The LSST and Observational Cosmology

Prof. David L. Burke

Kavli Institute for Particle Astrophysics and Cosmology

Stanford Linear Accelerator Center

Stanford University

LPSC

Grenoble

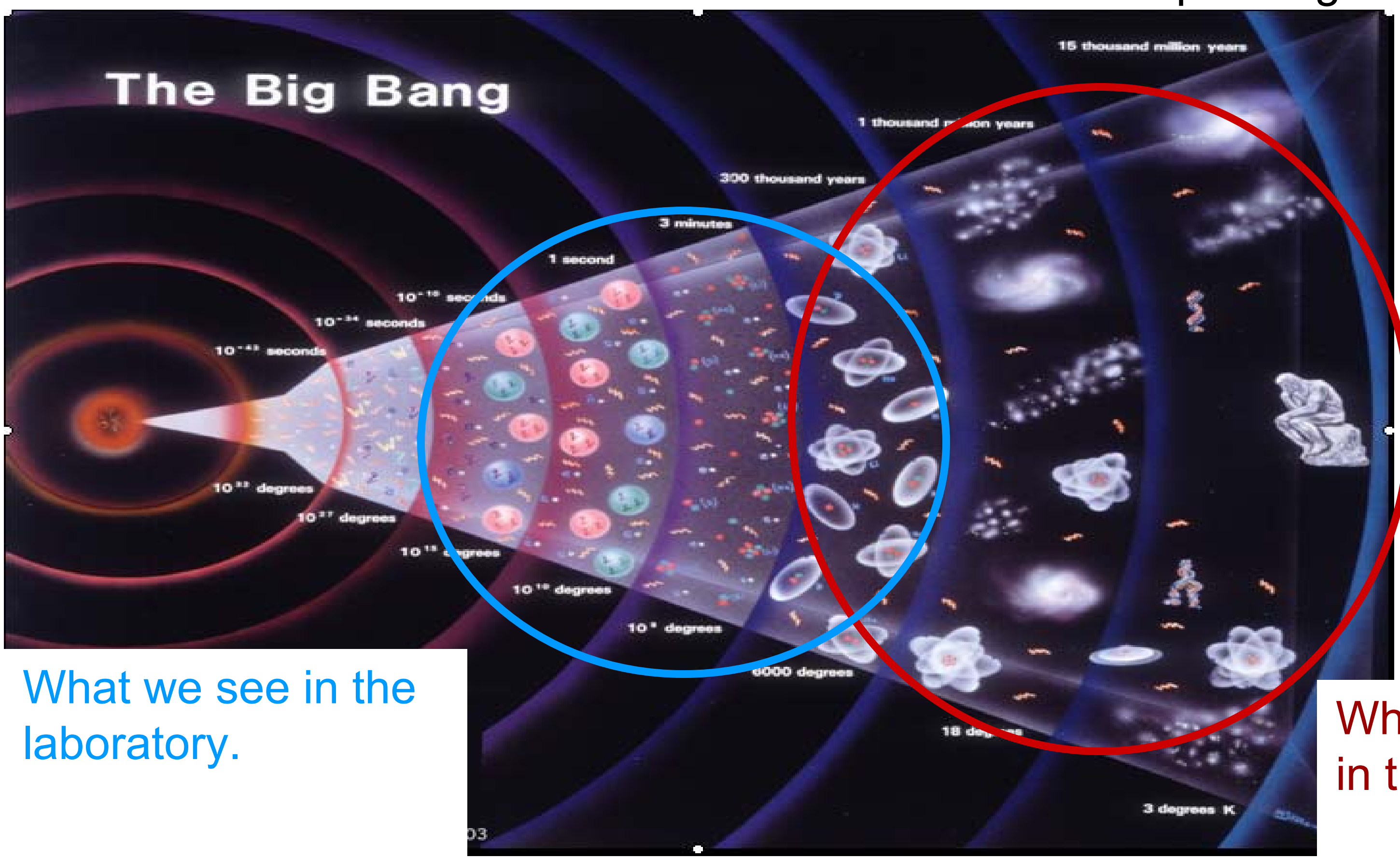
March 2008

Outline

- Observational Cosmology
- Gravitational Lensing
- The Large Synoptic Survey Telescope

Elements of Cosmology

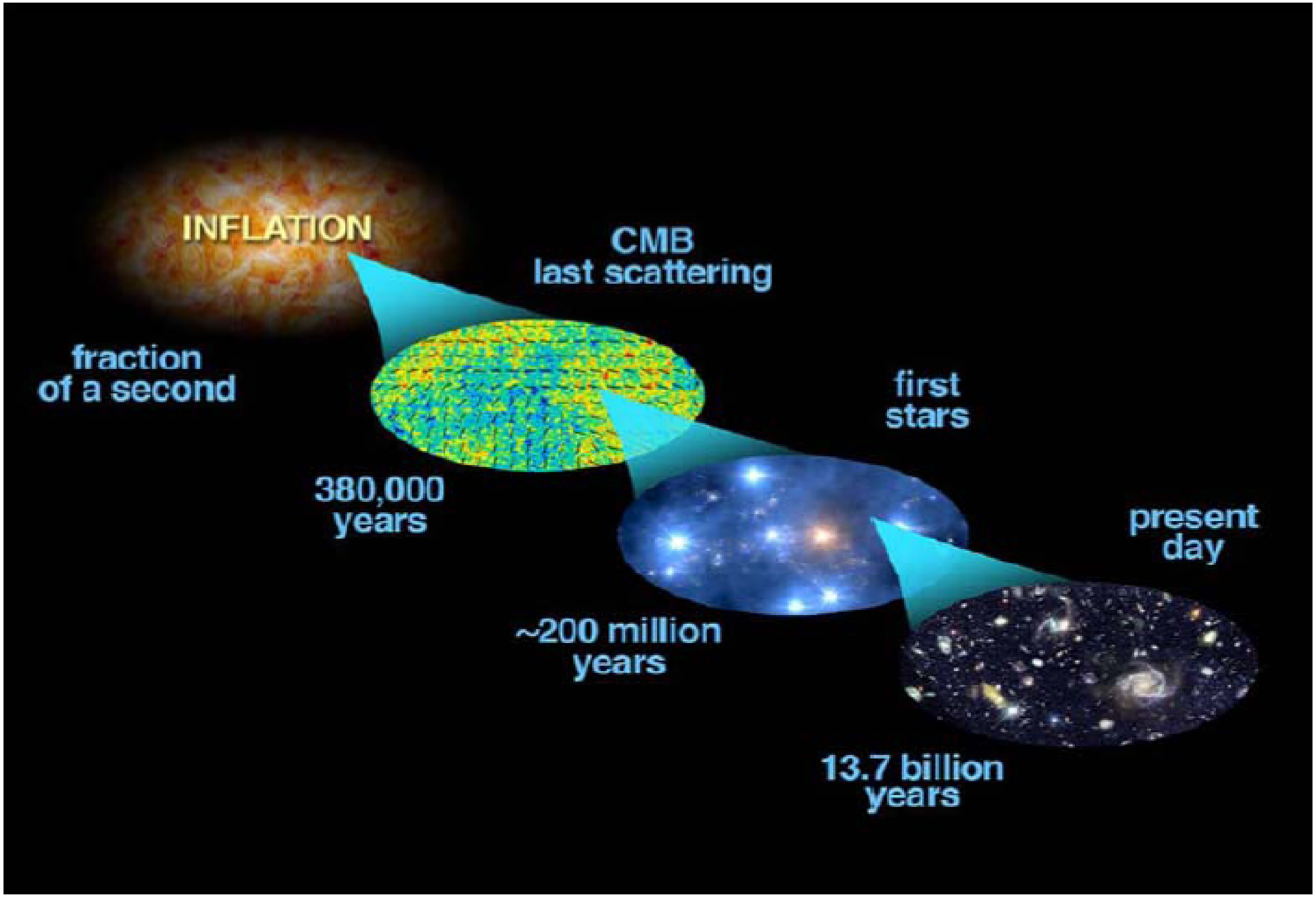
Matter and Energy		Space and Time
Particles and quantum interactions.	⟷	The Big Bang and inflation.
Mass and gravity.	⟷	Homogeneous, isotropic, expanding universe.



What we see in the laboratory.

What we see in the sky.

What We See in the Sky



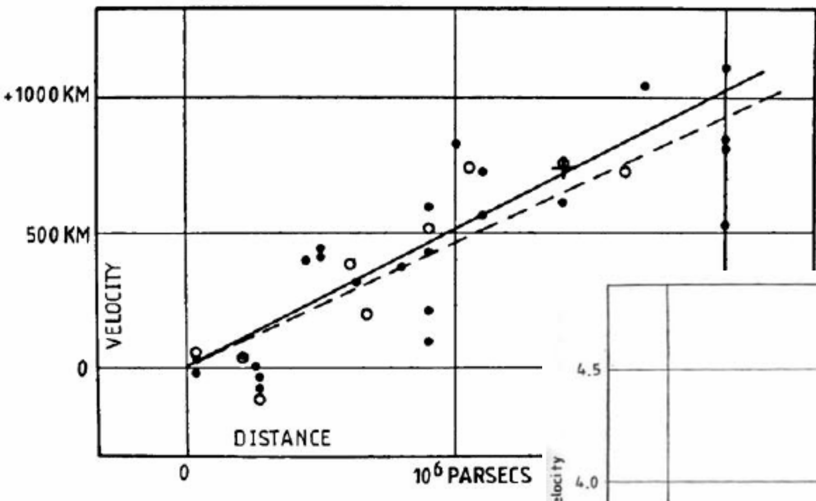
Redshift z = 3000 1080 ~15 0

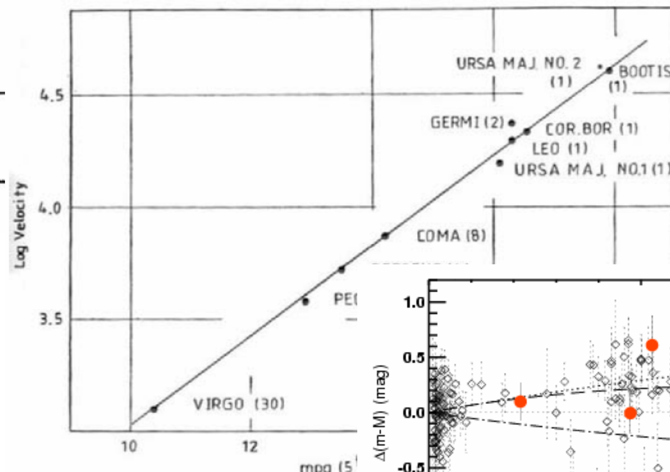
The Expanding Universe

Hubble 1929-1934

Isotropic linear distance-velocity relation,

→ “Hubble Parameter” H_0.

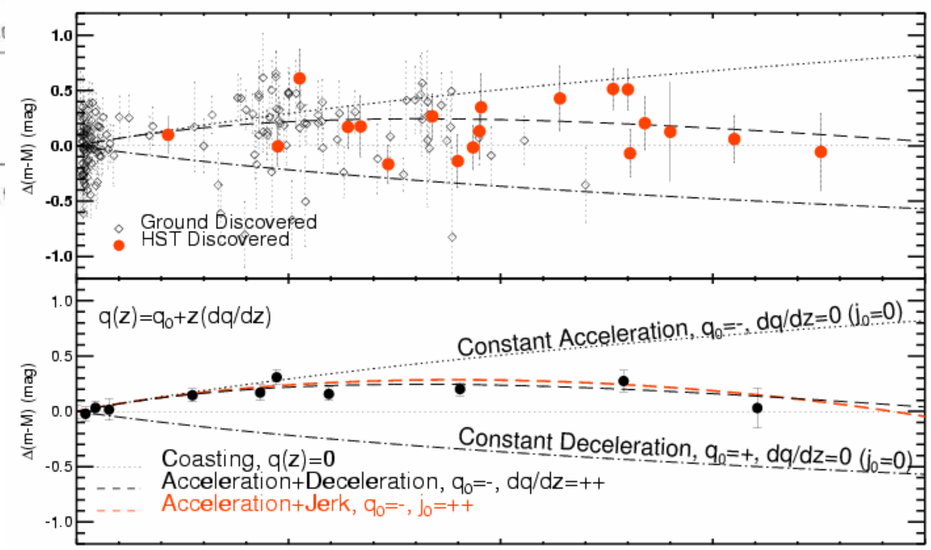




Perlmutter/Reiss 1998

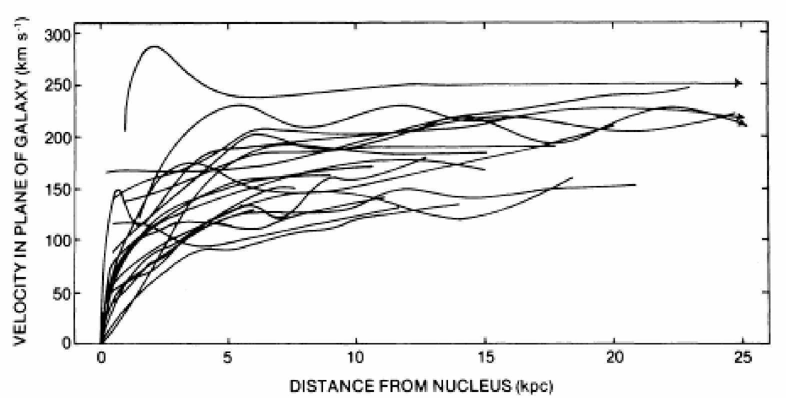
Non-linear distance-redshift relation,

→ Dark Energy and the Cosmological Constant Λ



Z = 0 1 2

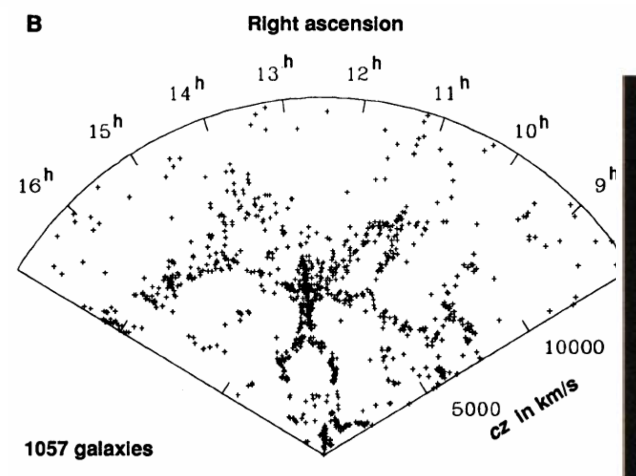
Matter in the Universe



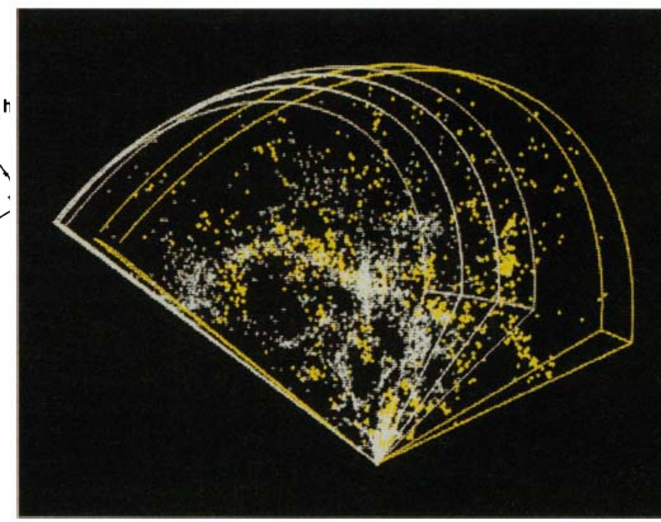
Zwicky 1933
Colma Galaxy Cluster

Rubin/Ford 1980
Galaxy Rotation Curves

Geller/Huchra 1989
Large Scale Structure



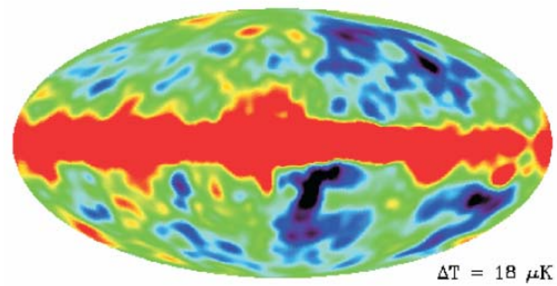
The "Great Wall"



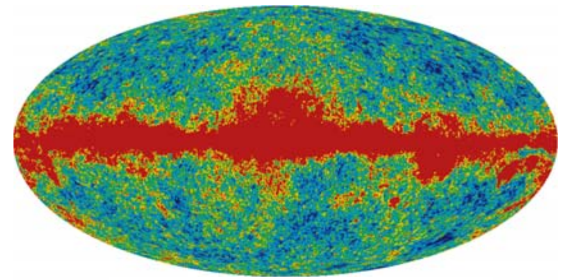
→ Dark Matter and Large-Scale Structure

Cosmic Microwave Background

Penzias/Wilson 1964



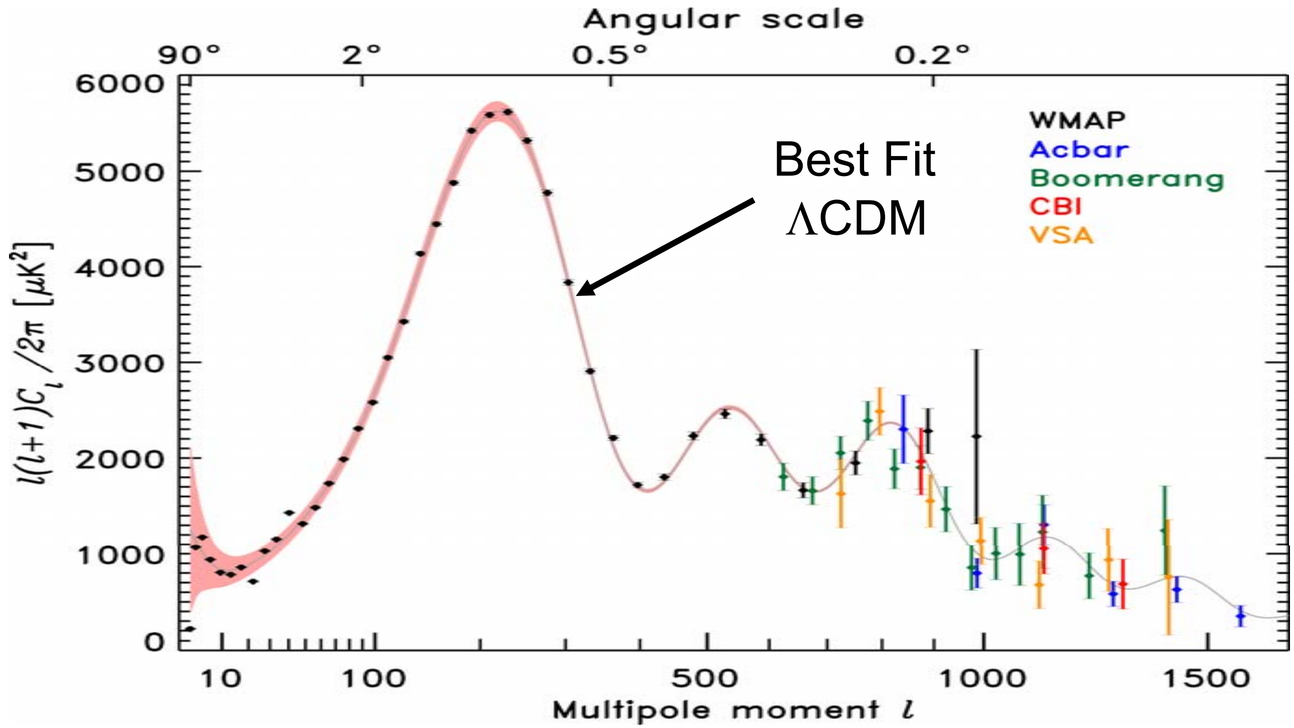
Mather/Smoot 1992



Wilkison 2006

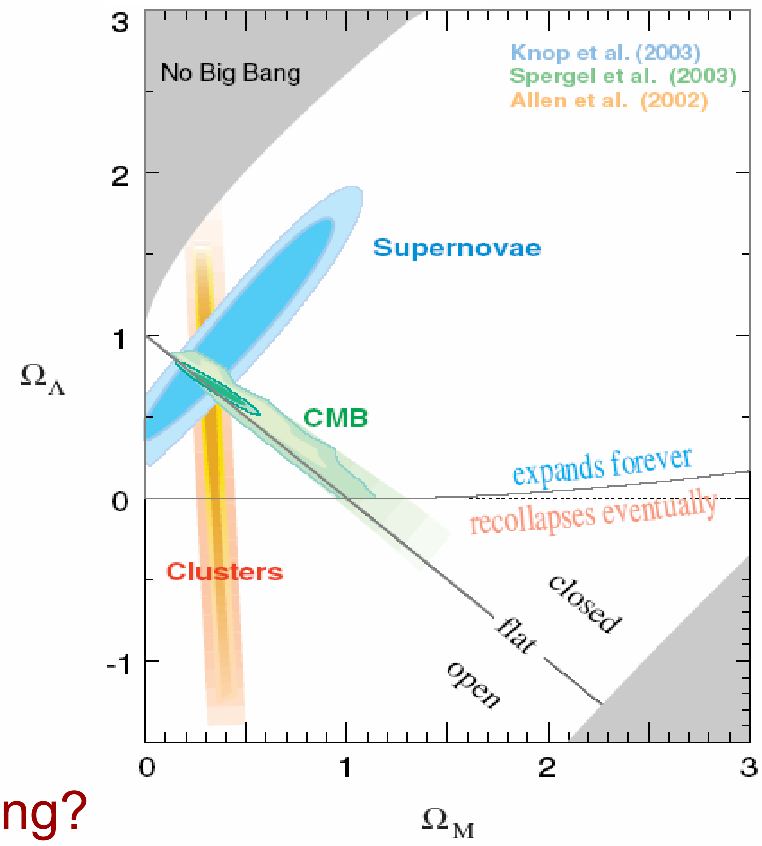
Seeds fertilized by cold dark matter grow into large scale structure.

→ "ΛCDM Model"



Concordance and Consternation

- Hubble's constant $H_0 = 72$ km s^{-1} Mpc^{-1}
- Baryonic density parameter $\Omega_B = 0.047$
- Cold Dark Matter density parameter $\Omega_D = 0.233$
- Total Matter density parameter $\Omega_0 = \Omega_B + \Omega_D = 0.28$
- Density Parameter in Vacuum Fields $\Omega_\Lambda = 0.72$
- Optical Depth for Thomson Scattering on Reheating $\tau = 0.17$
- Curvature of Space $\Omega_\Lambda + \Omega_0 = 1;\ \kappa = 0.$



Is ΛCDM all there is?

Is the universe really flat?

What is the dark matter? Is it just one thing?

What is driving the acceleration of the universe?

What is inflation?

Can general relativity be reconciled with quantum mechanics?

Observational Cosmology

CMB – $d_A(z)$ and $H(z)$.

Baryons, galaxies and clusters – $d_A(z)$, $H(z)$, and $C_l(z)$.

Supernovae – $d_L(z)$.

Gravitational lensing – $d_A(z)$ and $C_l(z)$.

Elements of General Relativity

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma}\frac{dx^\rho}{d\lambda}\frac{dx^\sigma}{d\lambda} = 0$$

[Geodesic Equation]

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

[Einstein Equation]

The metric $g_{\mu\nu}$, that defines transformation of distances in coordinate space to the distances in physical space we can measure, must satisfy these equations.

Homogeneous, isotropic, flat, expanding universe:

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a(t) & 0 & 0 \\ 0 & 0 & a(t) & 0 \\ 0 & 0 & 0 & a(t) \end{pmatrix} \longleftrightarrow d\tau^2 = dt^2 - a^2(t) \cdot d\vec{x}^2$$

More generally:

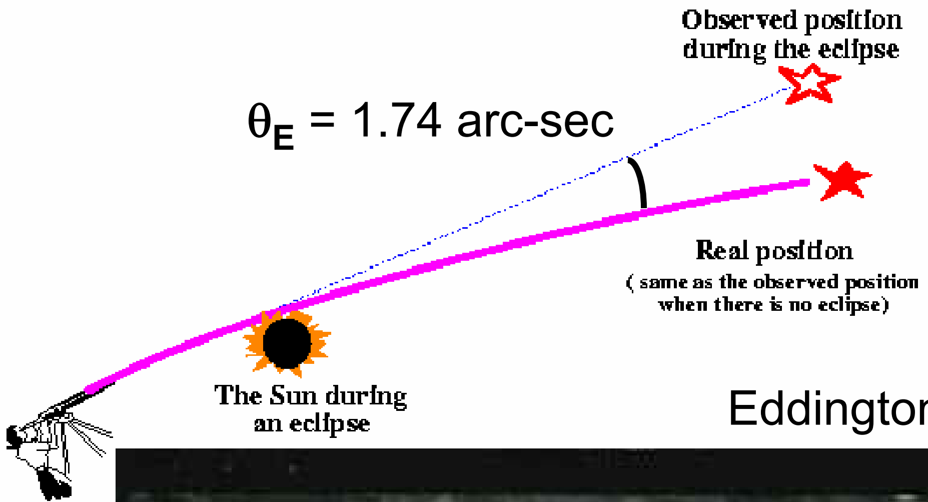
Curvature of space.

$$d\tau^2 = (1 + 2\Phi)dt^2 - a^2(t)(1 - 2\Phi)[dr^2 + S_k^2(r)d\psi^2]$$

Gravitational potential (weak)

“Size” of space relative to time.

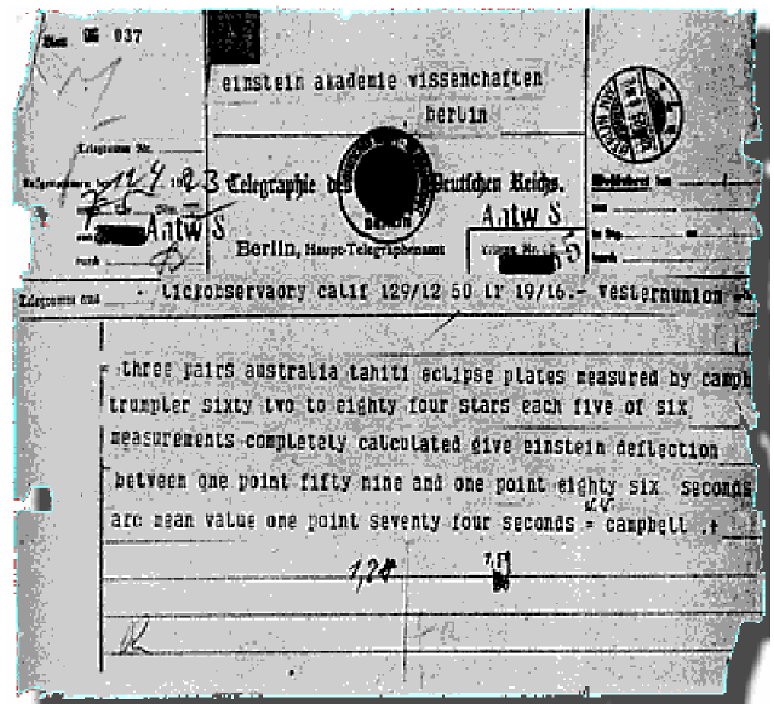
Newton, Einstein, and Eddington



Soldner 1801 $\quad \theta_N = \frac{2GM}{rc^2}$

Einstein 1915 $\quad \theta_E = \frac{4GM}{rc^2}$

Eddington 1919 → "between 1.59 and 1.86 arc-sec"



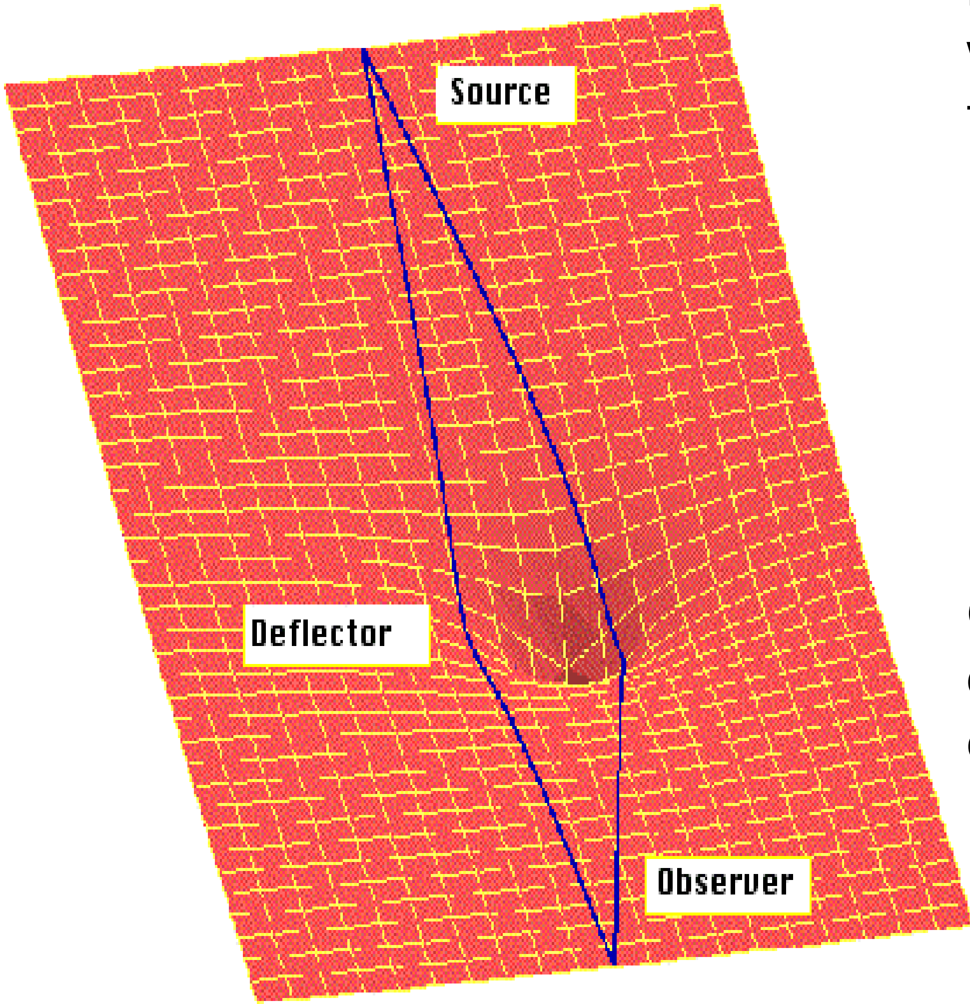
einstein akademie wissenschaften
berlin

Telegraphie des Deutschen Reichs.
Berlin, Haupt-Telegraphenamt

lickobservaory calif 129/12 50 lr 19/16.- westernunion

three pairs australia tahiti eclipse plates measured by campb
trumpler sixty two to eighty four stars each five of six
measurements completely calculated give einstein deflection
between one point fifty nine and one point eighty six seconds
arc mean value one point seventy four seconds = campbell .+

Propagation of Light Rays



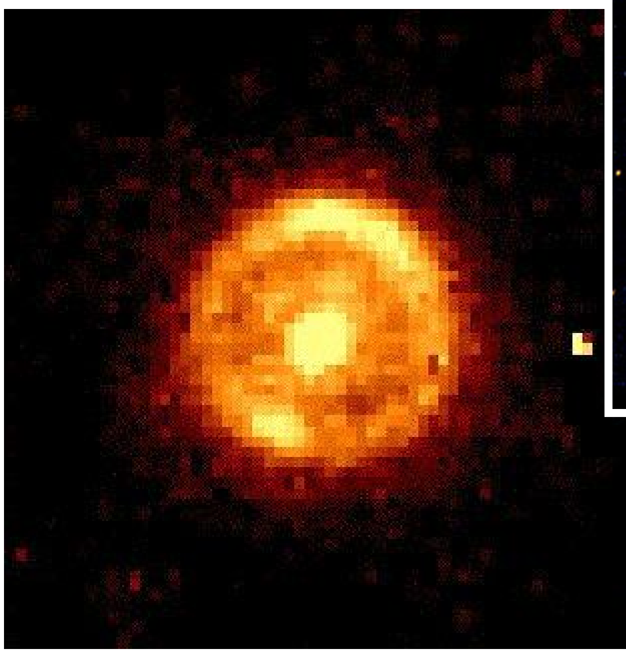
There can be several (or even an infinite number of) geodesics along which light travels from the source to the observer.

→ Displaced and distorted images.
→ Multiple images.
→ Time delays in appearances of images.

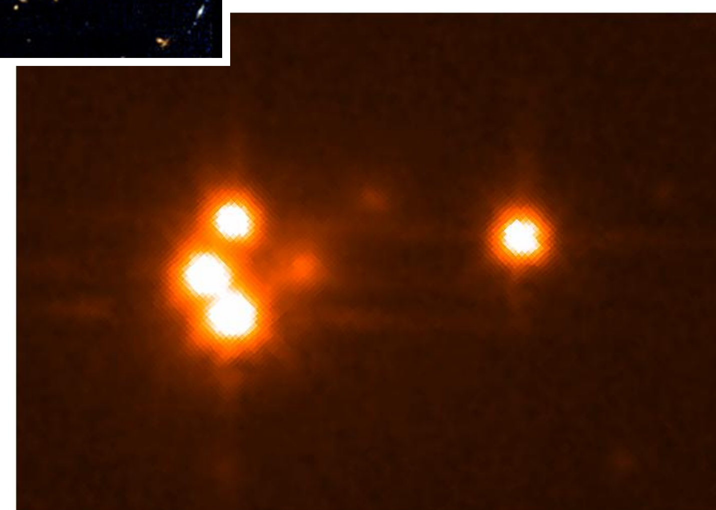
Observables are sensitive to cosmic distances and to the structure of energy and matter (near) line-of-sight.

Strong Lensing

A complete Einstein ring.

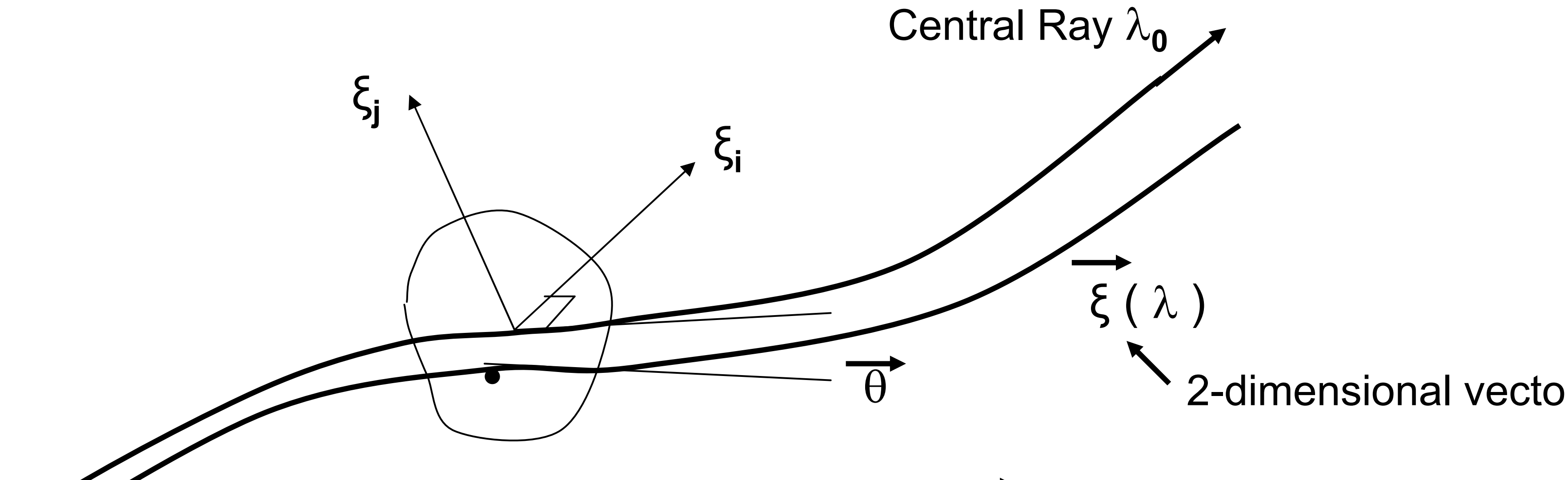


Galaxy at z =1.7 multiply imaged by a cluster at z = 0.4.



Multiply imaged quasar (with time delays).

Propagation of a Bundle of Light



Bundle of rays each labeled by angle $\vec{\theta}$ with respect to the central ray as they pass an observer at the origin.

Linear approximation, $\vec{\xi}\,(\lambda) = \overleftrightarrow{D}\,(\lambda) \bullet \vec{\theta}$

and $\Phi = 0$ case, $\overleftrightarrow{D}\,(\lambda) = d_A(\lambda) \bullet \overleftrightarrow{I}$

angular diameter distance

Weak Lensing Approximation

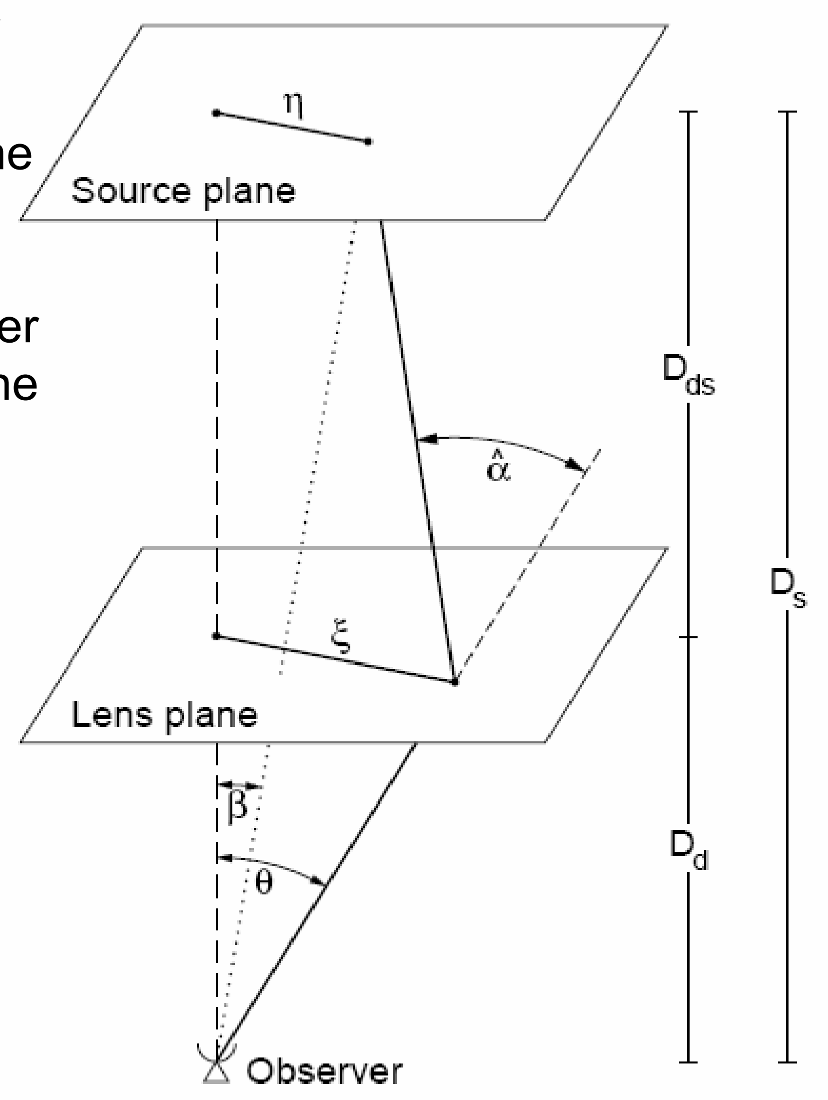
If distances are large compared to region of significant gravitational potential Φ, the deflection of a ray can be localized to a plane – the "Born" approximation.

Unless the source, the lens, and the observer are tightly aligned (Schwarzschild radius), the deflection will be small,

$$\hat{\alpha} = \frac{4GM}{c^2 \xi} \qquad \text{(Einstein)}$$

And the actual position of the source can be linearly related to the image position,

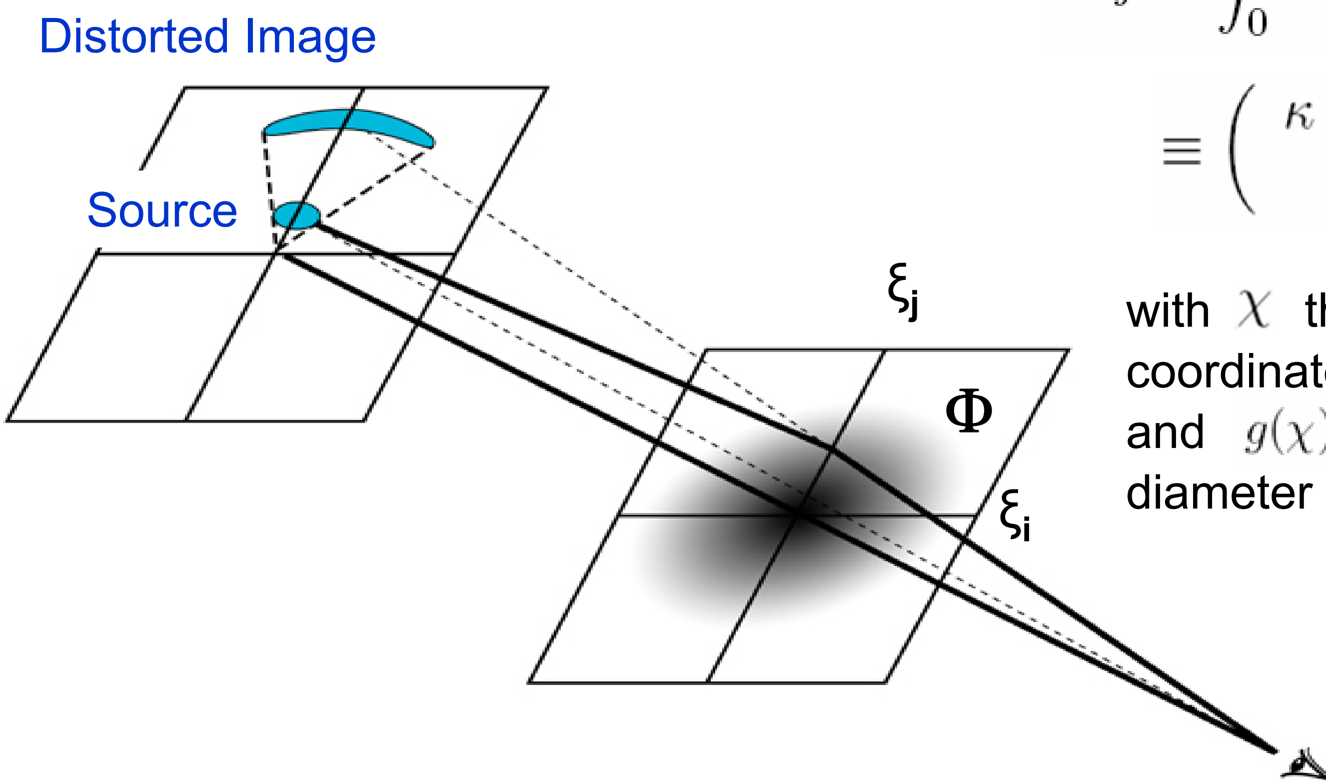
$$\vec{\eta} = \frac{D_s}{D_d}\vec{\xi} - D_{ds}\hat{\vec{\alpha}}(\vec{\xi})$$



Convergence and Shear

Distortion matrix $\Psi_{ij} = \int_0^{\chi_h} d\chi \; g(\chi)\partial_i\partial_j\Phi(\chi)$

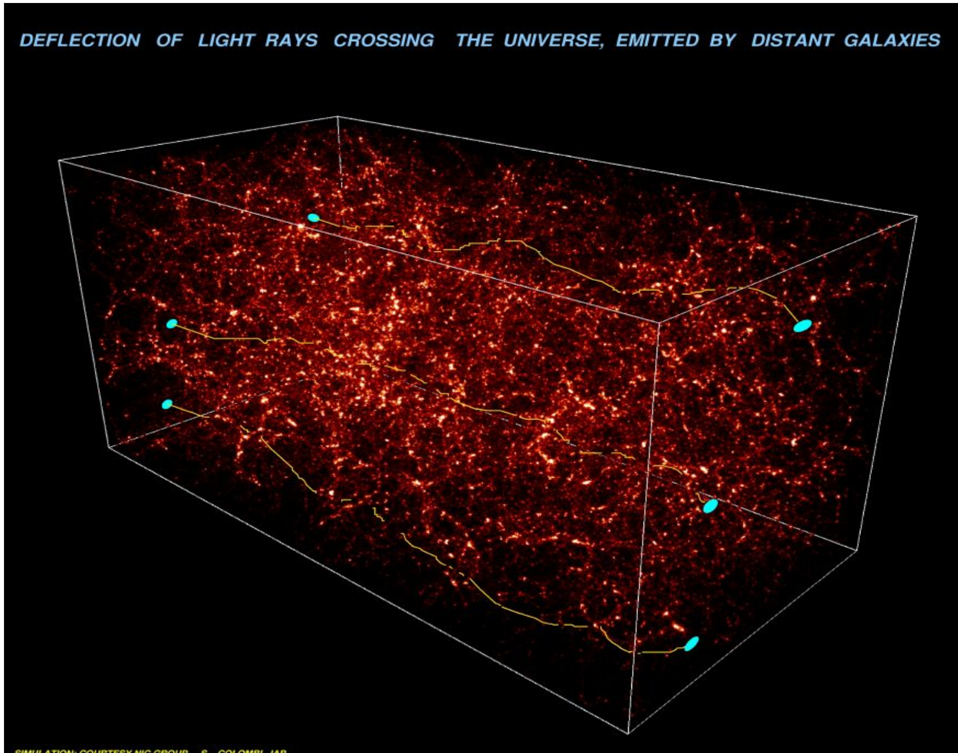
$$\equiv \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix}$$



with χ the co-moving coordinate along the geodesic, and $g(\chi)$ a function of angular diameter distances.

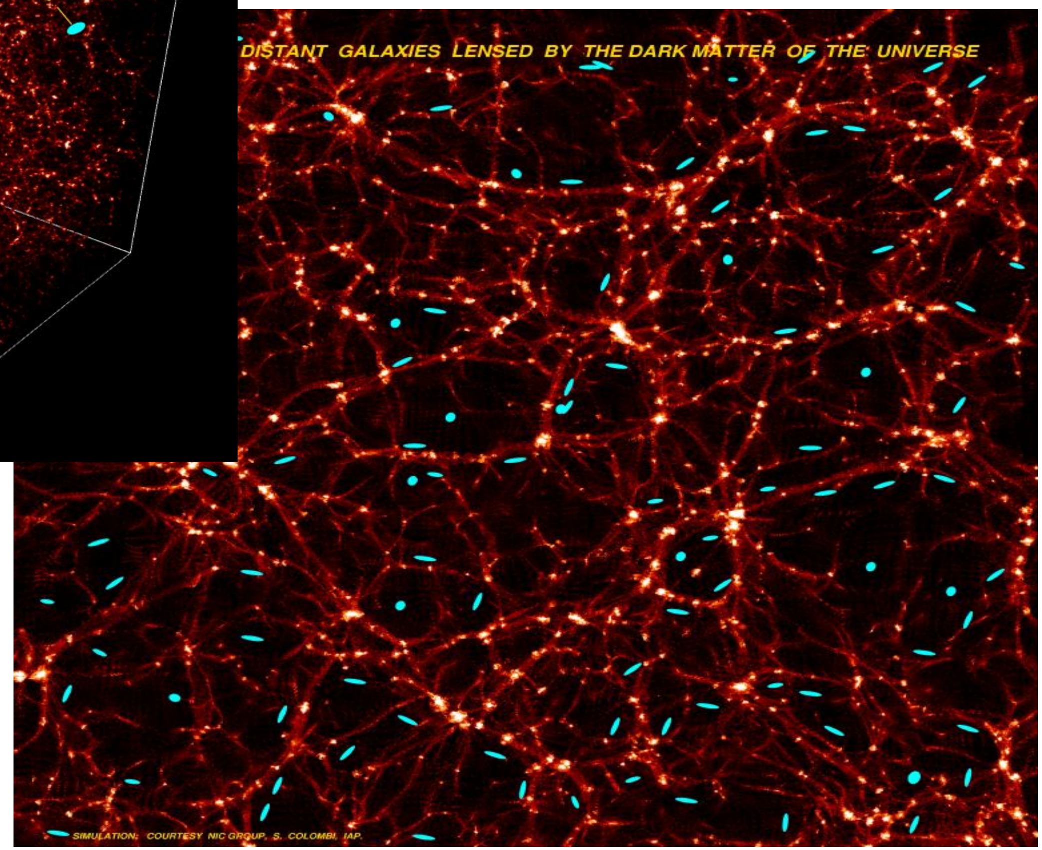
"Convergence" κ and "shear" γ determine the magnification and shape (ellipticity) of the image.

Weak Lensing of Distant Galaxies



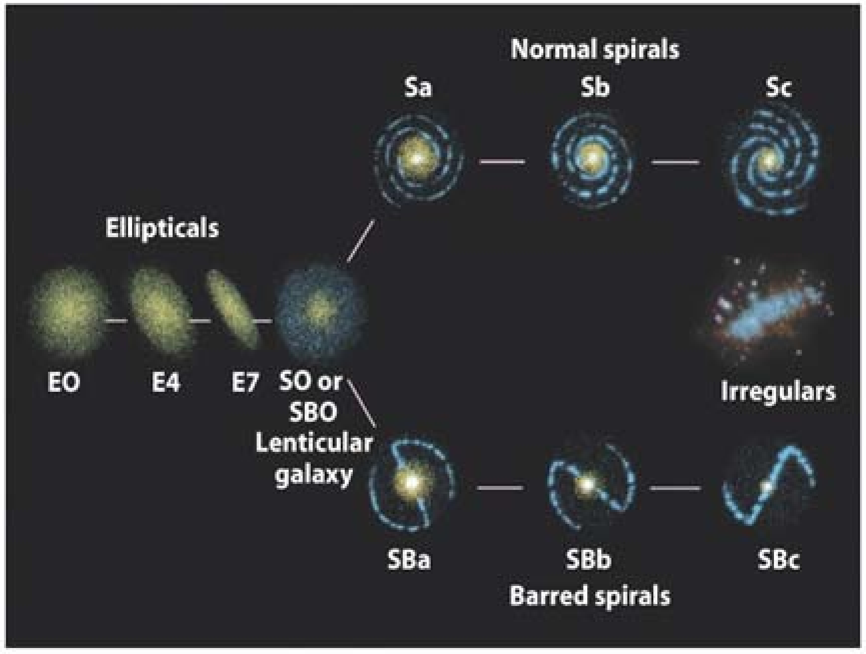
Simulation courtesy of S. Colombi (IAP, France).

Source galaxies are also lenses for other galaxies.



Sensitive to cosmological distances, large-scale structure of matter, and the nature of gravitation.

Observables and Survey Strategy

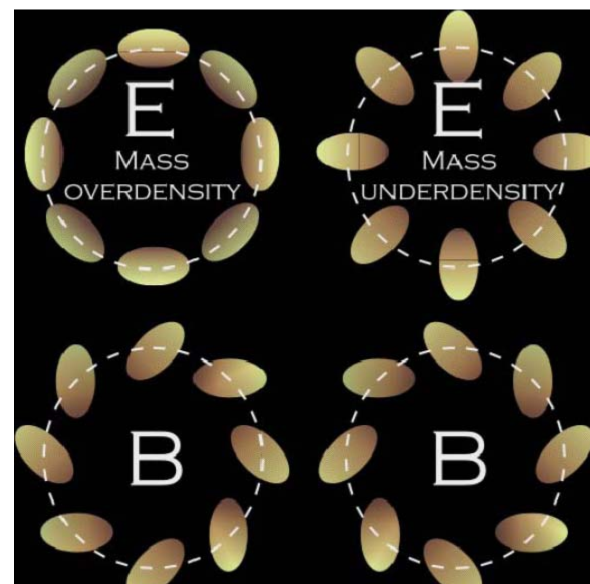


Galaxies are not round!

ε_g **~ 30%**

The cosmic signal is $\leq$ 1%.

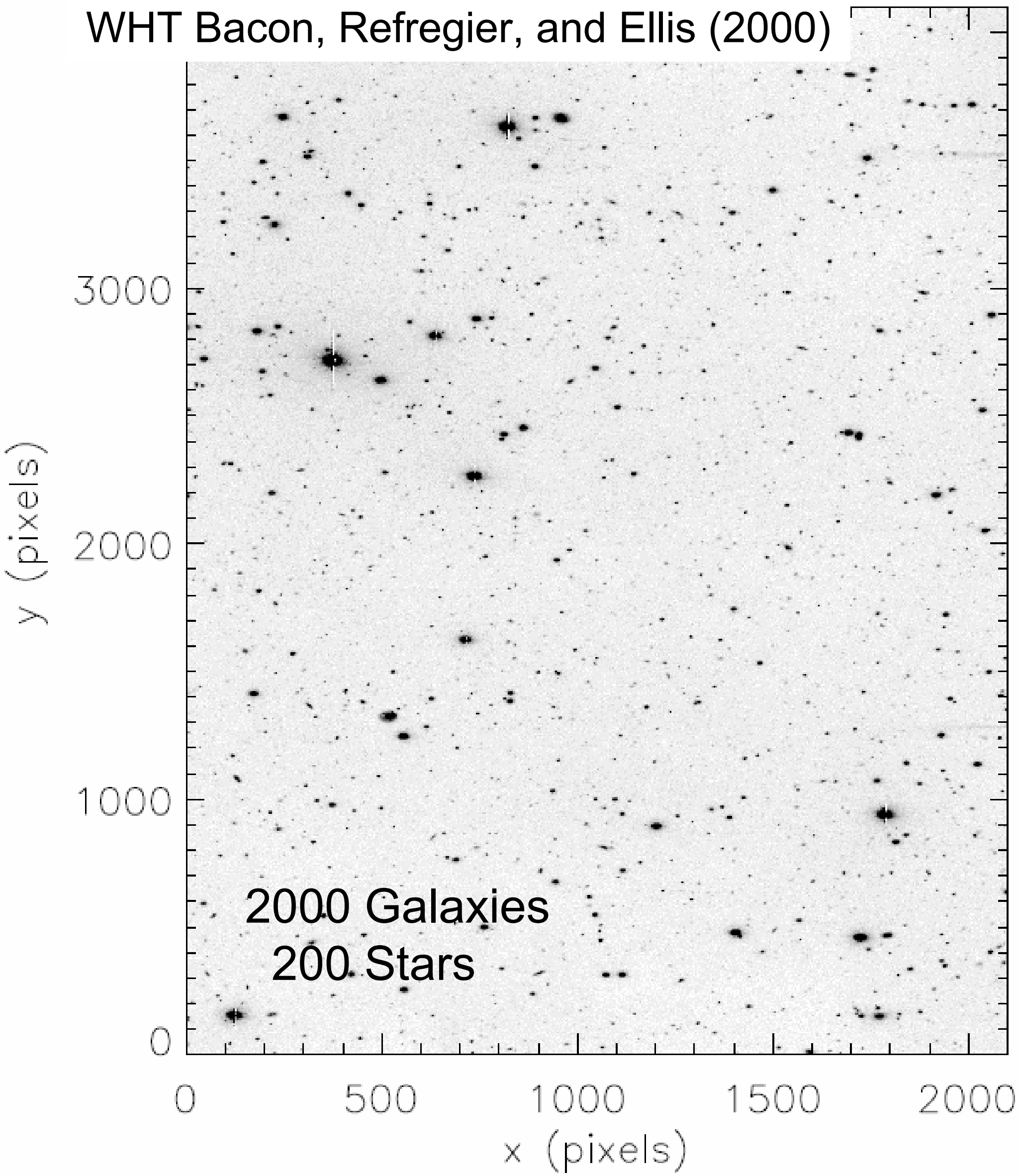
Must average a large number of source galaxies.



Signal is the gradient of Φ, with zero curl.

$\rightarrow$ "B-Mode" must be zero.

Ellipticity (Shear) Measurements

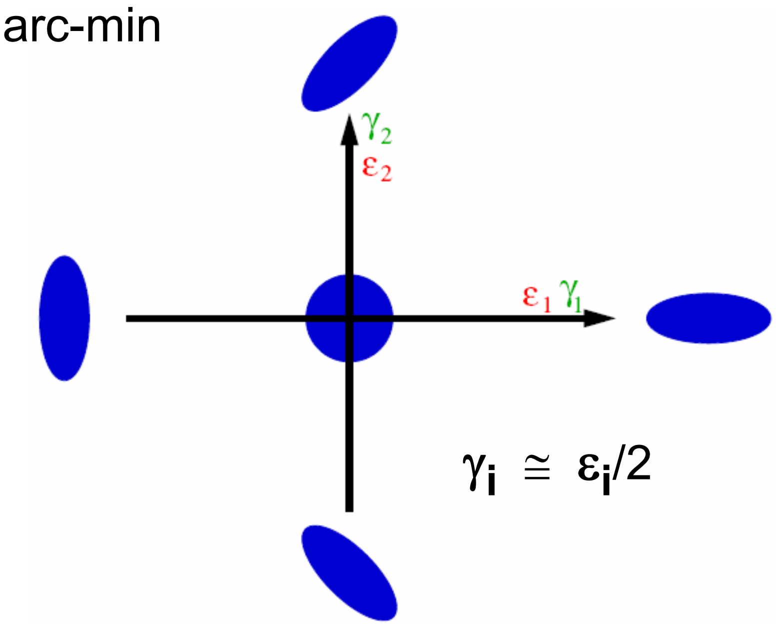


16 arc-min

$$Q_{ij} \equiv \int d^2x x_i x_j w(x) I(\mathbf{x})$$

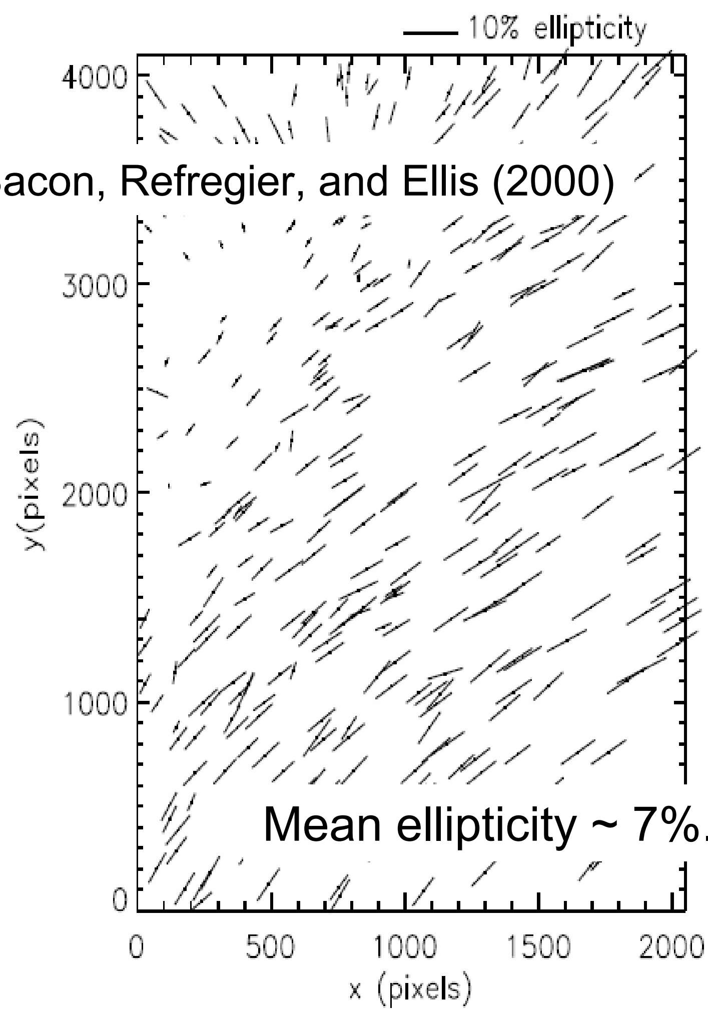
$$\epsilon_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}}$$

$$\epsilon_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}}$$



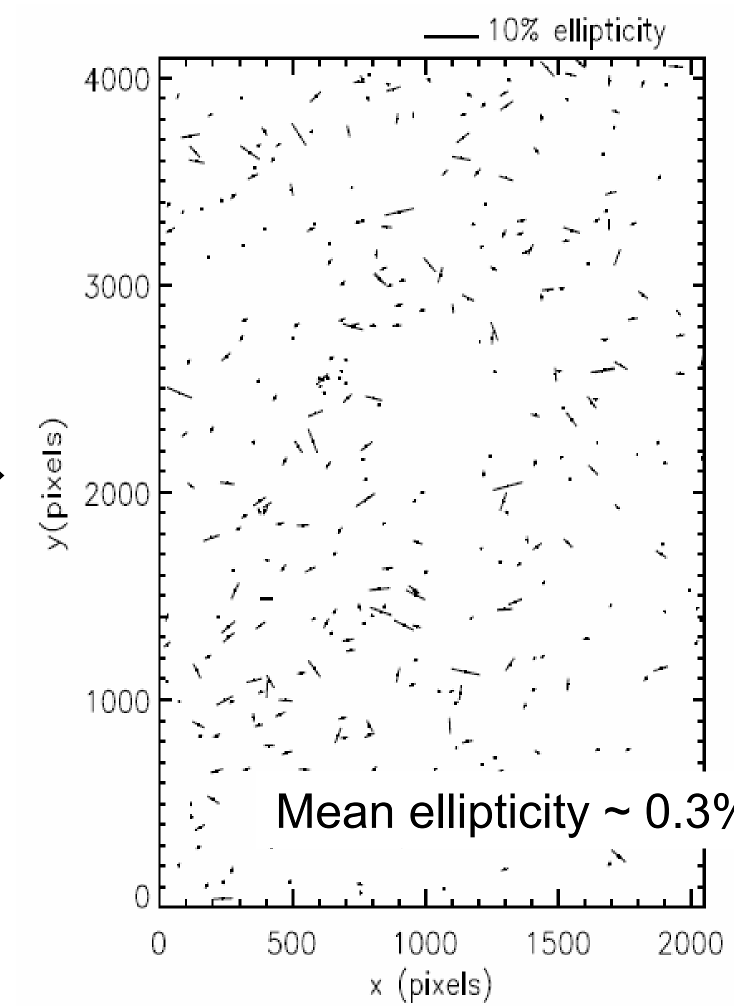
Instrumental PSF and Tracking

Images of stars are used to determine smoothed corrections.



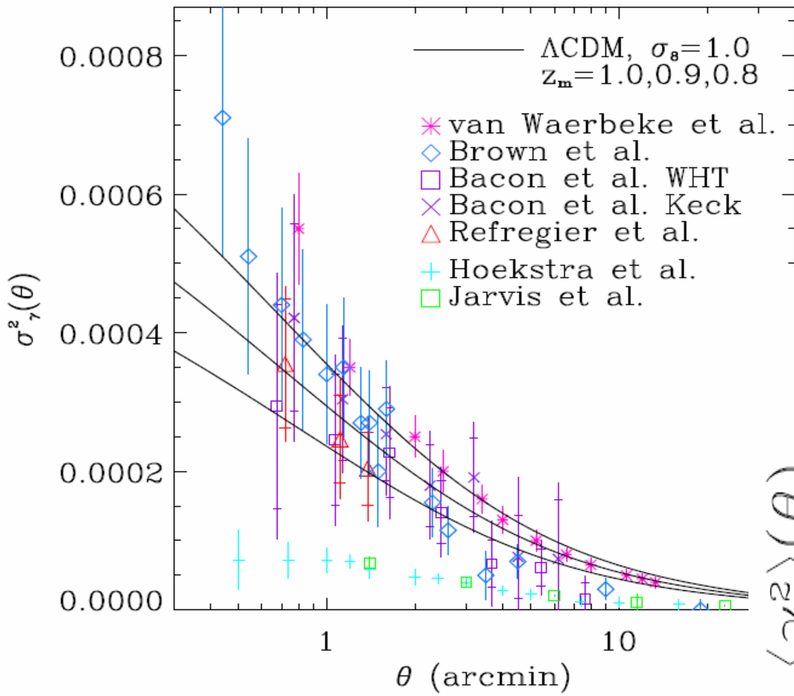
Bacon, Refregier, and Ellis (2000)

Mean ellipticity ~ 7%.



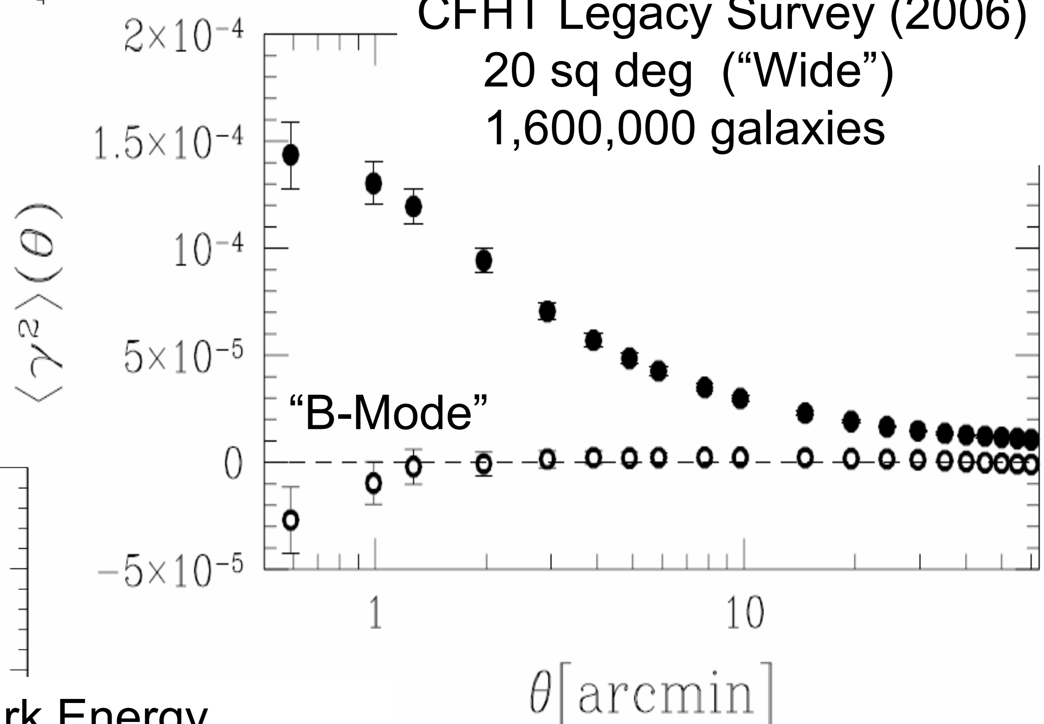
Mean ellipticity ~ 0.3%.

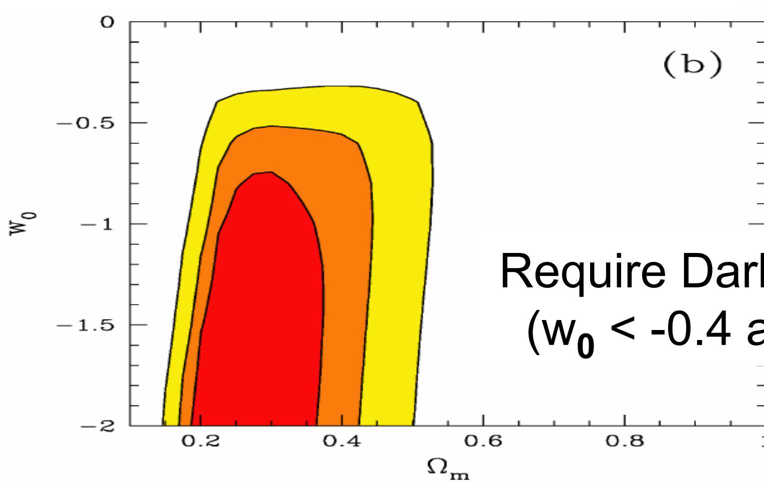
Cosmological Weak Lensing Results



Discovery (2000 – 2003)
1 sq deg/survey
30,000 galaxies/survey

CFHT Legacy Survey (2006)
20 sq deg ("Wide")
1,600,000 galaxies





Require Dark Energy
($w_0 < -0.4$ at 99.7% C.L.)

Size of "patch"
on the sky.

Shear-Shear Correlations and Tomography

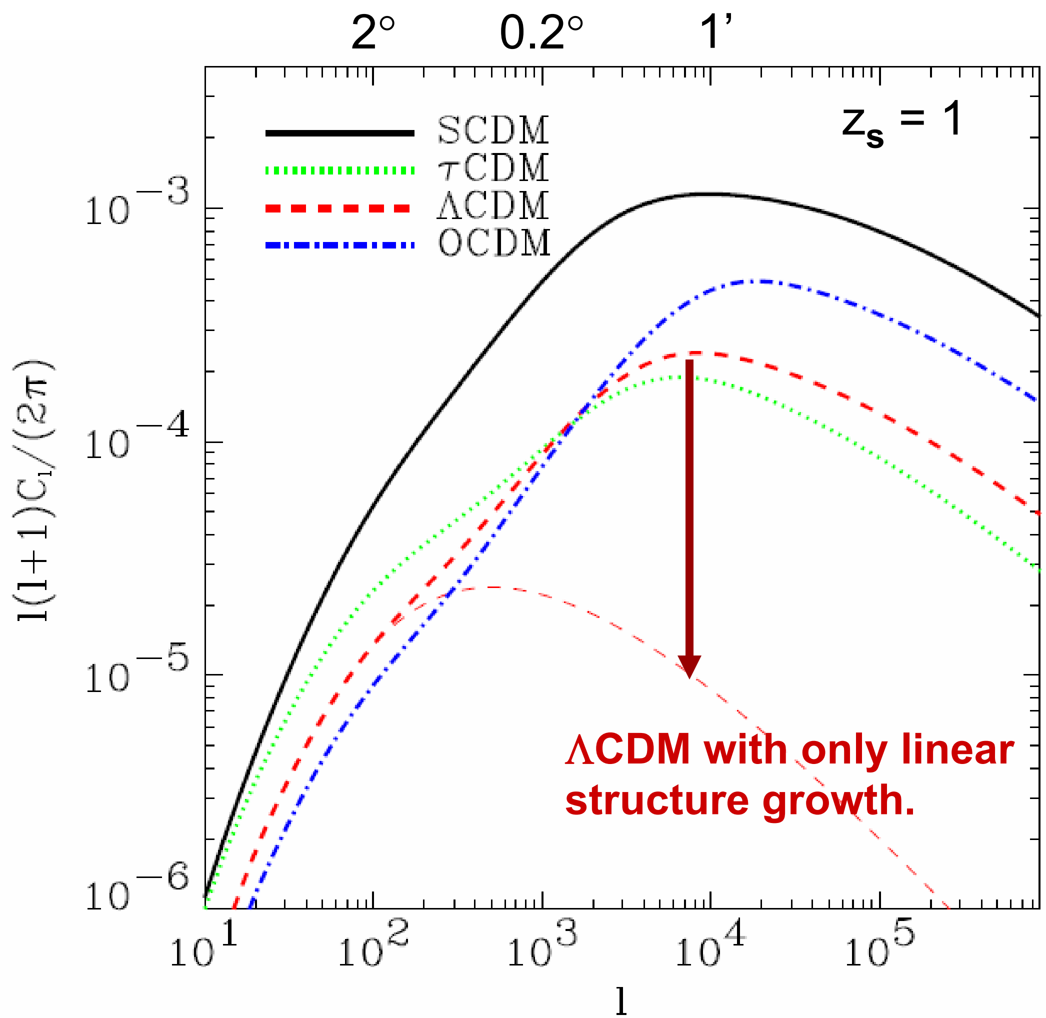
Two-point covariance computed as ensemble average over large fraction of the sky

$$\xi^2(\theta) = \langle \vec{e}(r) \bullet \vec{e}(r+\theta) \rangle$$

Fourier transform to get power spectrum C(l). →

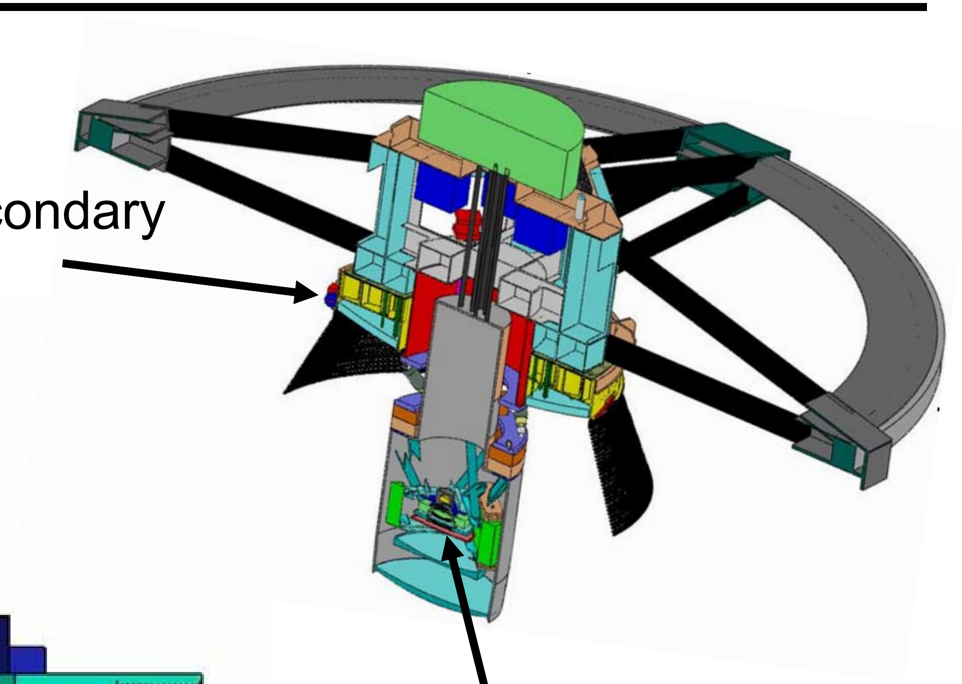
Tomography
– spectra at differing z_s.

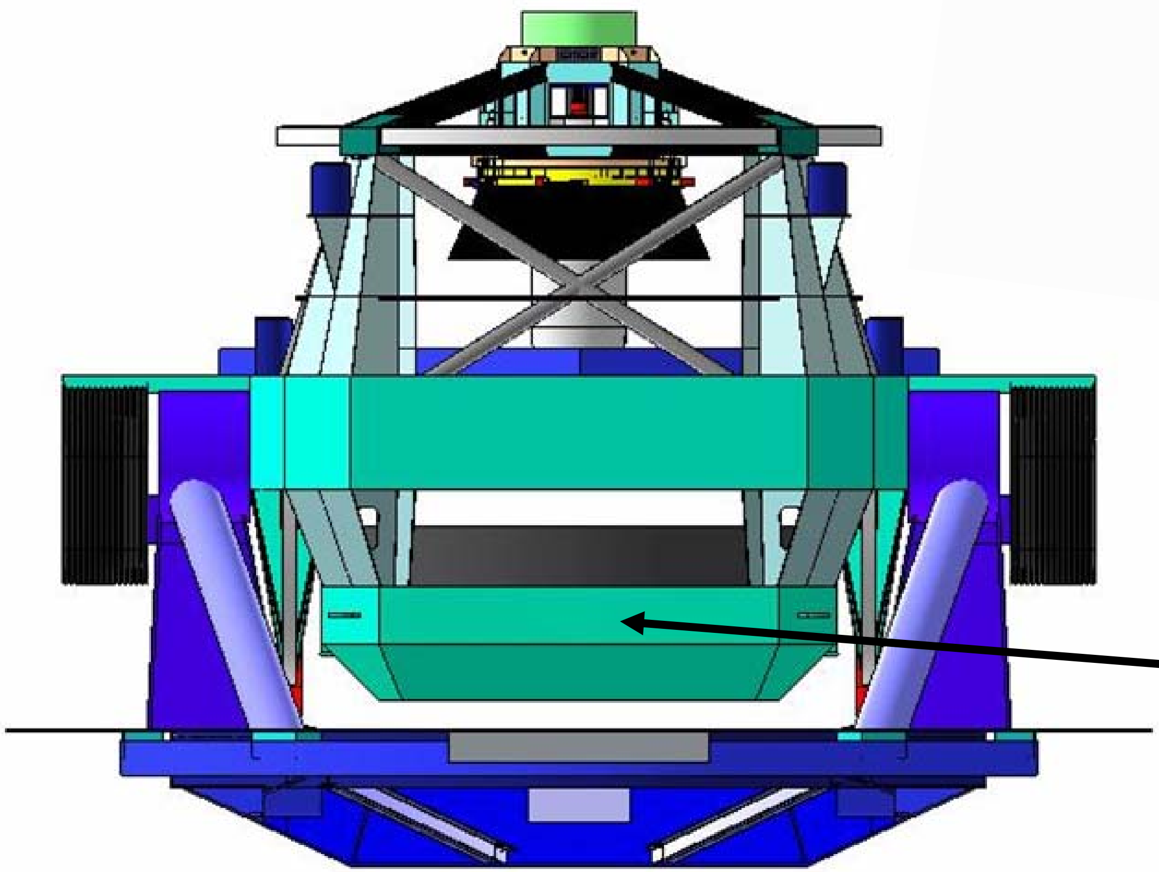
Maximize sky covered (small l), and reach $z_s \sim 3$ to optimize sensitivity to dark energy.



Large Synoptic Survey Telescope

LSST Large Synoptic Survey Telescope





3.4m Secondary Mirror

3.5° Photometric Camera

8.4m Primary-Tertiary Monolithic Mirror

The LSST Mission

Photometric survey of half the sky (≅ 20,000 square degrees).

Multi-epoch data set with return to each point on the sky approximately every 4 nights for up to 10 years.

A new 10 square degree field every 40 seconds.

Prompt alerts (within 60 seconds of detection) to transients.

Deliverables

Archive over 3 billion galaxies with photometric redshifts to $z = 3$.

Detect 250,000 Type 1a supernovae per year (with photo-z < 0.8).

The LSST Collaboration

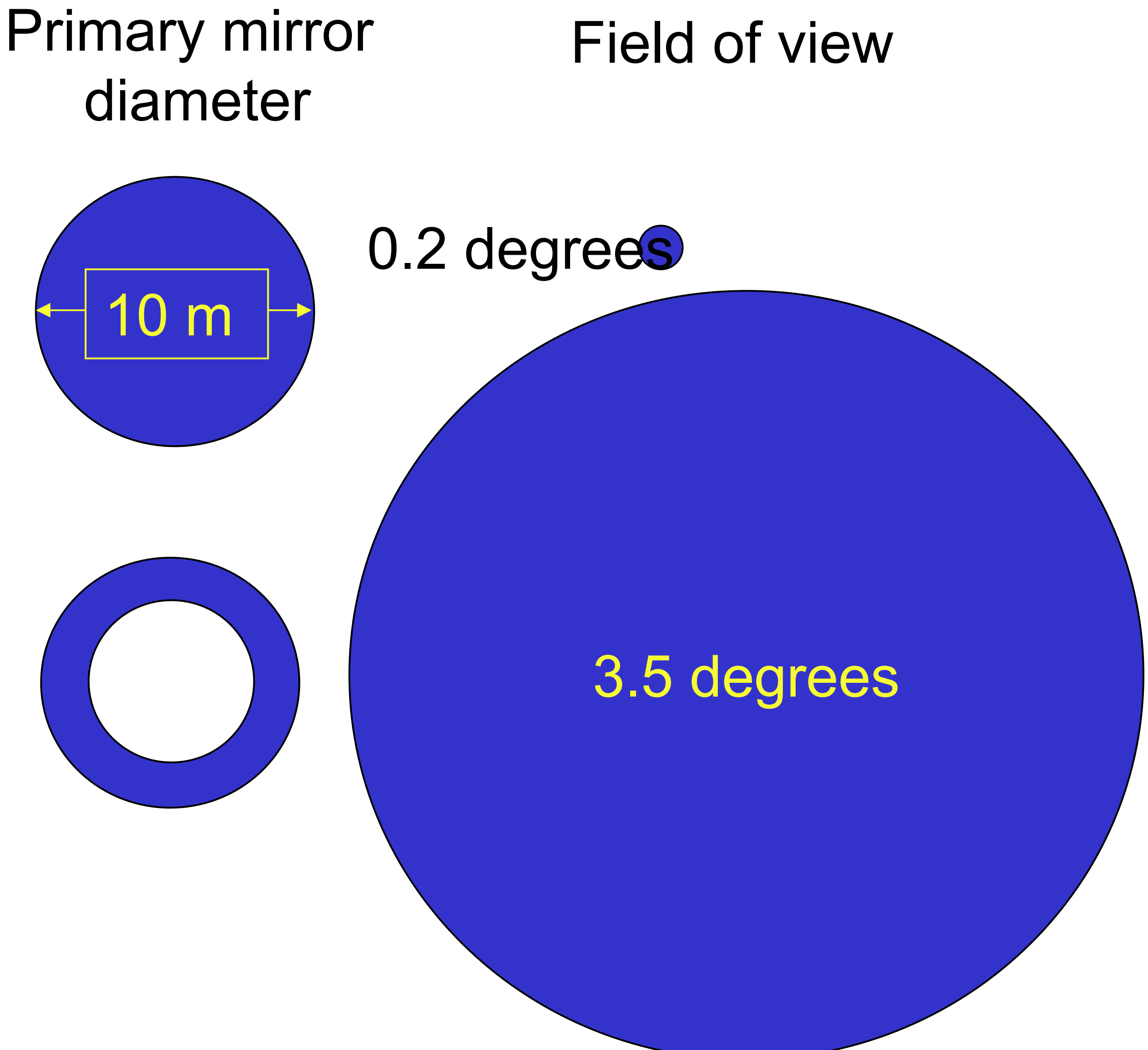
Large Synoptic Survey Telescope

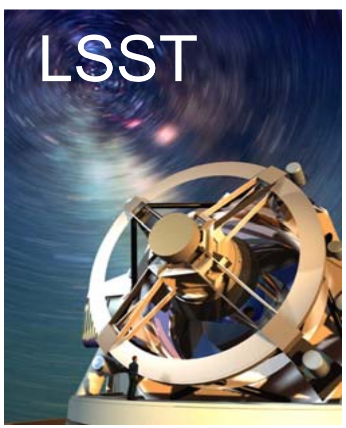
Brookhaven National Laboratory
California Institute of Technology
Carnegie Mellon University
Columbia University
Google Corporation
Harvard-Smithsonian Center for Astrophysics
Johns Hopkins University
Las Cumbres Observatory
Lawrence Livermore National Laboratory
National Optical Astronomy Observatory

IN2P3 Consortium
- APC (Paris)
- LAL (Orsay)
- LPNHE (Paris)
- LPSC (Grenoble)

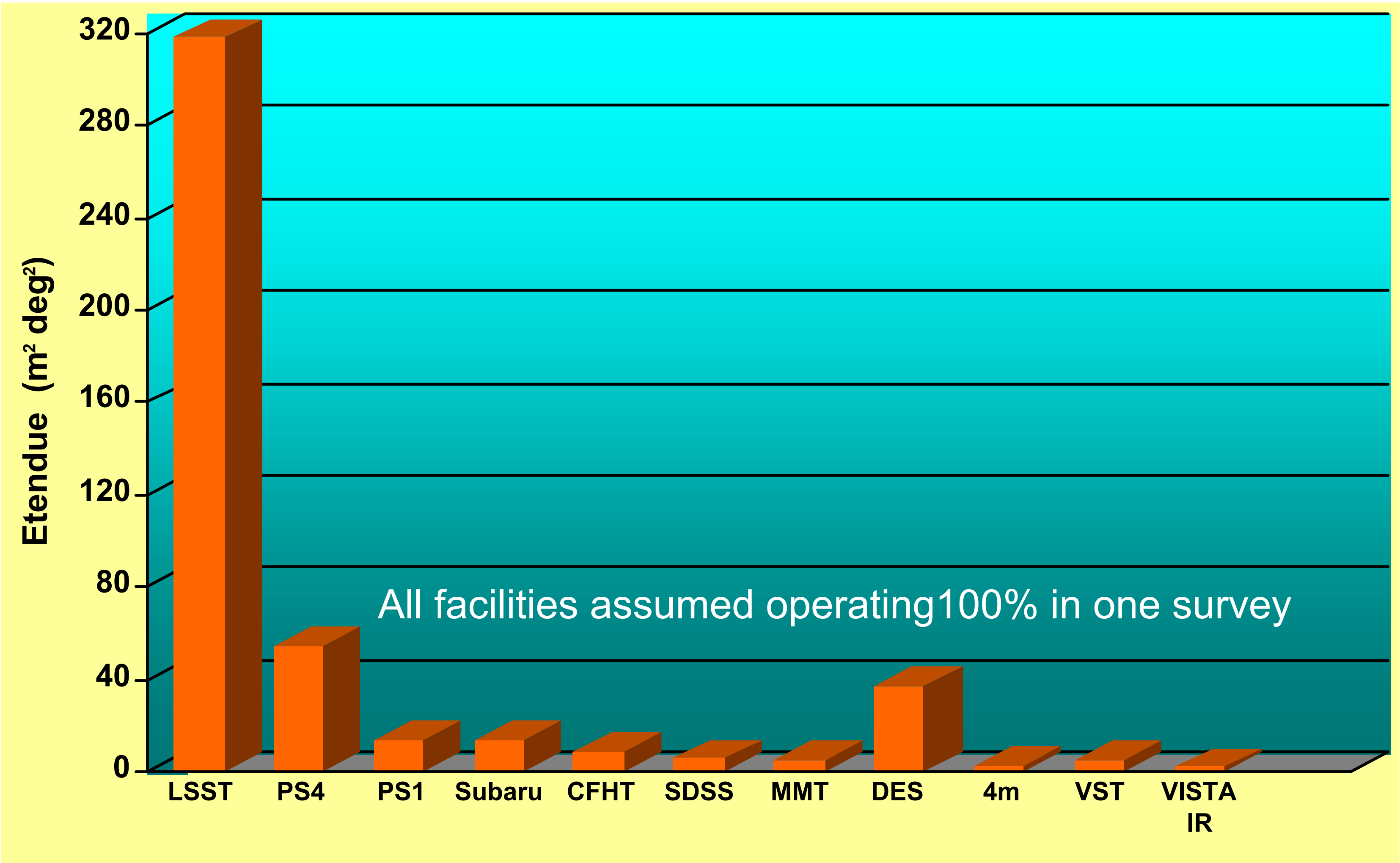
Pennsylvania State University
Princeton University
Purdue University
Research Corporation
Stanford Linear Accelerator Center
Stanford University
University of Arizona
University of California, Davis
University of California, Irvine
University of Illinois
University of Pennsylvania
University of Pittsburgh
University of Washington

Aperture and Field of View





Optical Throughput – Eténdue AΩ



Cosmology with LSST

- Weak lensing of galaxies to z = 3.

  Two and three-point shear correlations in linear and non-linear gravitational regimes.

- Supernovae to z = 1.

  Lensed supernovae and measurement of time delays.

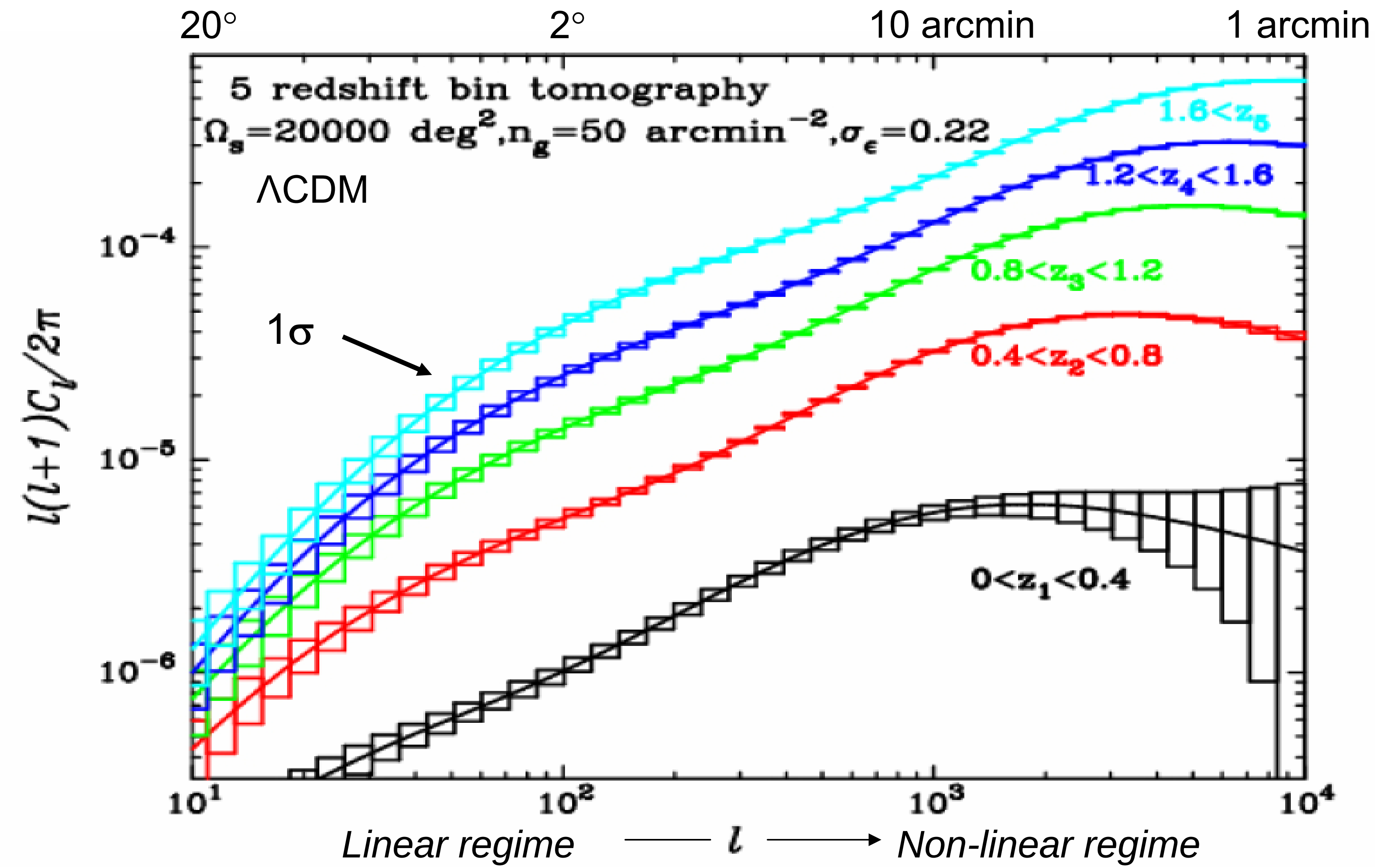
- Galaxies and cluster number densities as function of z.

  Power spectra on very large scales $k \sim 10^{-3}\ h\ \mathrm{Mpc}^{-1}$.

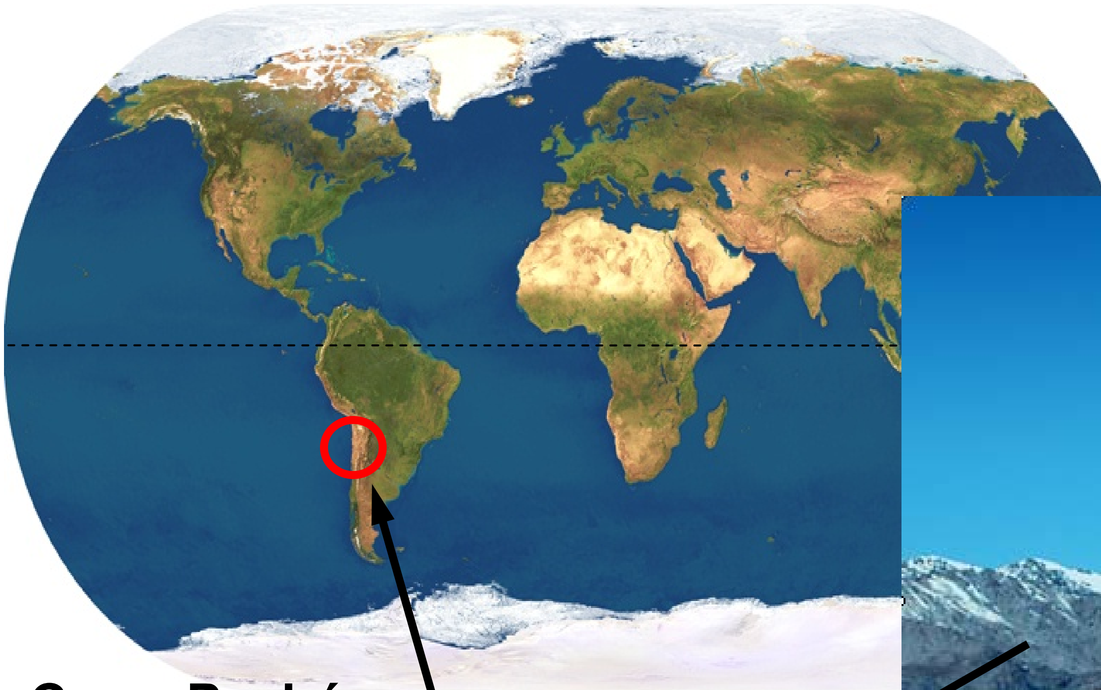
- Baryon acoustic oscillations (2 dimensions).

  Power spectra on scales $k \sim 10^{-1}\ h\ \mathrm{Mpc}^{-1}$.

Shear Power Spectra Tomography



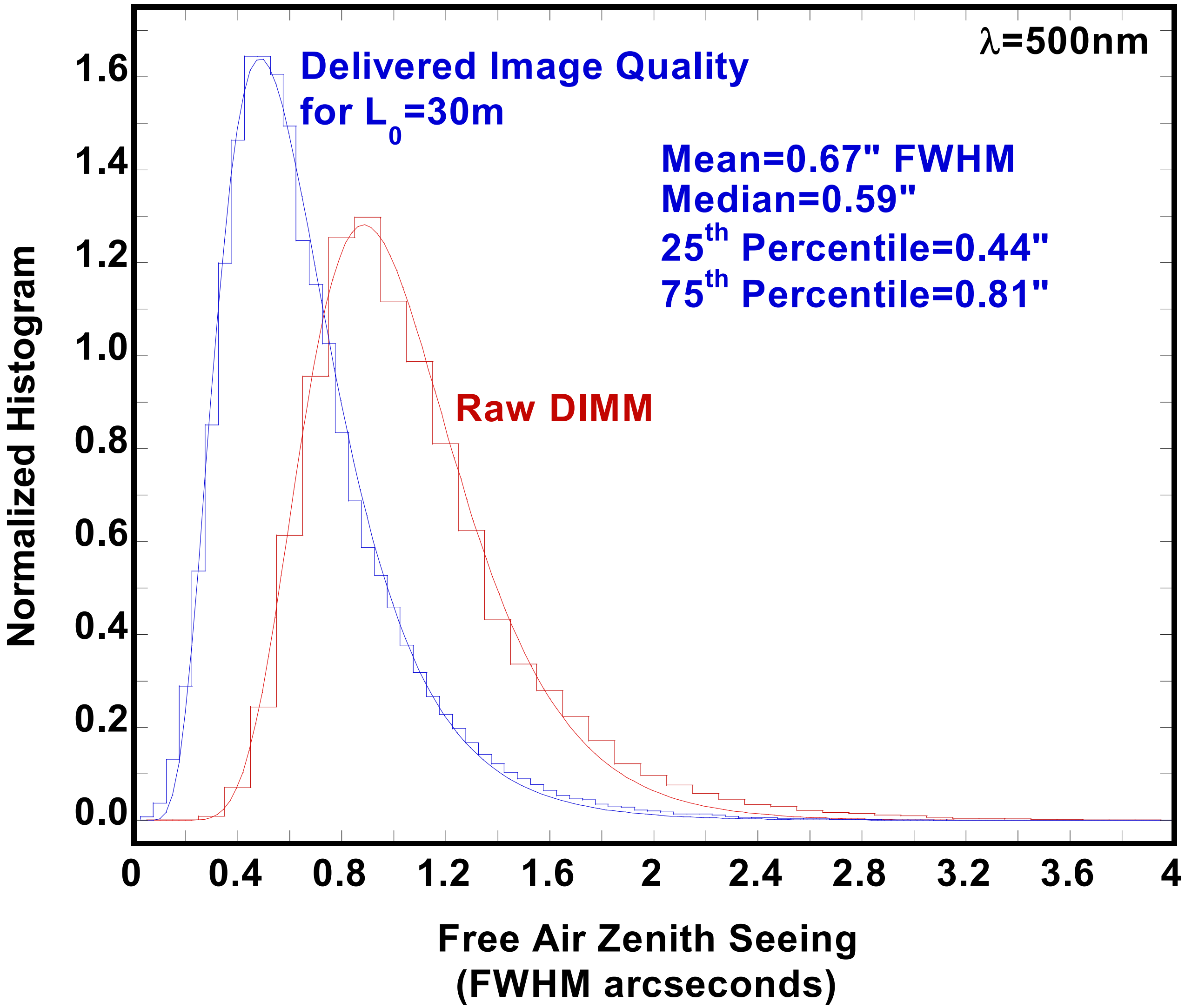
LSST Site and Observatory



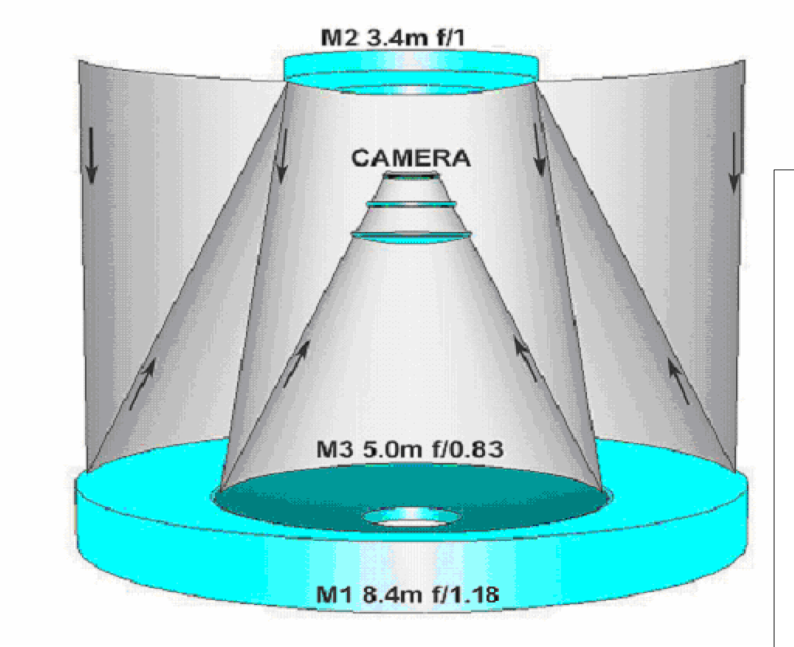
Cerro Pachón

Gemini South
and SOAR

Cerro Pachon Observing



Telescope Optics

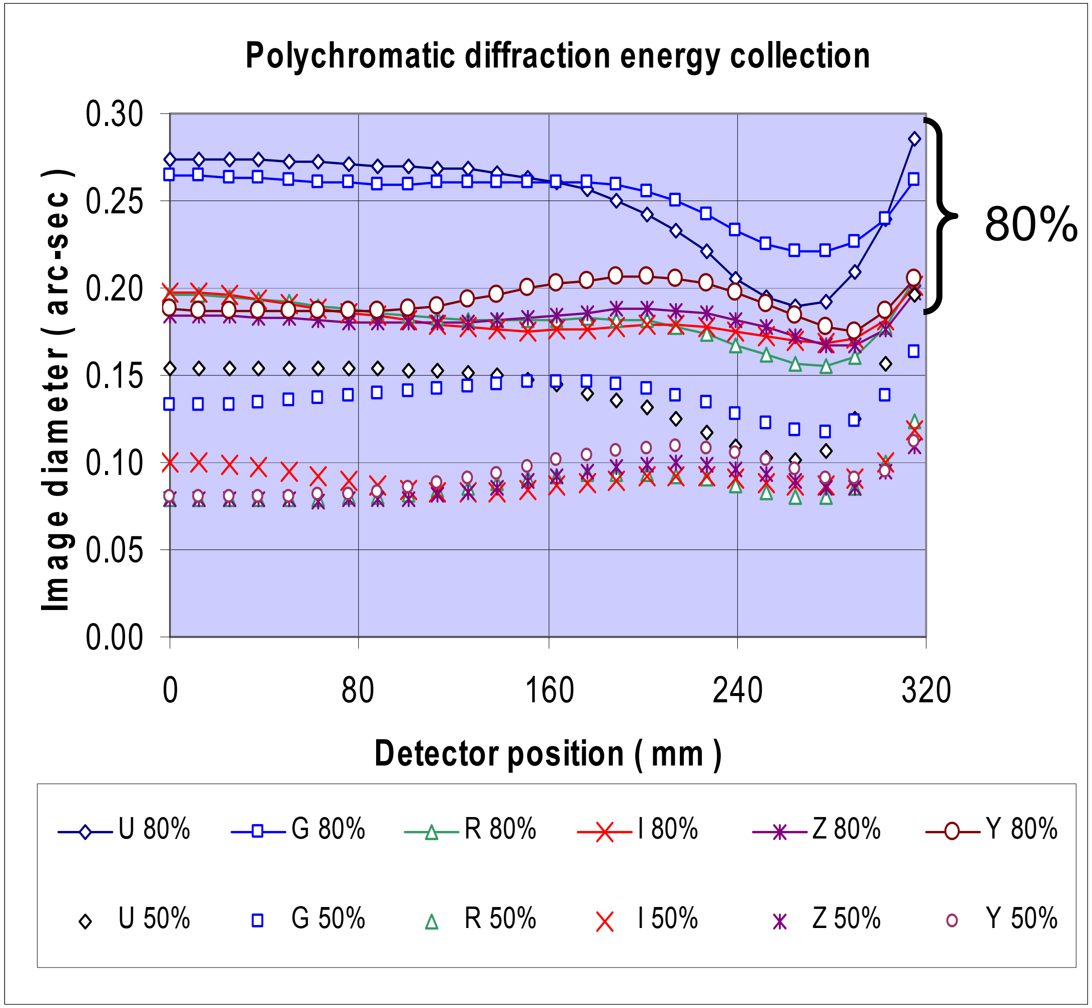


8.4 meter primary aperture.

3.5° FOV with f/1.23 beam and 0.20” plate scale.

Paul-Baker Three-Mirror Optics

→ PSF well-controlled over full FOV.



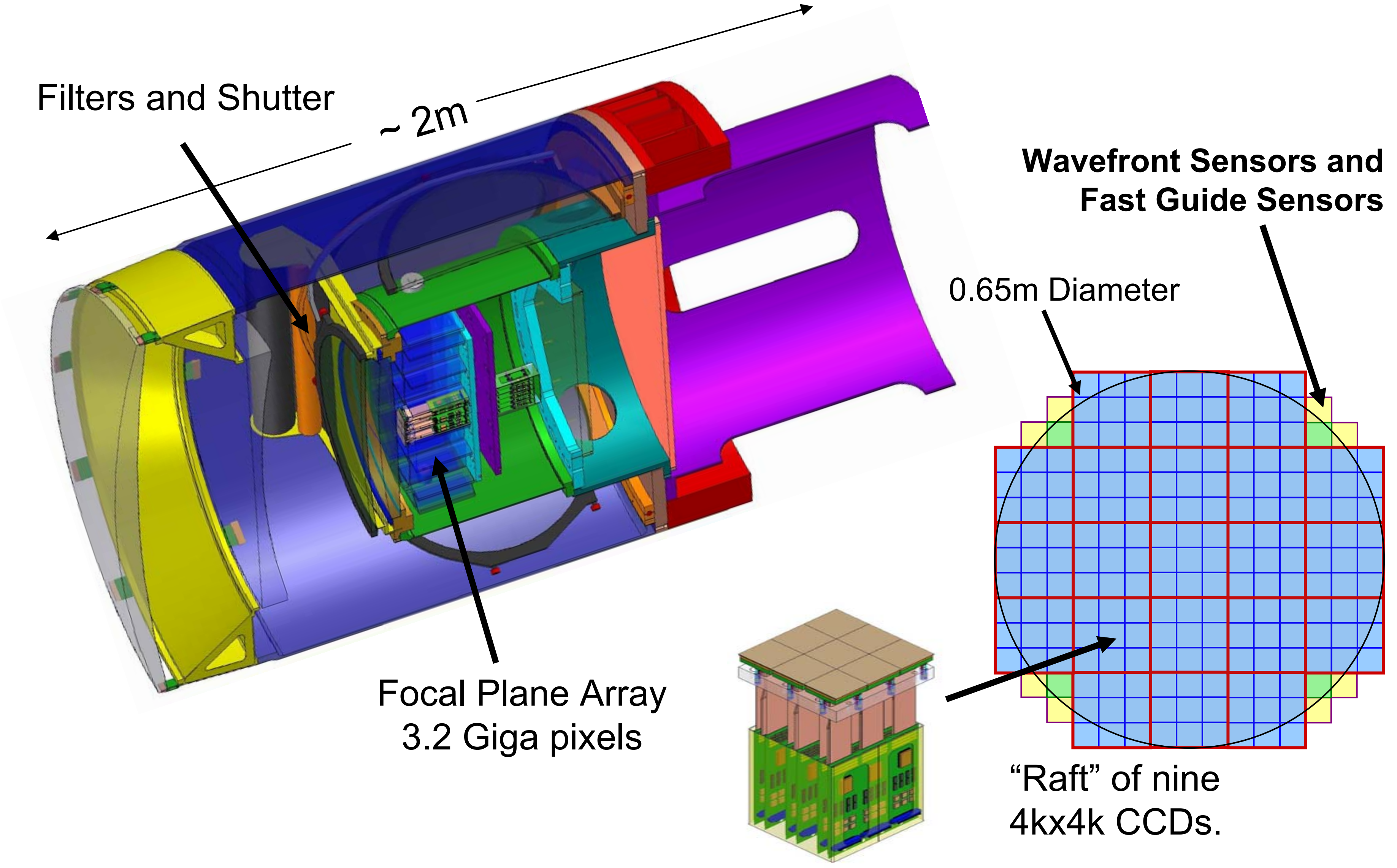
Contract with Arizona Mirror Lab

- **Casting (peak-temperature) date March 29, 2008**
- **Mirror contract completion date Dec 20, 2011**
- **Total mirror cost ~$21M (private funding)**

NOAO

Casting for LSST 8.4m monolithic primary-tertiary mirror being prepared.

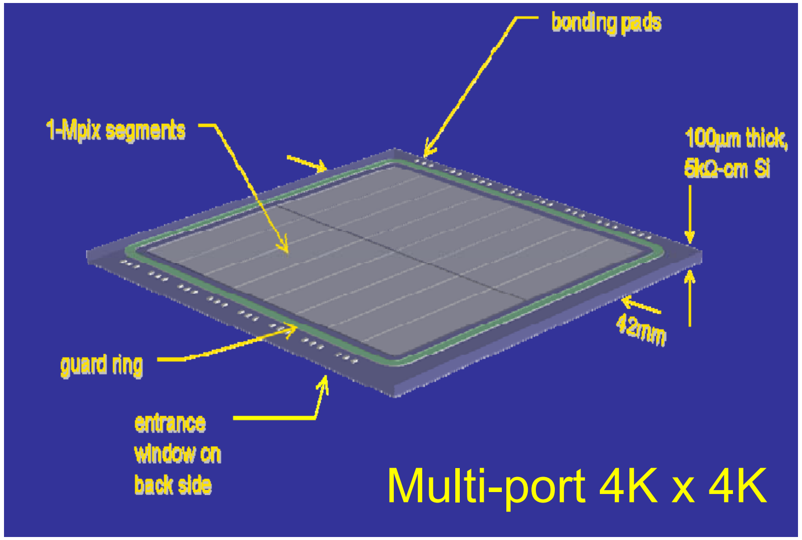
Camera and Focal Plane Array

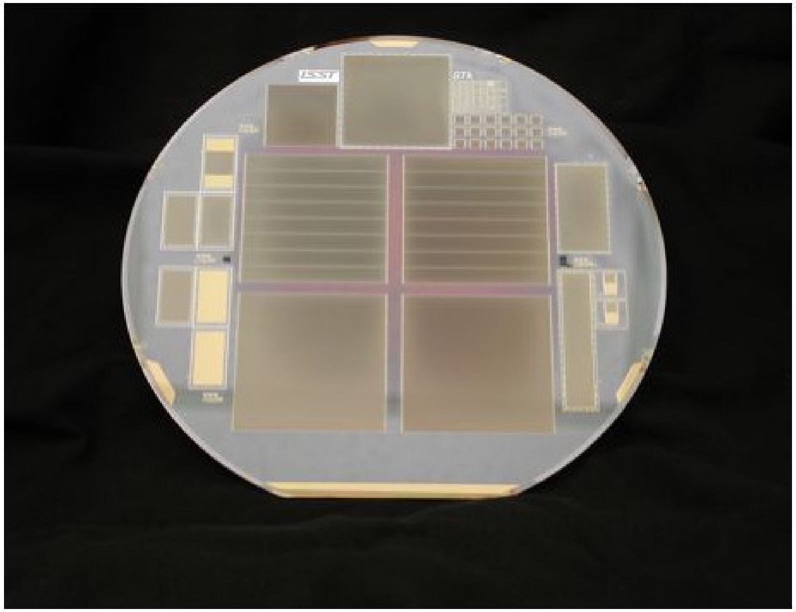


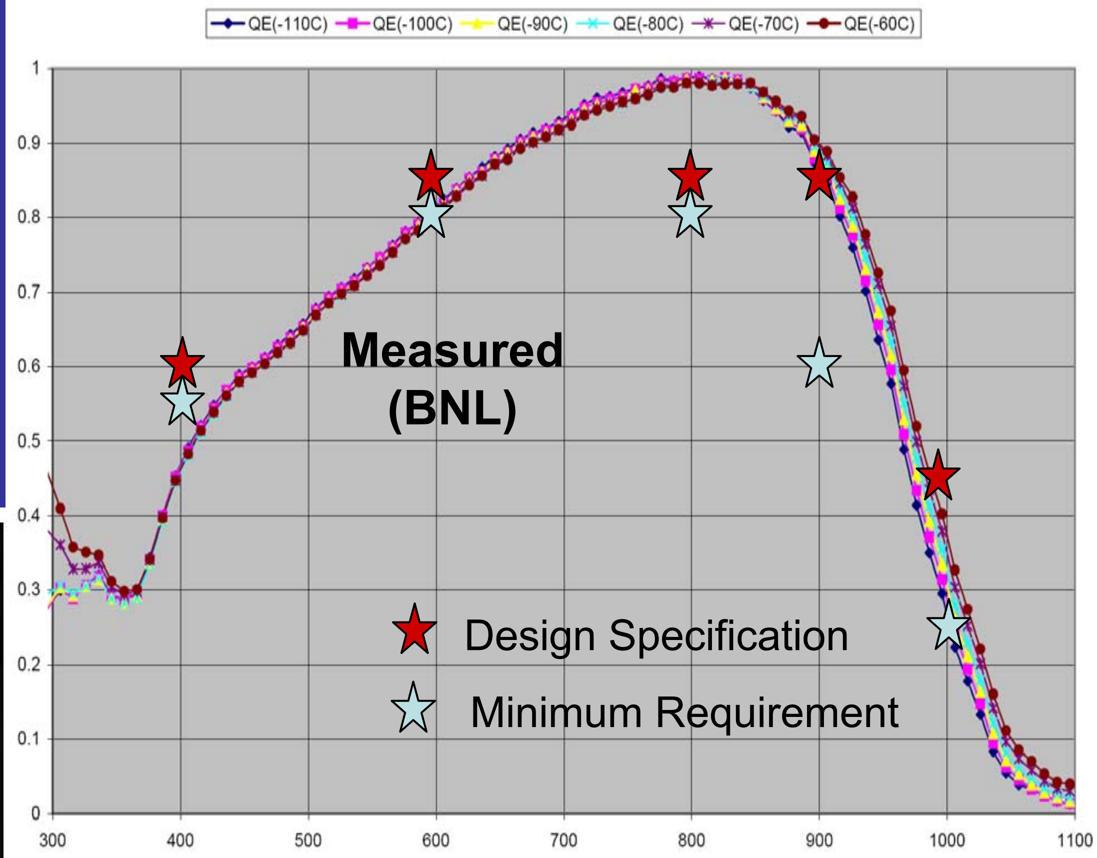
Focal Plane Sensors

BNL

Large Synoptic Survey Telescope







Vendor X Study Contract Device ##

(Full-performance contracts moving forward with private funding.)

DAQ Back-End Functional Prototypes

Large Synoptic Survey Telescope

SLAC

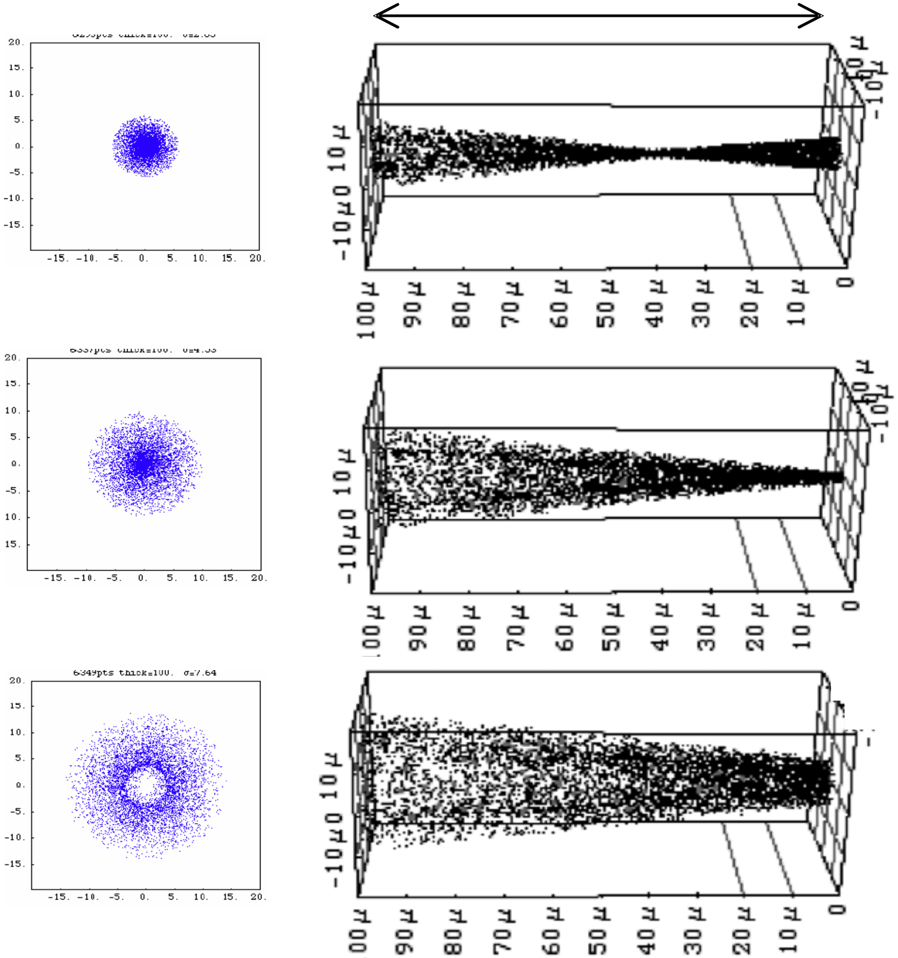
Focal Plane Metrology

Simulated LSST photon beam in silicon.

PSF

CCD Thickness (100μm)

Silicon Displacement:

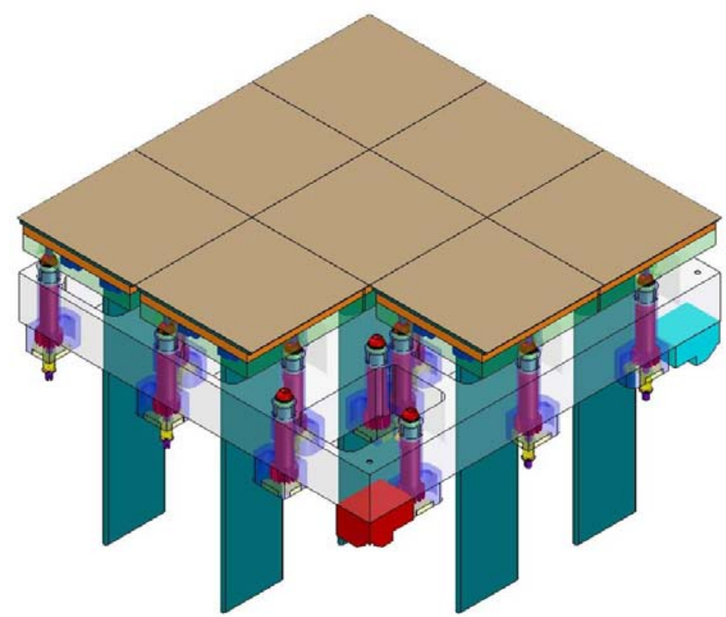


+10 μm

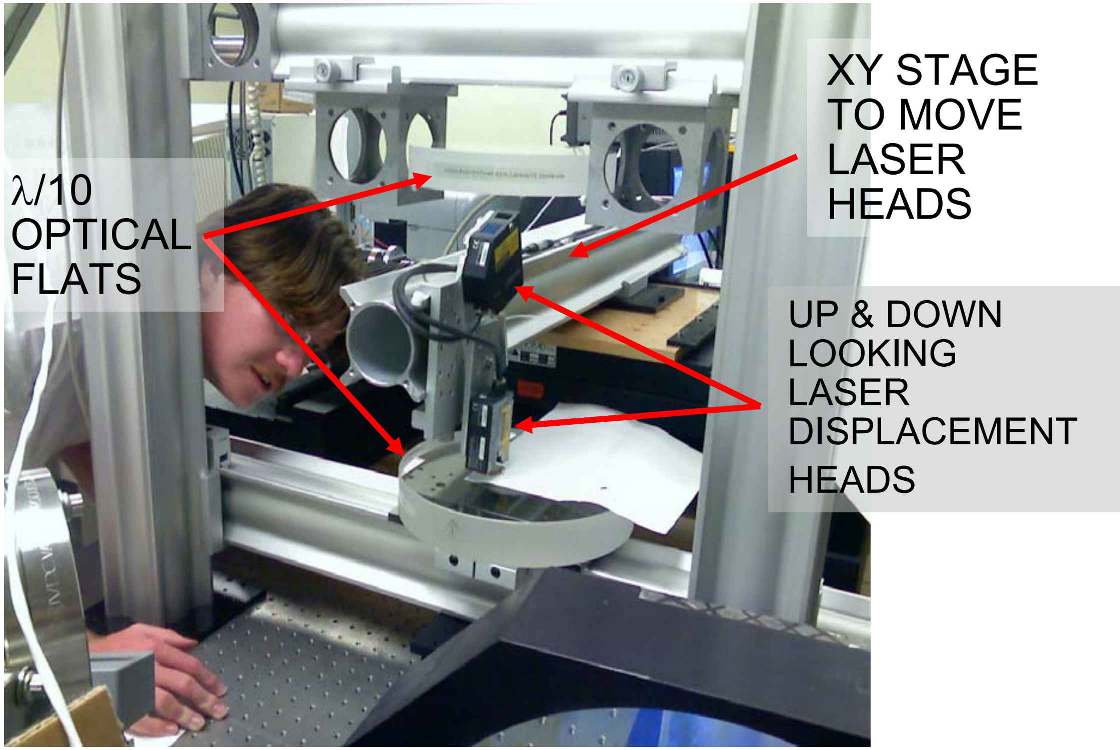
0 μm

-10 μm

Assembly-stage adjustment to achieve tolerance of 10 microns peak-to-valley surface flatness.

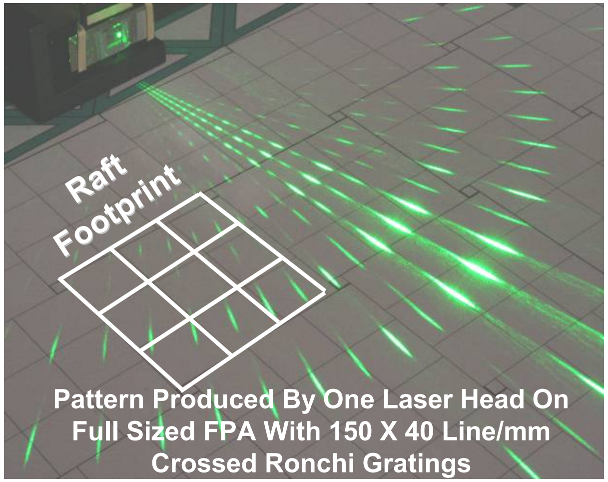


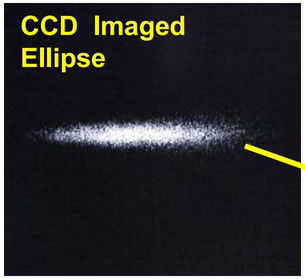
Non-Contact Metrology

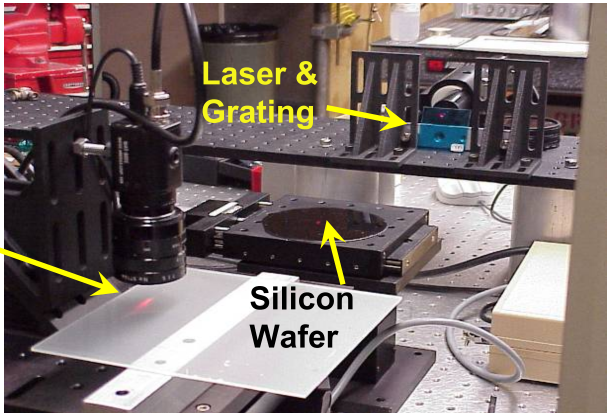


Laboratory Assembly

Camera In-Situ







Weak Lensing Errors

Systematic errors will dominate LSST results.

→ Drives instrument design and survey strategy.

- Image quality (PSF).
  - Multiplicative shear errors from size of PSF.
  - Additive shear errors from shape of PSF.

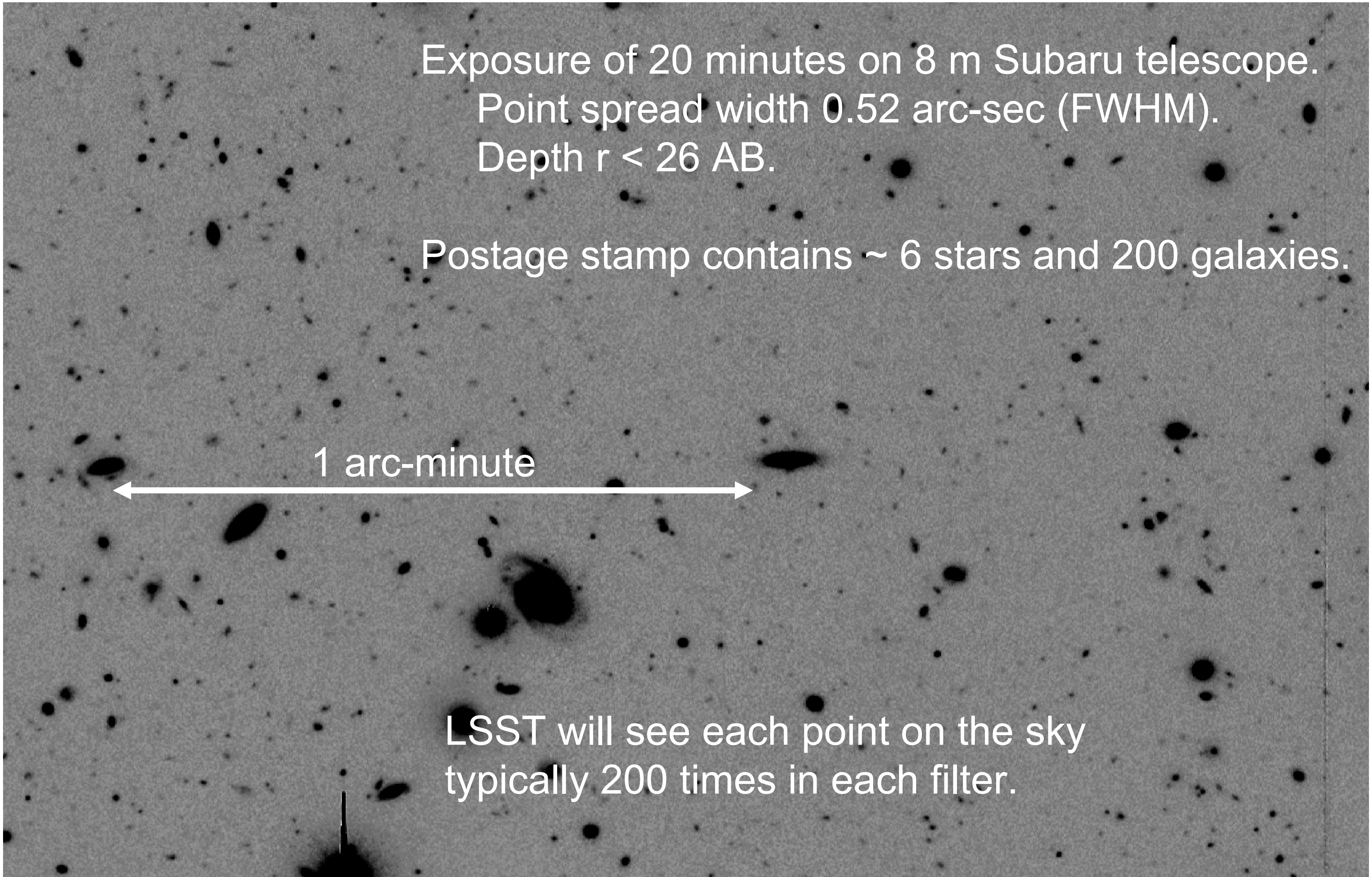
    → Multi-epoch survey "averages down" errors.

    → Optics design specification on ellipticity of PSF.

- Photometric redshifts.
  - "Balmer Break" moves into the NIR at $z > 1.5$.

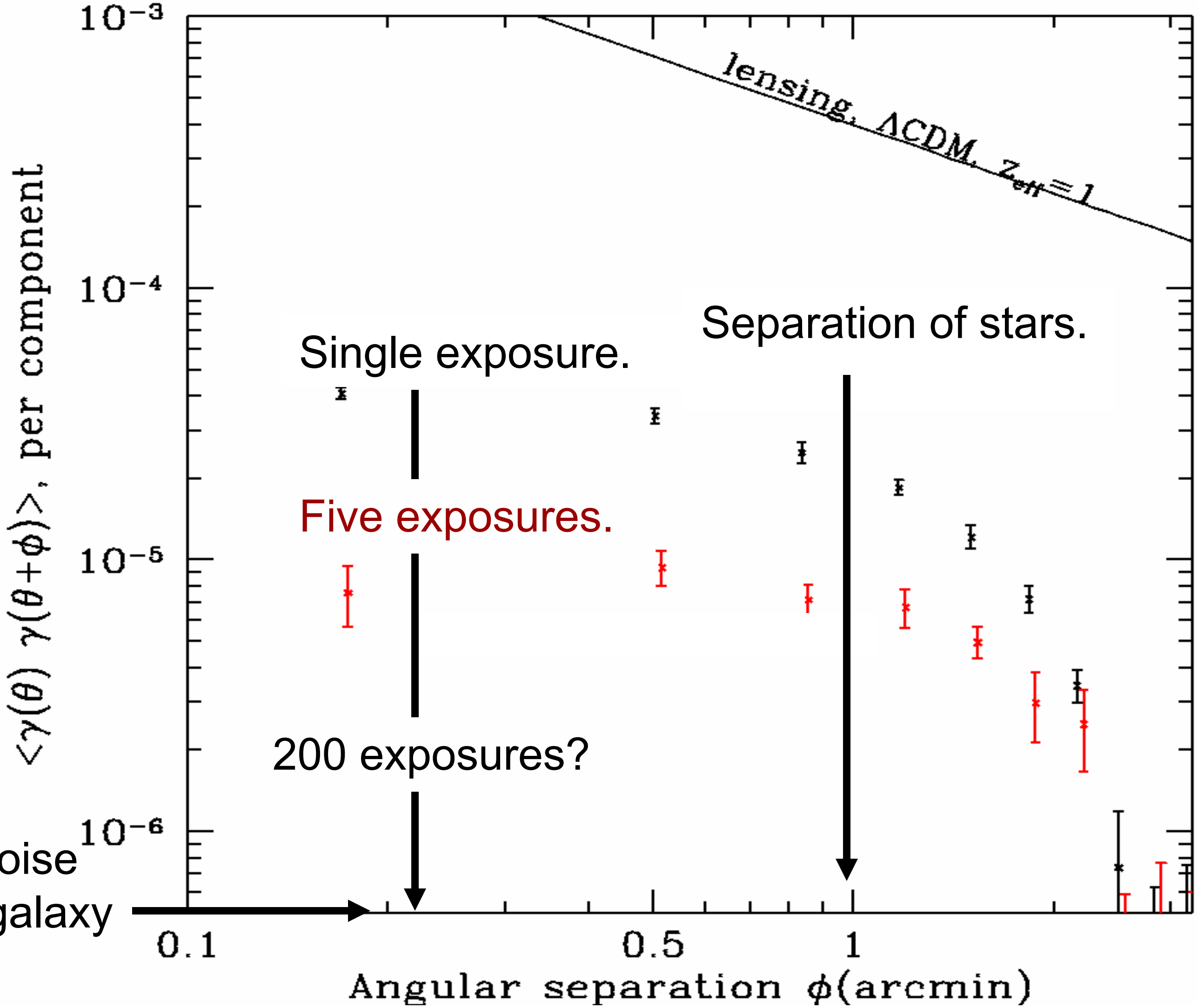
    → Calibrate with spectroscopically measured sample.

LSST Postage Stamp
(10^{-4} of Full LSST FOV)



Test of Residual Shear Error

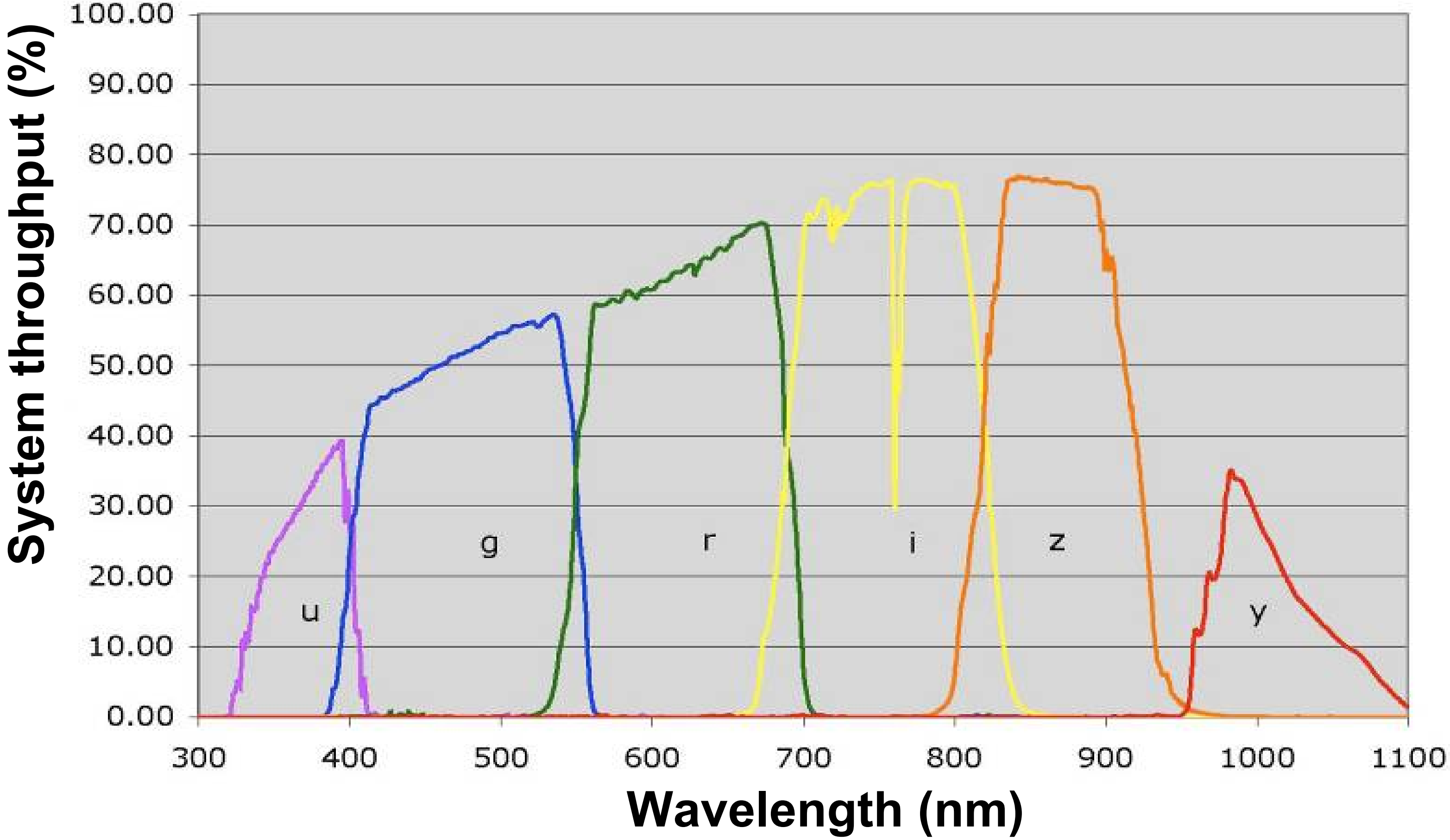
Stars in 10-sec exposures with Suprime-Cam on Subaru.



Approx shot-noise from intrinsic galaxy shapes.

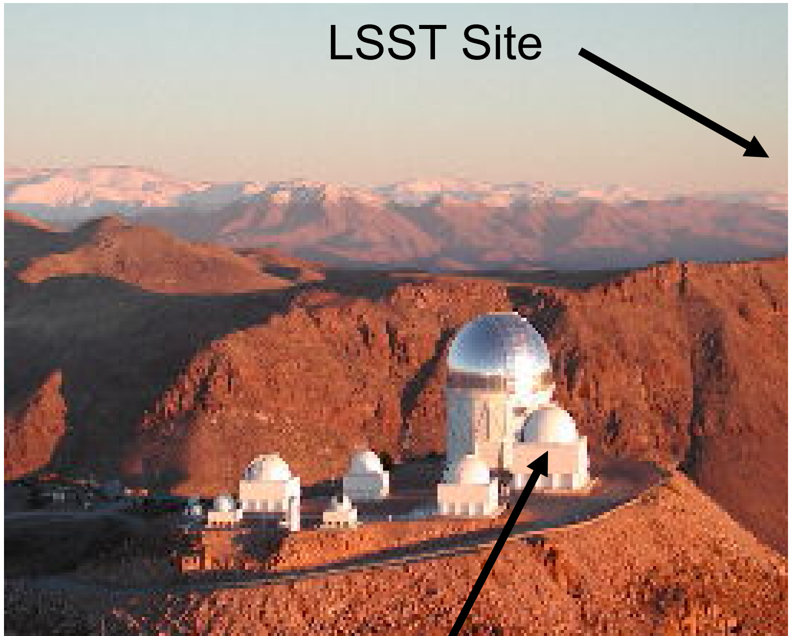
Optical Filter Bands

Transmission – including atmosphere, telescope, and detector QE.



⟶ Photometric determination of galaxy redshifts.

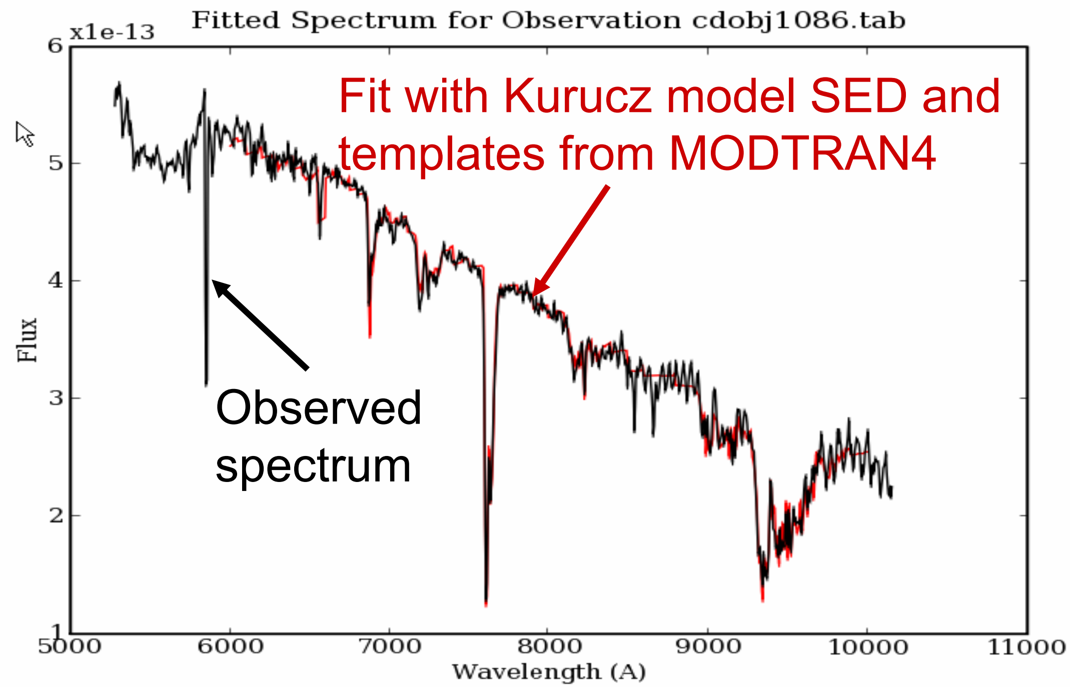
Data Calibration Tests
(CTIO on Tololo)

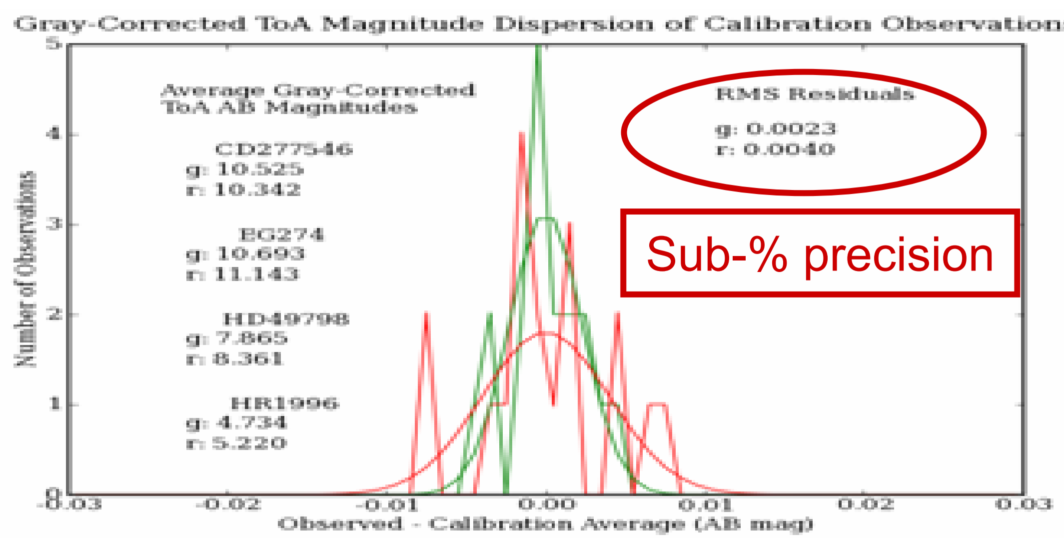


Observing with 1.5m and RCSpec

- 6 nights in 2007A/B completed
- 6 nights in 2008A approved

DLB





Photometric Measurement of Redshifts
"Photo-z's"

Large Synoptic Survey Telescope

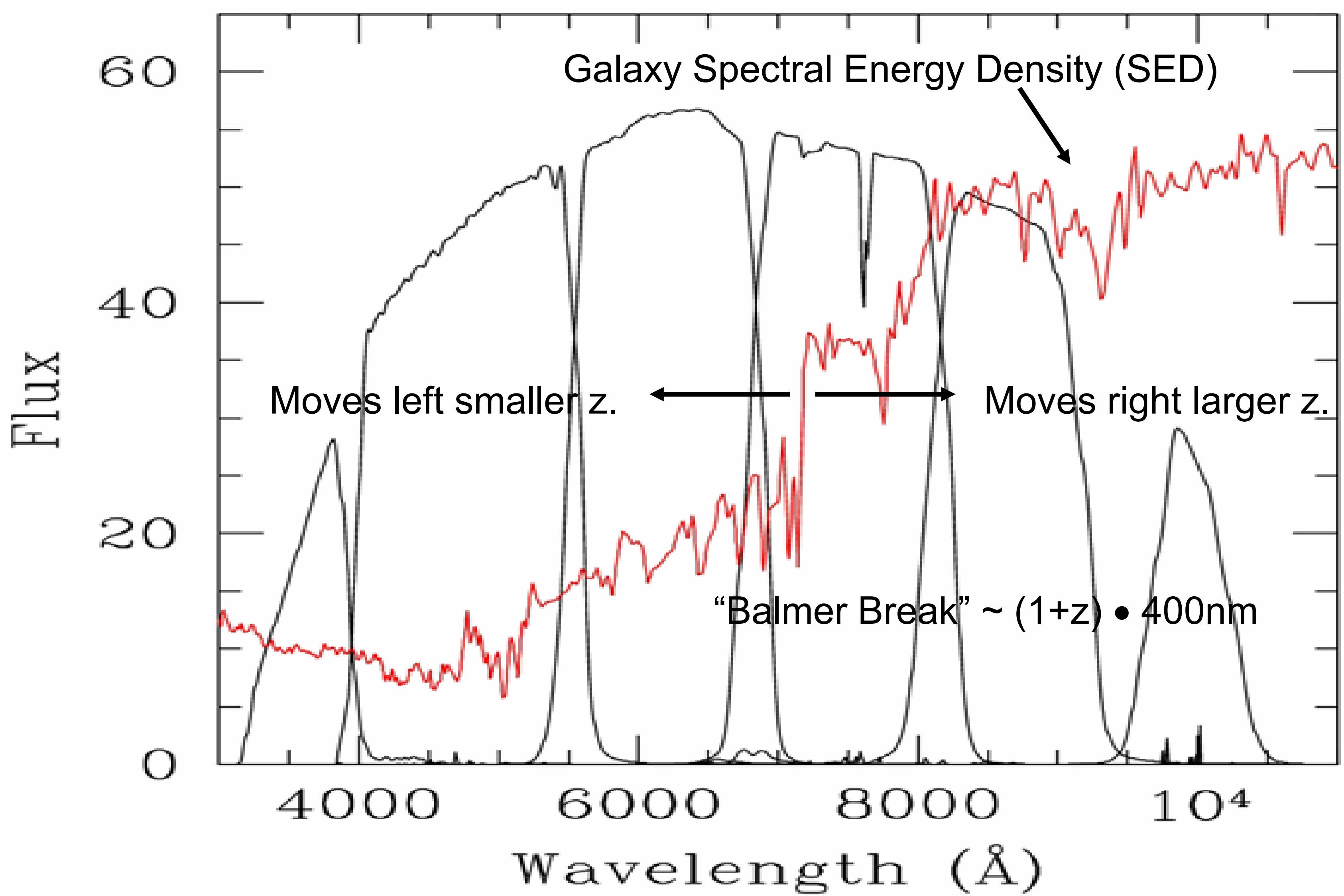


Photo-z Reconstruction

Simulation of LSST 6-band photometric redshifts with no calibration corrections.

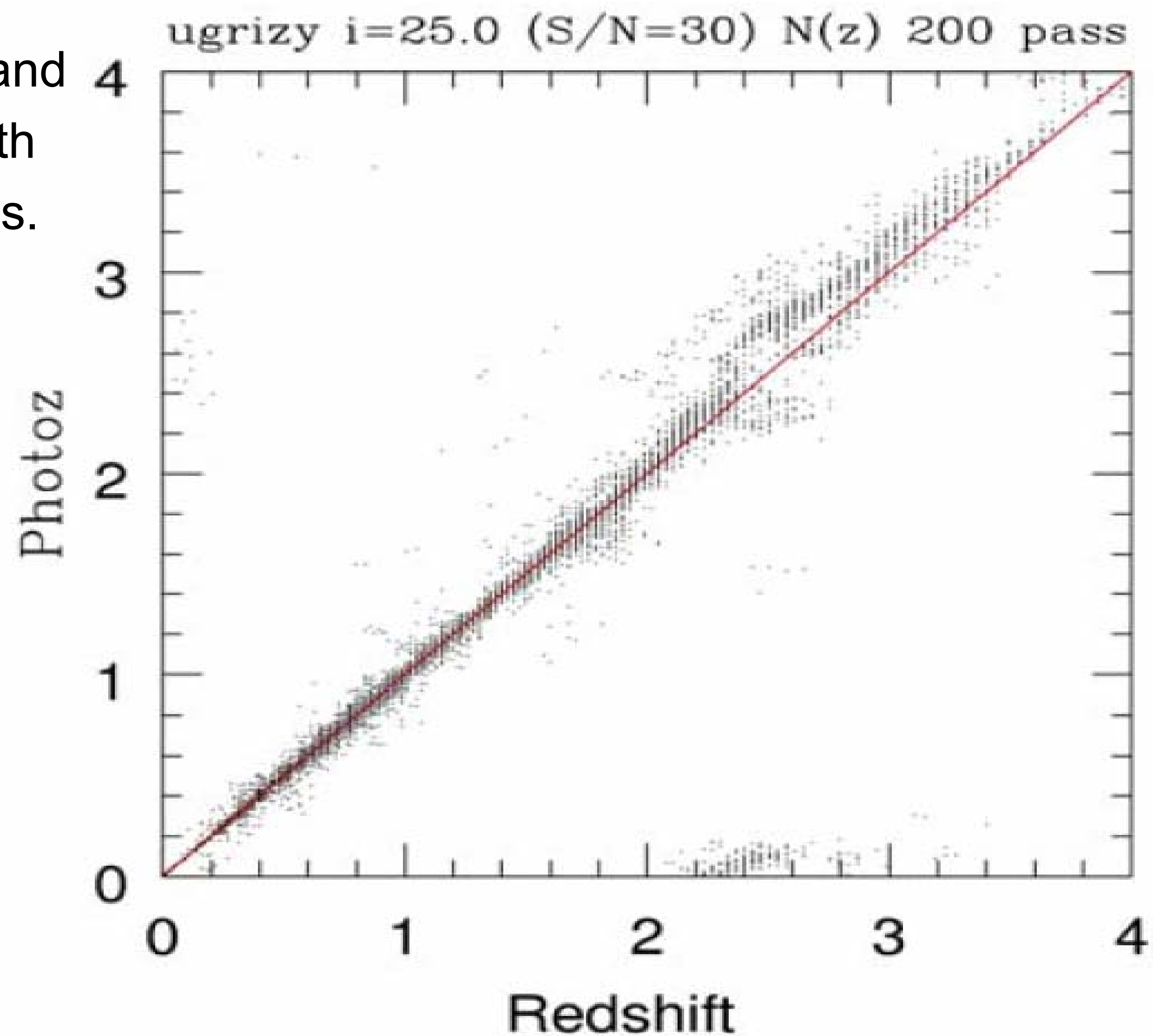
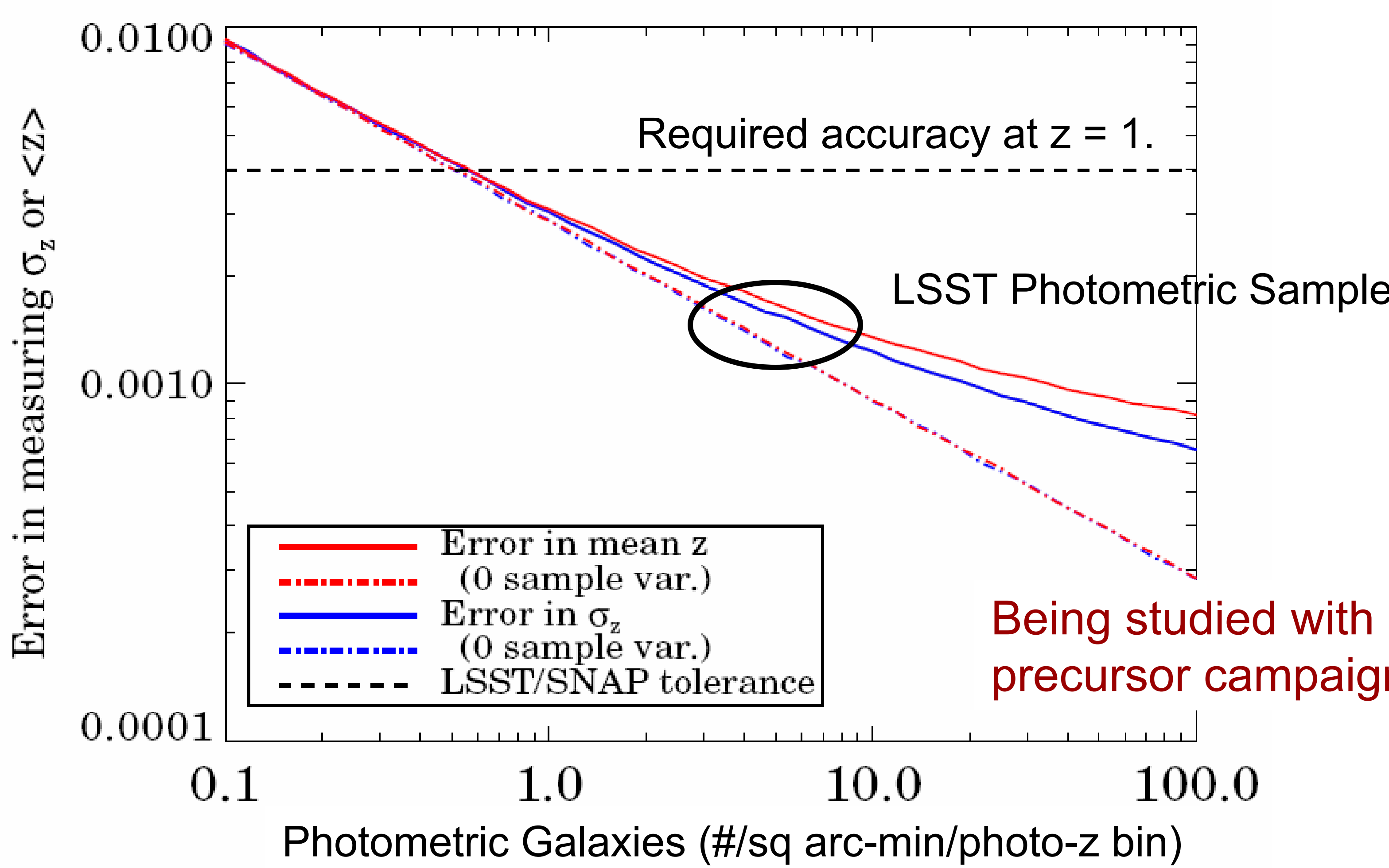


Photo-Z Calibration

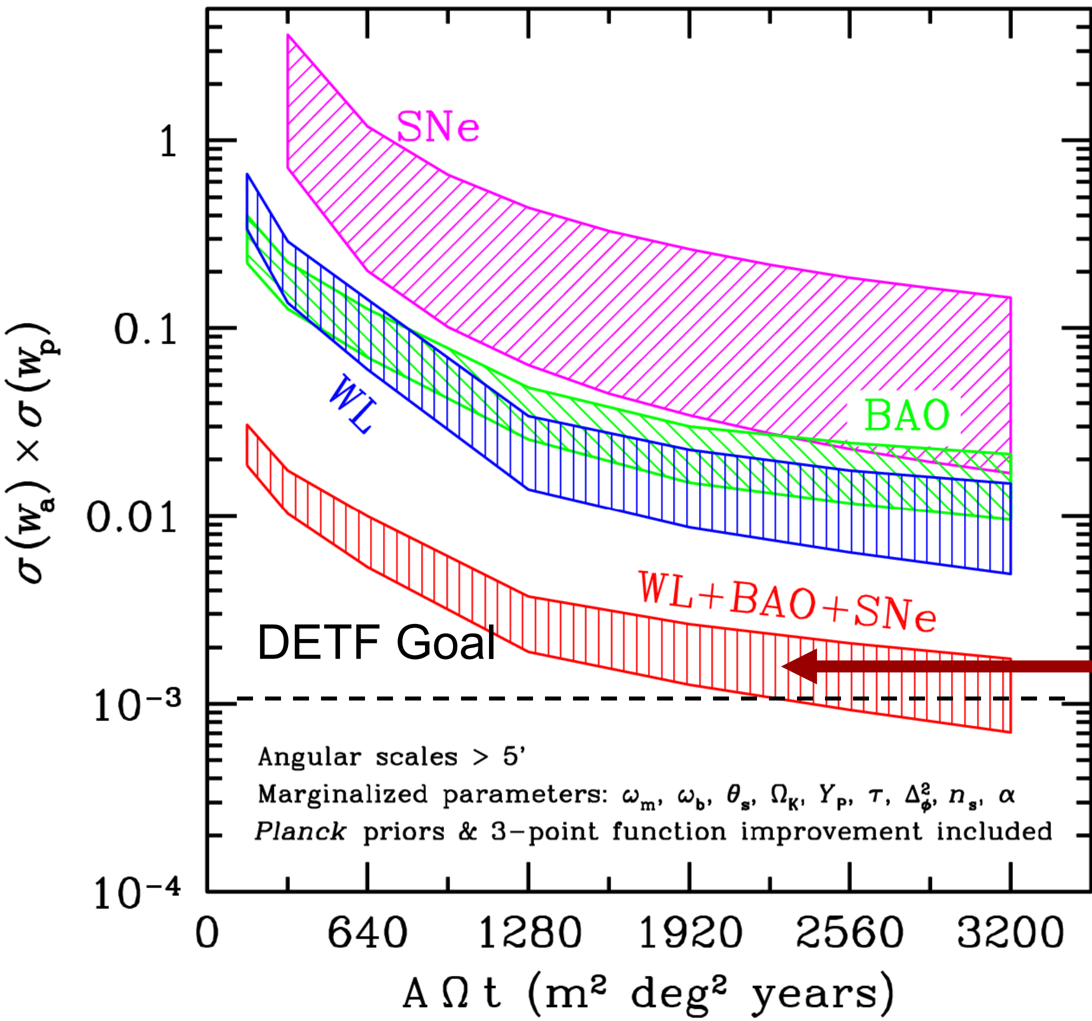
Calibrate to z=3 with 75,000 spectroscopic redshifts … about half exist today.



Being studied with precursor campaigns.

Precision on Dark Energy Parameters

Large Synoptic Survey Telescope



Measurements have different systematic limits.

Combination is significantly better than any individual measurement.

Project Schedule

Large Synoptic Survey Telescope

2006-2007 Site Selection
Primary Mirror Contract (Arizona Mirror Lab)
Construction Proposals (NSF and DOE)
→ NSF Conceptual Design Review

Done

2008-2010 Complete Engineering and Design
Mirror Construction/Sensor Contracts
Long-Lead Procurements

Underway

2011-2014 Construction and First Light

2015 Commissioning and First Science