THE LARGE SYNOPTIC SURVEY TELESCOPE

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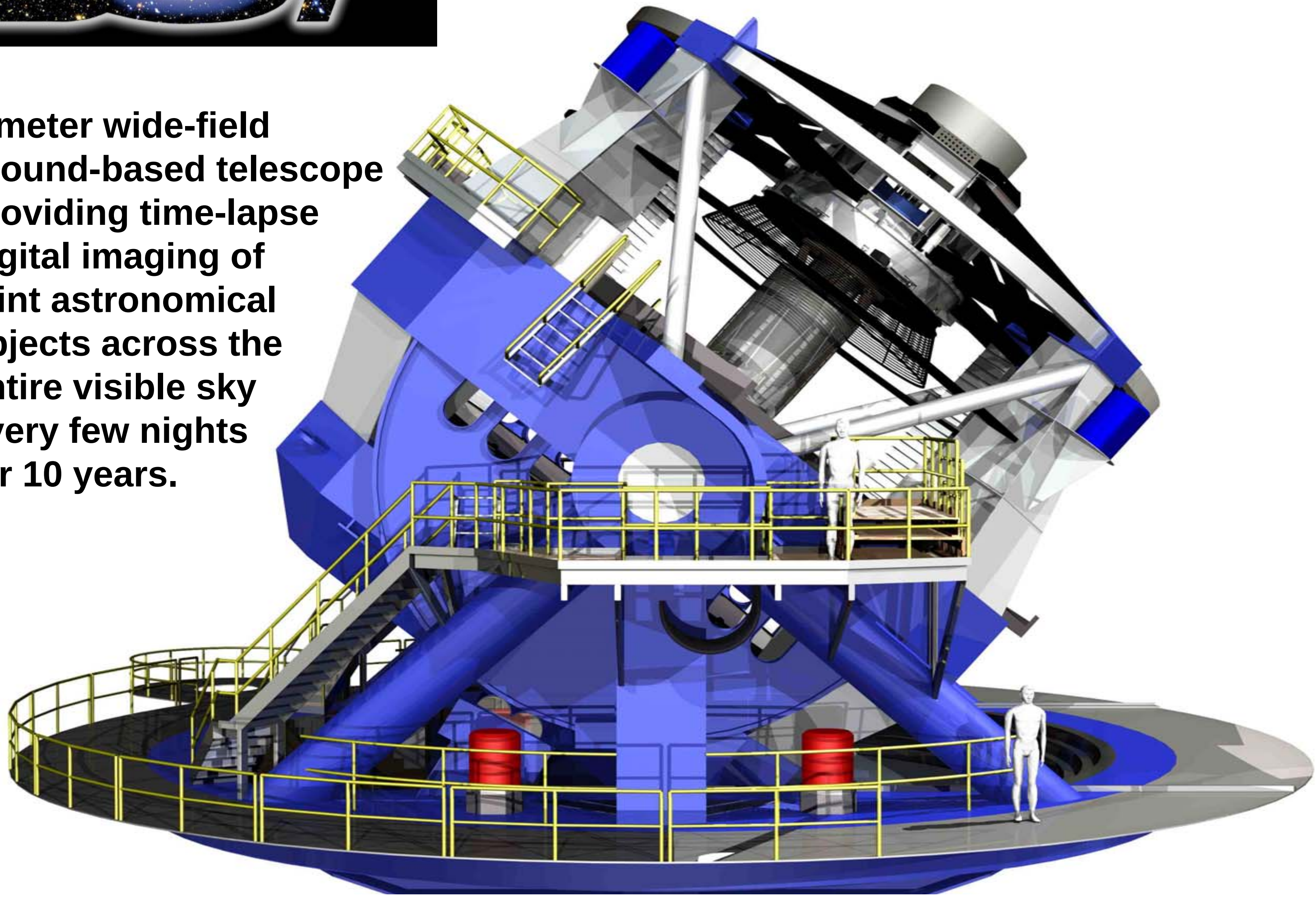
(for the LSST Collaboration)

DPF2009, July 27, 2009

Progress in Astronomy

- Bigger Telescopes: *Keck to GSMT*
- Angular resolution: *Hubble to JWST*
- All Sky Survey: *SDSS to LSST*

8 meter wide-field ground-based telescope providing time-lapse digital imaging of faint astronomical objects across the entire visible sky every few nights for 10 years.



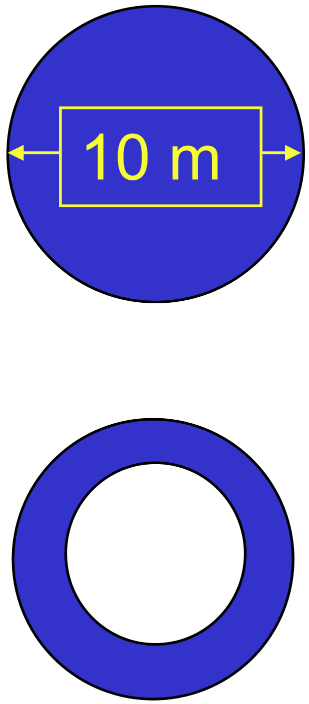
Comparison of LSST To Keck

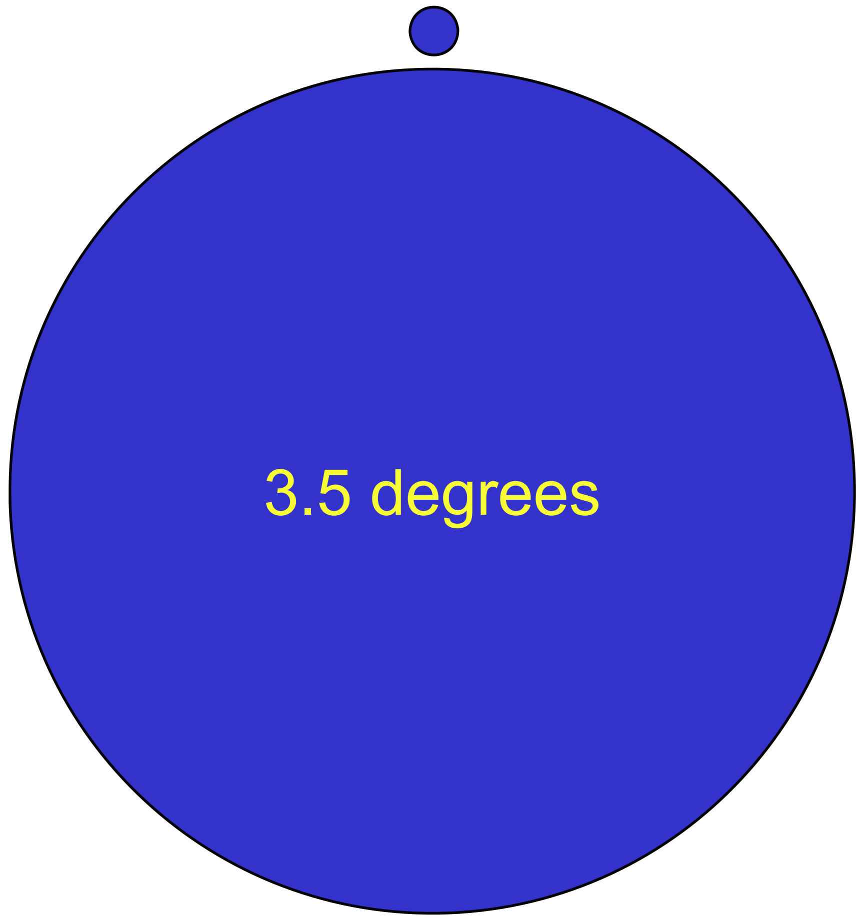
Primary mirror diameter

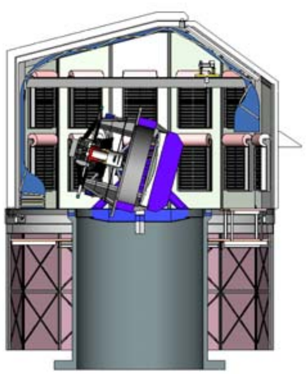
Field of view
(full moon is 0.5 degrees)

0.2 degrees

Keck Telescope







LSST

Hubble deep field

UNIVERSE
OF
GALAXIES

3000
here →

100 billion
over entire
sky

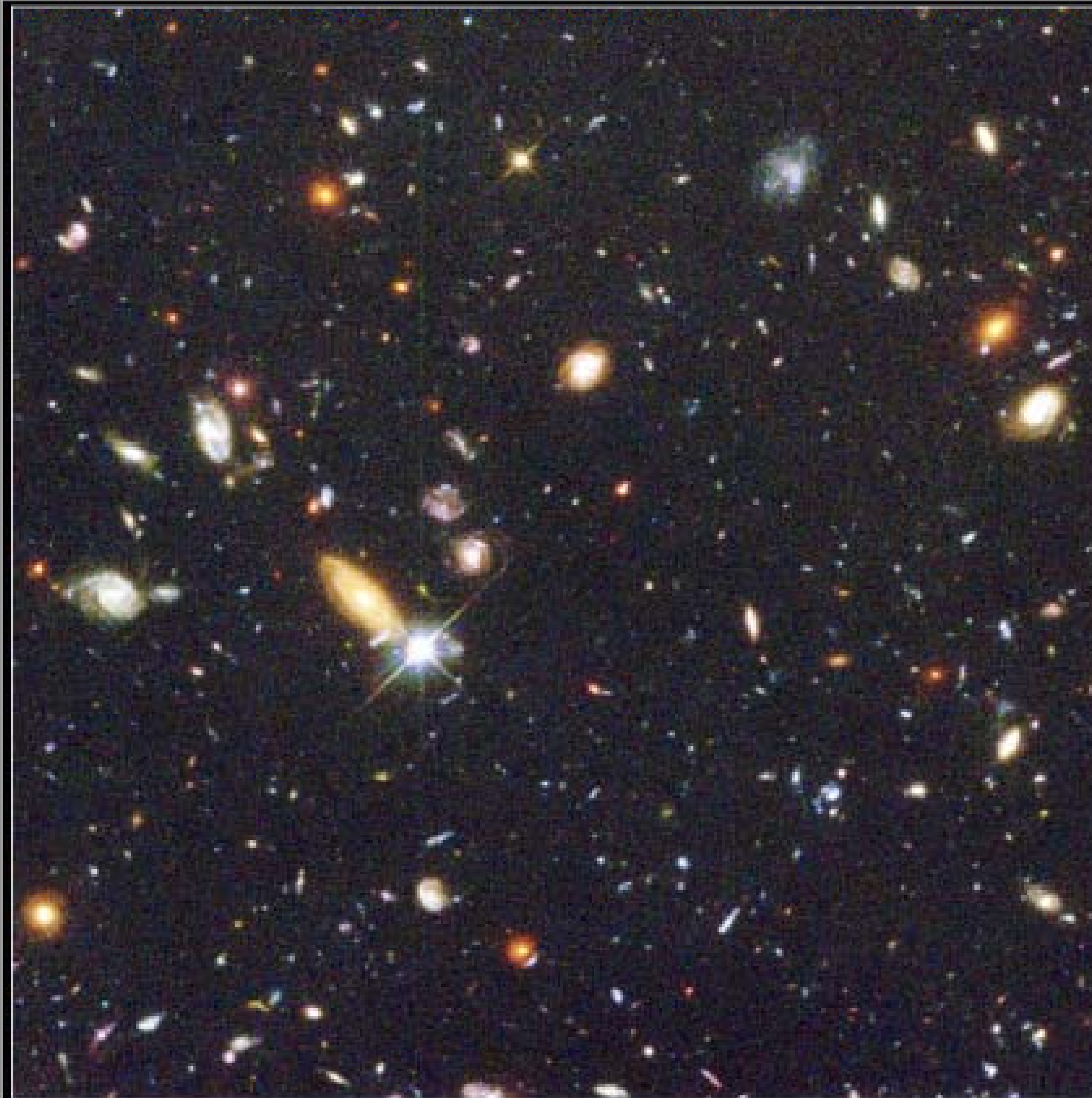


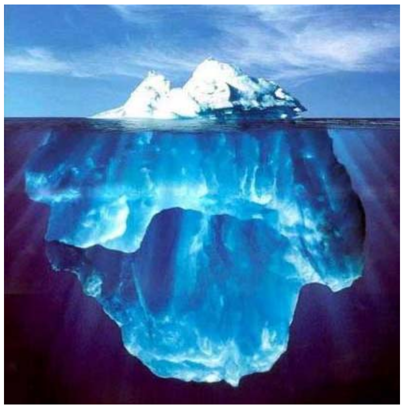
Image sizes LSST, Moon, HST

LSST survey of 20,000 sq deg (half the sky)

- 4 billion galaxies with redshifts
- Time domain:
  5 million asteroids
  10 million supernovae
  1 million gravitational lenses
  100 million variable stars
  + new phenomena

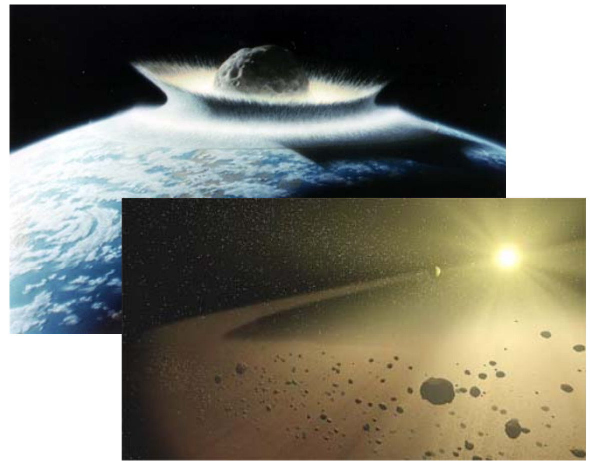
LSST 4 Science Missions

Dark Energy-Dark Matter



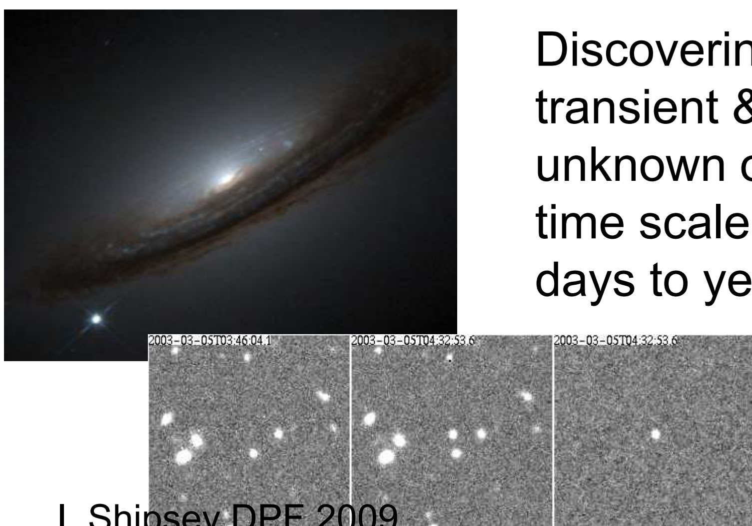
Multiple investigations into the nature of the dominant components of the universe

Inventory of the Solar System



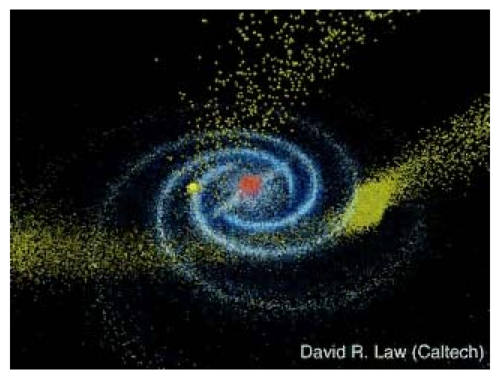
Find 90% of hazardous NEOs down to 140 m over 10 yrs & test theories of solar system formation

"Movie" of the Universe: time domain



Discovering the transient & unknown on time scales days to years

Mapping the Milky Way



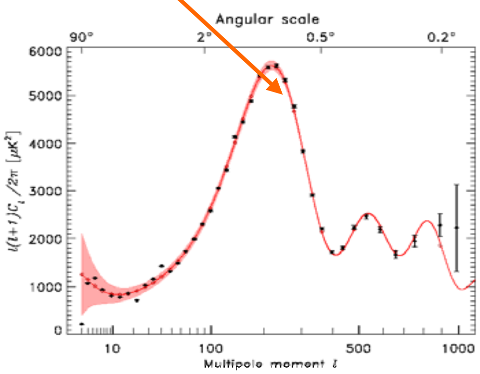
Map the rich and complex structure of the galaxy in unprecedented detail and extent

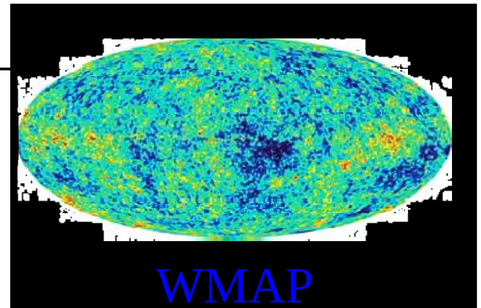
All missions conducted in parallel

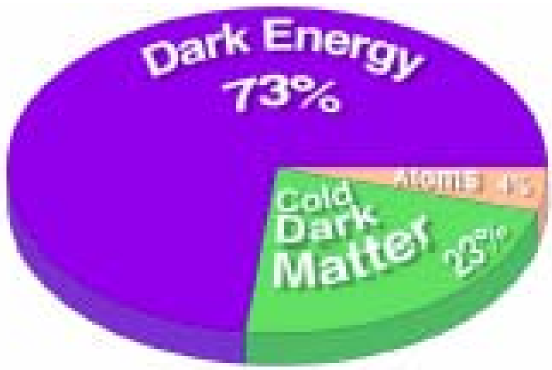
LSST Science Drivers 1 The Fate of the Universe

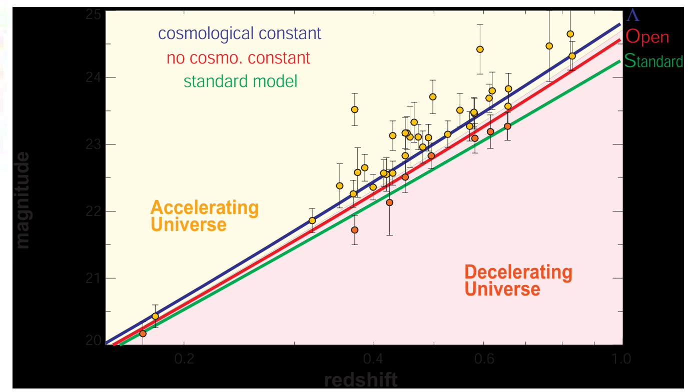
Flat universe

Ω_{total}= 1.02+/-0.02









Dark Energy "the essence of space"
Dark Matter "most of the matter"
Together they govern the evolution & fate of the universe.

Their nature ranks as one of the greatest questions in the physical sciences

Probing Dark Energy

Is the accelerated expansion a cosmological constant ? $w = P/\rho = -1$

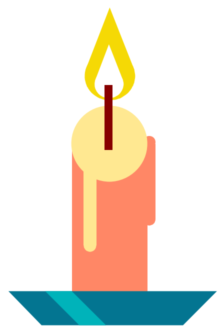
Or does w vary with time, equivalently red shift, z?

$$w = \underbrace{w_0}_{\text{now}} + \underbrace{w_a\left(\frac{z}{1+z}\right)}_{\text{evolution}}$$

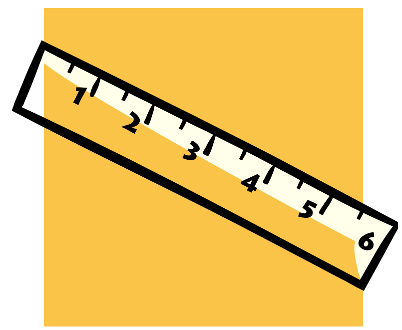
status: $\begin{cases} w_0 \simeq -1 \pm 0.2, \\ w_a \simeq 0 \pm 1 \end{cases}$

- **The probe of dark energy is the expansion history of the universe, parameterized by the Hubble parameter H(z)** $H(z) = \frac{\dot{a}}{a}$
- **Cosmic distances are proportional to integrals of *H(z)*$^{-1}$ over redshift.**
- ***H(z)* can be constrained by measuring:**

Luminosity distances of standard candles (Type 1a SNe)



Angular diameter distances of standard rulers (baryon acoustic oscillations).

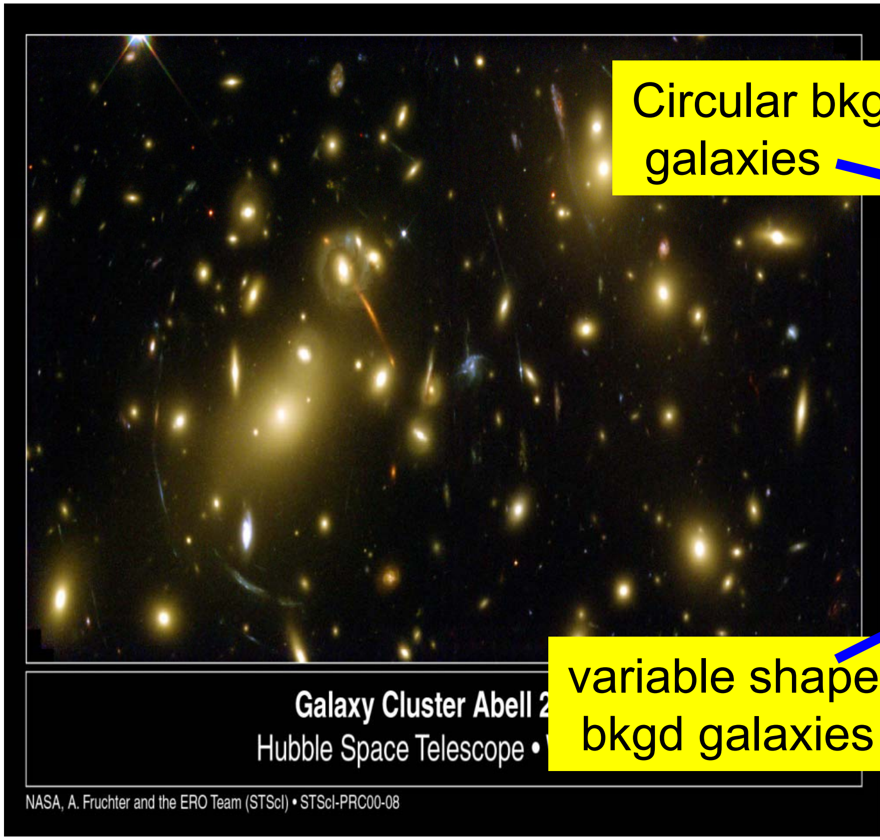


Weak Lensing Surveys & Galaxy Cluster Surveys probe growth of structure & angular diameter distances

LSST uses all techniques in synergy

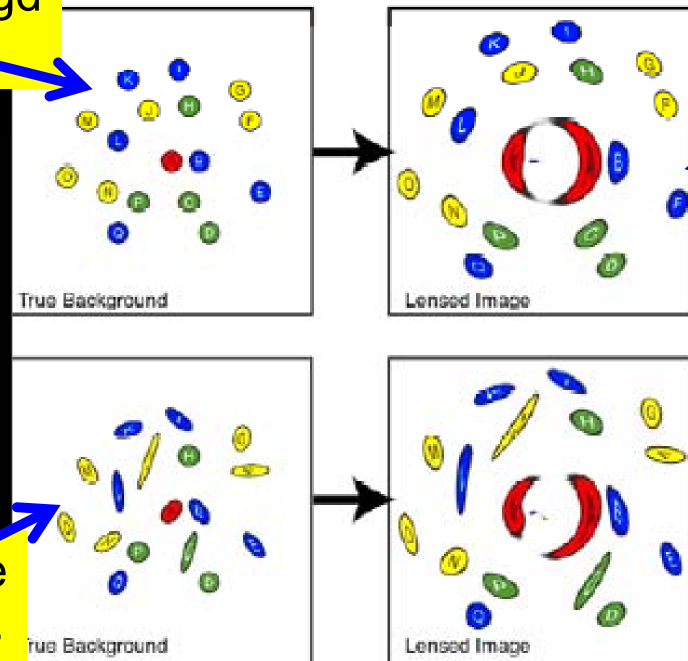
Gravitational Lensing & Shear

Red galaxy on axis strongly lensed. other galaxies weakly lensed: sheared images



Circular bkgd galaxies

variable shape bkgd galaxies



what is observed

Weak Lensing shear pattern less obvious but detectable statistically

- **Cosmic Shear** **is the *systematic and correlated* distortion of the appearance of background galaxies due to weak gravitational lensing by the clustering of dark matter in the intervening universe.**

The shearing of neighboring galaxies is correlated, because their light follows similar paths on the way to earth.

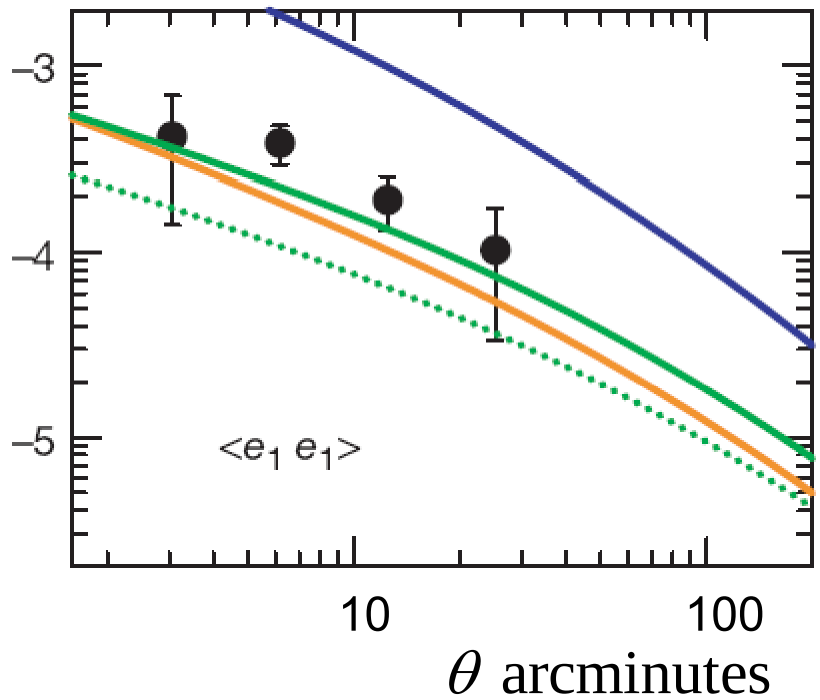
Cosmic shear: ~ 0.01 e.g. circular galaxy → ellipse with a/b ~ 1.01

1st Detections of Cosmic Shear

The simplest measure of cosmic shear is the 2-pt correlation function of the ellipticities measured with respect to angular scale.

$$< e(r) \bullet e(r+\theta) >$$

Log ellipticity correlation



Whitman 2000
145,000 galaxies
~1 degree

No dark energy

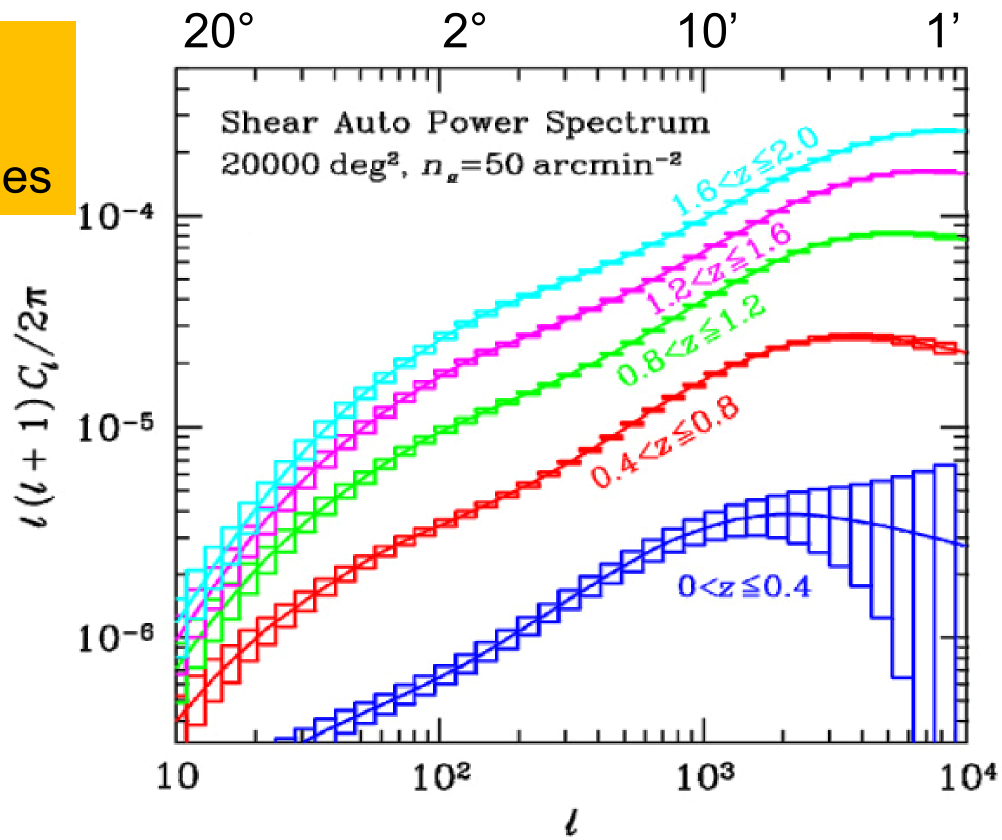
Ω(DE) =0.67

More recent survey
CFHT (2006)
1.6 million galaxies
~20 sq degree

LSST and Cosmic Shear

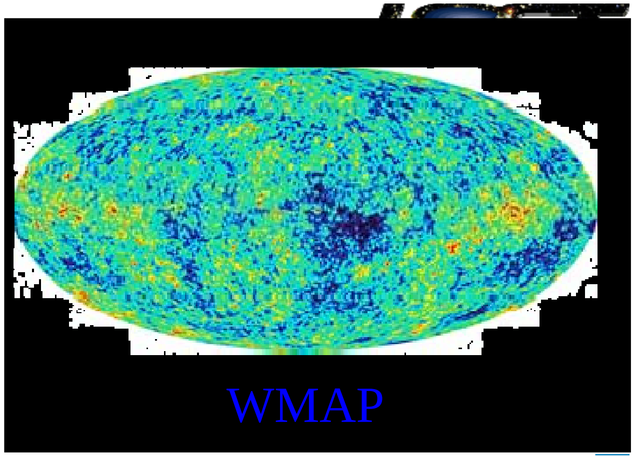
CFHT		LSST
1.6 million galaxies	→	3 billion galaxies
~20 sq degree		20,000 sq. degrees

- **Same 2-pt correlation function**
- **Fourier transform → power spectrum as a function of multi-pole moment (similar to CMB temperature maps).**
- **The growth in the shear power spectrum with the red shift of the background galaxies is very sensitive to *H(z)*. This provides the constraints on dark energy.**
- **3-point correlations will also be possible**

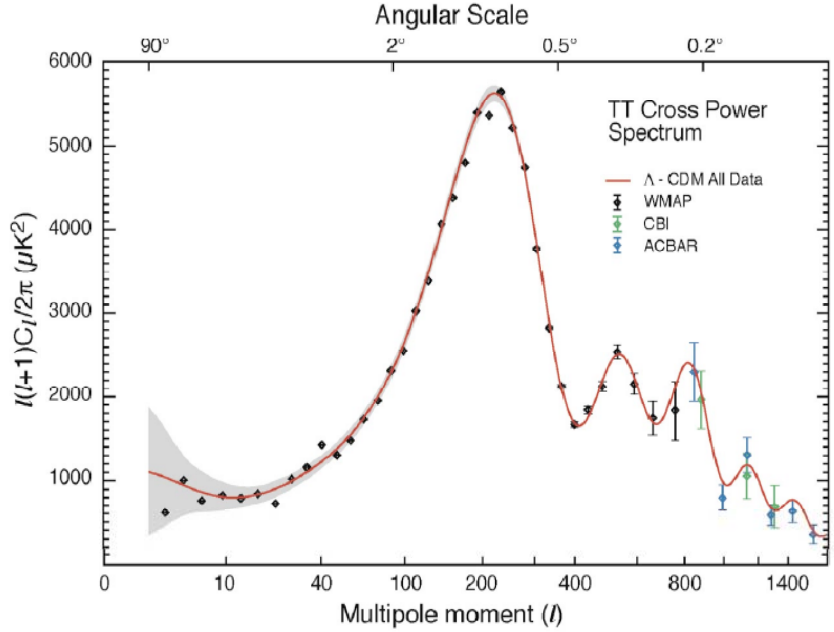


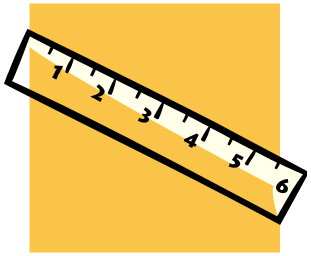
linear non-linear

Baryon Acoustic Oscillations



- **Prior to the formation of atoms (recombination) the baryons are tightly coupled to the radiation in the universe.**
- **An overdensity perturbation gives rise to an acoustic wave in this tightly coupled fluid, which propagates outward at the speed of sound**
- **After recombination, the matter and radiation decouple. The sound speed drops to zero, and the propagating acoustic wave stops.**
- **This gives rise to a characteristic scale in the universe: 150 Mpc, the distance the sound waves have traveled at the time of recombination.**

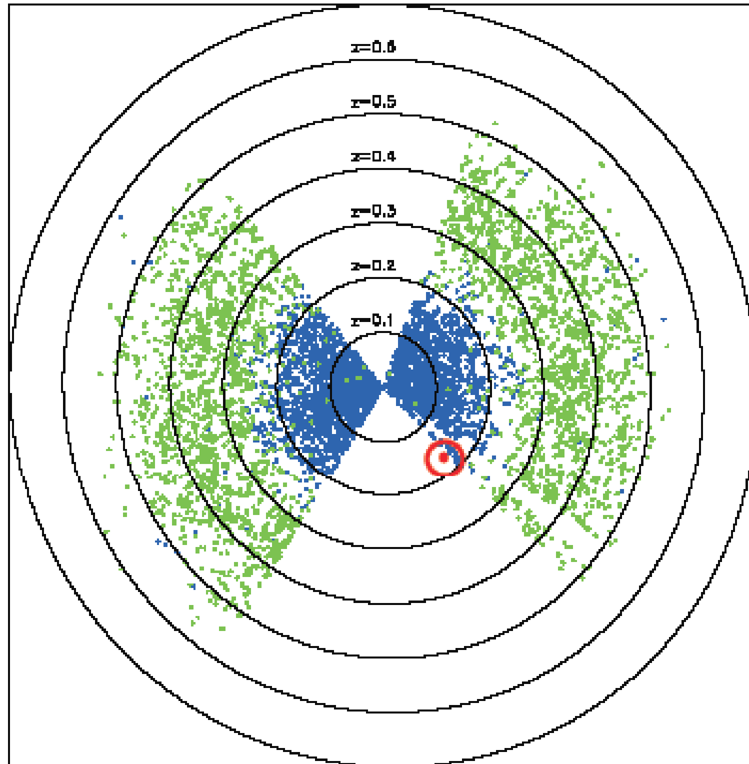


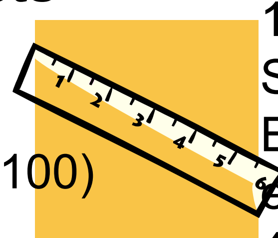


These acoustic waves are visible as the peaks in the CMB power spectrum.

Baryon Acoustic Oscillations

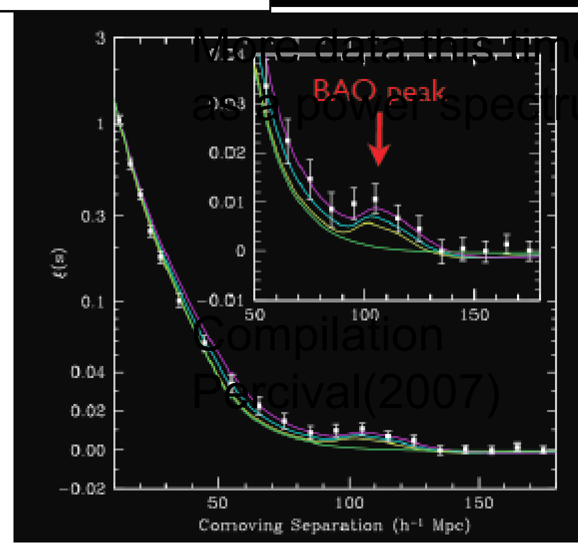
- **Following recombination, gravitational instability causes the birth of stars and galaxies.**
- **Gravitational coupling between dark matter and baryons creates an imprint of the acoustic oscillations in the galaxy distribution.**
- **This persists as the universe expands, although it gets weaker with time.**





Same physics as CMB (Z~1100) but at a time when Dark Energy is becoming important (z<3)

1st observation
SDSS
Eisenstein et al (2005)
40,000 galaxies
0.16<z<0.47



~~More data this time as a power spectrum~~

Compilation Percival(2007)

I. Shipsey DPF 2009

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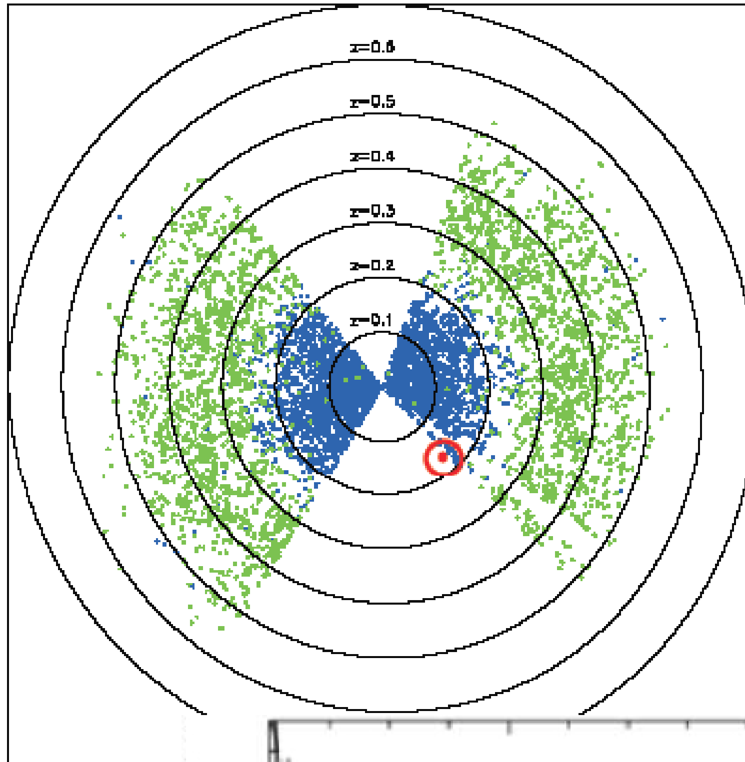

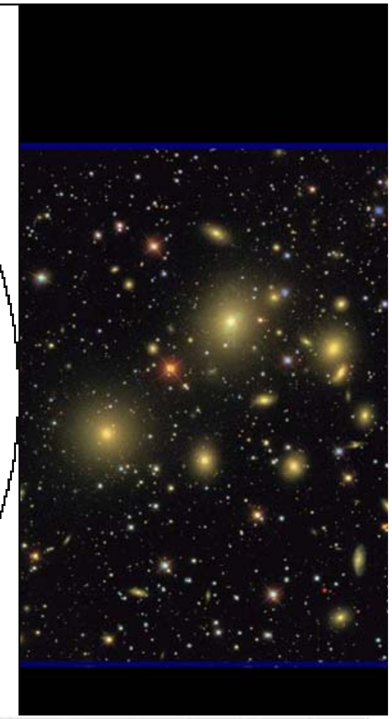

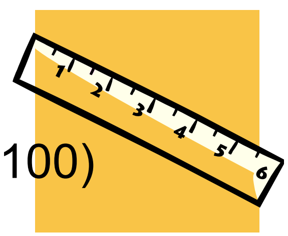

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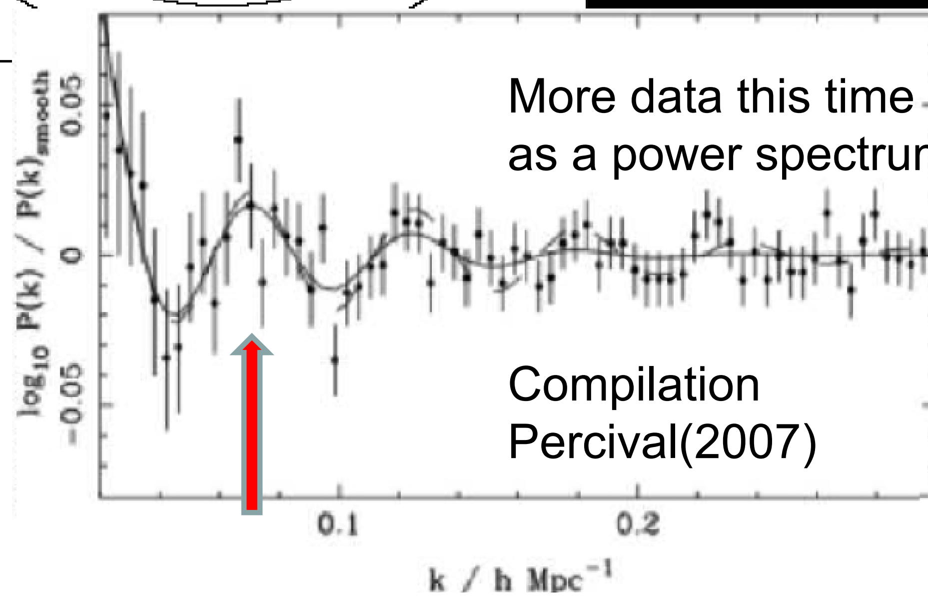

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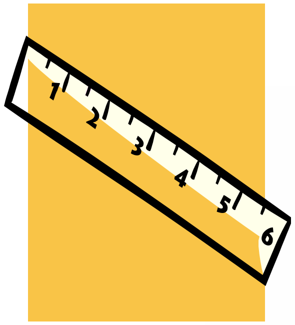
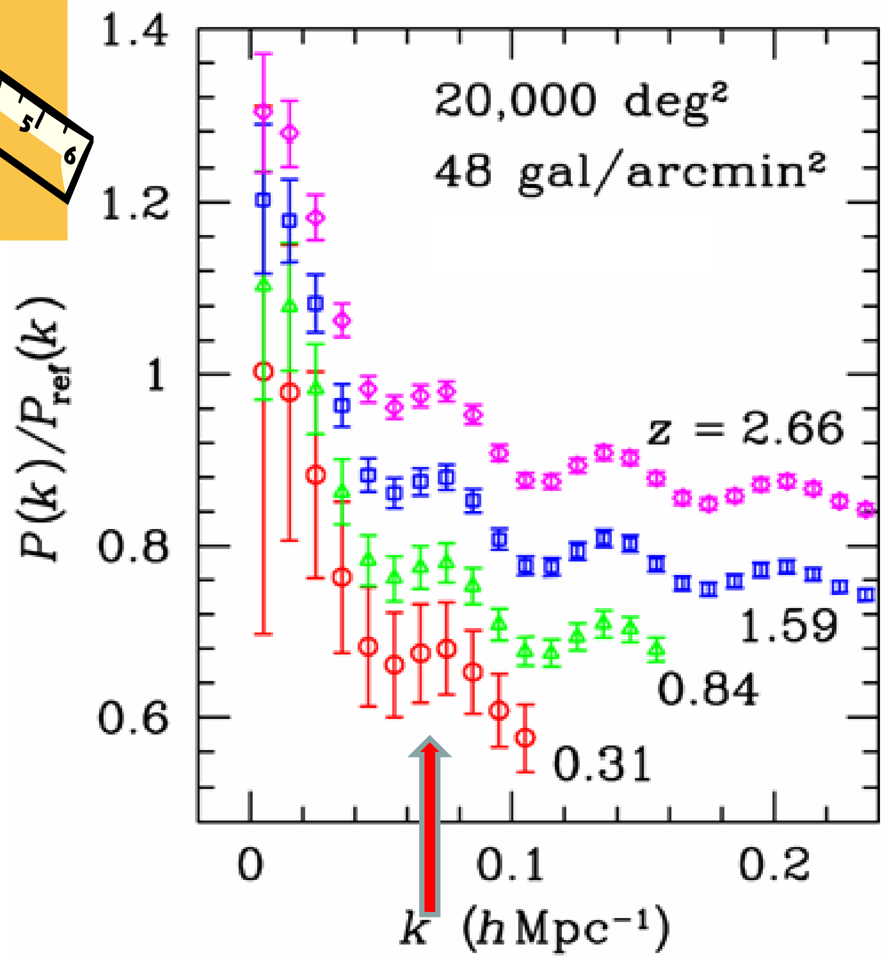
Baryon Acoustic Oscillations and LSST

- **How the length scale evolves with redshift is dependent on the Hubble parameter and therefore sensitive to dark energy**



- **Measure the galaxy angular power spectrum at different red shifts. Require high statistics over the redshift range.**



Simulations of LSST measured galaxy power spectrum divided by a featureless reference power spectrum, shifted vertically for clarity

SDSS		LSST
40,000 galaxies	→	3 billion galaxies
$0.15 < z < 0.6$		$0.15 < z < 3$

Predicted LSST Constraints on Dark Energy from multiple techniques

$$w = P/\rho$$

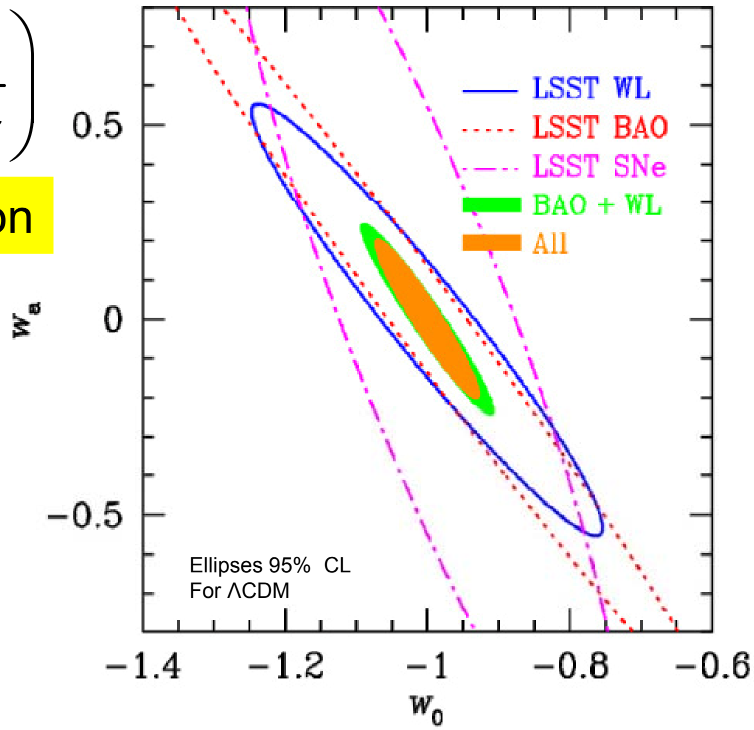
$$w = w_0 + w_a \left(\frac{z}{1+z} \right)$$

now evolution

$w_0 = -1,\ w_a = 0$

(ΛCDM assumed)

Prediction:
Zhan (2006)



WL: weak lensing
BAO: Baryon Acoustic Osscillatiions
SNe:Supernovae

$w_0 \simeq -1 \pm 0.2,\ \ w_a \simeq 0 \pm 1$
[Kowalski (2008)]

higher-order statistics of the shear and galaxy data will further tighten the constraints on dark energy.

- Combined constraints significantly more powerful than individual probes
- Statistical uncertainties are small, measurement is systematics limited
- Systematics include photo-z reconstruction and shear shapes

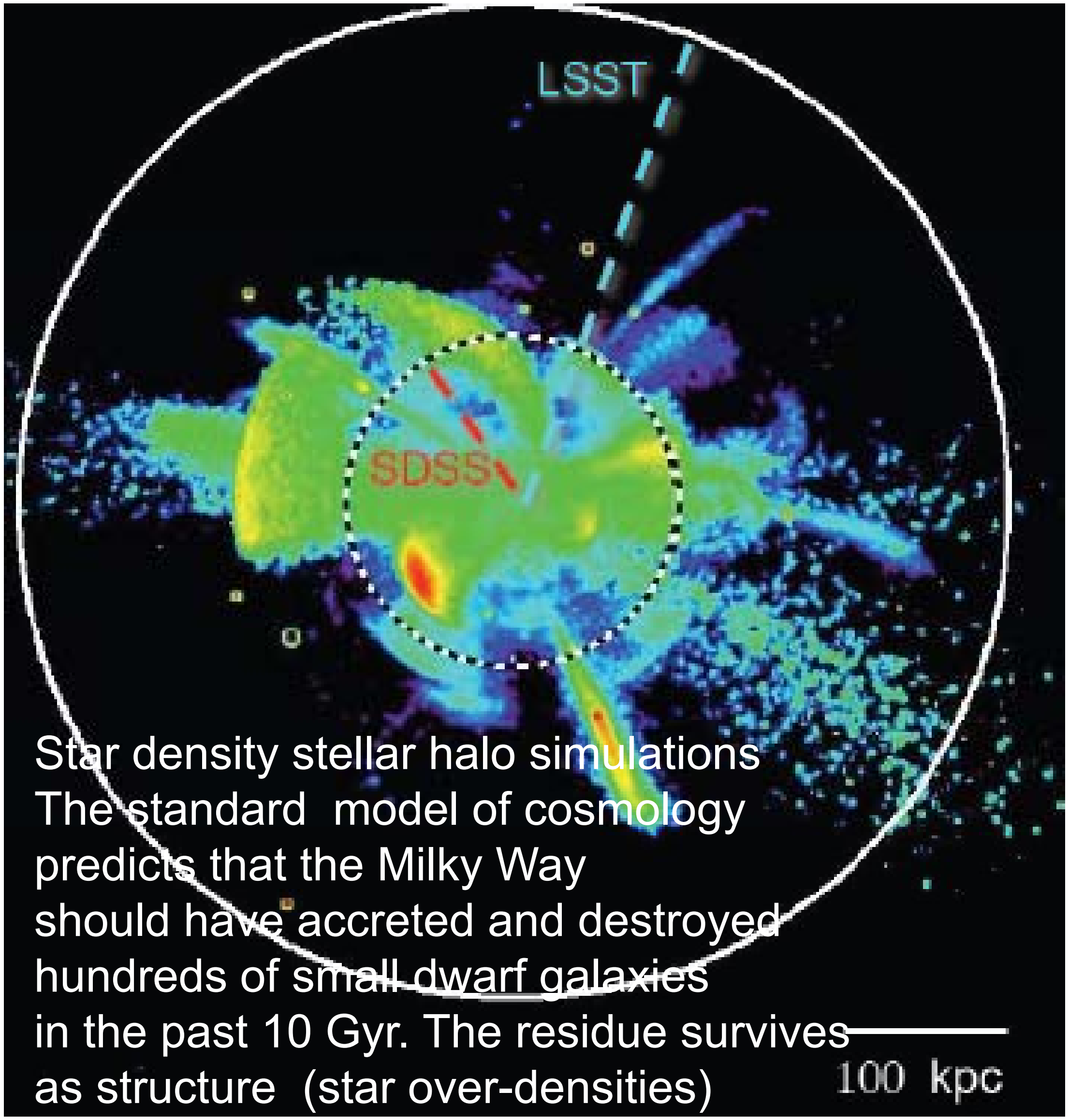
LSST : an important contribution to measuring dark energy, commensurate with a Stage IV experiment & complementary to JDEM (need both).

Science Driver 2: Mapping the Milky Way

An SDSS image of the Cygnus Region

With LSST:
About 200 images, each 2 mag deeper
The co-added images will be 5 mag. deeper
Precise proper motion & parallax measurements will be available for r<24 (4 magnitudes deeper than the Gaia survey)

Example: structure of outer milky way



Star density stellar halo simulations
The standard model of cosmology predicts that the Milky Way should have accreted and destroyed hundreds of small dwarf galaxies in the past 10 Gyr. The residue survives as structure (star over-densities)

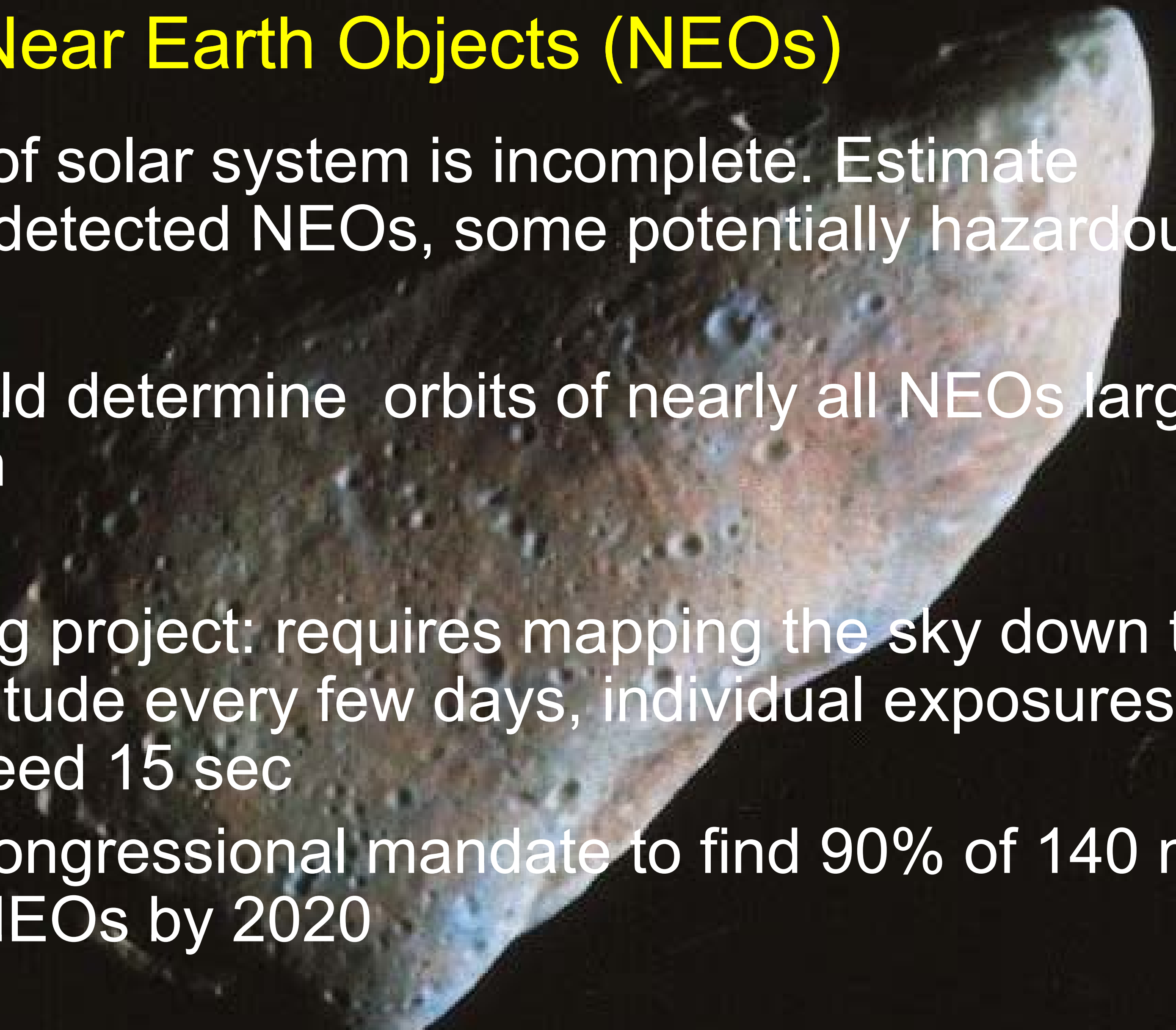
RR Lyrae stars are luminous enough and copious enough to map the outer galaxy

Overdensities found in SDSS star count studies to 100 kpc

LSST RR Lyrae to 400 kpc, extending SDSS mapping volume by a factor of 50.

An important test of the small-scale accretion history of the Galaxy and a test of standard model of cosmology

Bullock and Johnston (2005)



Science Driver 3 Inventory of the Solar System Example: Near Earth Objects (NEOs)

- Inventory of solar system is incomplete. Estimate 17,000 undetected NEOs, some potentially hazardous
- LSST would determine orbits of nearly all NEOs larger than 140m
- Demanding project: requires mapping the sky down to 24th magnitude every few days, individual exposures not to exceed 15 sec
- Fulfills a congressional mandate to find 90% of 140 m or larger NEOs by 2020

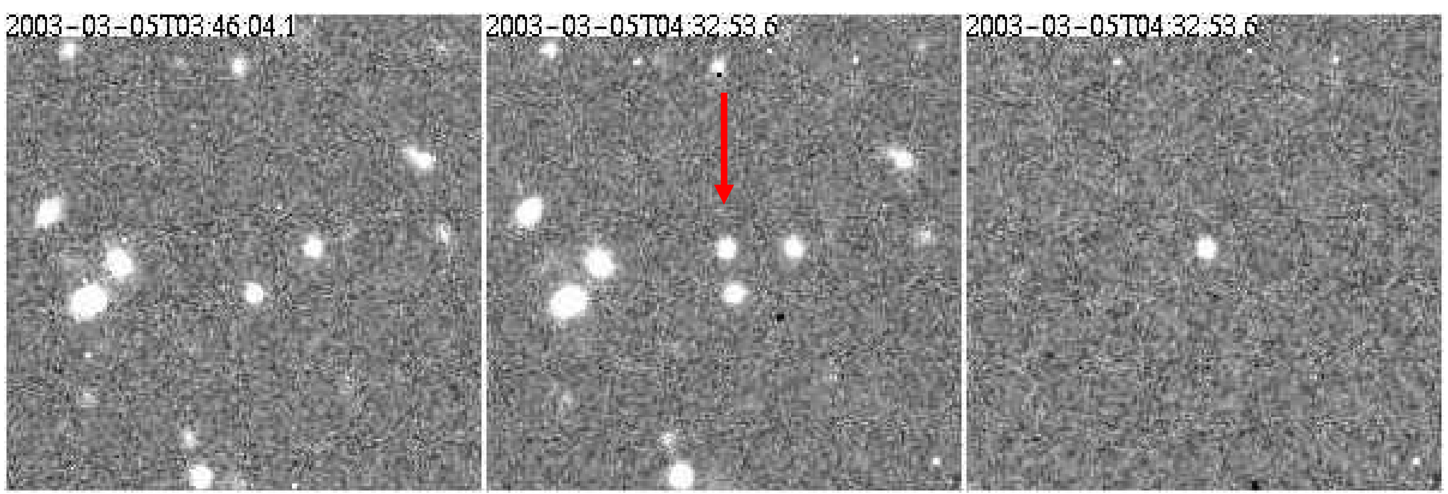
Science Driver 4: Transients & variable objects

The twentieth century discovery of explosions (supernovae), eruptions (novae) and variable stars (Cepheid variables), Gamma Ray Bursts

LSST: large etendue and cadence can characterize known classes of transient and variable objects and discover new ones.
A variety of time scales from 10 seconds to the whole sky every 3 nights & up to 10 years
Expect as many variable stars in LSST dataset as all stars in SDSS ~ 100 million

Optical flashes

Image 1 (t=0) **Image 2 (t'>t=0)** **Image 2- Image 1**

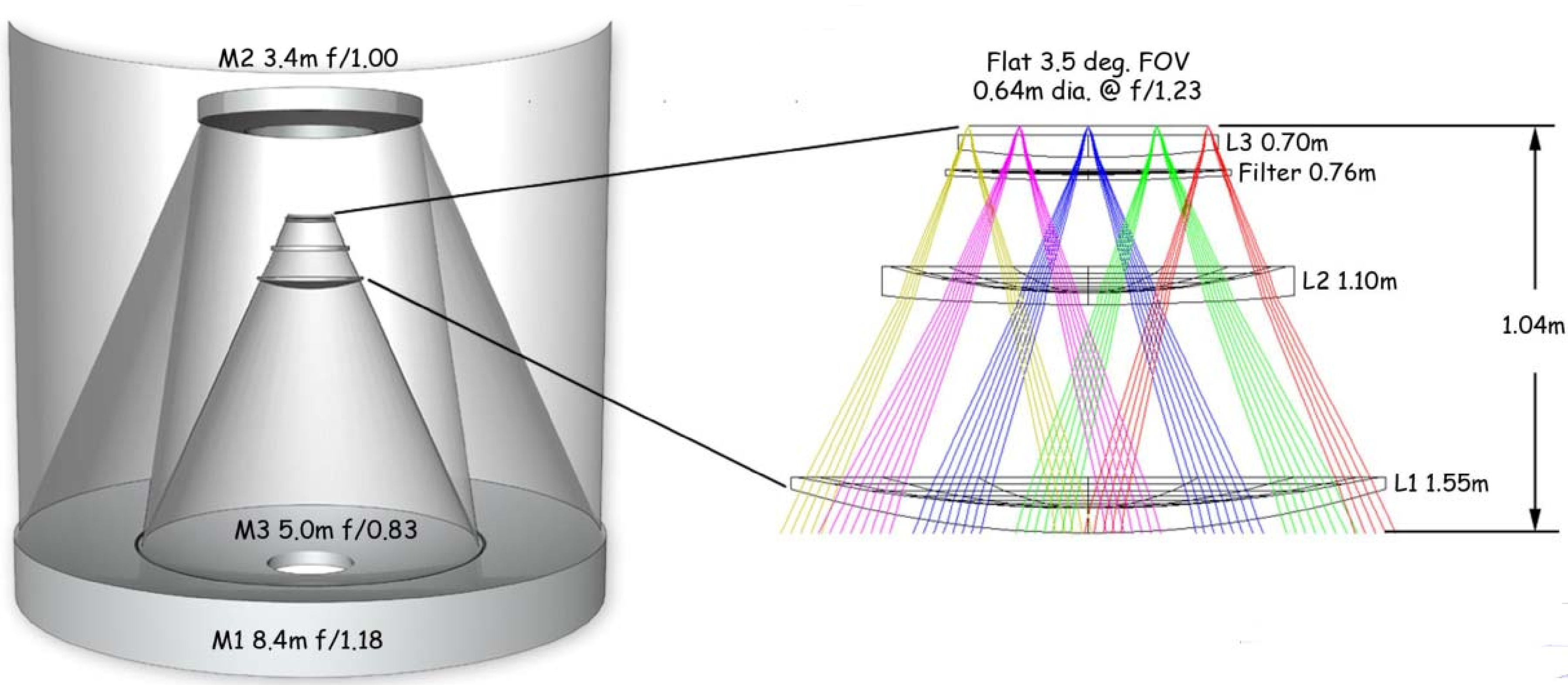


Becker, A.C., et al. 2004, Astrophysical Journal, 611, 418

Deep Lens Survey

LSST Optical Design

- *f/1.23* Very short focal length gives wide field of view
- 3.5 ° FOV over a 64 cm focal plane, Etendue = 319 m^2deg^2
- < 0.20 arcsec FWHM images, 6 wavelength bands: 0.3 - 1 μm



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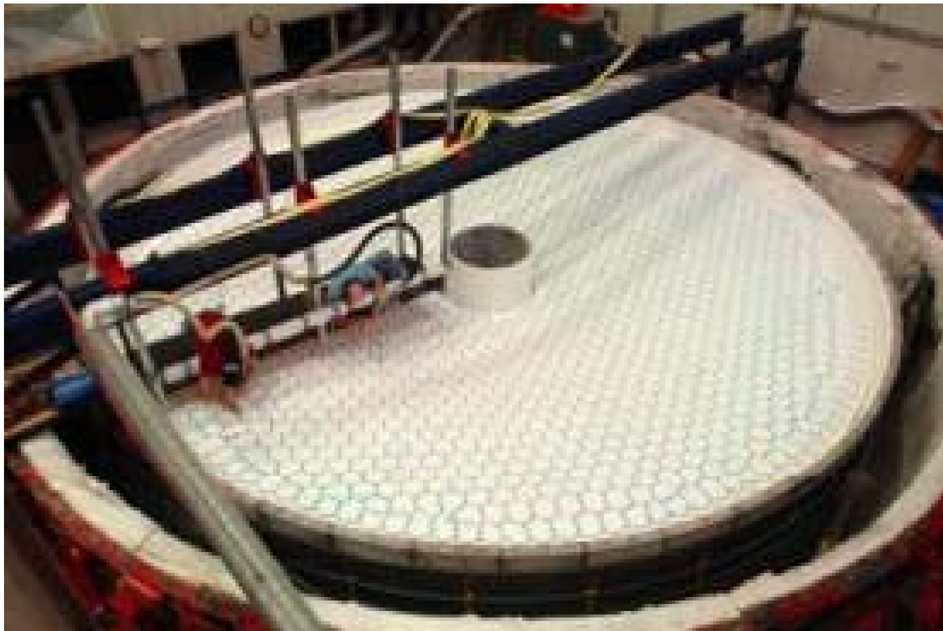
The primary/tertiary mirror is being fabricated



Stewart Observatory Mirror
Lab Tucson, AZ

High Fire, March 29 2008

2 September 2008

1165ºC (2125ºF). Then anneal & cool gradually to room temp.

Now mirror ready for grinding & polishing.

Delivery:2011

The secondary mirror is also being fabricated

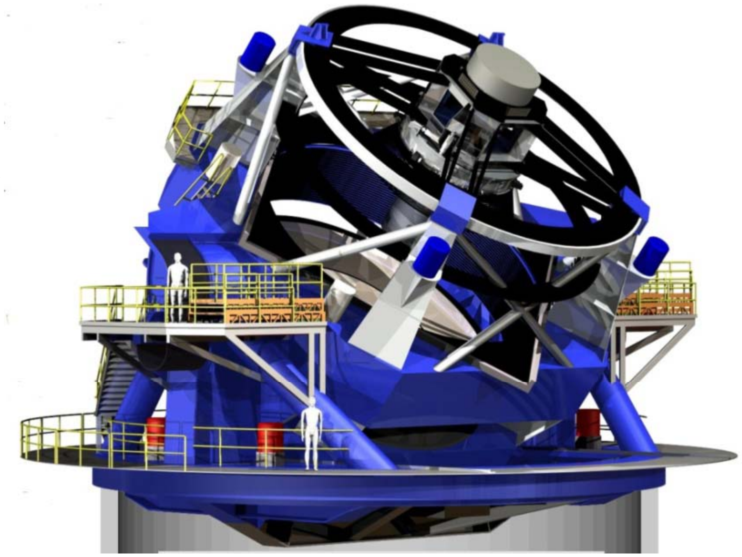
Corning, Canton , NY

March, 2009

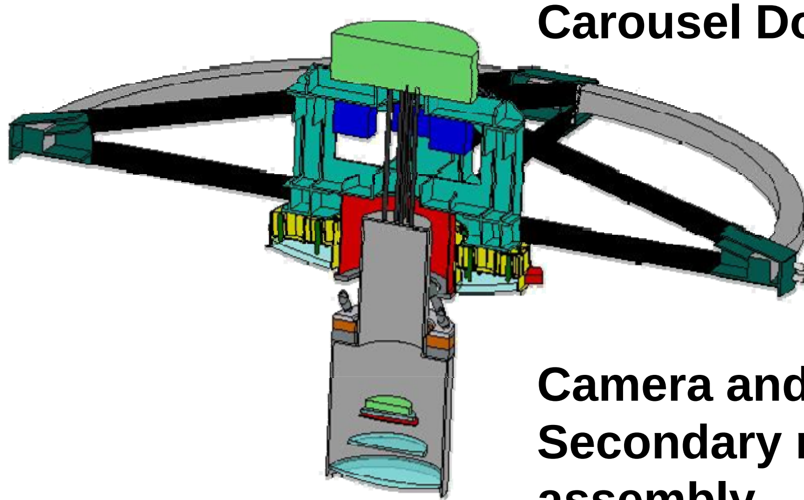
The Telescope

The high curvature mirrors allow a short, light, stiff , stable and agile telescope

1.5 m atmosphere monitoring telescope



Altitude over azimuth Carousel Dome (not shown)

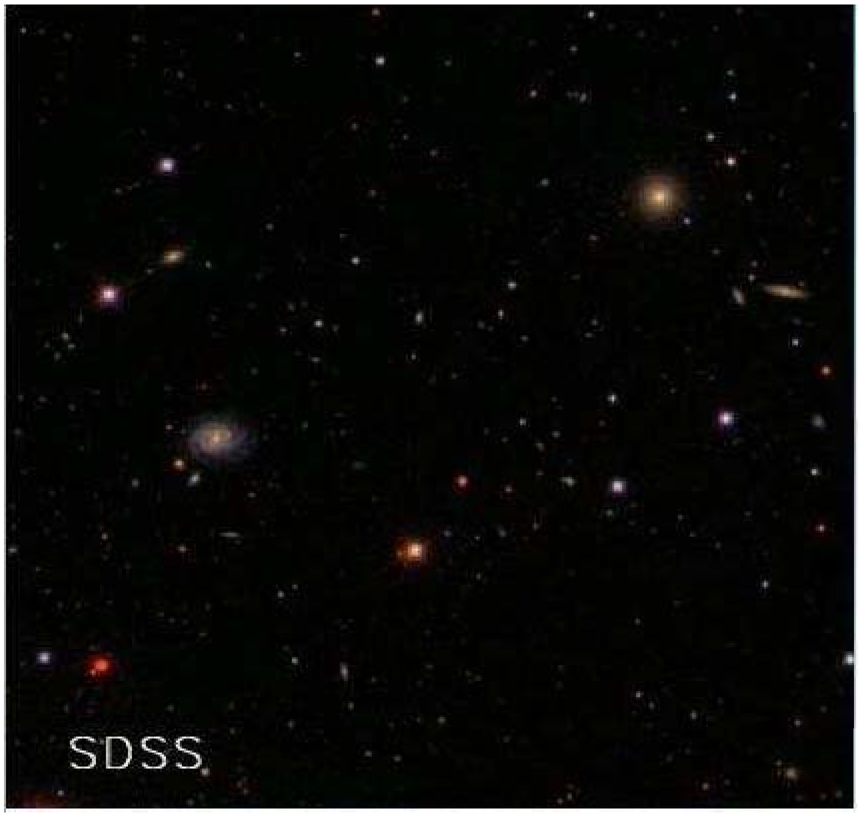


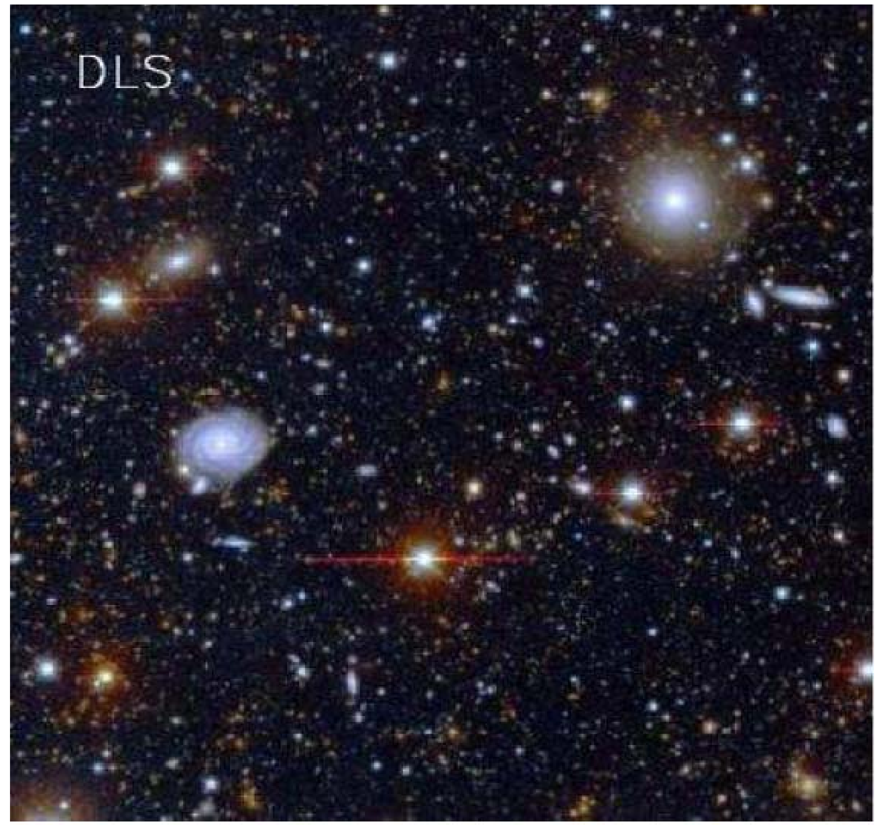
Camera and Secondary mirror assembly

Optical Quality at the LSST site

These two images are of the same patch of sky

LSST Chile , 0.67 arcsec seeing



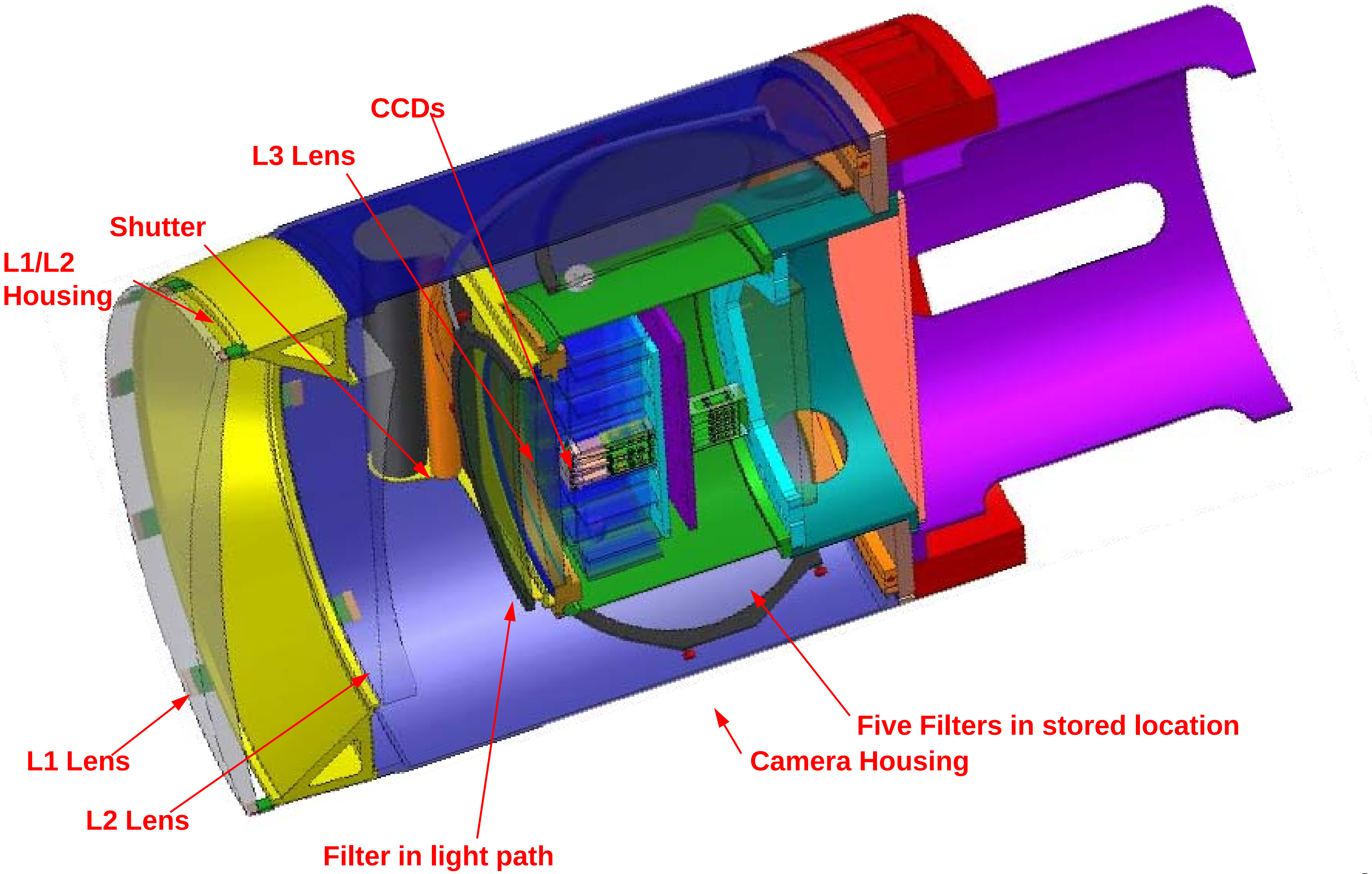


SDSS Apache Point NM, 1.3 arc sec seeing

x2 better x5 fainter per image (1,000 images at each sky location will be obtained over 10 years)

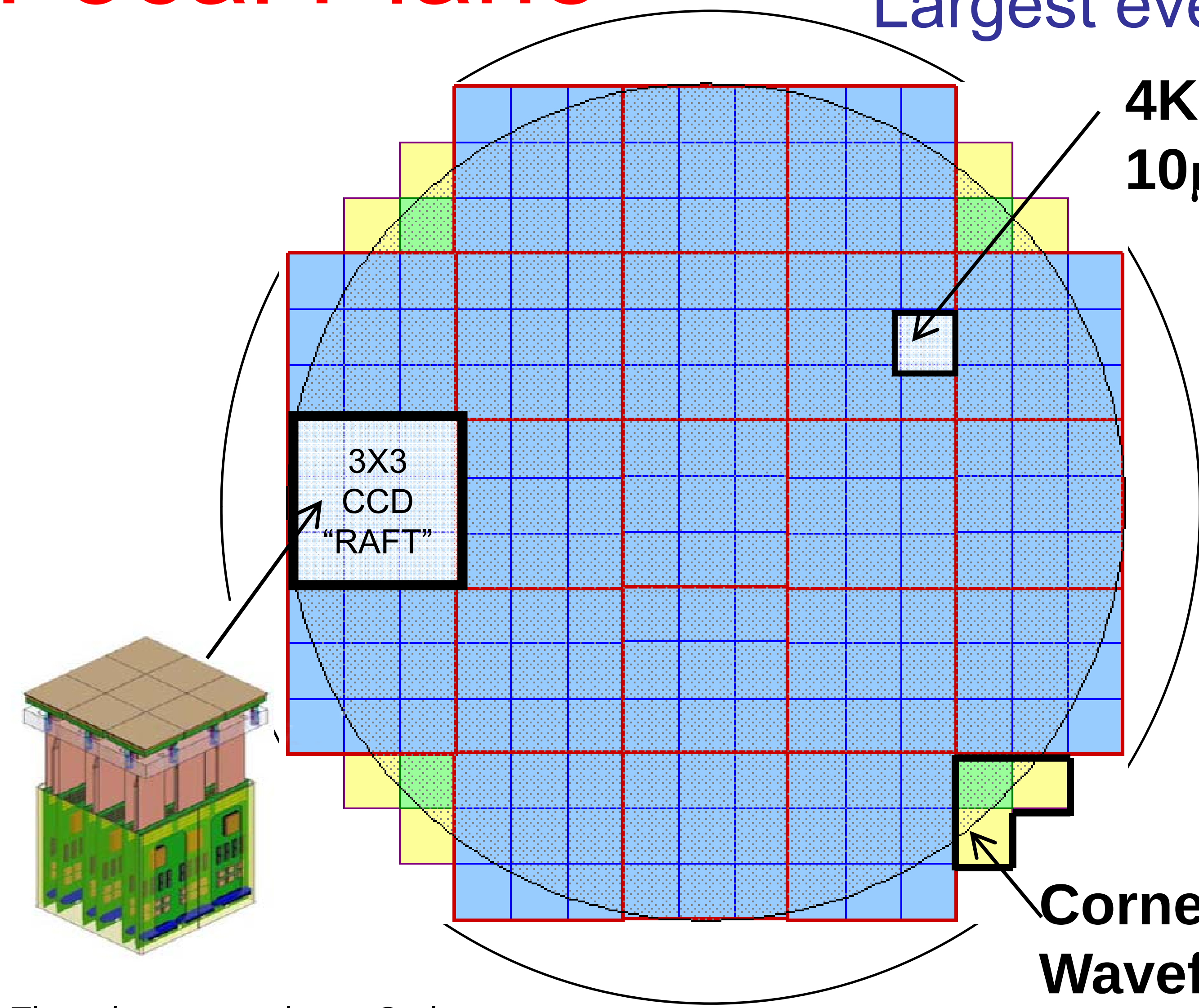
The LSST 3 Gigapixel Camera

The telescope optics produce a large, 64 cm, image plane requiring a high pixel count



Focal Plane

Largest ever for astronomy



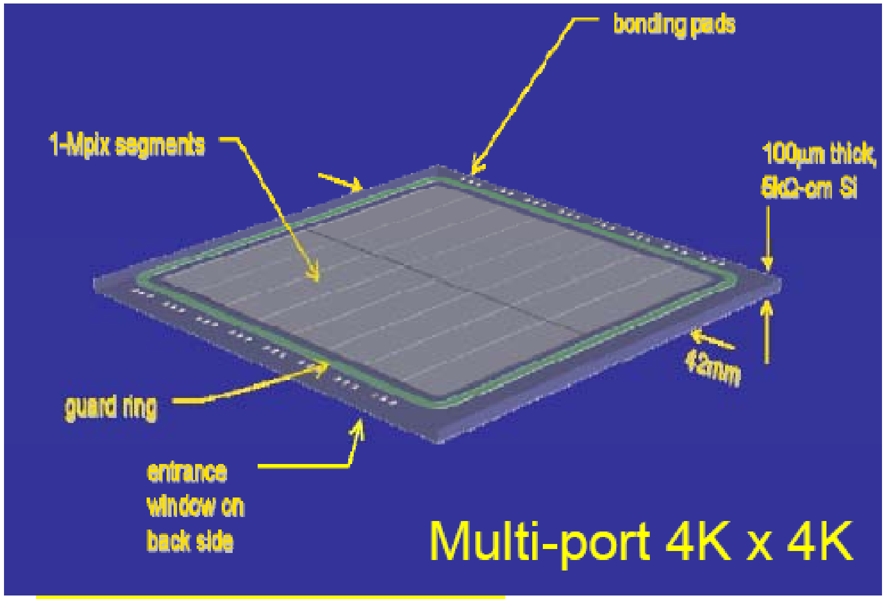
4KX4K CCD
10μm pixels

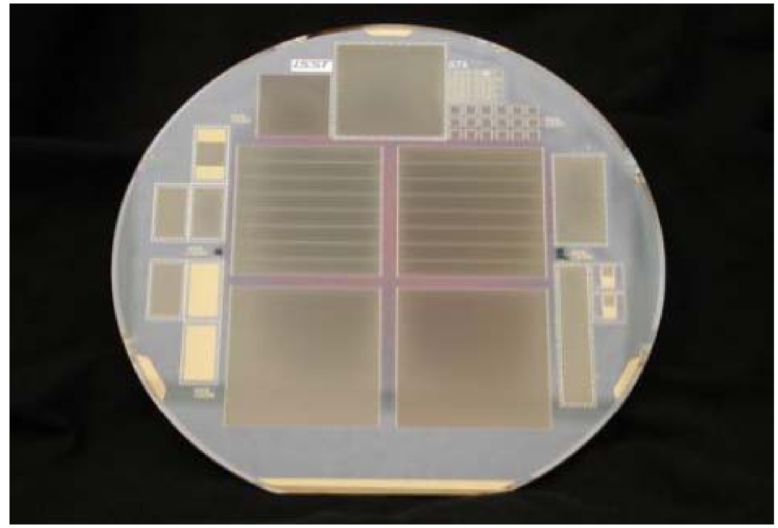
189 CCDs
3.2 Gpix
-100°C
Vacuum
2 sec readout

Corner area
Wavefront sensing
and guiding

The sciences requires a Cadence:
15+1 sec exposure/shutter, 2 sec readout,
15+1 sec exposure/shutter, 2 sec readout, 5 sec slew

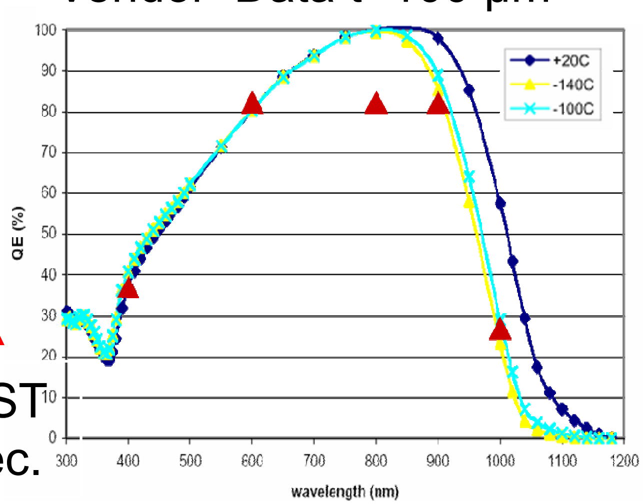
Focal Plane Sensors





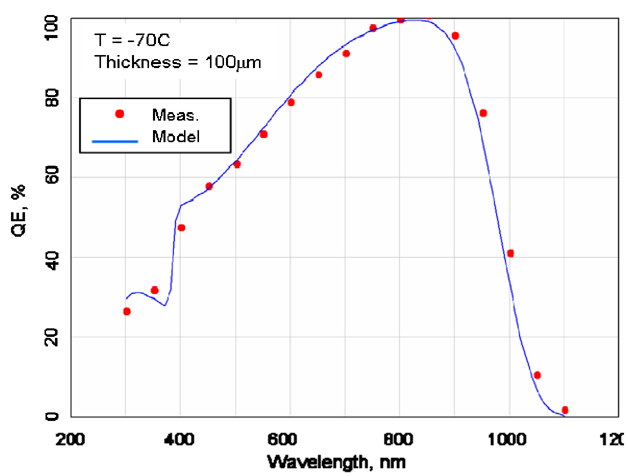
Quantum Efficiency

Vendor Data t=100 µm



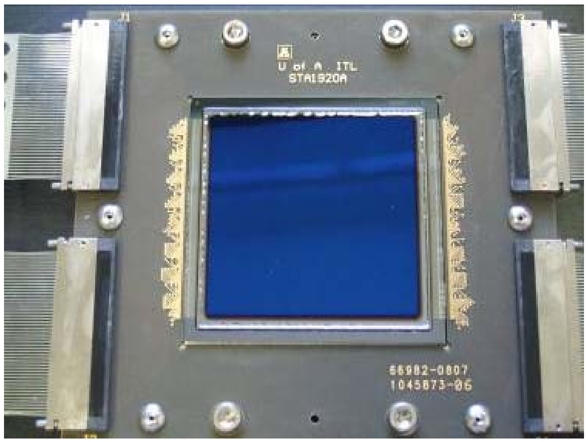
LSST spec.

LSST (BNL) DATA



Sensors meet LSST QE spec.

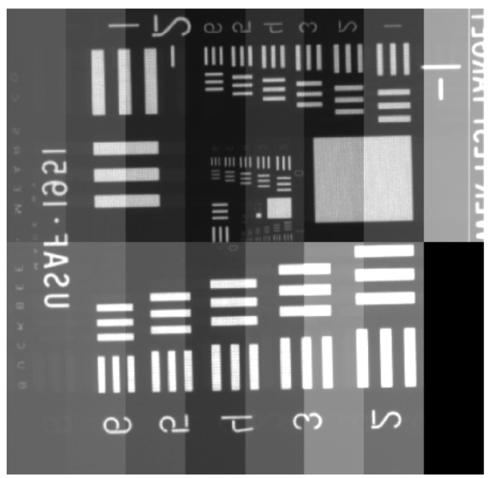
The LSST sensor will be tested this summer on-the sky



4K x 4K with 10μm pixels
100 μm thick
16 amplifiers
4 side buttable

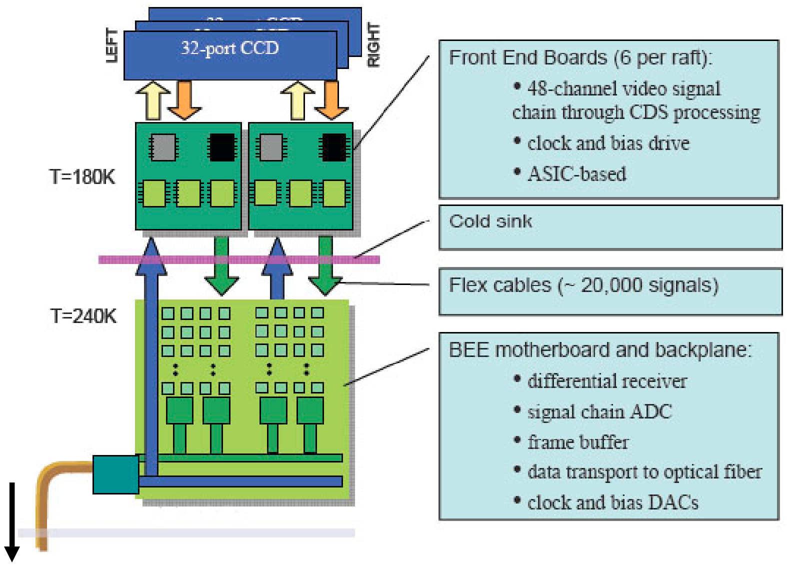
1.2m LSST calibration telescope* will be used to test the CCDs in the field.

Image results on prototype sensor

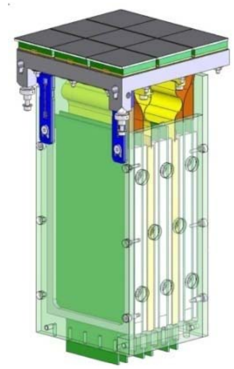


**also known as Calypso at Kitt Peak*

Camera → Data



CCD Raft Tower

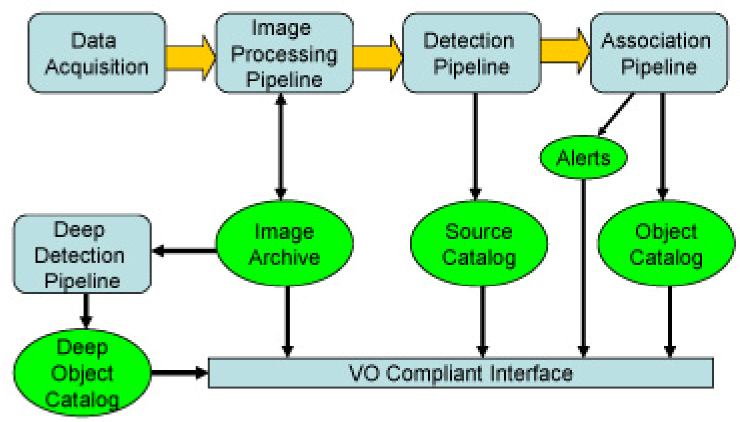


144 Mpix
Autonomous
camera

camera calibration data

raw image data

- Every 15 sec: 6GB
- Nightly data generation rate: 15 TBytes
- Yearly data generation rate: 6.8 Pbytes



- Pipeline to go from raw image + calibration data to science images & science data products (many in real time) is shown at right
  Total data volume after processing will be several 100 PB over 10 years
- LSST is a data management/data mining challenge

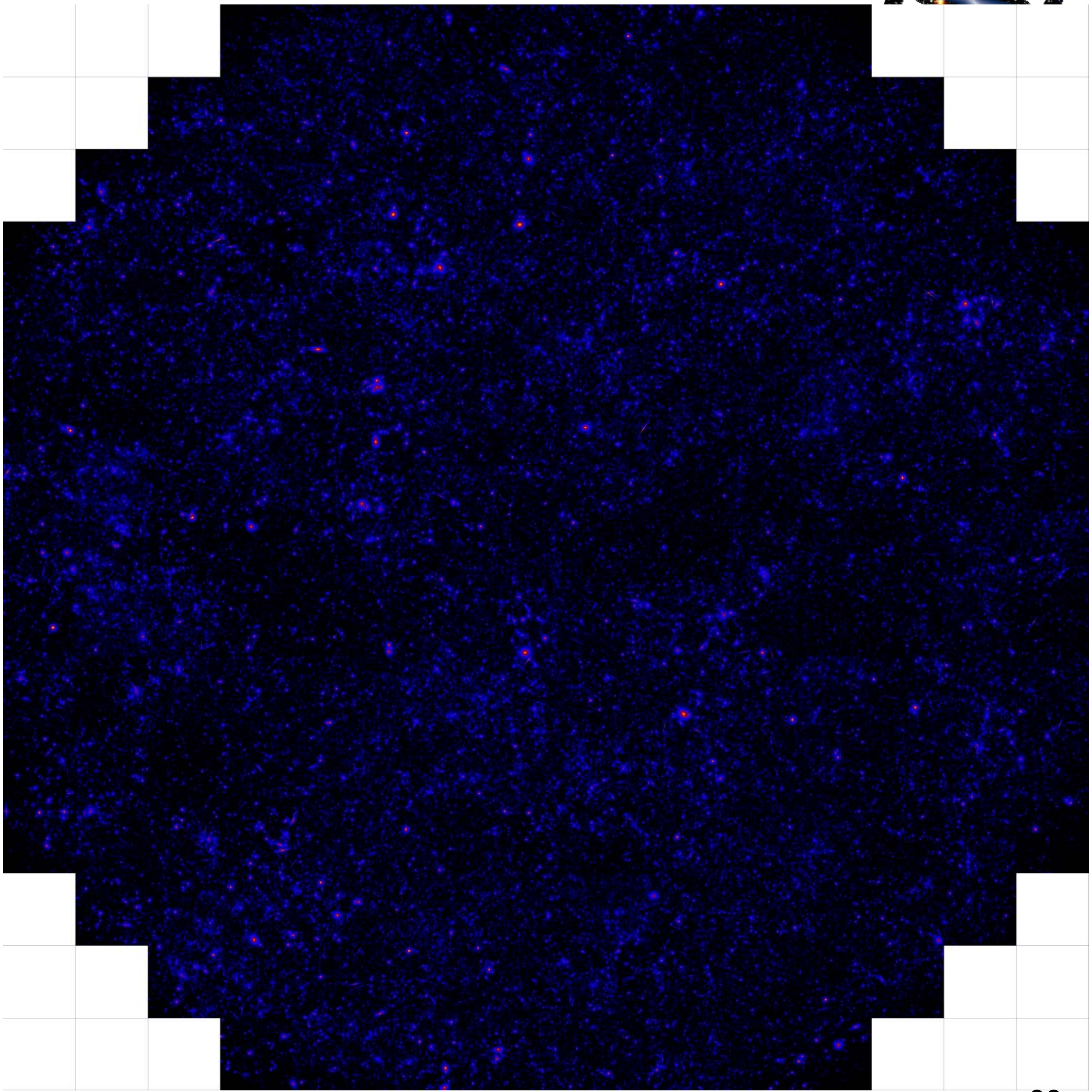
Full LSST end-to-end photon simulation

Cosmological Models
-->
Galaxy Spatial Models & spectra
->
Atmosphere
->
Optics
->
Detector

All 3 billion pixels

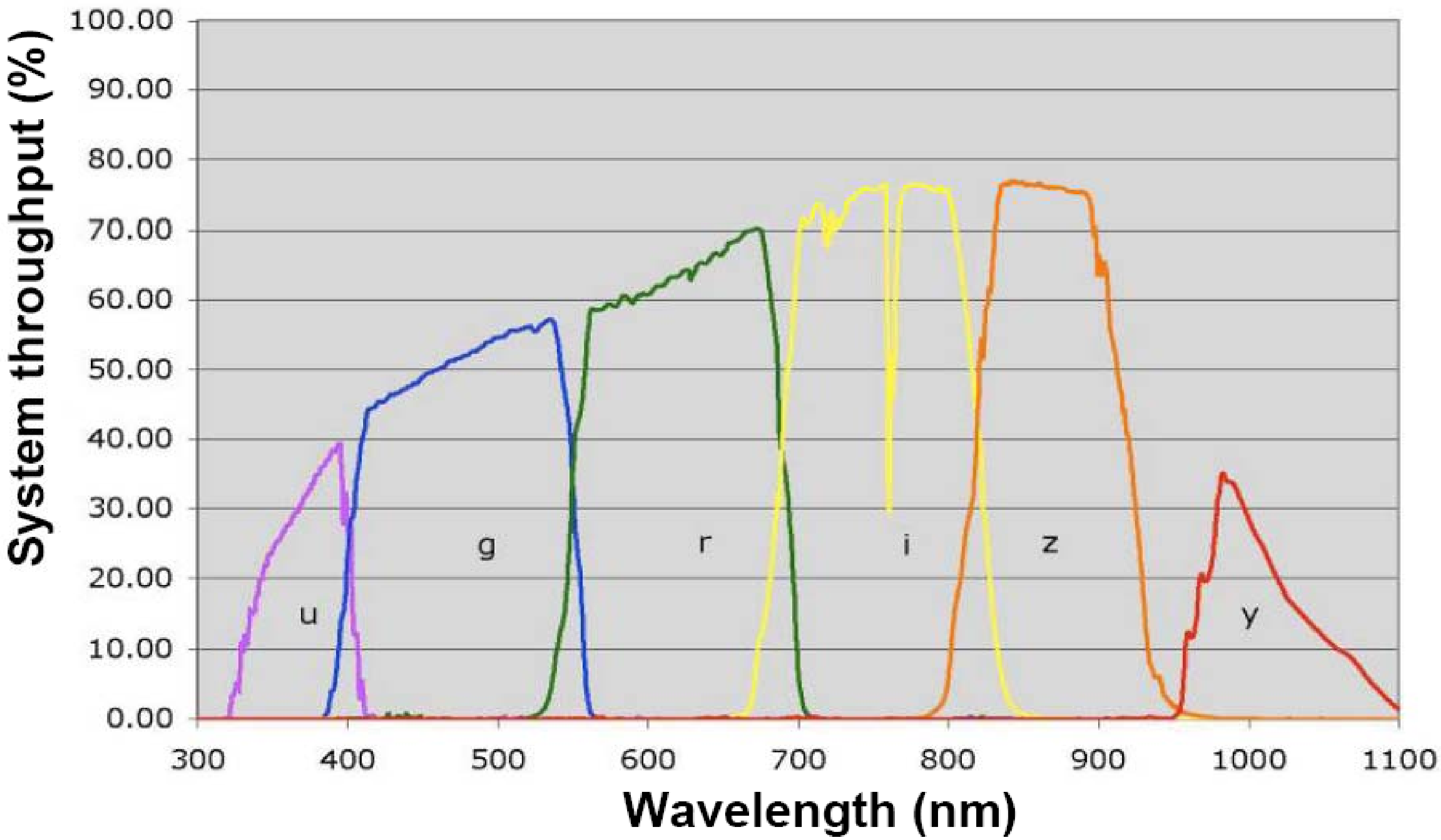
In one image:
12 million objects,
billions of raytraced photons

I. Shipsey DPF 2009



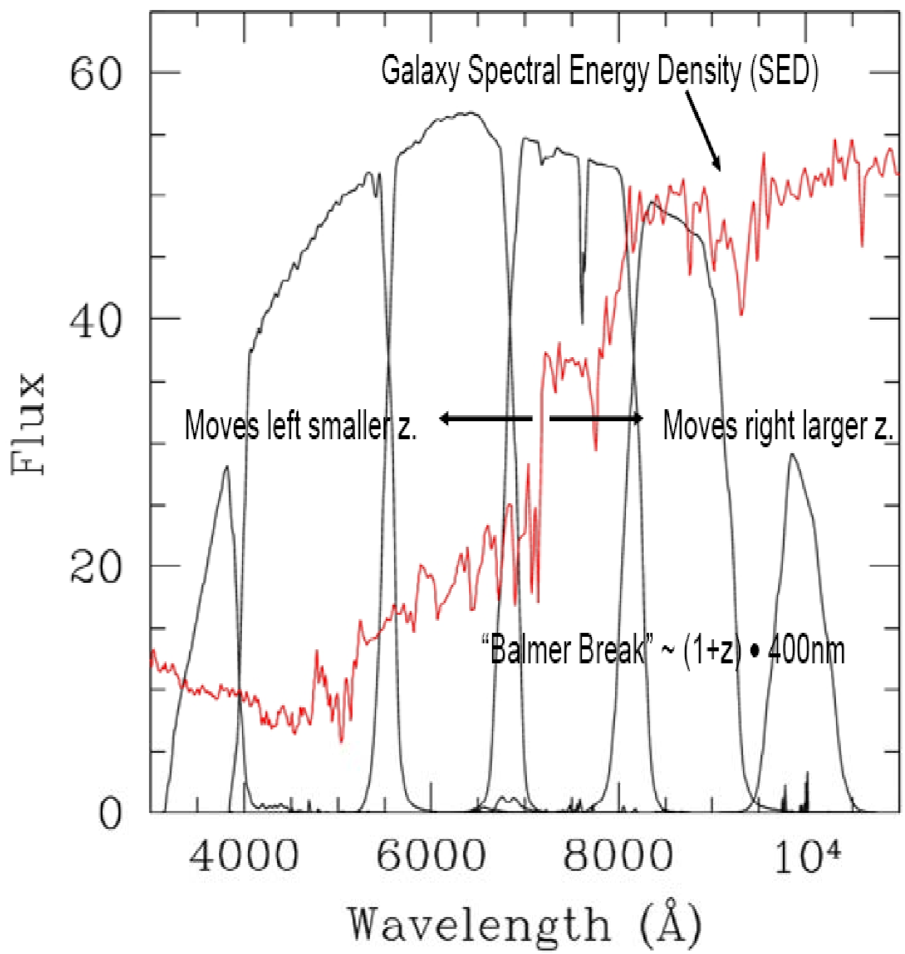
LSST Optical Filter Bands

Transmission- atmosphere, telescope, & detector QE



→ Photometric determination of galaxy redshifts

Photometric Redshifts

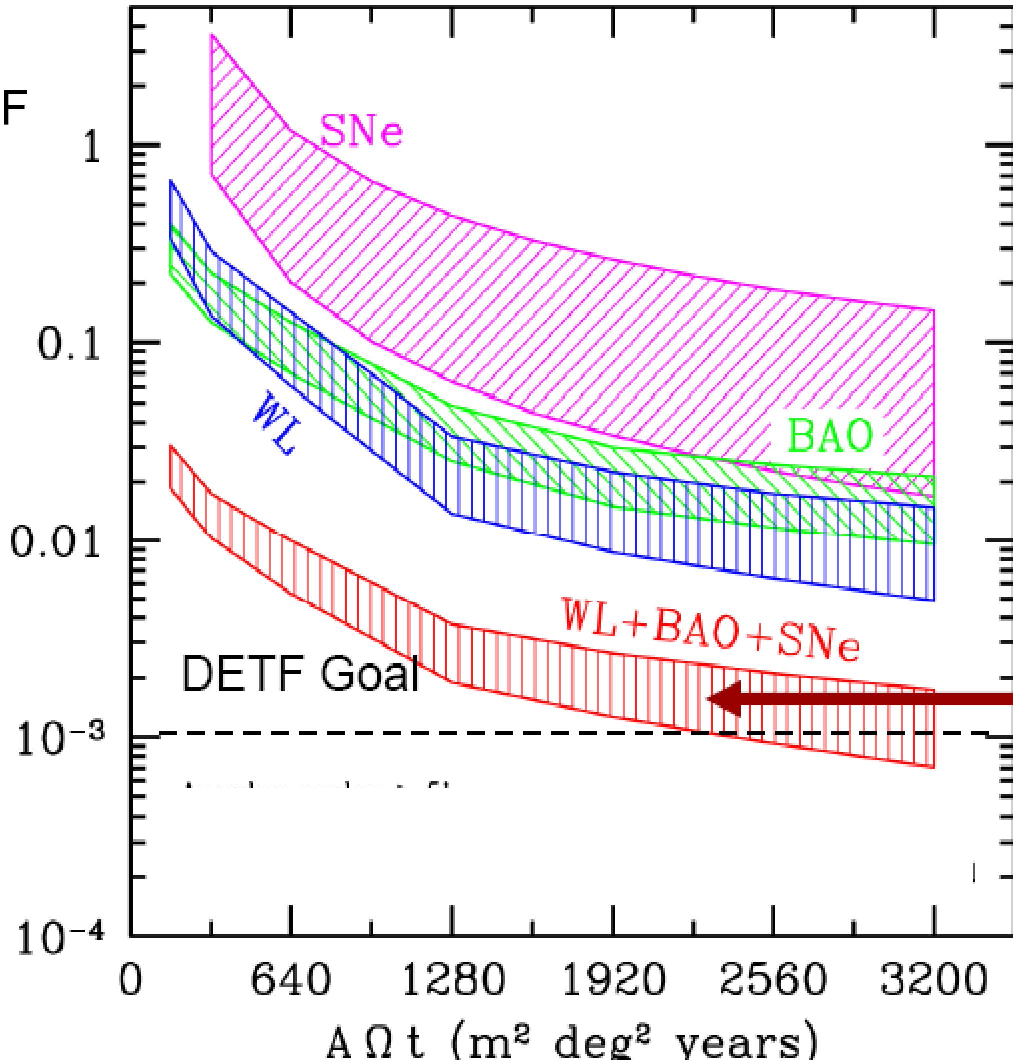


- Galaxies have distinct spectra, with characteristic features at known rest wavelengths.
- Accurate redshifts can be obtained by taking spectra of each galaxy. But this is impractical for the billions of galaxies in the LSST
- data set.
- Instead, the colors of the galaxies are obtained from the images themselves. This requires accurate calibration of both the photometry and of the intrinsic galaxy spectra as a function of redshift. Require accuracy of 0.003(1+z) and similar precision to not degrade cosmological parameters

Precision on dark energy parameters

DETF FoM

σ(w_o) x σ(w_a)



Year 1 5 10

Combination is significantly better than any individual measurement.

LSST Education & Public Outreach

Reaching for the sky has always inspired the deepest questions and boldest expeditions of discovery.

Now we can reach more of the Universe, through the vastness of time, in unprecedented detail.

- **Open data, no proprietary period**
- **LSST is Telescope for Everyone**

LSST will discover 4 billion new galaxies– enough for everyone

A school child in South Africa, Chile,
or Detroit can discover an island universe

Project Update & Schedule

Funding: Public-Private Partnership NSF, DOE, Private

1. The Collaboration

   A. 200+ members 29 universities/national labs incl. IN2P3 (France) & Google, and growing…..groups from astronomy & particle physics

2. Recent Project Developments

   A. $20M Charles Simonyi & $10M Bill Gates - mirror development

   B. $1.5M from Keck Foundation w/total ~$2.75M - Sensor prototyping

   C. Conceptual Design Review (CoDR-NSF) 9/07 successful

   D. LSST science & design "living document "Astro-ph:0805.2366

   E. AAS 1/09- 30 Posters http://www.lsst.org (D.& E. are a good overview)

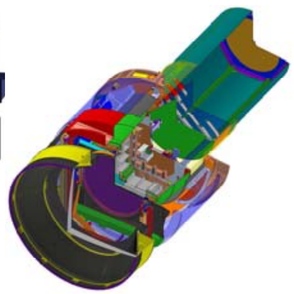
   F. Strong Endorsement from P5 panel (May/08)

   G. 80 papers → Astro2010 on LSST , LSST Science Book (9/09)

   H. Astro2010 & PASAG reviews

3. Schedule

   With appropriate funding from NSF and DOE the project is on-track to achieve commissioning and early science in the second half of the next decade.



Summary

- LSST will be a world-leading facility for astronomy and cosmology. A single database enables massively parallel astrophysics. With broad support in the astronomy community, it is a key component of NSF's long-term plan.
- LSST probes dark energy via weak lensing, baryon oscillations, Type 1a supernovae, and clusters of galaxies, & probes dark matter through strong lensing, it will map the Milky Way, survey the solar system and likely discover entirely new classes of object. No other existing or proposed ground-based facility has comparably broad scientific reach.
- Synergy in technical & scientific expertise between the astronomy & particle physics & Computer Science communities will be essential for success.

- Data with no proprietary period maximizes discovery potential & provides unprecedented outreach opportunities
- A detailed initial design is in place for all major components . Private funding has enabled mirror fabrication to begin, & sensor R&D. With appropriate funding from NSF and DOE: the project is on-track to achieve commissioning and early science in the second half of the next decade.