Physics With Astronomical Surveys

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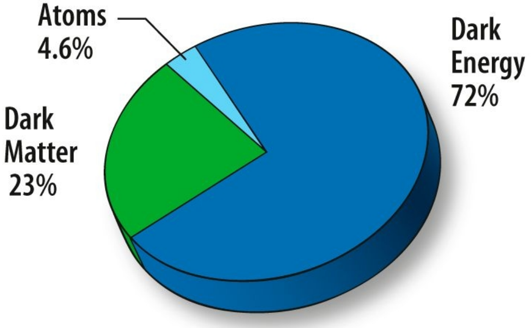
Physics with Astronomical Surveys

- Why are high energy and nuclear physicists interested in this?
- Cosmology and astrophysics basics
- Surveys past and future… LSST
- Physics with surveys
  - Gravitational lensing as a new observational tool
  - Photometry and calibration

Why are physicists looking up instead of down?

Particle physicists want to understand what the universe is made of, and how its constituents interact with each other… for the last century, the best way to explore that has been to study the interaction of matter in the laboratory… but then, observations converged at the end of the last century on a flat universe that mostly is made up of things for which there is no direct laboratory evidence of their existence

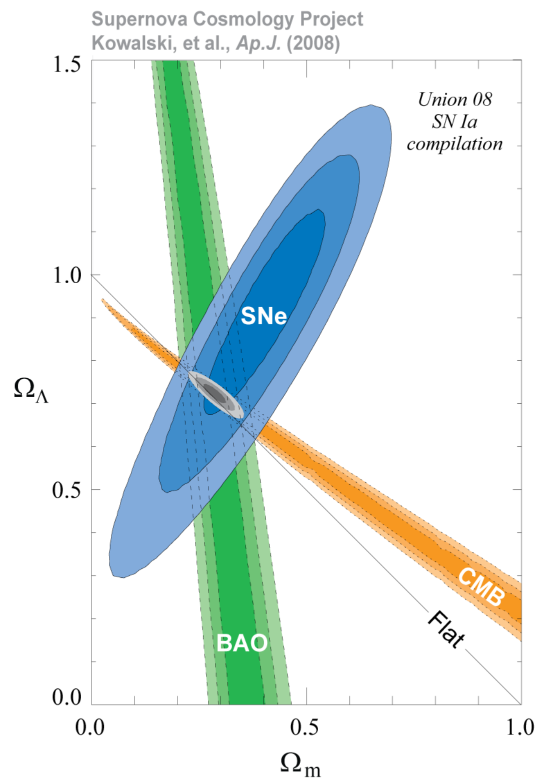


The pillars of the standard model of cosmology

- Flat spacetime Inflation at early times; caused by unknown scalar field?
- Dark matter Could be supersymmetric particle; only known through gravitational effects at galactic scale and larger
- Dark energy The cosmological constant? Or something else?

Results from many directions

- Observations of supernovae (SN), the cosmic microwave background (CMB), and large scale structure (LSS) paint a consistent picture
- A science long driven by theory is being driven by new experimental techniques
- Some of the techniques are quite mature (CMB, SN), others are still in their infancy (BAO, WL); all benefit from improved instrumentation



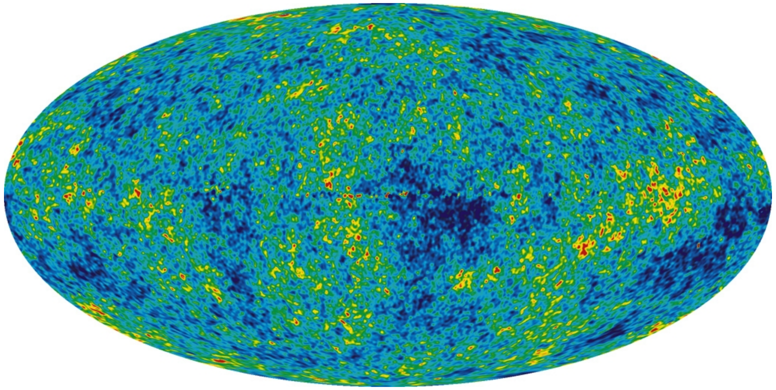
Units and terminology

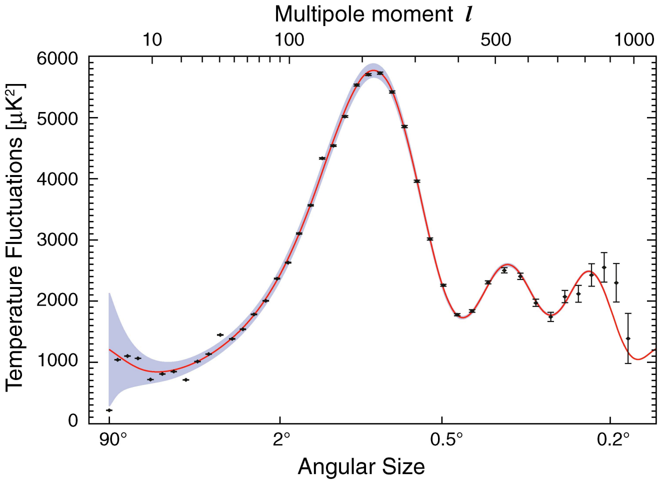
You have to get used to "astronomer units" and cosmological parameters, some of them invented thousands of years ago… here's a a short dictionary

- Ω_Λ , Ω_M are the ratios of the density to the critical density ($3H_0^2/8\pi G$)
- Magnitude: traditionally, flux in a spectral band b is quoted in magnitudes where $m_b = -2.5 \log_{10}(F_b/F_{AB})$ and F_{AB} is 3631 Jy ($3.631\ 10^{-20}$ erg s^{-1} Hz^{-1} cm^{-2}); there are actually many complications (a factor of 100 difference in flux is 5 magnitudes, the brightest stars are around magnitude 0 and the faintest objects are in the high 20's); distance modulus μ is a measure of distance in magnitudes
- The redshift z is defined as the ratio of wavelengths $\lambda_{obs}/\lambda_{emit}$ and $1+z=1/a$ where a is the "scale factor"
- A parsec is a measure of distance (parallax of 1 arc-second, ~3.26 light years)
- σ_8 is rms mass fluctuation amplitude in an 8 Mpc sphere
- w is the ratio p/ρ which defines the equation of state of a fluid

See the Paul Stankus "Cosmology for Beginners" lectures(http://www.bnl.gov/video/lectures.asp)

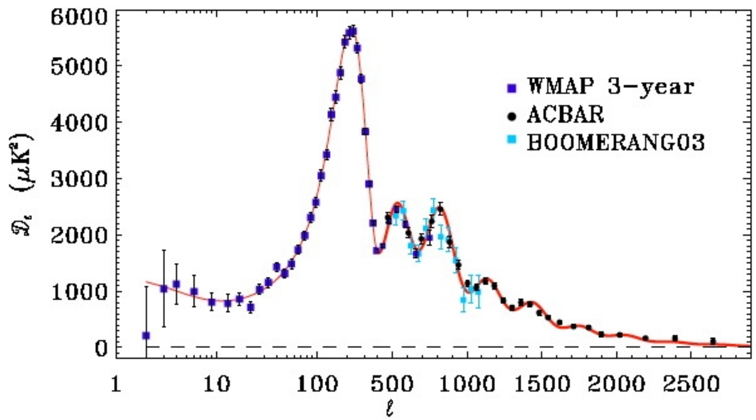
CMB





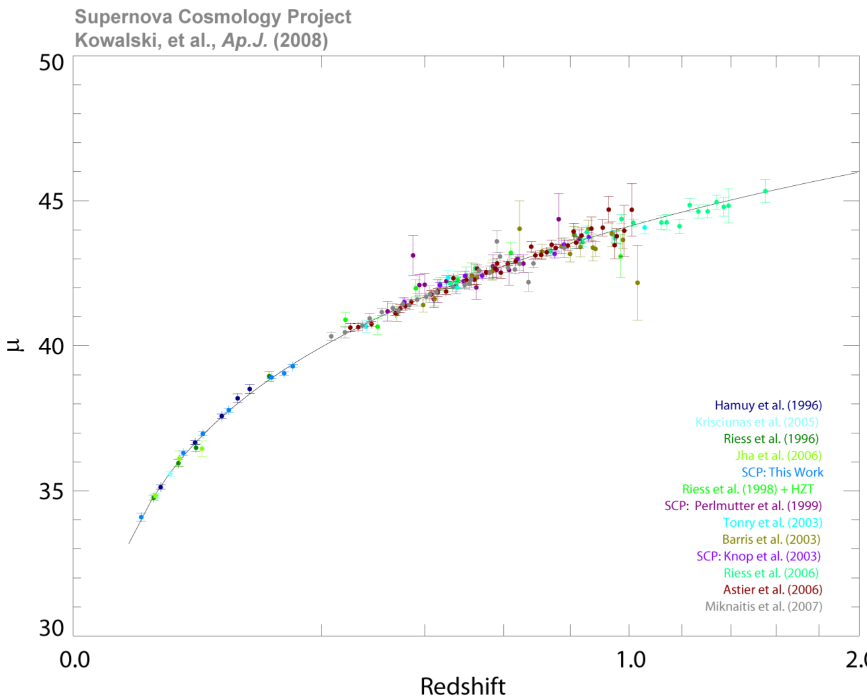
Extraordinary WMAP 5 year results (arXiv:0803.0547)

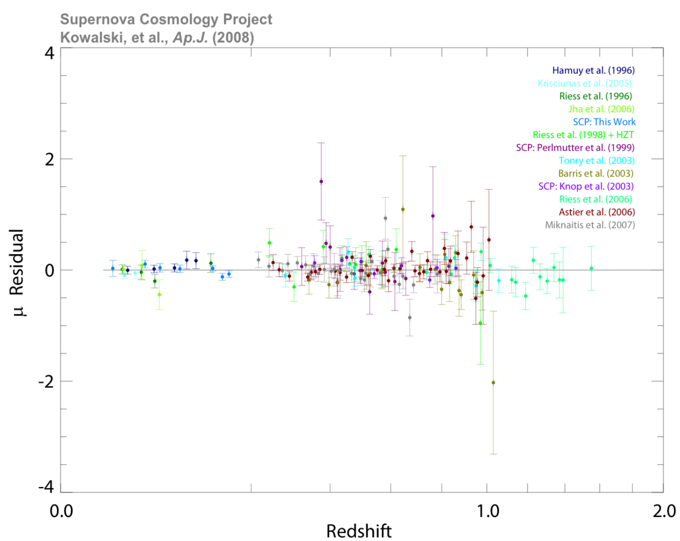
…but it is not the only interesting CMB experiment (ACBAR arXiv:0801:1491) and Planck launches on Halloween



Supernovae

Hubble diagram from SCP "Union" of 307 SN Ia (arXiv:0804.4142)





Best fit ΛCDM cosmology, but used to look at alternatives

The motivation for survey astronomy

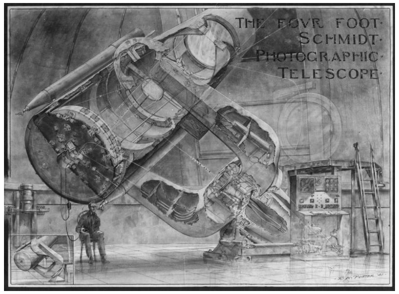
- The CMB gives us a map of the fluctuations that eventually became the universe we see today
- How did that happen?
- Can the evolution of structure in the universe be explained by gravity and dark energy?
- Do we understand the laws governing gravity and dark energy back to earliest times?

The way to find out is to map the structure of the universe and measure everything you can with statistically significant samples.

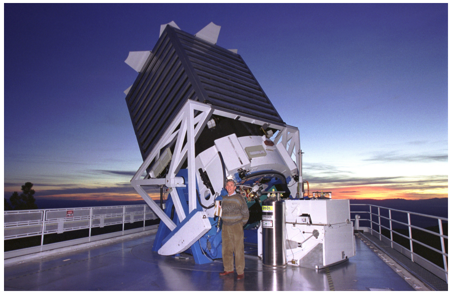
Survey survey

- Although sky surveys started millennia ago, surveys of the entire sky with good image quality and precise photometry are a relatively recent innovation
- Palomar Sky Survey 6° square fields, 2×936 14” photographic plates (blue and red); 1.2m telescope
- Sloan Digital Sky Survey was the first large area digital sky survey, 2.5m telescope, 287 million objects, 10 Tbyte of images, 9583 square degrees, 5 filters, 3° field (DR6)

Chinese star chart, 940 A.D.



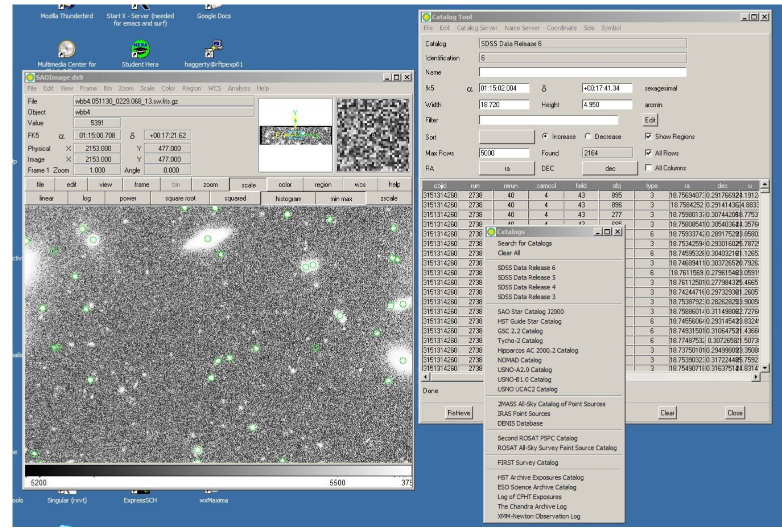
Palomar Sky Survey 1950-1958



SDSS 1998-

Yet more about surveys

- There has been an explosion in the amount of data which is available for doing science… not just pretty pictures
- For many objects, multiple wavelengths from X rays to radio wavelengths are cataloged
- Data at this scale requires databases… computing… calibration… and good ideas
- SDSS, CFHT, DES, Pan-STARRS… lots of progress



ds9 with an ESSENCE image and the available catalogs (http://heawww.harvard.edu/RD/ds9/)

What do you want in a future survey?

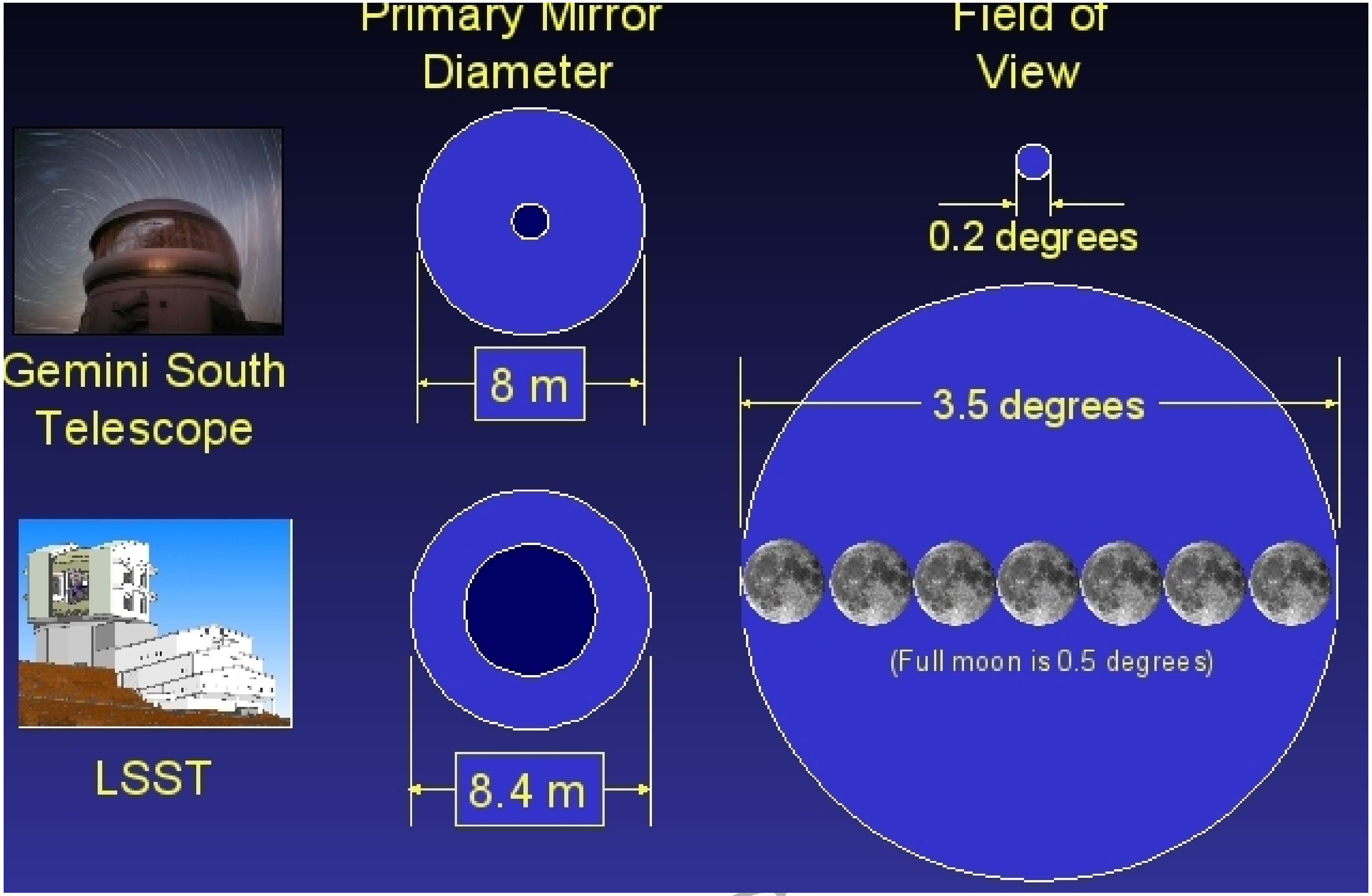
- Wide You want to explore a wide swath of sky both because there are interesting features on wide angular scales and because it increases statistics on rare objects
- Fast You want to look for rare transient objects like supernovae and microlensing events that happen on short timescale
- Deep You want to look far enough back in time to see the universe evolving

So why LSST?

It's not the only survey proposed or ongoing, but a group of us here at Brookhaven in the Instrumentation Division and Physics Department have been participating in the development of the **L**arge **S**ynoptic **S**urvey **T**elescope

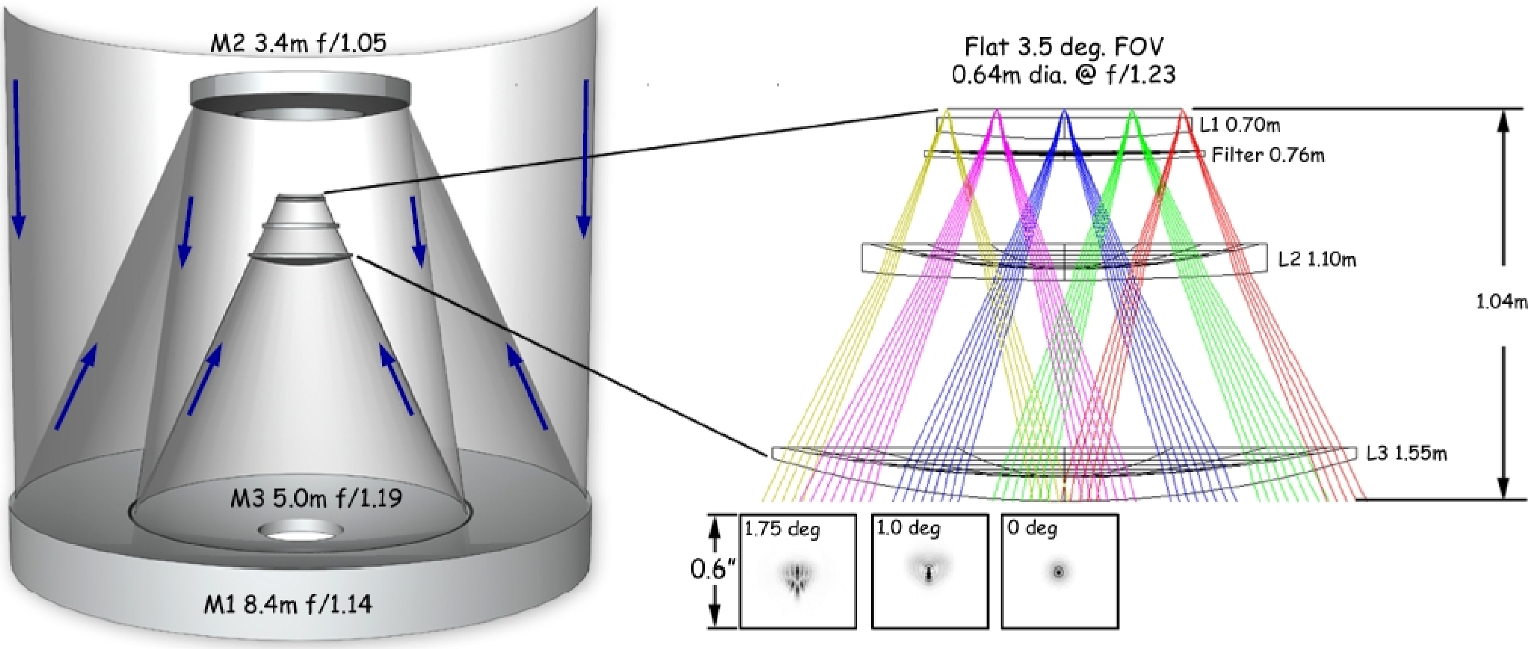
We think that this telescope stretches the optics, electronics, and data management to the limits of today's technology to create a revolutionary astronomical instrument

Wide and deep



Demanding optical design

A 10 square degree field of view is about as large as practical



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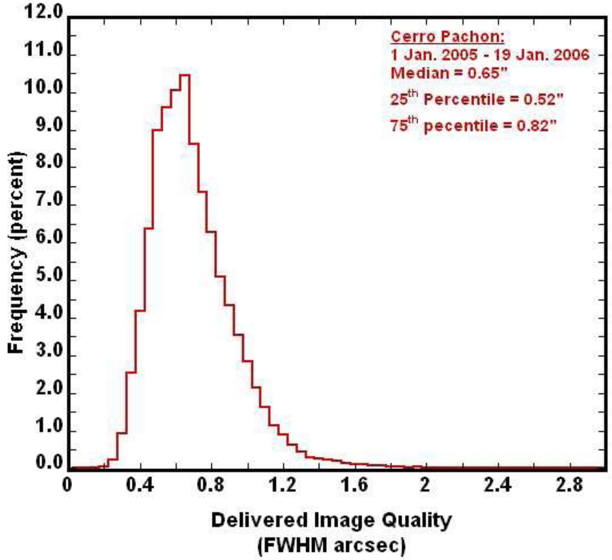
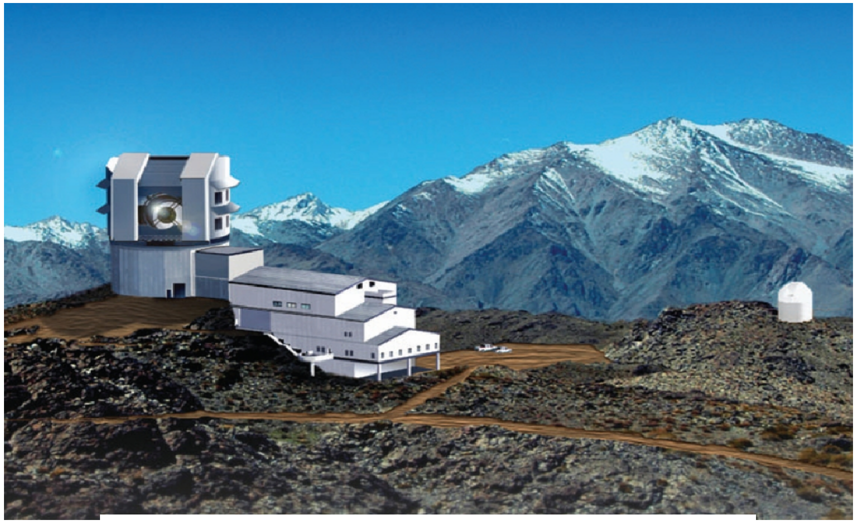
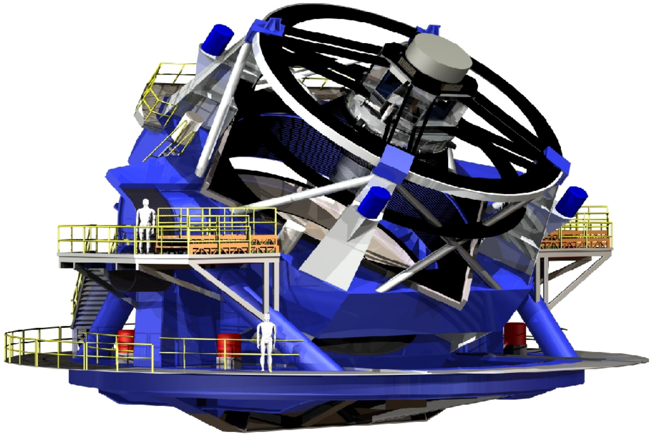
Excellent site



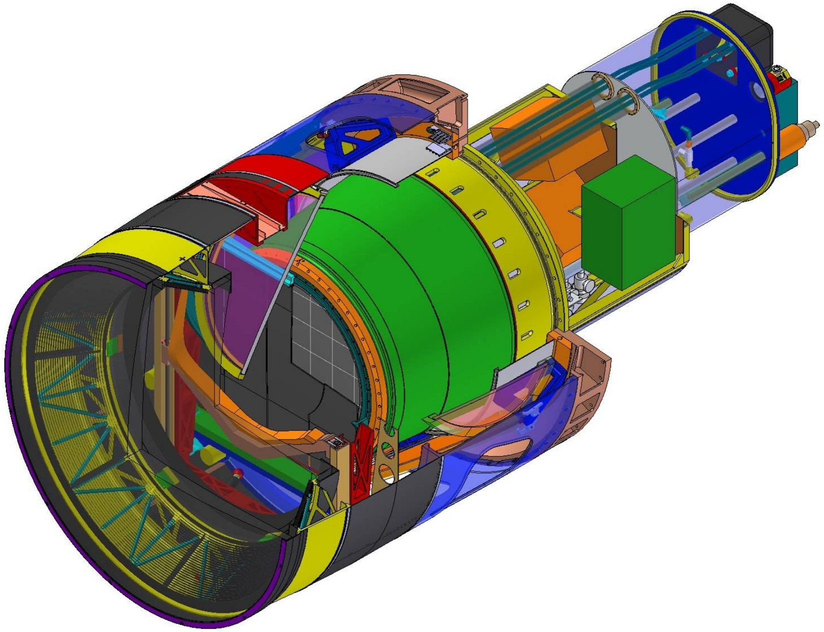


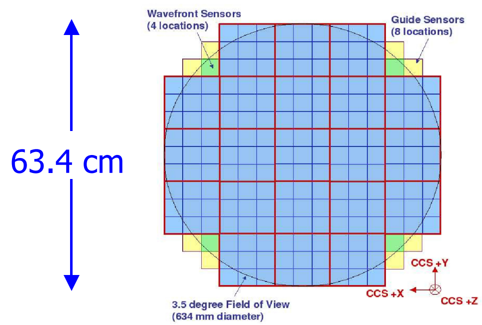


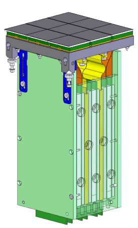
Site at Cerro Pachon in Chile
Excellent seeing at 2200m

Camera

- 189 4k×4k CCD's read out with 16 amplifiers/CCD
- Readout 3.2 Gpixel every 15 seconds
- 6 filters 320-1050 nm



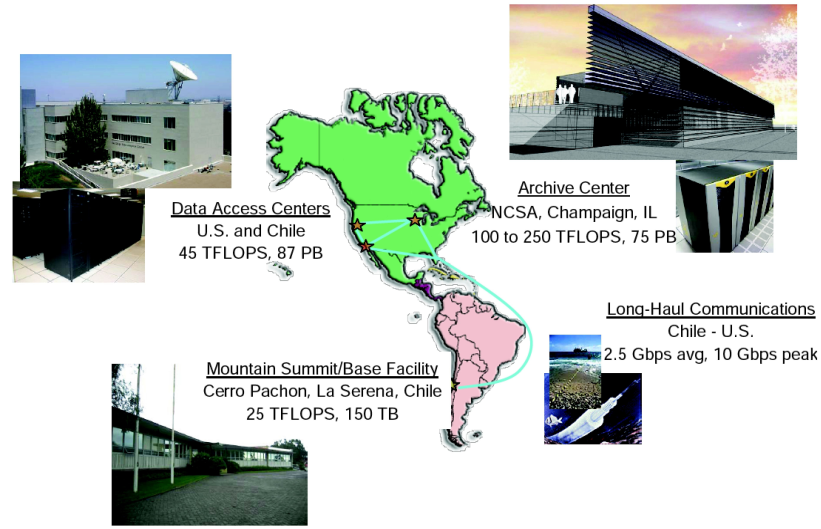




Made from 3 × 3 "rafts"

Data management

- Collecting and processing LSST data is another step forward
- Open access to data and software enabling wide range of science



- SDSS ~10 Tbyte
- PHENIX ~1 Pbyte/year
- LSST ~10 Pbyte/year

LSST numbers

- 6-band Survey: 320–1100 nm
- Sky area covered: >20,000 deg^2*
- Each 9.6 deg^2 field revisited ~2000 times
- Limiting magnitude: 27.6 AB magnitude (5σ)
- Photometric precision: 0.01 magnitude (1%)

*the sky is 41,253 deg^2

Some examples

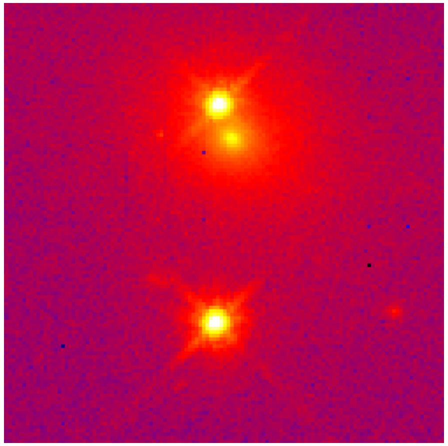
A survey like LSST has an incredible range of science open to it, from the solar system, to Milky Way structure, to high statistics on almost any kind of imaginable object

Concentrate here on a few topics interesting to me…

Gravitational lensing

- Even before Einstein there were predictions of deflection of starlight by gravitation (of course Einstein got right the factor of two compared to Newtonian deflection)
- There was some theoretical speculation, but not much happened until 1979, when the double quasar Q0957+561 was found to be a lens
- Lots of review articles

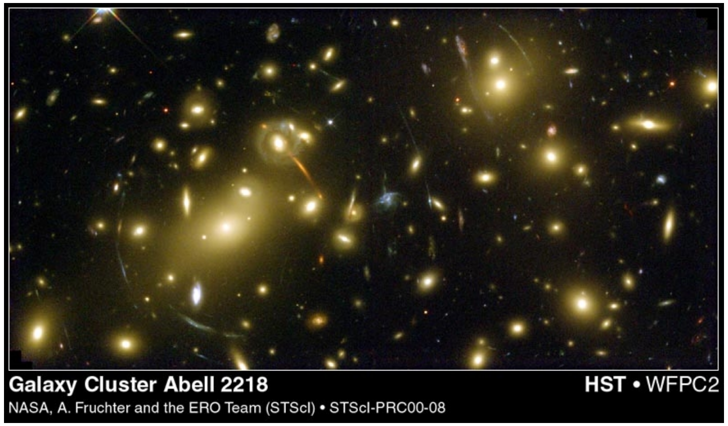
(Wambsganns, http://www.livingreviews.org/lrr-1998-12, e.g.)

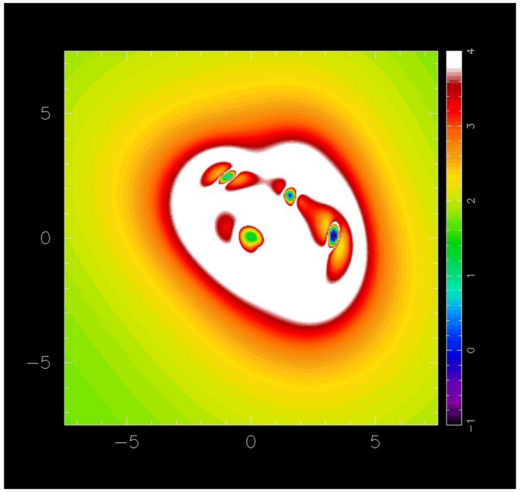


CASTLES survey:
http://www.cfa.harvard.edu/glensdata/

Strong lensing

- If you can see it, it's strong lensing
- Interesting physics that's still developing as lensed objects are found and shown to be lenses
- Quiet a bit of complexity still developing in modeling lenses and reconstructing mass from observation (http://www.qgd.uzh.ch/projects/pixelens/)

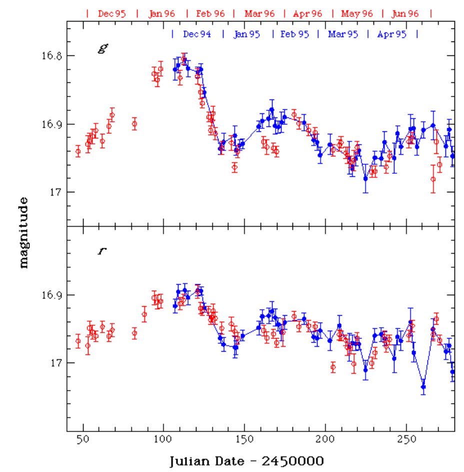




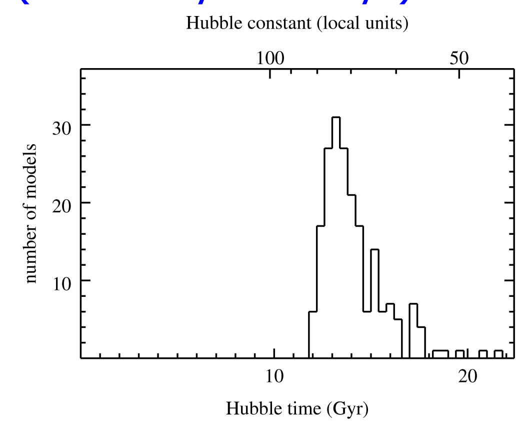
GLAMROC simulation of strong lens
(Ted Baltz, http://kipac.stanford.edu/collab/research/lensing/glamroc/)

Physics with time delays

- If you can observe variations in brightness of two lensed objects, you can make a pretty direct measurement of the Hubble constant based on the different path lengths followed by photons
- An example of physics that's possible now that will be changed completely by large statistics and better measurement



Q0957+561 light curves (shifted by 417 days)



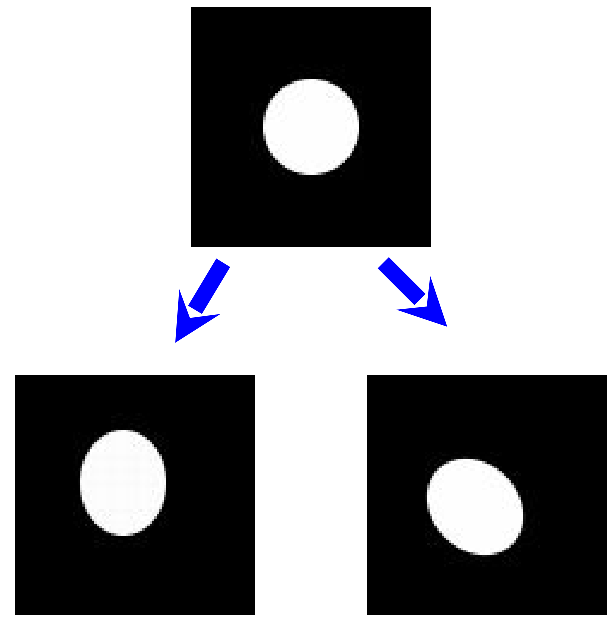
11 lenses, multiple models

Coles, arXiv:0802.3219v1

Weak lensing

- Weak lensing is gravitational lensing you can't see… except statistically. Mass (galaxy cluster) in the foreground distorts the shapes of background galaxies
- The approximation for weak lensing:

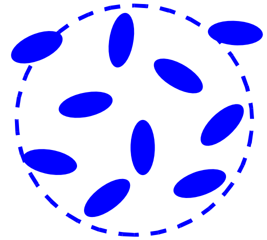
$$\begin{pmatrix} x_u \\ y_u \end{pmatrix} = \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$



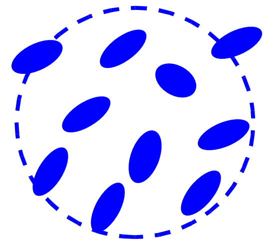
g_1=0.1 g_2=0 g_1=0.0 g_2=0.1

Using shear

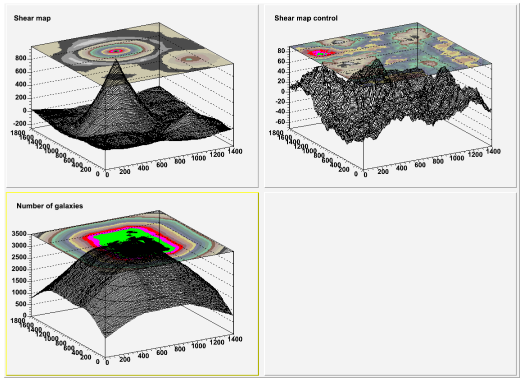
- Assuming the orientation of background galaxies is random, we can extract from the galaxy shapes effectively a mass distribution
- Simulation essential!



Without lensing, the "average" ellipticity vector is 0



With lensing ≈γ (figure by Hoekstra)



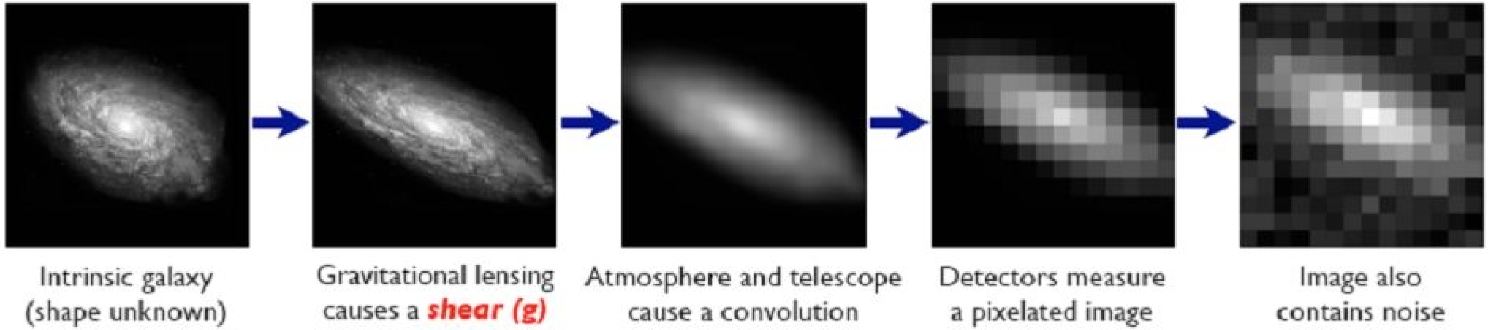
Simulated data from Wittman that I reconstructed

Improving shear determination

It isn't so easy in practice…

- Instrument and atmosphere fuzz up the image
- The detector and sky add noise
- The distant background galaxies are small and faint

There's a communal attempt to reduce systematics



Bridle et al., great08 challenge http://www.great08challenge.info/

Add them up

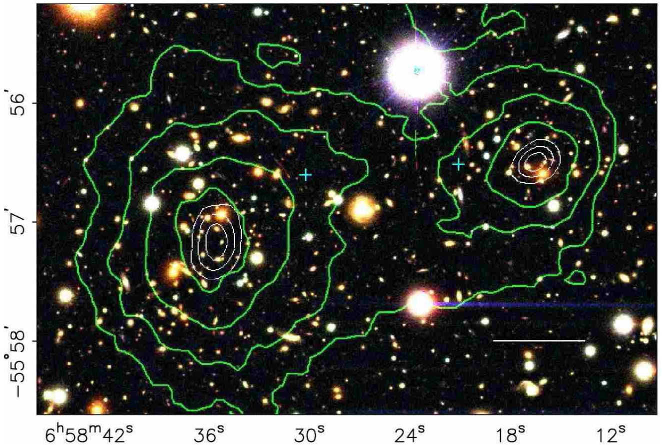
LSST has to do all that… but then extract the shear signal from ~1000 "co-added" images

Lots of interesting ideas about how to do that

Simulation is an important component

Lensing as an observational tool

- WL played a featured role in the recent excitement about the Bullet Cluster, merging galaxy clusters
- Short story: by providing a way to map mass instead of light, we have a new way to see that maps mass instead of light

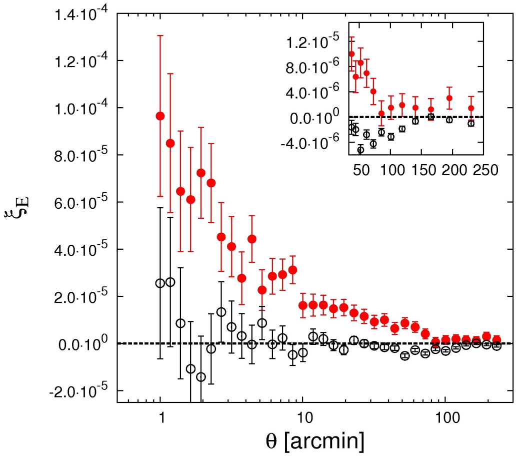


In green, weak lensing analysis of Bullet Cluster (arXiv:astro-ph/0608407v1)

Cosmic shear

The push for precision in weak lensing is to measure cosmological shear; it's a long story, but sensitive to the matter power spectrum (measures a combination of σ_8 and Ω_m and is complementary to other techniques for extracting cosmology)

- Deep survey (statistics)
- Want to bin in redshifts (tomography)
- Want to cover large angular scales



CFHTLS 57 sq deg arXiv:0712.0884

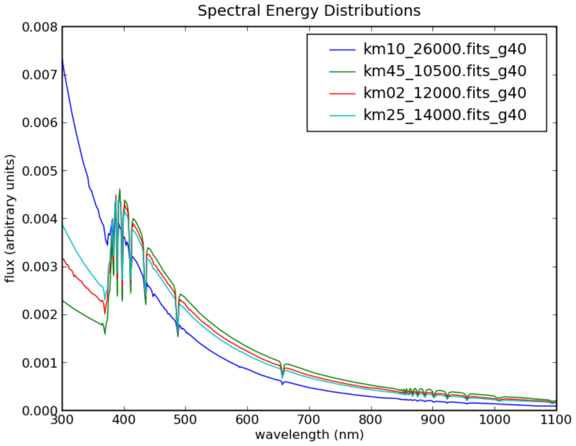
Development of technique

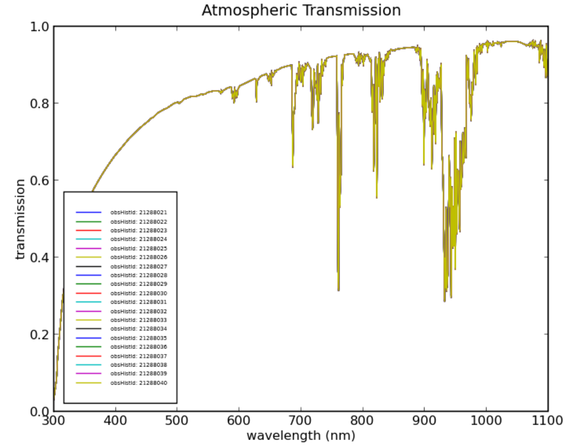
- As Edison meant to say, research is 99% calibration and 1% inspiration
- Precision photometry enables a host of scientific topics (photometric redshifts, for example, allow a distance determination without spectroscopy)
- Precision shape measurements, only possible with careful attention to the point spread function, are what enable the measurement of “cosmic shear” with weak lensing
- Precision astrometry is necessary if you want to co-add many images of the same field in order to reach fainter objects

Photometry

- Calibration sources in each field are used to calibrate the photometry
- Would like at least 1 per amplifier… 3k amplifiers… 300k pointings/year… >1 billion calibration sources/year
- How will we use these observations to calibrate the survey?
- Tests taking place at CTIO with nights of repeated observations and with simulation

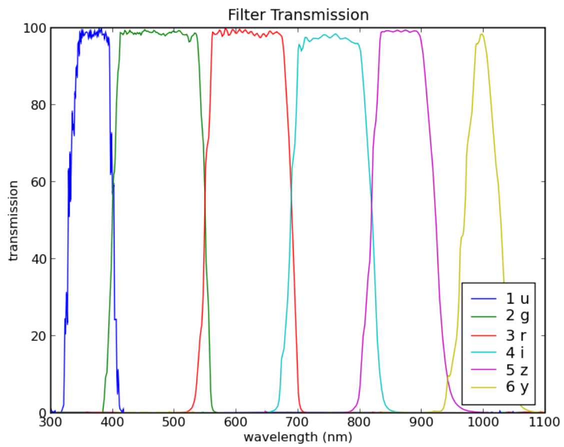
Simulating the photometry

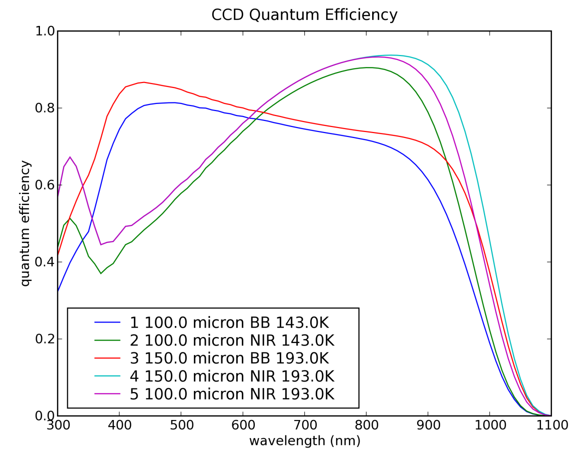




"calibration" sources (aka "stars") have spectral features

the atmosphere has absorption that varies with wavelength (water, ozone, aerosols, dust)





The telescope optics and filters… do they vary?

The sensors vary with wavelength and aren't all the same

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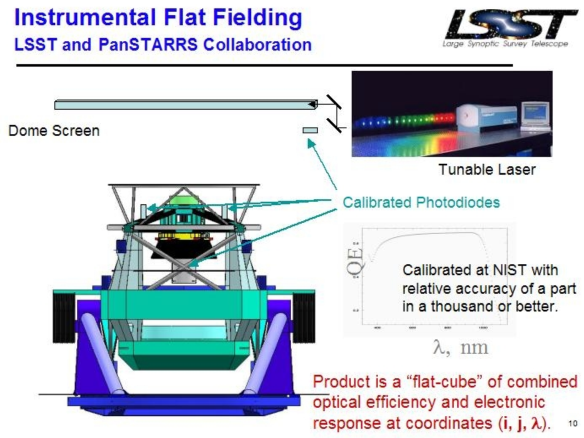
Precision photometry

- So all those effects have been explored, but in LSST we want to do better… SDSS was able to achieve ~2% photometric precision for the whole survey, LSST would like to get to 1% or better:
  - Atmospheric modeling and monitoring (MODTRAN, auxiliary telescope)
  - Variable wavelength "dome screen"
  - Simulation



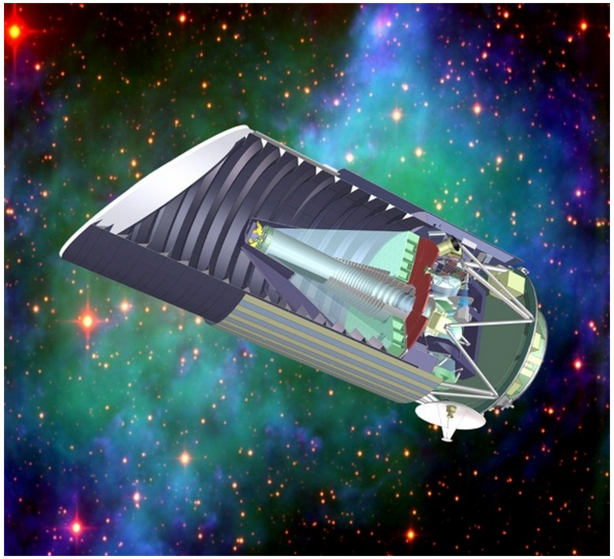
Stubbs and Tonry (arXiv:astro-ph/0604285v1)

Photometric redshifts

- Among the many reasons precision photometry is important, determination of redshifts is one of the keys to being able to do cosmology with LSST
- Spectroscopic redshifts are not practical for the kind of sample that LSST will accumulate: 20 billion sources, 3 billion galaxies to measure
- Spectral breaks allow one to combine measurements in the six filter bands to measure the redshift of the object
- It's a whole story in its own right, with technique still being developed and systematics explored

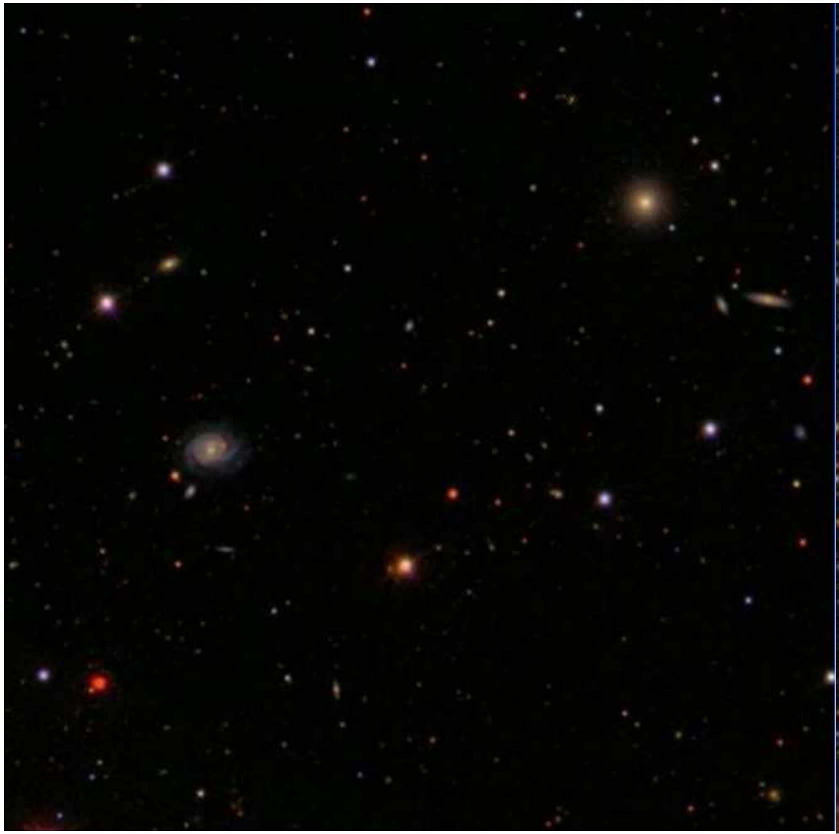
Wouldn't all this be better in space?

- The short answer is certainly "sure" and there are proposals
  - In the US JDEM is
    - SNAP (LBL SN and WL probe)
    - ADEPT
    - DESTINY
  - ESA EUCLID
    - DUNE
    - SPACE

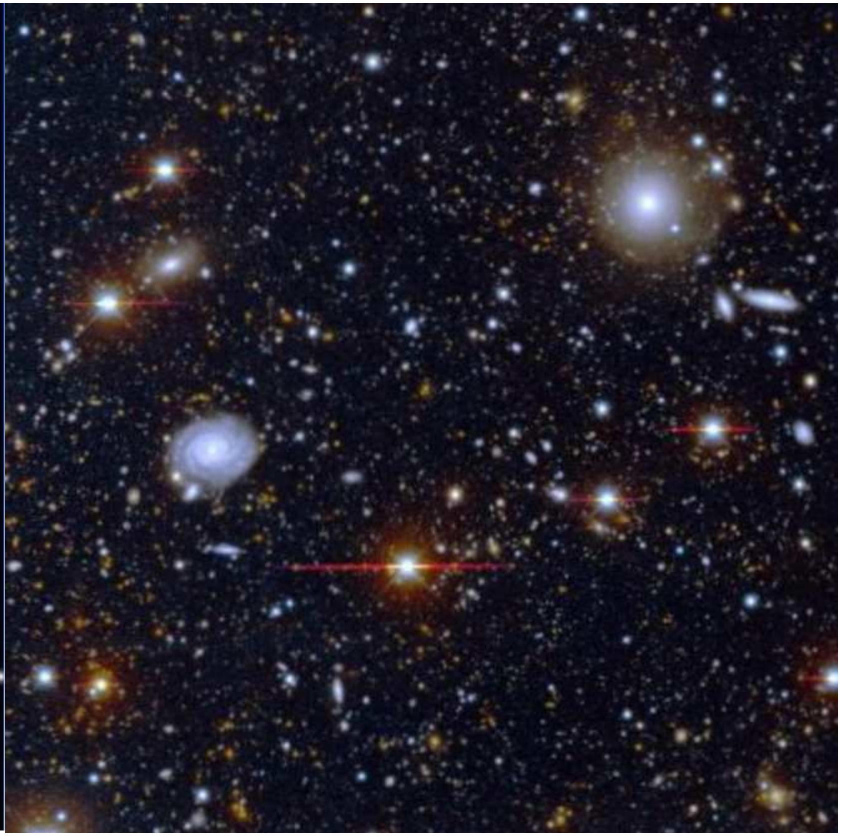


SNAP

What will an LSST image look like?



SDSS



LSST quality image

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Politics, sociology, and all that

- It's all complicated and acronym-rich… but the bottom line is that this is the first time in history that a survey this rich is possible
- We can learn a lot from astronomers, but I think experimental physicists have some important contributions to make
- Dark Energy Task Force/FoM SWG/JDEM decision… PDR early 2009

Conclusion

- The technology exists today to survey the universe with unprecedented depth and precision
- Gravitational lensing is a relatively new tool which requires new instruments and higher precision but which offers a new window into the physics of gravity, dark matter, and dark energy
- To learn more about LSST's plans, see "LSST: from Science Drivers to Reference Design and Anticipated Data Products" (http://arxiv.org/abs/0805.2366)