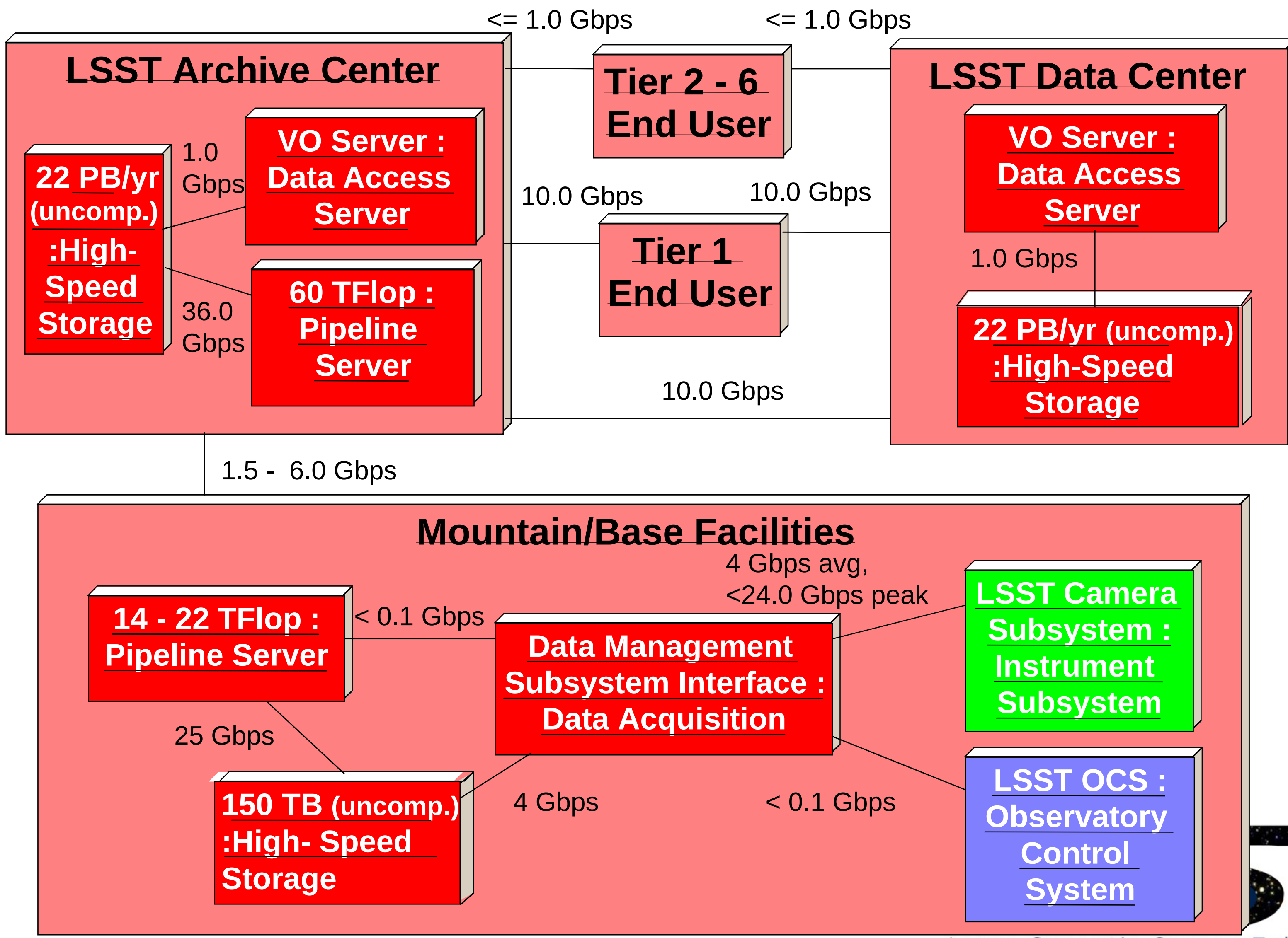
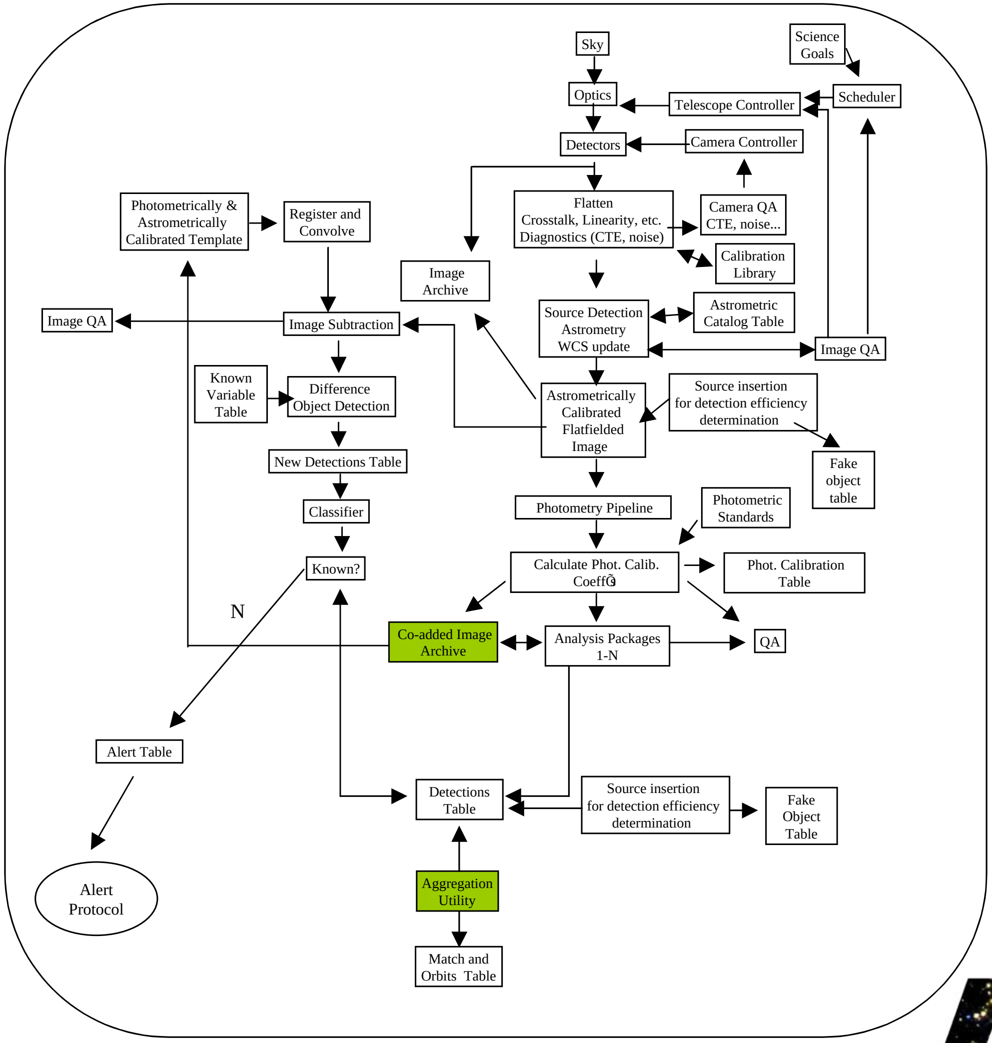
Computation and Communications Load



Nominal Flow Diagram



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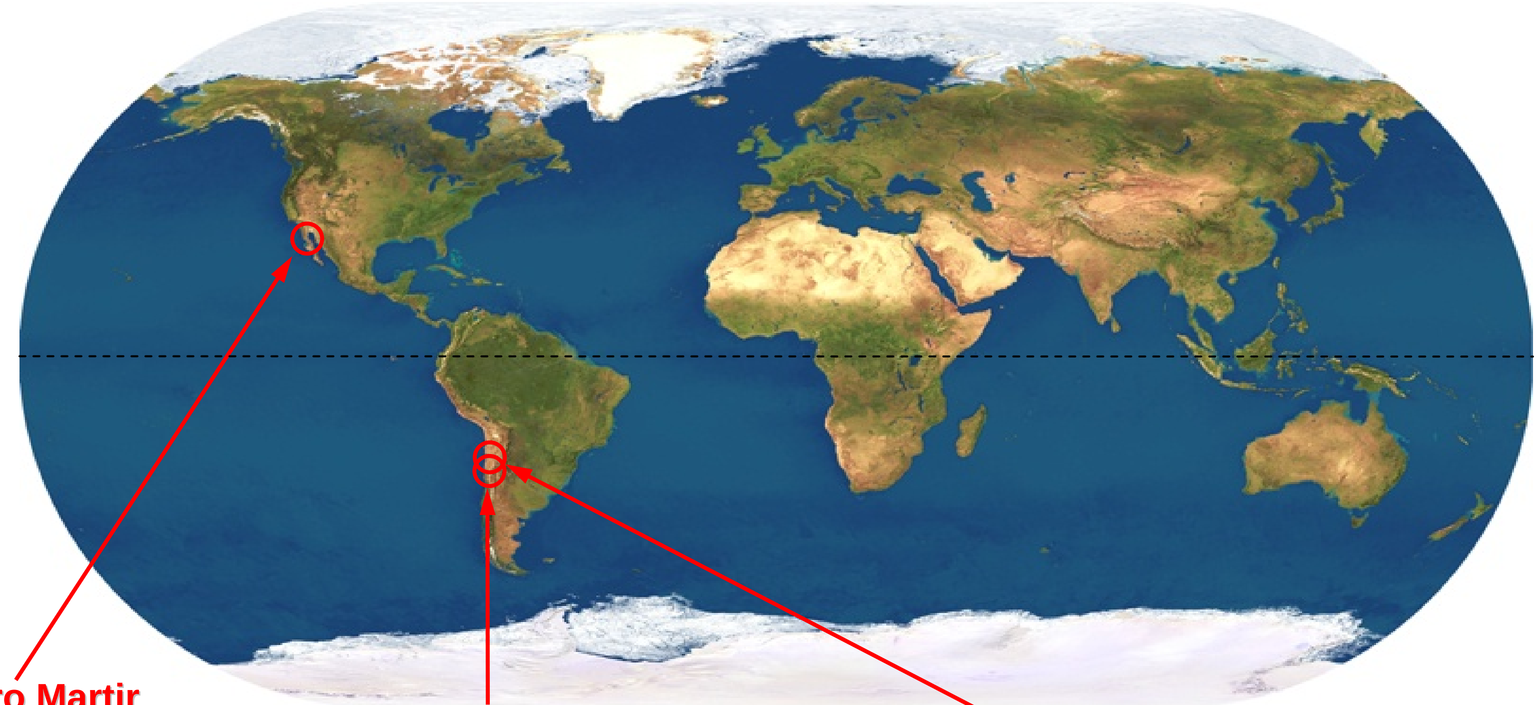
LSST Final Three Sites

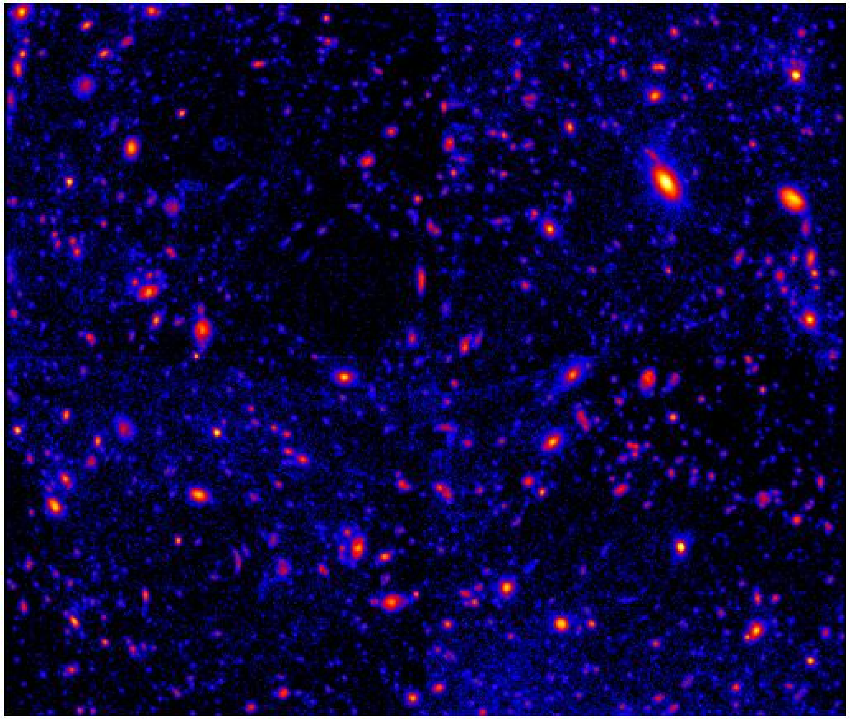


San Pedro Martir

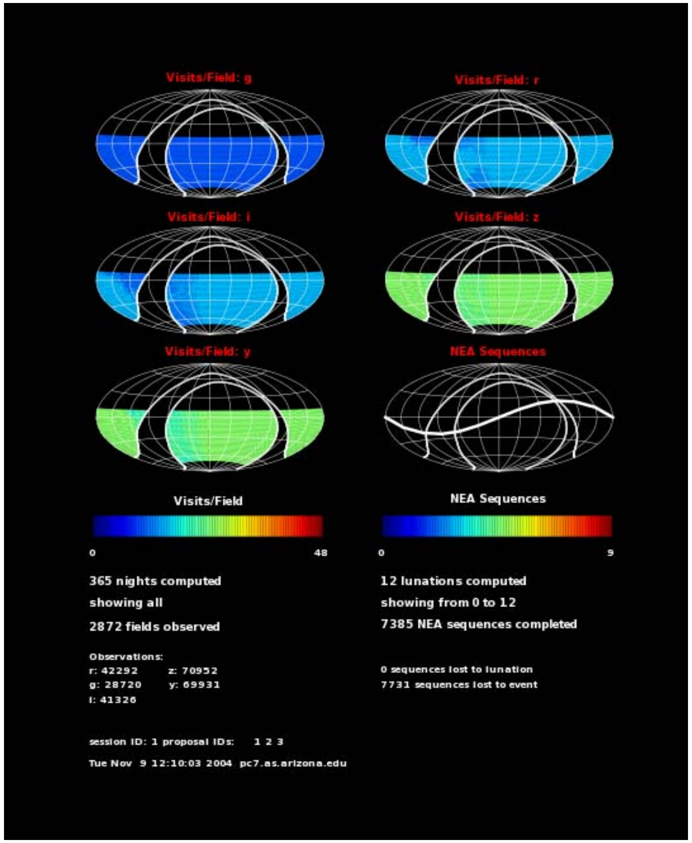
Cerro Pachon

Las Campanas

LSST Simulators



Sheared HDF raytraced + perturbation + atmosphere + wind + pixel



LSST Operations, including real weather data: coverage + depth

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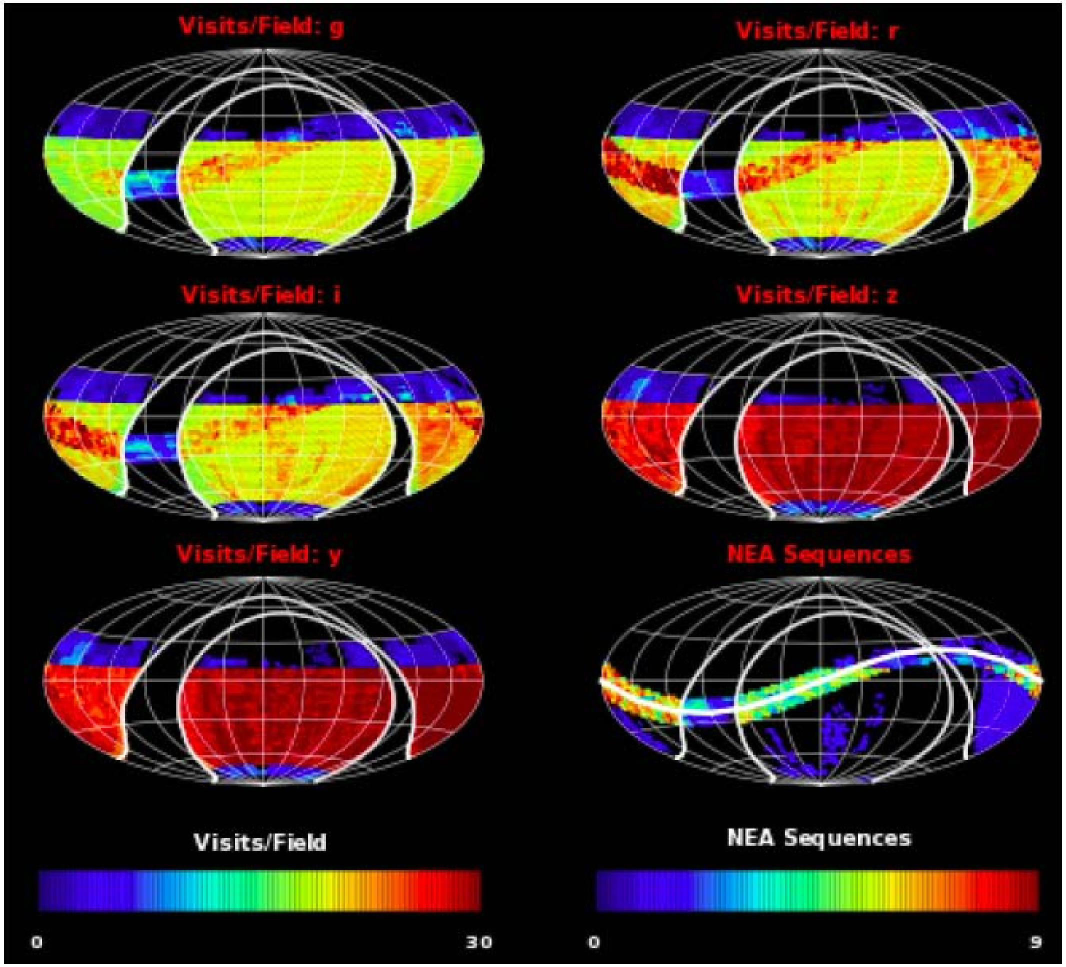
Observation Simulator



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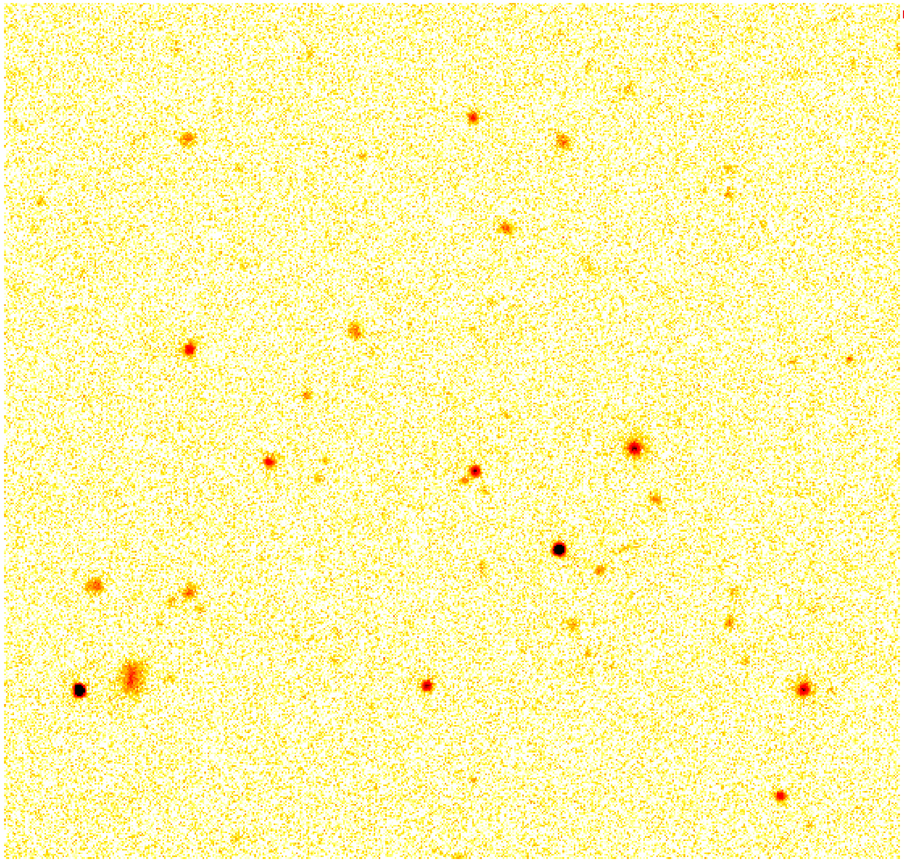
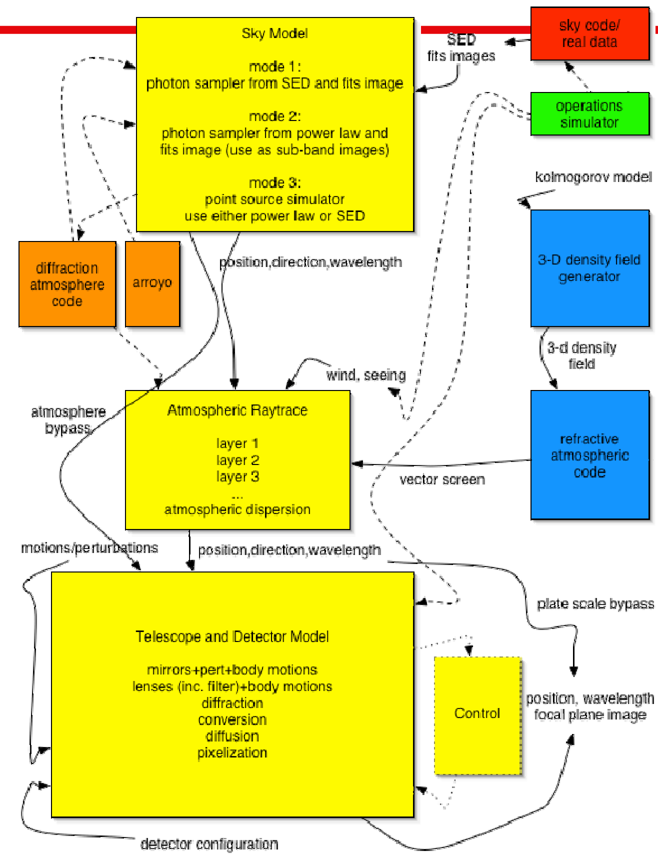
End-to-End Simulations



Piece of complete Monte Carlo Simulation of the UDF through Atmosphere and optics
$3\ 10^8$ photons in 20 cpu hours



End to End Simulator:
Accepts Sky images and SEDs
Uses refractive raytrace through screens of Kolmogorov atmospheric turbulence
Raytraces complete LSST optics+pert
Simulates detector conversion/diffusion

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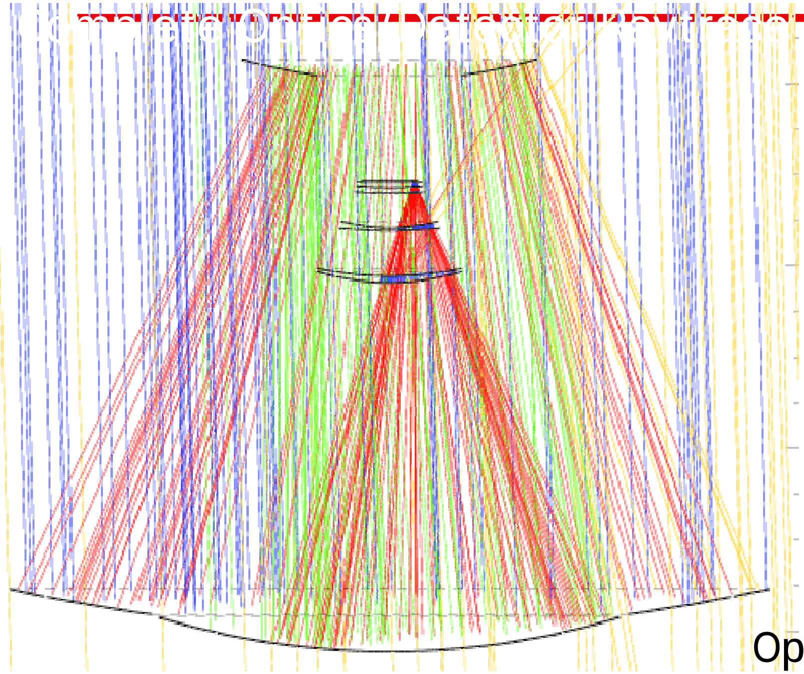
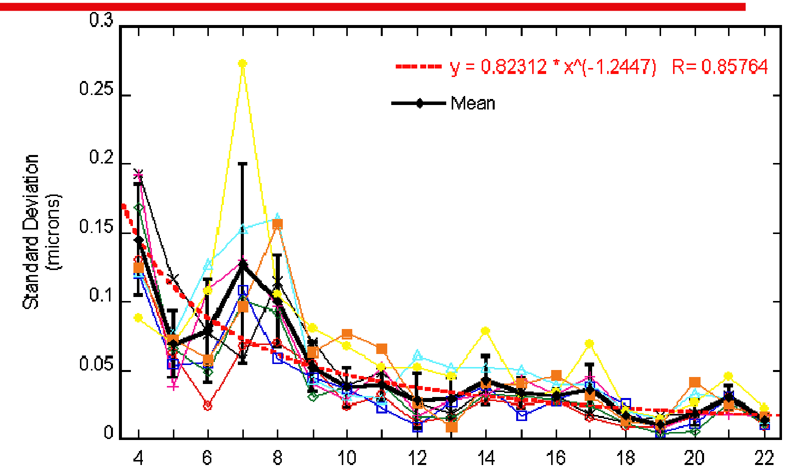
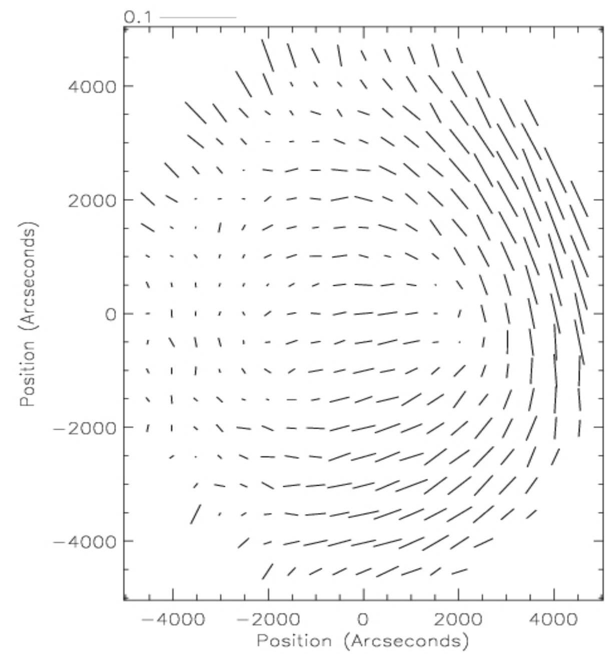
Optics/Detector Simulations

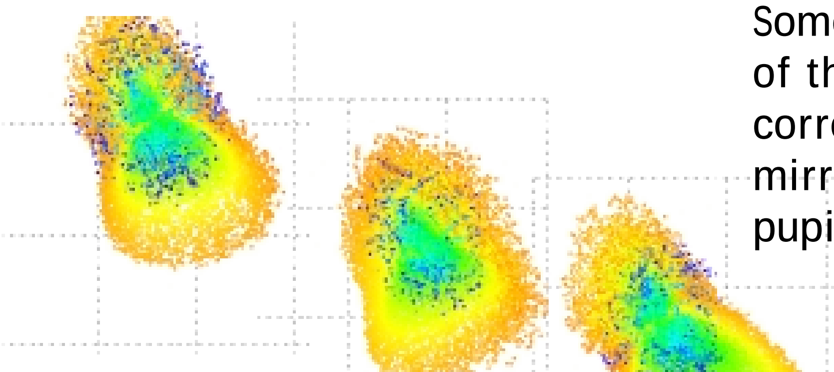




Perturbation amplitude vs. Zernike number

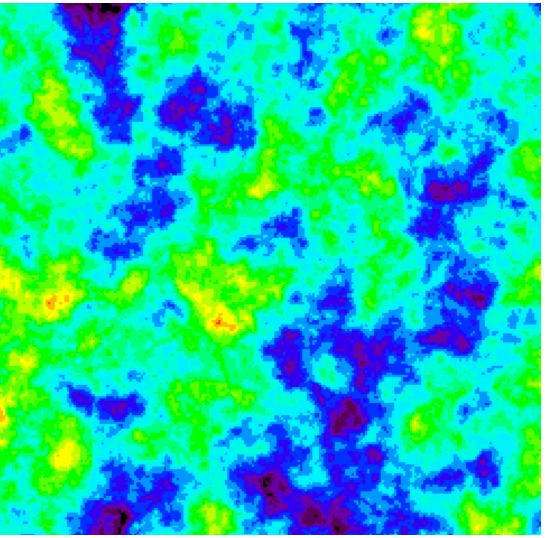
Optics may contribute
Some to the ellipticity
of the PSF, but it is highly
correlated since the three
mirrors are close to the
pupil plane



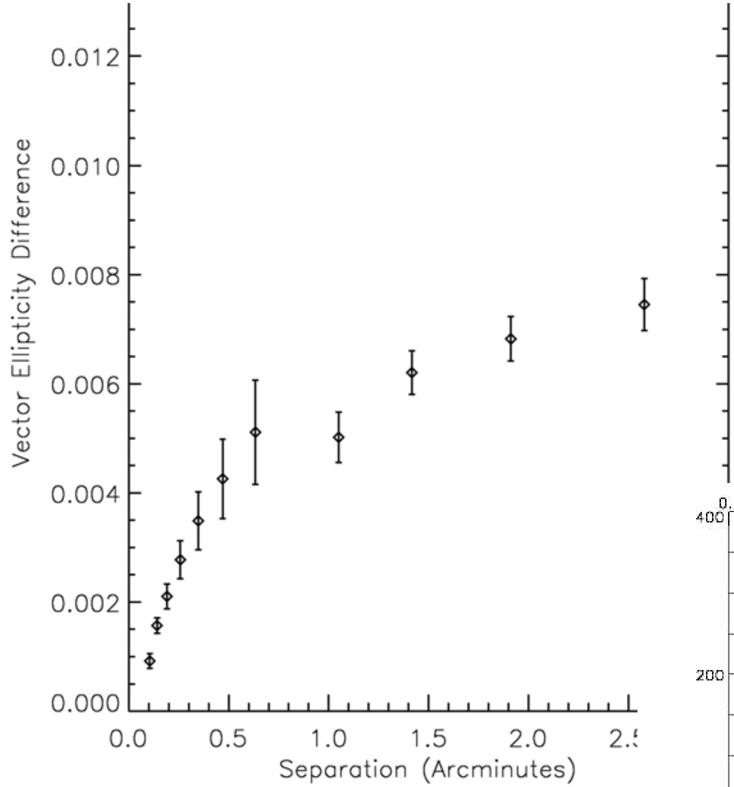


Spot diagrams of optics only
simulation separated by 0.5 degrees

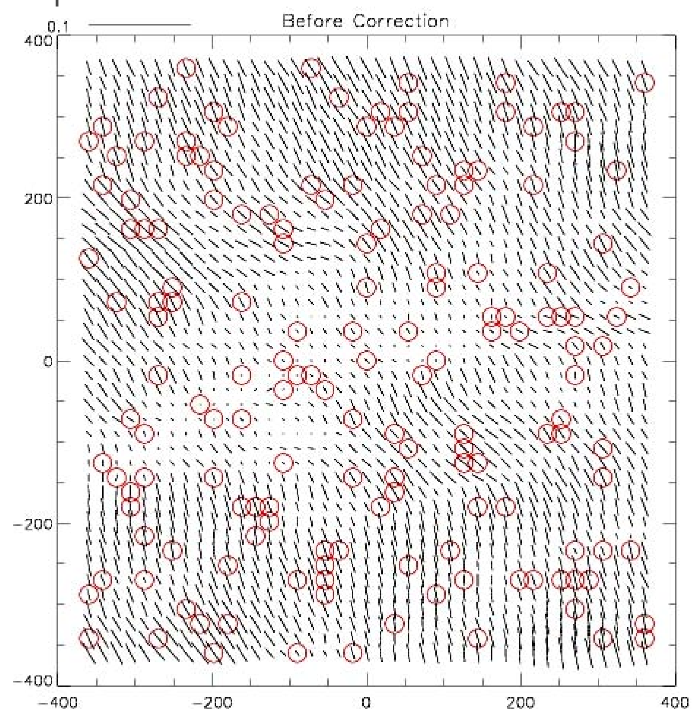
Atmospheric Simulations



Kolmogorov Phase Screen



PSF ellipticity due to averaging over a finite number of turbulent cells. Decorrelates due to high altitude layers but will have enough stars to interpolate at LSST depth and correlation scale



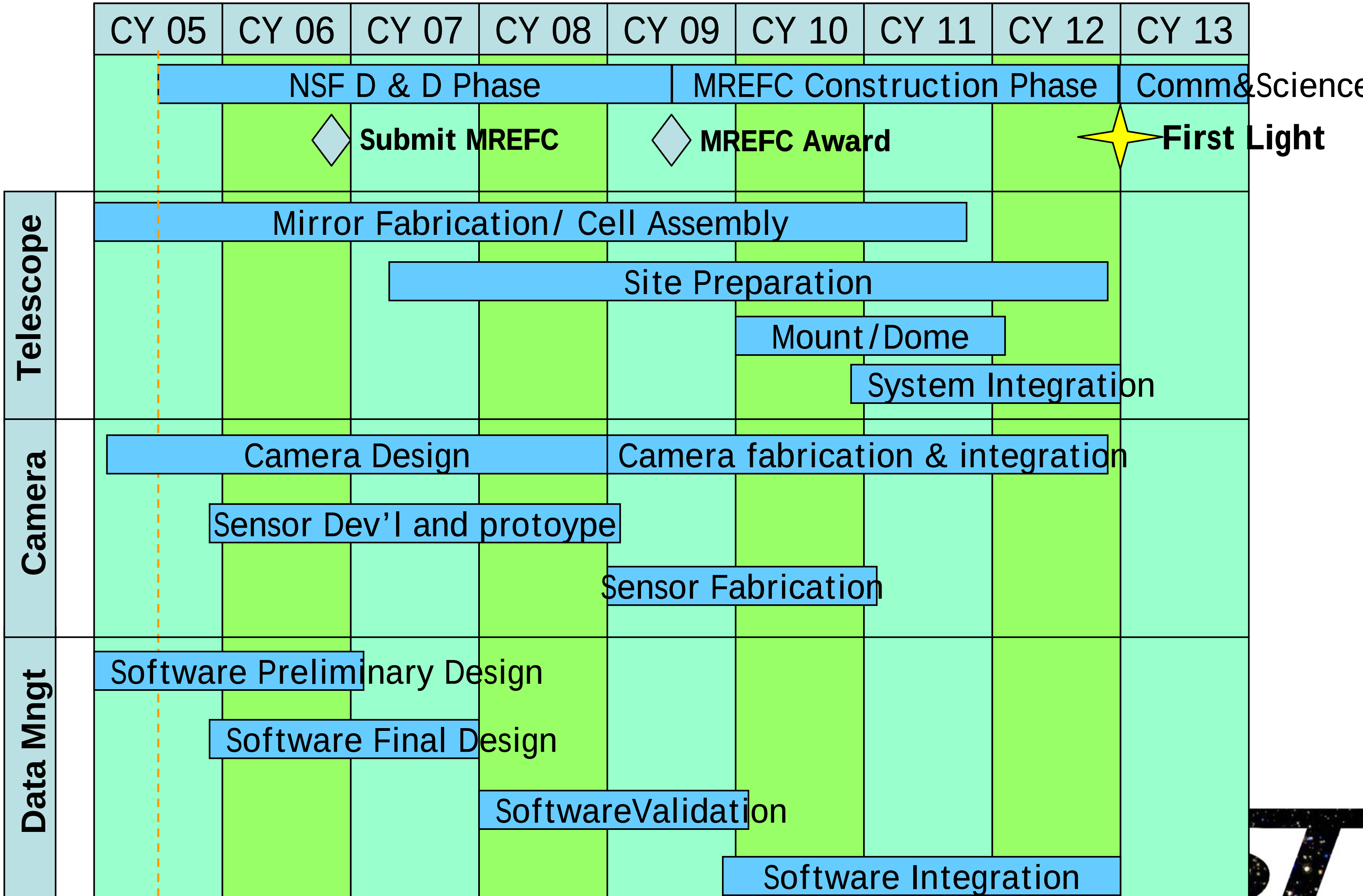
Number of cells ~ (D w t)

<e> ~ (D w t)$^{0.5}$ ~ D$^{0.5}$/ (A w t)$^{0.5}$

Correlation angle ~ D / h

-> Decorrelation ~ 1/D$^{0.5}$ for same depth

Project Baseline Schedule Plans



Large Synoptic Survey Telescope

Summary

* The LSST will enable many diverse investigations in astronomy through a single common database.

* Of particular interest for cosmology, it will provide a rich sample of high-z lensed galaxies that will yield multiple probes of the concordance cosmological model.

* The LSST camera presents many interesting experimental challenges. While a basic strawman design exists, a significant R&D effort is required in several key areas.

* Additional effort is needed to address the demanding requirements on the data management system imposed by the very high data rate, high data volume, and real-time alert functions.

* Ultimately, however, we expect the LSST to have very high impact on the field.

Large Synoptic Survey Telescope