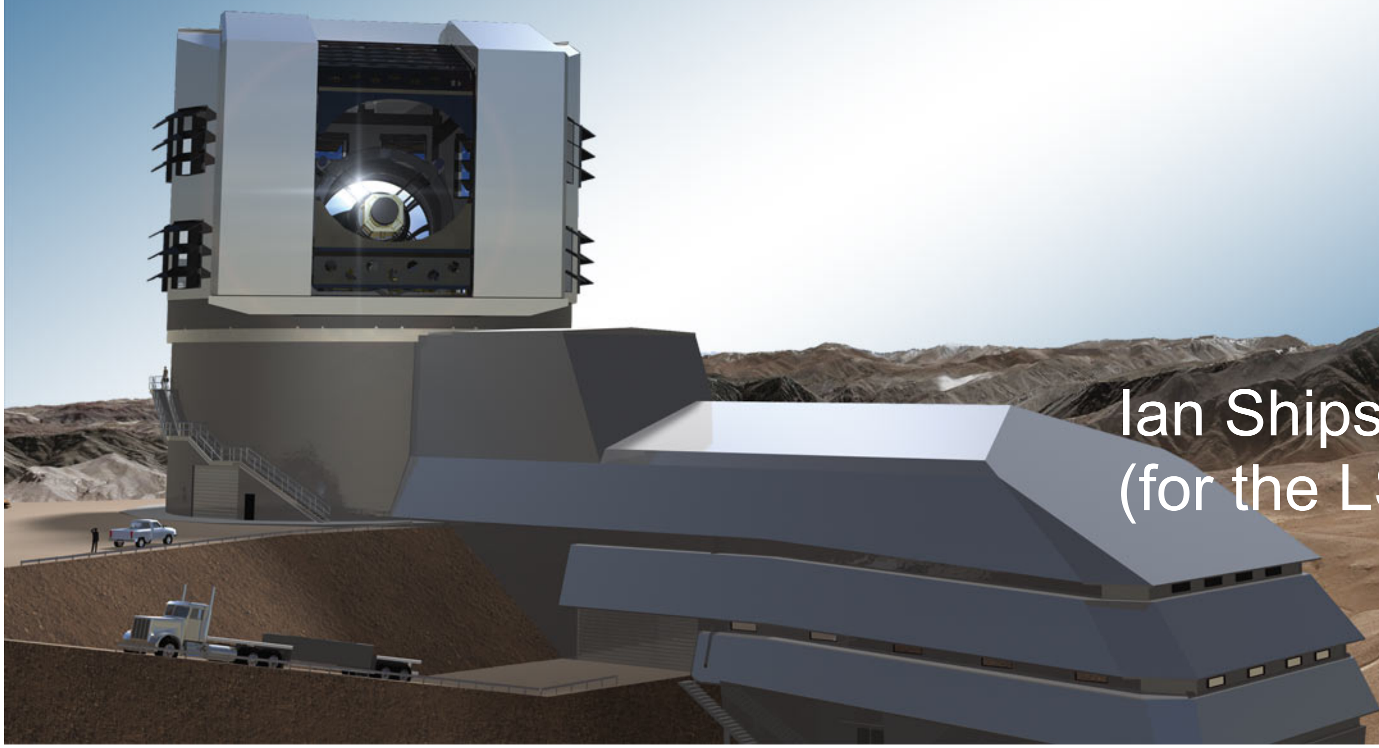
THE LARGE SYNOPTIC SURVEY TELESCOPE



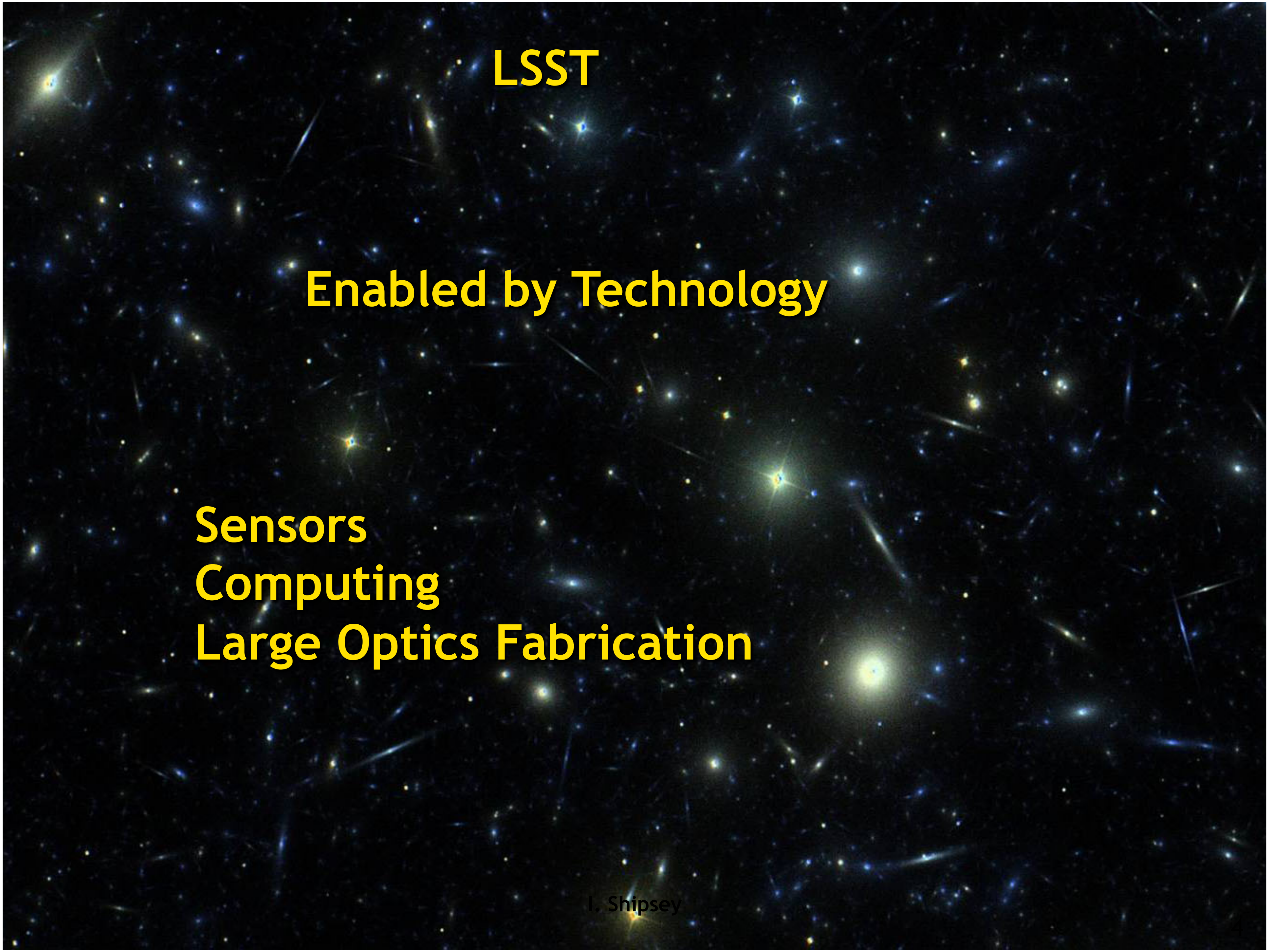
Ian Shipsey
(for the LSST Collaboration)

Oxford
March 19, 2014

Progress in Astronomy

- Bigger Telescopes: *Keck to E-ELT*
- Angular resolution: *Hubble to JWST*
- All Sky Survey: *Sloan Digital Sky Survey to LSST*

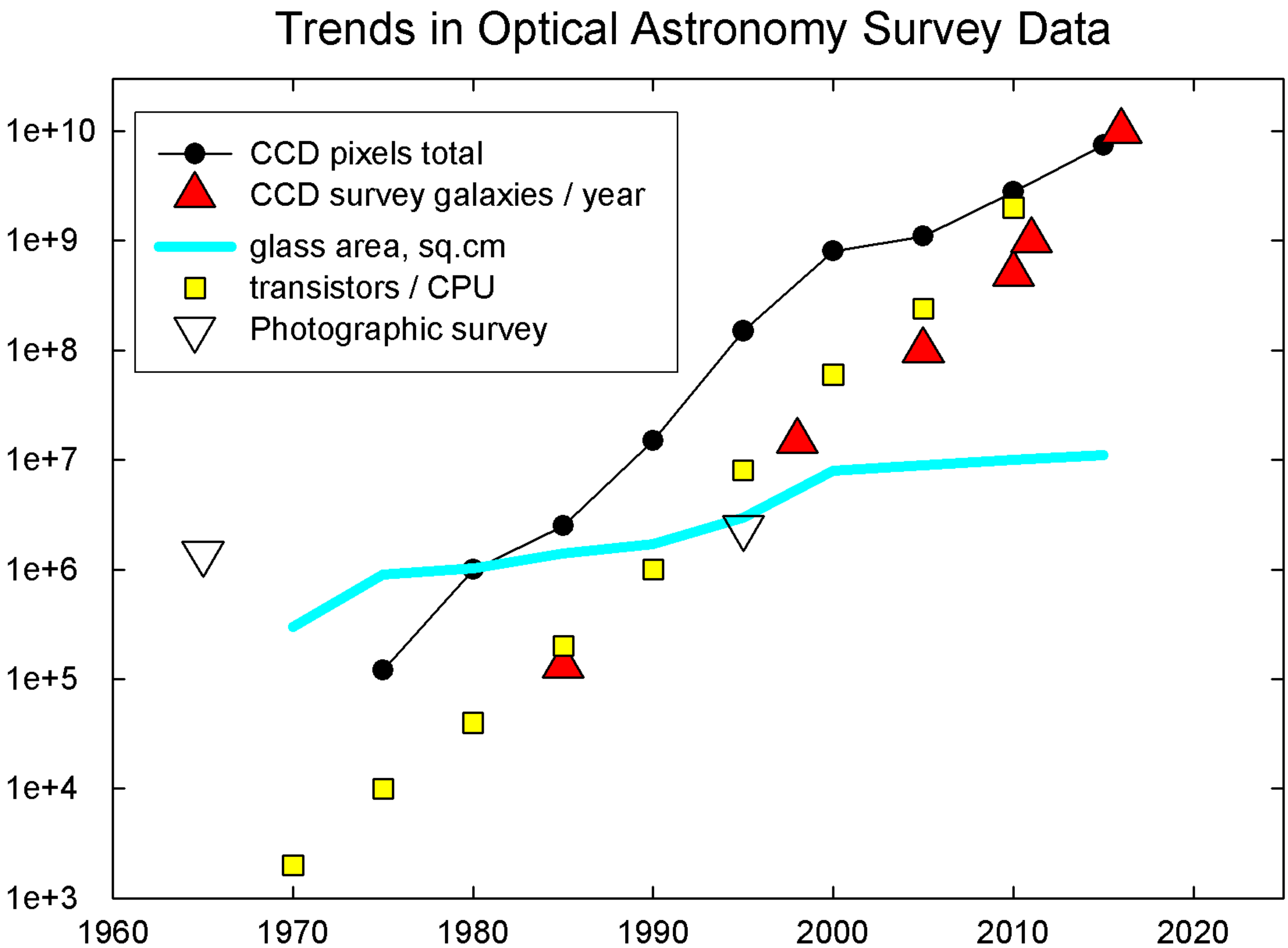

LSST
wide fast deep
I. Shipsey



LSST

Enabled by Technology

Sensors
Computing
Large Optics Fabrication



Trends in Optical Astronomy Survey Data
CCD pixels total
CCD survey galaxies / year
glass area, sq.cm
transistors / CPU
Photographic survey
1e+10
1e+9
1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1960
1970
1980
1990
2000
2010
2020

LSST in a nutshell

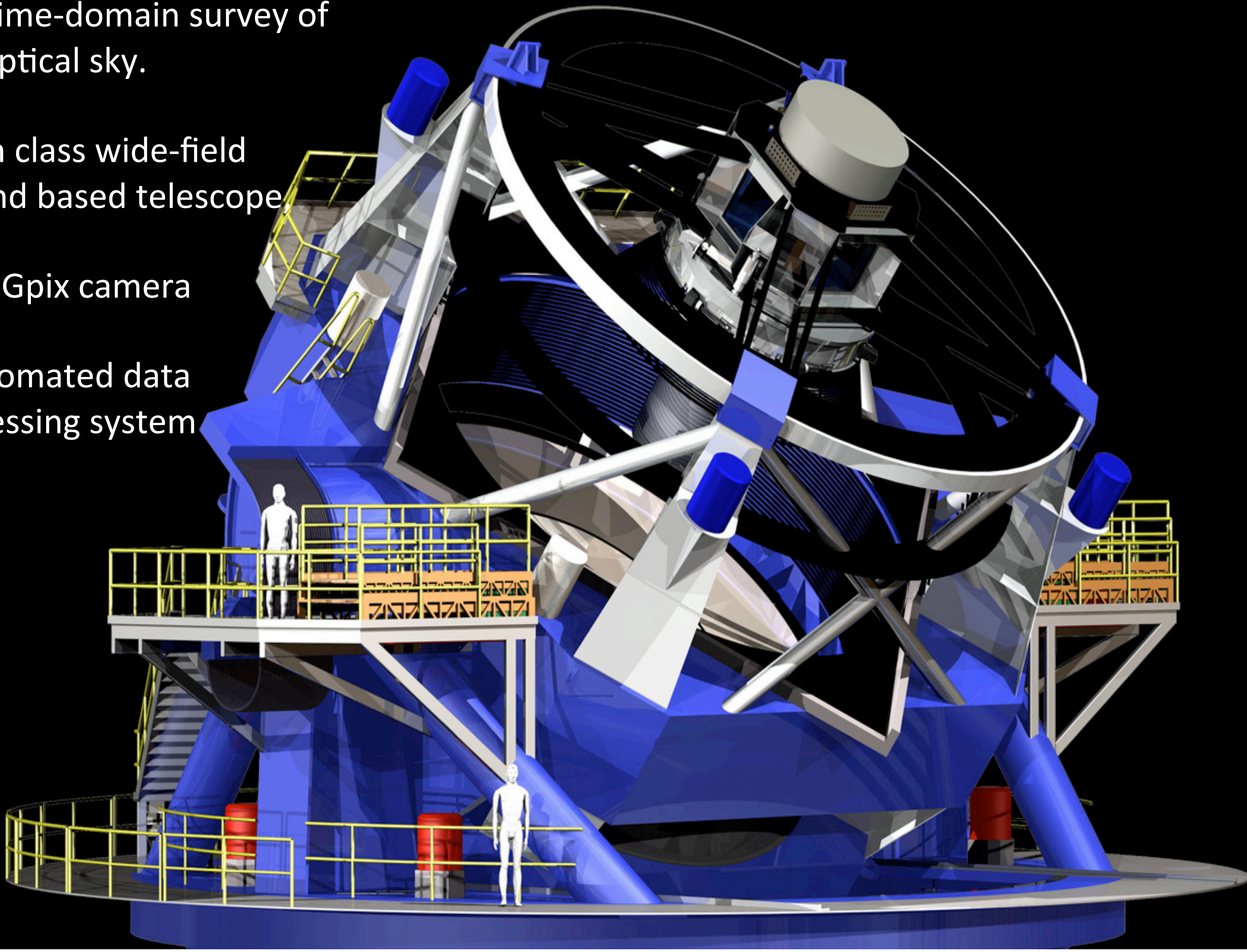
Synoptic = Big Picture

LSST : an integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky.

* 8-m class wide-field ground based telescope

* 3.2 Gpix camera

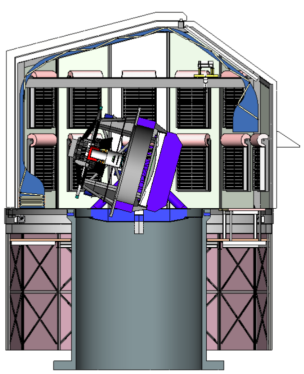
* automated data processing system



Wide

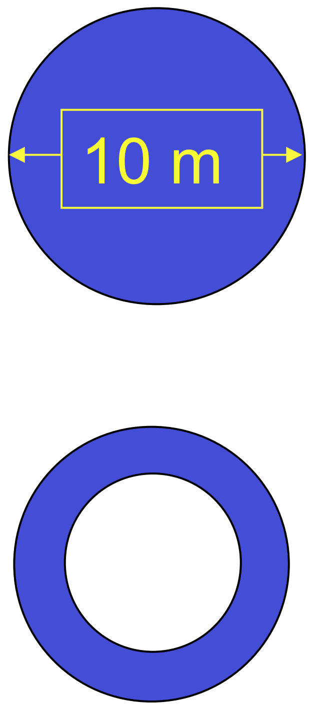
Comparison of LSST To Keck

Keck Telescope



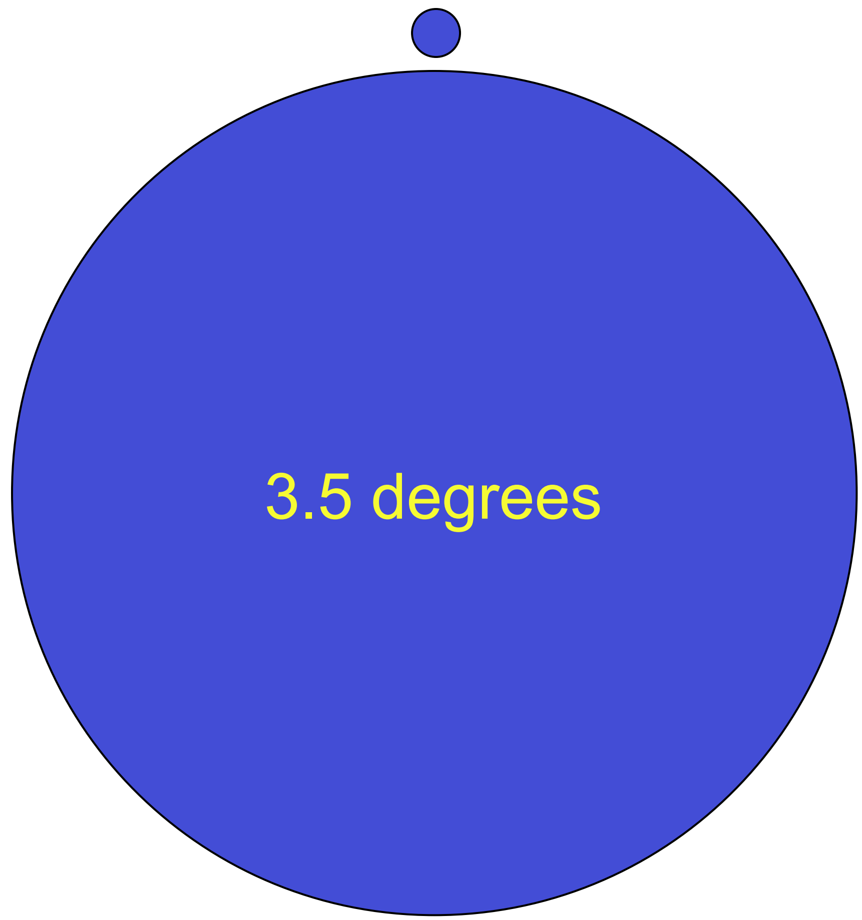
LSST

Primary mirror diameter



Field of view
(full moon is 0.5 degrees)

0.2 degrees



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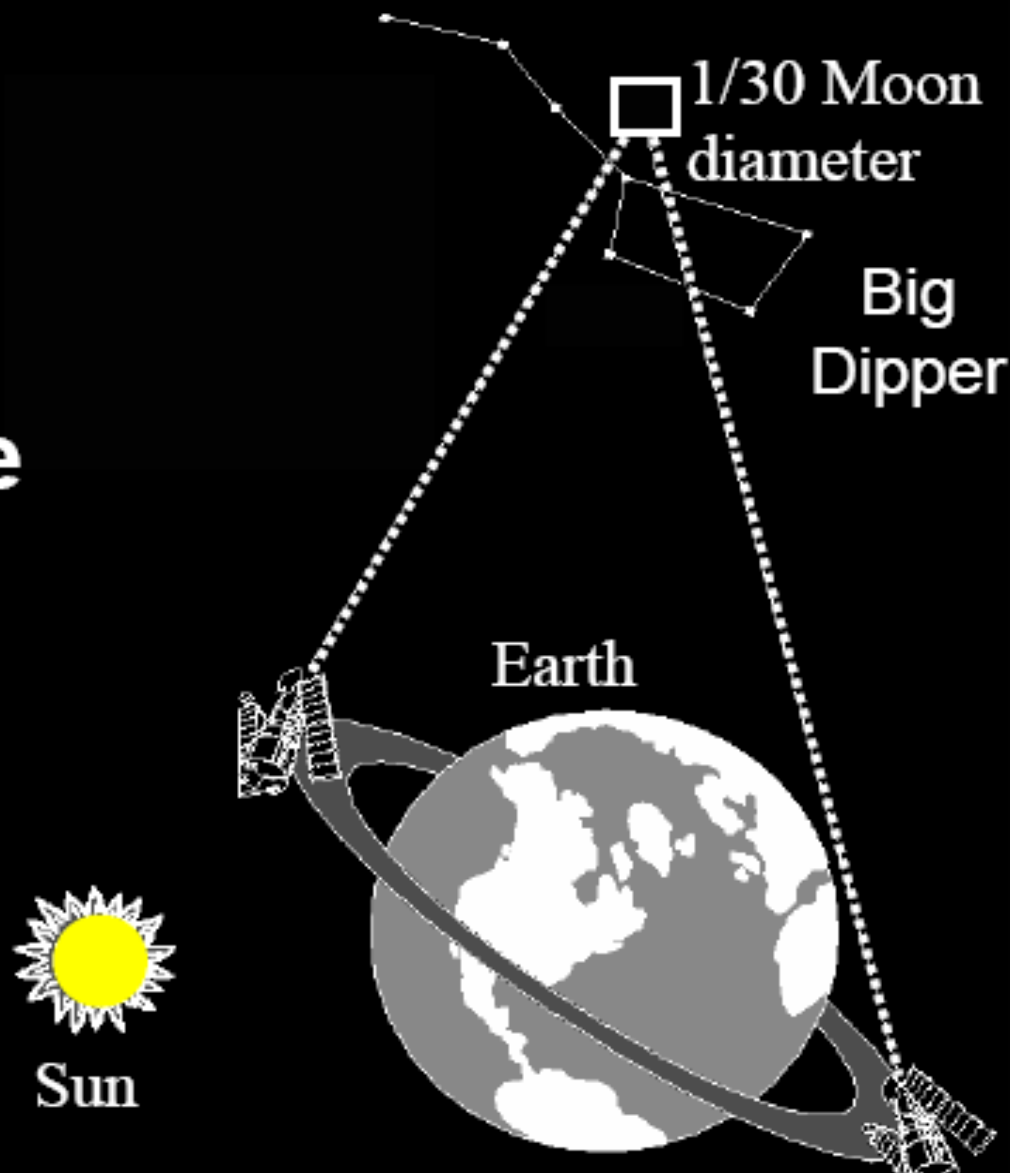
Outer Space - The Cosmos

The Hubble Deep Field



Hubble deep field

UNIVERSE
OF
GALAXIES

3000
here →

100 billion
over entire
sky

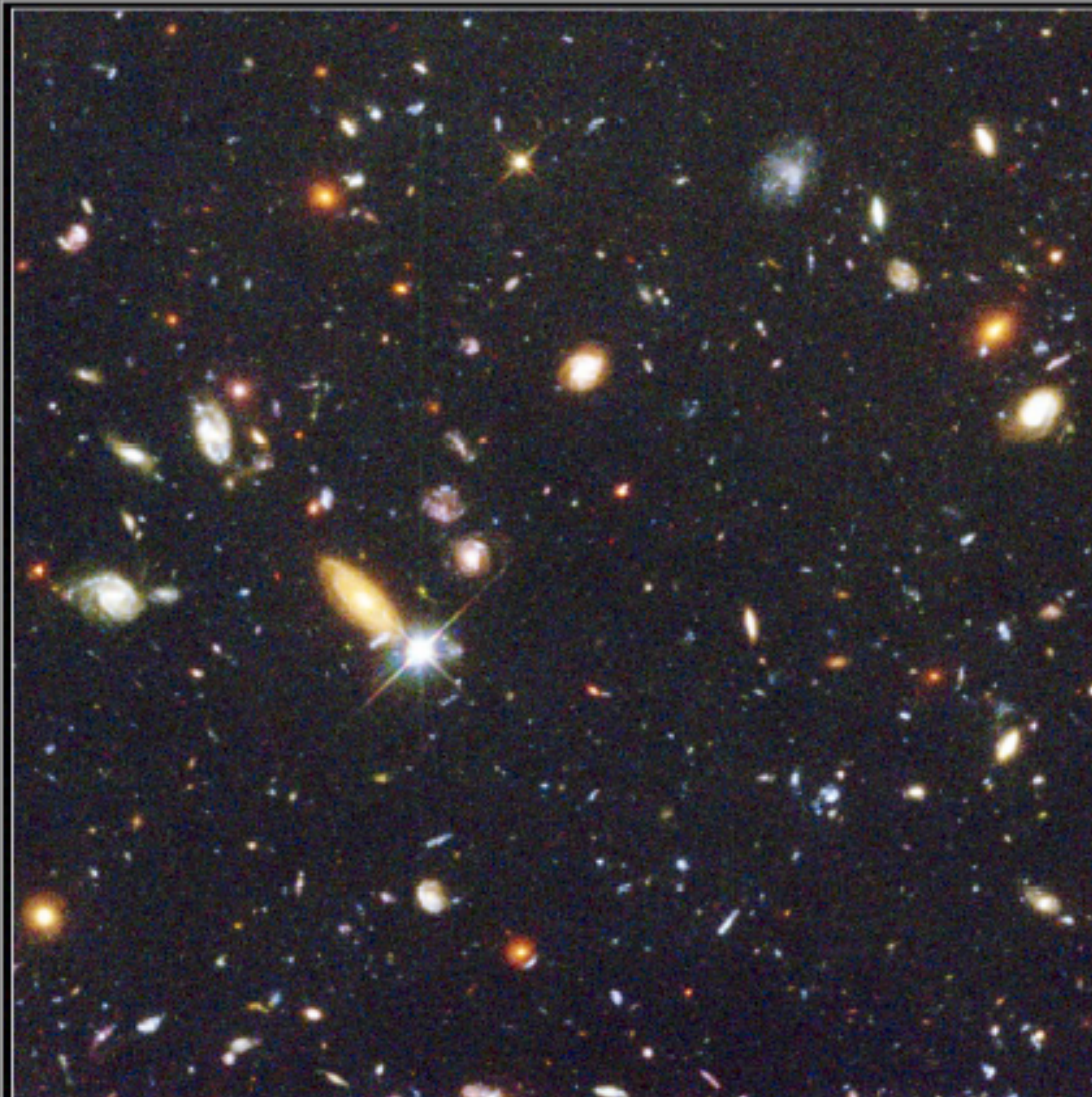


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Image sizes LSST, Moon, HST
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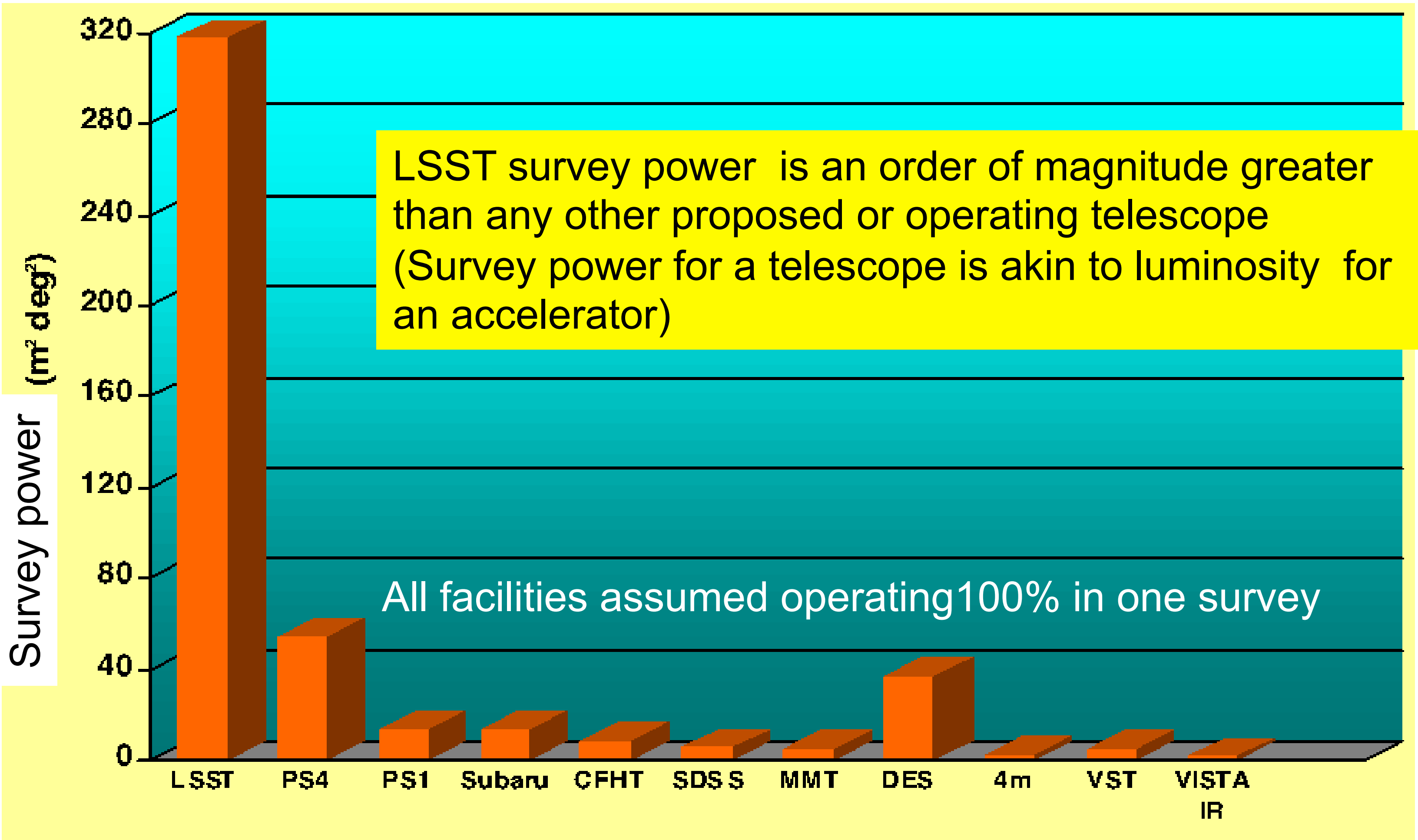
Survey Power = aperture x field of view



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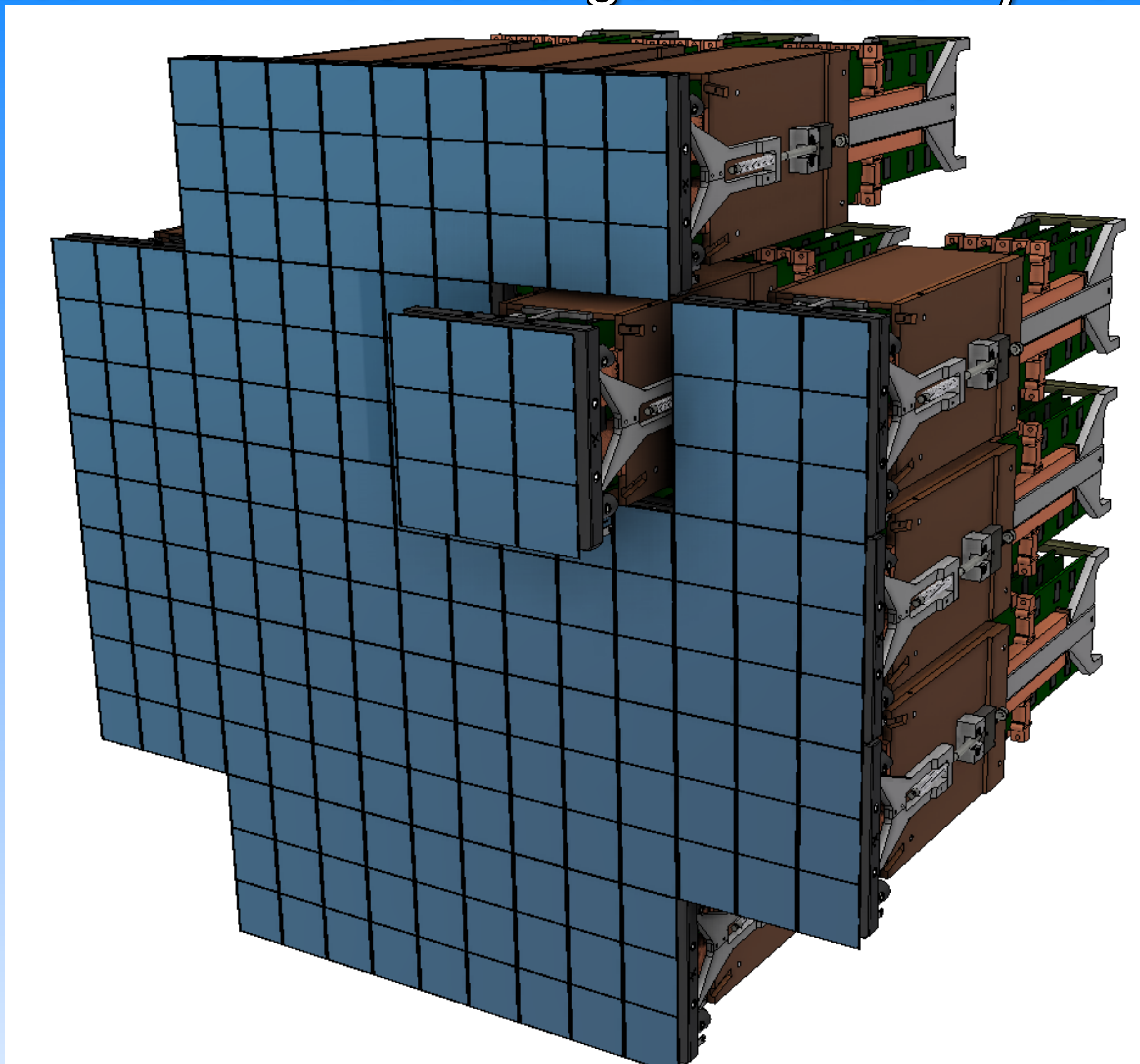
Fast

189 4K x 4K CCDs Largest astronomy CCD camera



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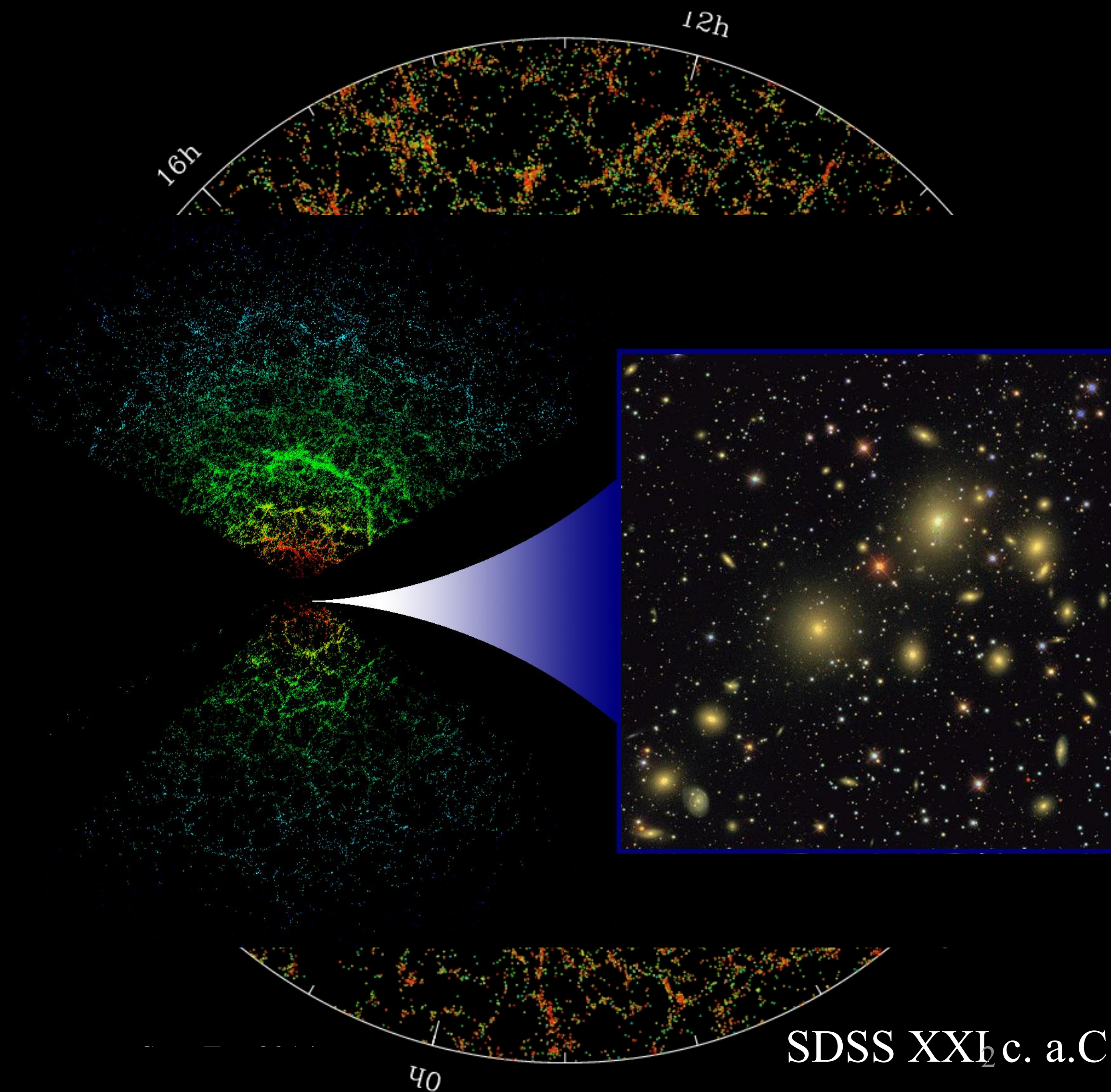
3 Gpix multiport CCDs

Record image in 15 seconds

Readout image In 2 seconds

DEEP

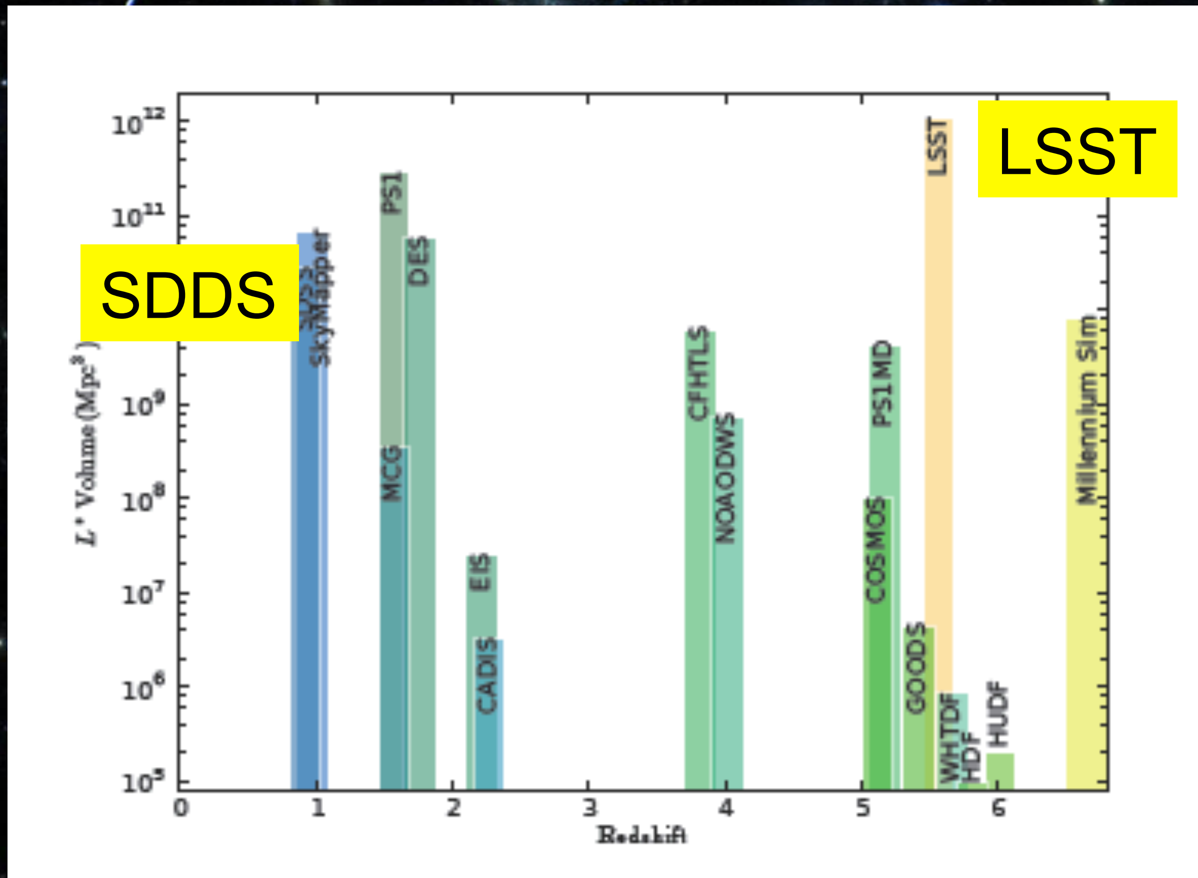
Kosmas IV c. a.C



SDSS XXI c. a.C.

DEEP

LSST Probes a Volume an Order of Magnitude Larger than Current or Near-Future Surveys



- LSST ~100 times fainter than the Sloan Digital Sky Survey
- a legacy dataset ~1000 times as large
- ~800 images of every field will open up the time domain for large-scale study for the first time

LSST survey of 18,000 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

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LSST Wide-Fast-Deep survey

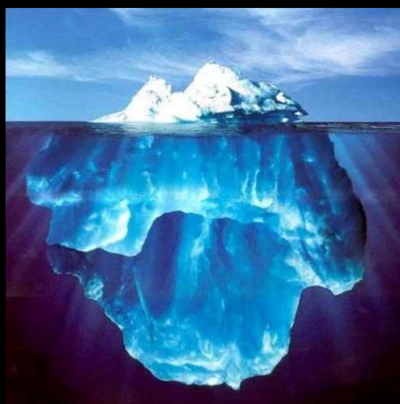
A survey of 37 billion objects

in space and time

30 trillion measurements

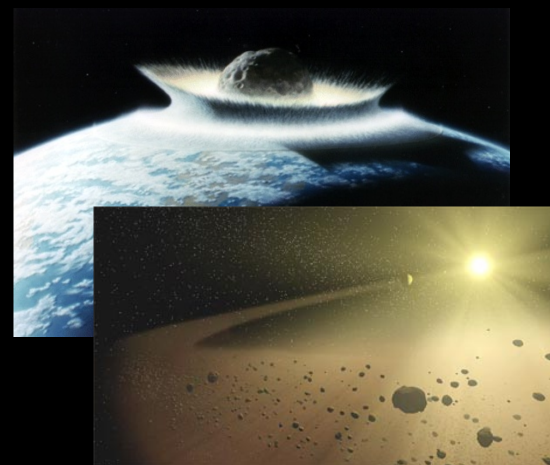
LSST 4 Science Missions

Dark Energy-Dark Matter



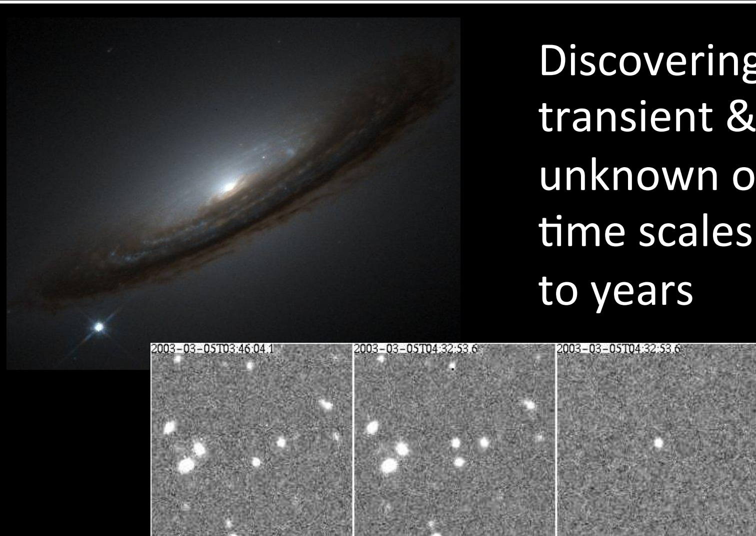
Multiple investigations into the nature of the dominant components of the universe

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

T. Shipsey

Summary of High Level Requirements

Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

The Science Opportunities are summarized in

Quick read:

LSST: FROM SCIENCE DRIVERS TO REFERENCE DESIGN AND ANTICIPATED DATA PRODUCTS

http://arxiv.org/pdf/0805.2366v2.pdf
(last update June 2011)

Reference:

http://www.lsst.org/lsst/scibook

Written by 11 science collaborations

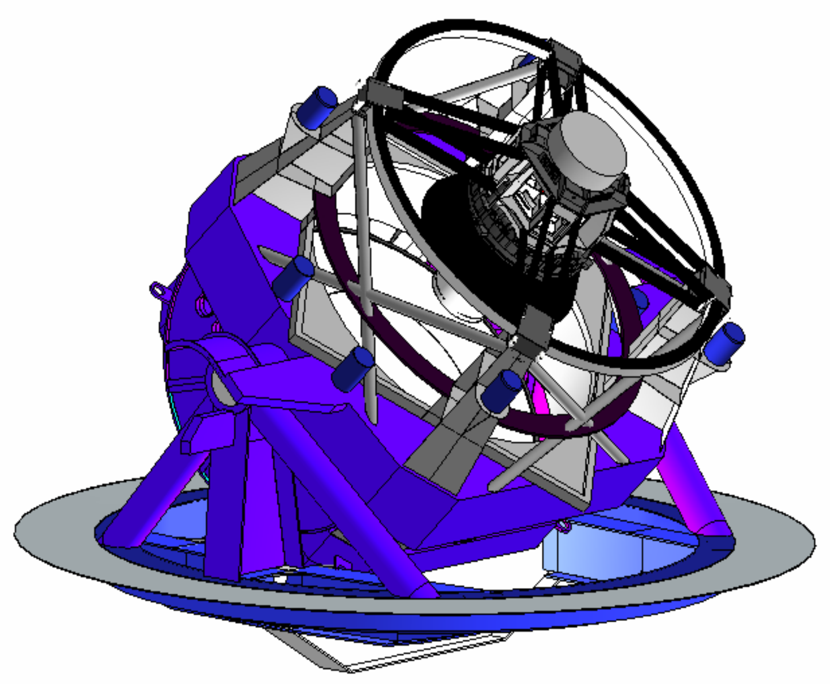
The idea: 1996

The need for a facility to survey the sky *Wide, Fast and Deep*, has been recognized for many years.

1996-2000 "*Dark Matter Telescope*"
Emphasized mapping dark matter

2000- "*LSST*"
Emphasized a broad range of science from the same multi-wavelength survey data

LSST has been highly ranked by numerous US Astronomy and Particle Physics Review committees
Including NRC Astronomy Decadal Survey: Astro2010



We have been going through the approval process @ DOE and NSF

NSF $466M Telescope & Data Management
DOE $163M Camera
Private $40M (already received)
NSF $270M operations (10 years)
Non-US $100M operations (10 years)

Senate-House Omnibus Spending Bill
January 13, 2014

NSF:

"This Act includes $200,000,000 for Major Research Equipment and Facilities Construction. Funds are provided at the requested level for all projects for which construction has already begun, and remaining funds are for the initiation of the Large Synoptic Survey Telescope (LSST) project. If NSF determines that LSST requires additional funding in fiscal year 2014, NSF may submit a transfer proposal to provide such funds."

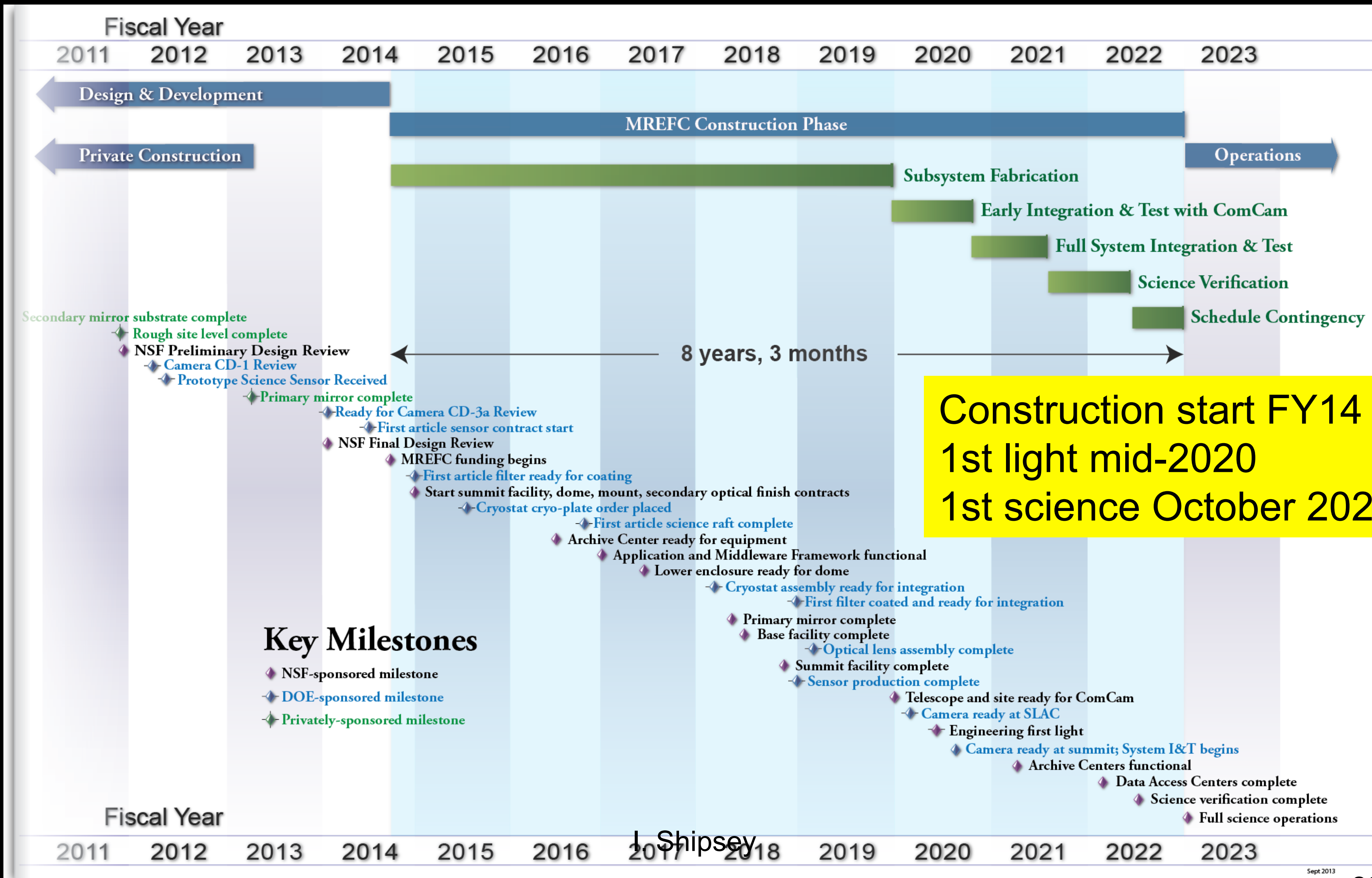
The PBR was at $210,120,000 for MREFC, including $27,500,000 for LSST. So at least $17.38M is available for LSST in FY14.

Next step is National Science Board approval at their meeting on May 6, leading to a *construction start* on July 1.

DOE:

Office of High Energy Physics budget was $5,000,000 *above* the PBR. We will definitely receive the $22,000,000 expected for the camera in FY14.

Integrated Project Schedule with Key Milestones



Construction start FY14
1st light mid-2020
1st science October 2022

LSST

A next generation wide field optical survey is well-justified by the cartography, cinematography and photometry it will perform and the huge range of astrophysics and physics at the boundary between particle physics and astrophysics it will address.

LSST is the missing piece in the UK's future ground-based astronomy programme

Astrophysicists at 30 UK institutions have recently formed LSST:UK and are seeking to join as a national consortium

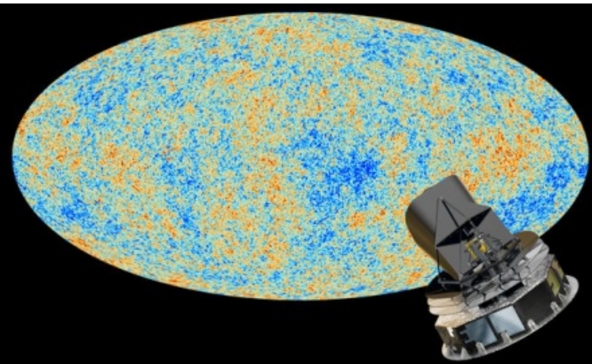
Oxford is 1st UK institution to join

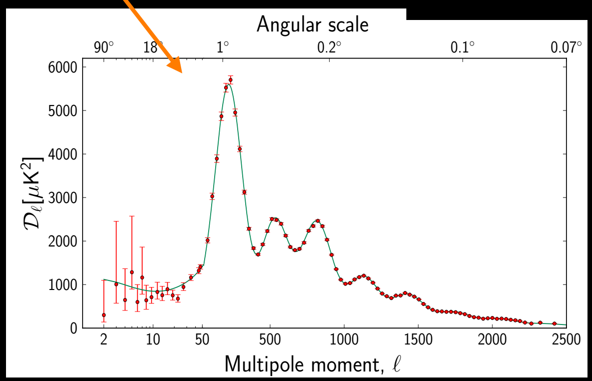
LSST Science Drivers 1 The Fate of the Universe

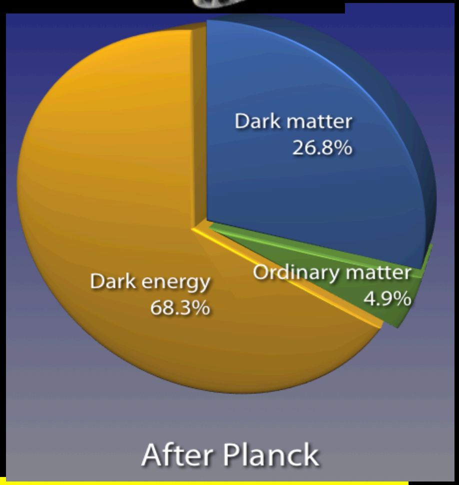
Flat universe

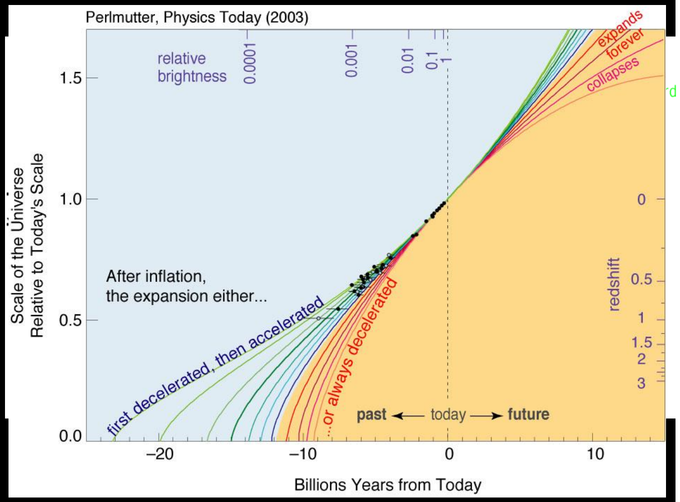
Ω_{total}= 1.02+/-0.02

WMAP+Planck







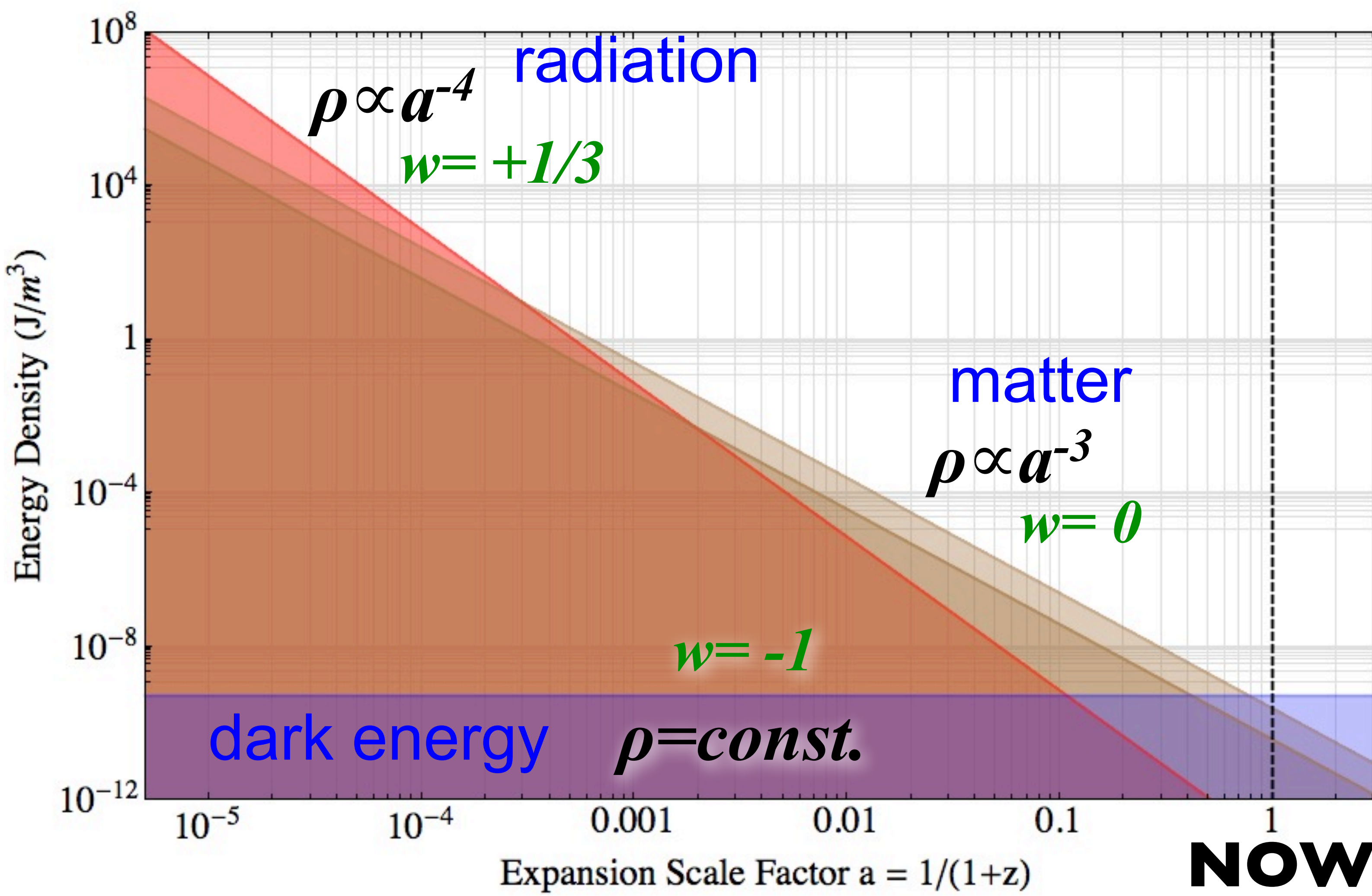


Dark Energy “the essence of space”
Dark Matter “most of the matter”
Together they govern the evolution & fate of the universe.

Nobel 2011

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

Evolution of the energy density of the universe : $\rho \propto a^{-3(1+w)}$

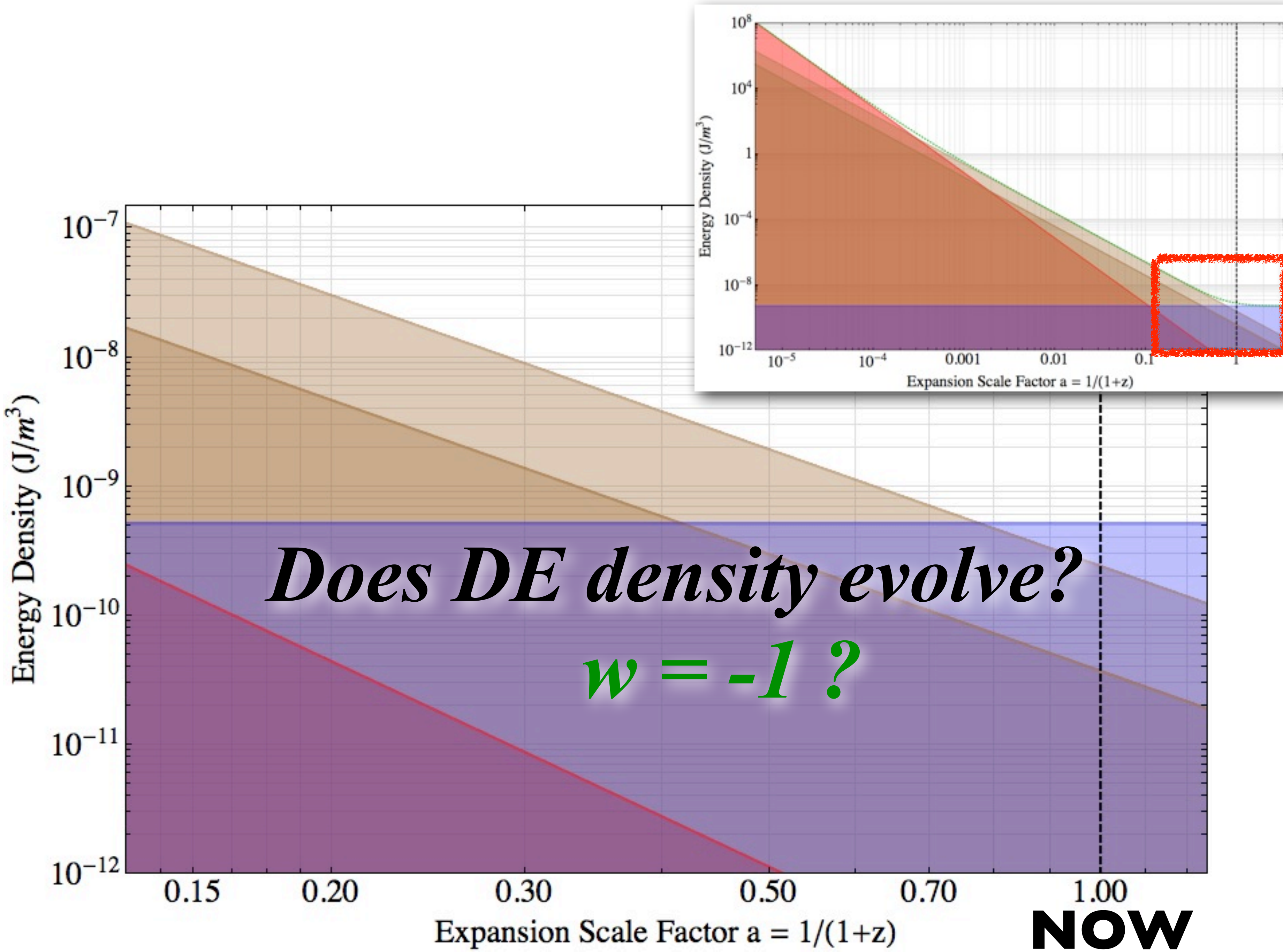


Dark Energy: An unprecedented opportunity

Either:
two thirds of the energy in the Universe is of unknown origin,
Or:
General Relativity is wrong at large scales

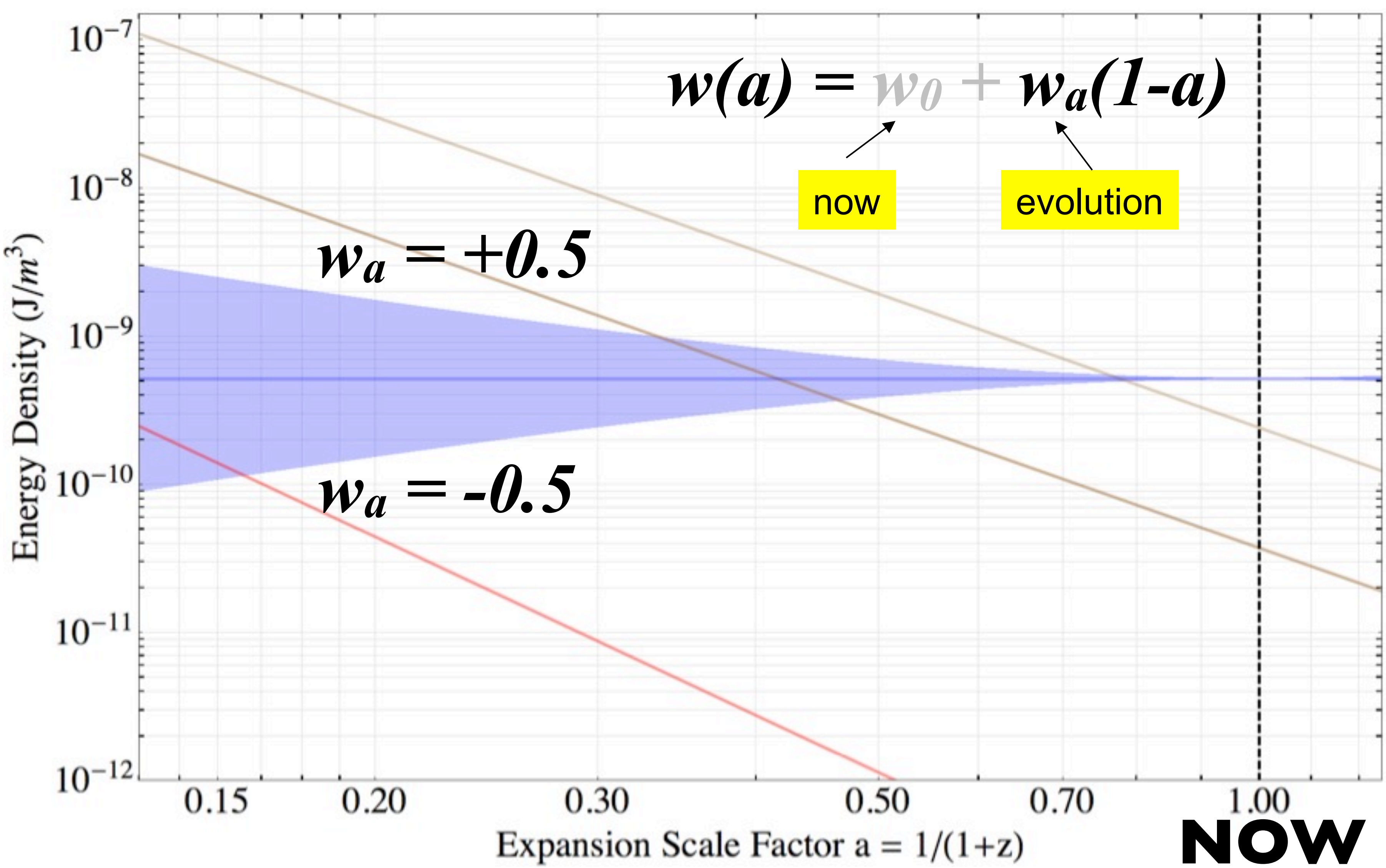
Challenge: determine origin of Dark Energy or disprove GR

Approach: measure DE equation of state, w and its evolution, to the systematic limit with *multiple probes*



Does DE density evolve?
w = -1 ?
NOW
Energy Density (J/m^3)
Expansion Scale Factor a = 1/(1+z)
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
0.15
0.20
0.30
0.50
0.70
1.00
10^8
10^4
1
10^-4
10^-8
10^-12
10^-5
10^-4
0.001
0.01
0.1
1

Dark energy equation of state parameters:



Does DE density evolve?

YES

NO

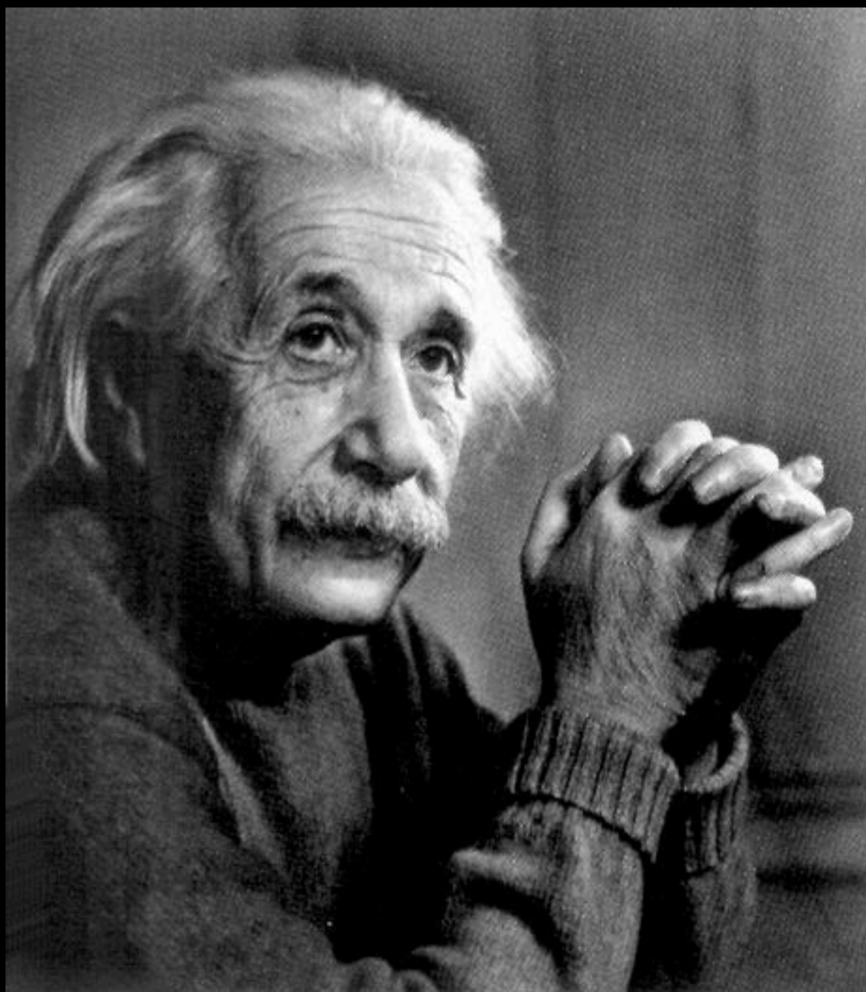
Are DE observations self-consistent within general relativity?

New form of energy

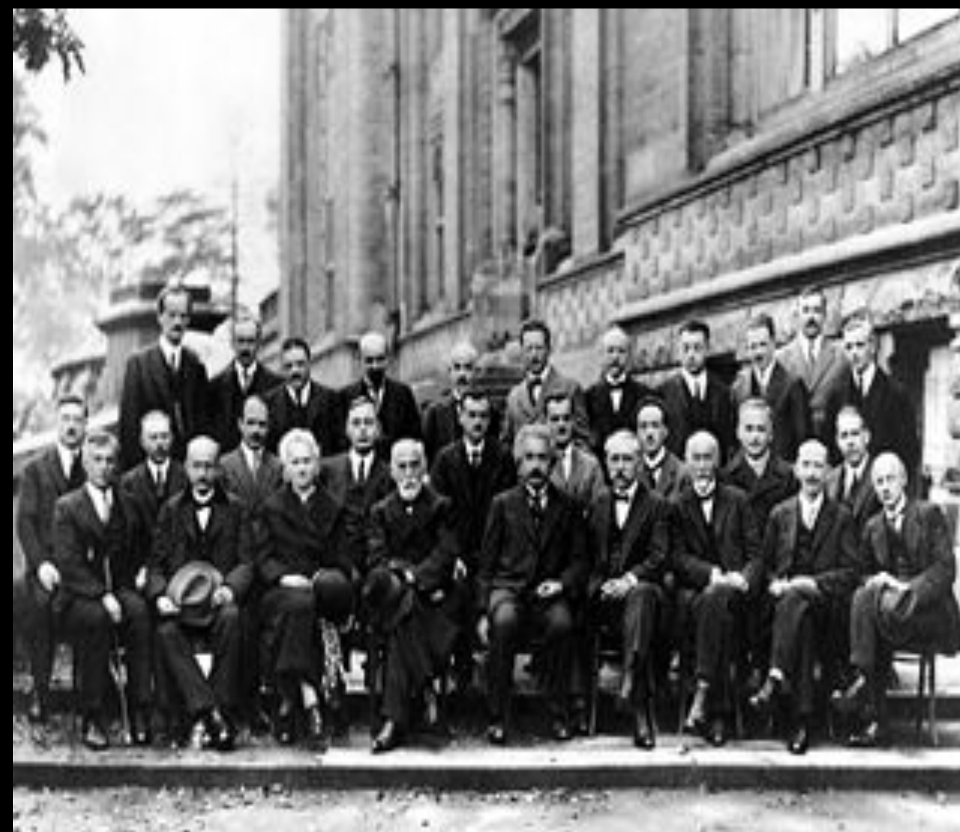
New theory of gravity

Cosmological constant

Studying Dark Energy is one of the ways we may bring the greatest prize in Physics within reach:
reconciliation of the two great edifices



General Relativity



Quantum Mechanics

Probing Dark Energy

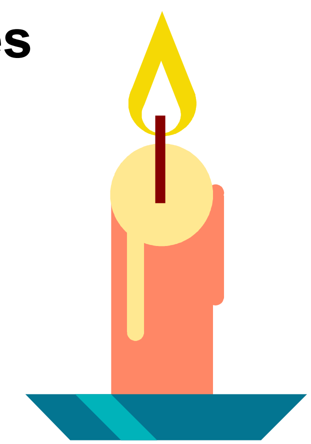
- **The observable probing the properties of dark energy is the expansion history of the universe, and parameterized by the Hubble parameter H(z)**

$$H(z) = \frac{\dot{a}}{a}$$

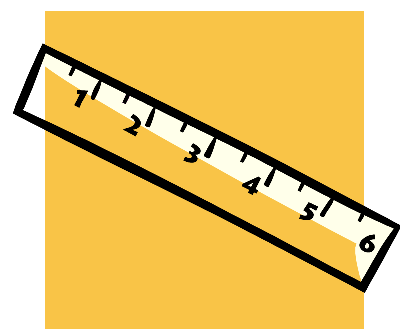
- **Cosmic distances are proportional to integrals of *H(z)*$^{-1}$ over redshift.**

- ***H(z)* can be constrained by measuring**

luminosity distances of standard candles (Type 1a SNe)

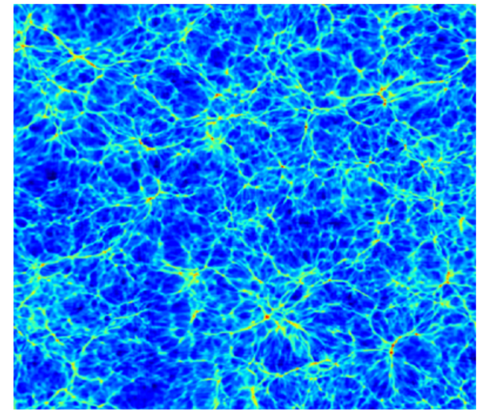


angular diameter distances of standard rulers baryon acoustic oscillations (BAO)



Probing Dark Energy

•Second approach: measure growth of structure as function of redshift



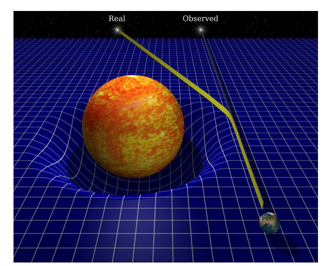
•Stars, galaxies, clusters of galaxies grow by gravitational instability as the universe cools.

•Acceleration: The stretching of space – shuts off growth by keeping galaxies apart

• A cosmic “clock”

Measuring growth history, i.e. - the redshift at which structures of a given mass start to form is sensitive to the level of acceleration i.e. amount of dark energy

• Galaxy Cluster surveys & Weak Lensing (WL) Surveys probe growth of structure as well as angular diameter distances



•Growth is described by GR, if GR needs modification w for WL may not agree with w from BAO and SN

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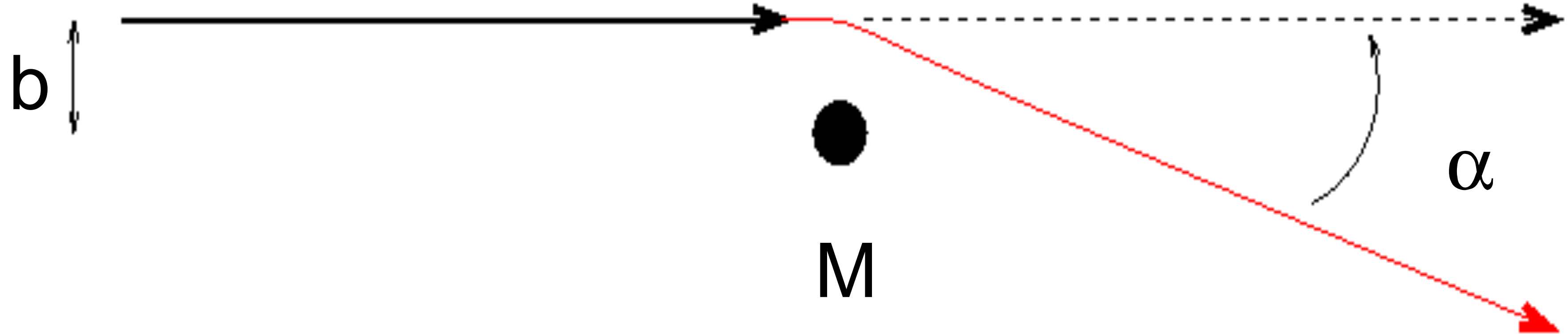
Gravitational Lensing

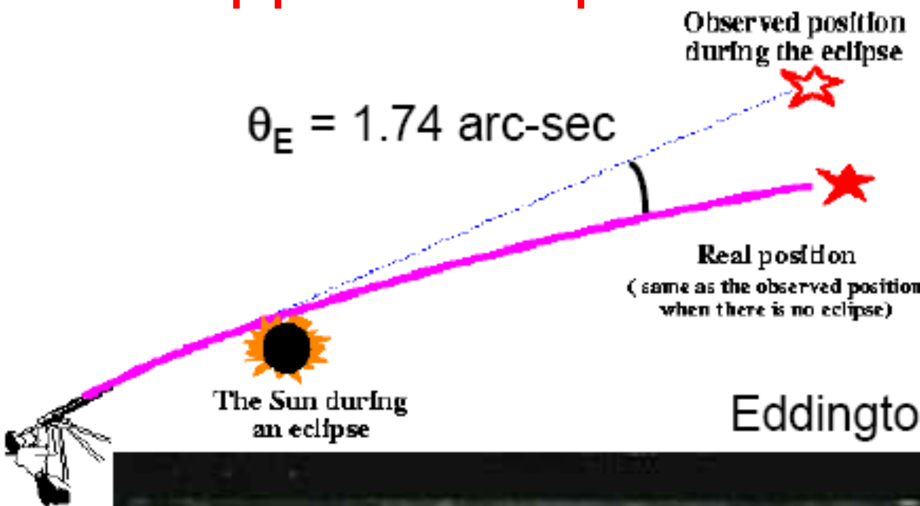


$$\alpha = 4\,G\,M\,/\,(c^2\,b)$$

Bending of star light (point-like) by the Sun - star appears displaced

Large Synoptic Survey Telescope

θ_E = 1.74 arc-sec



Newton 1704

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

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

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

einstein akademie wissenschaften berlin

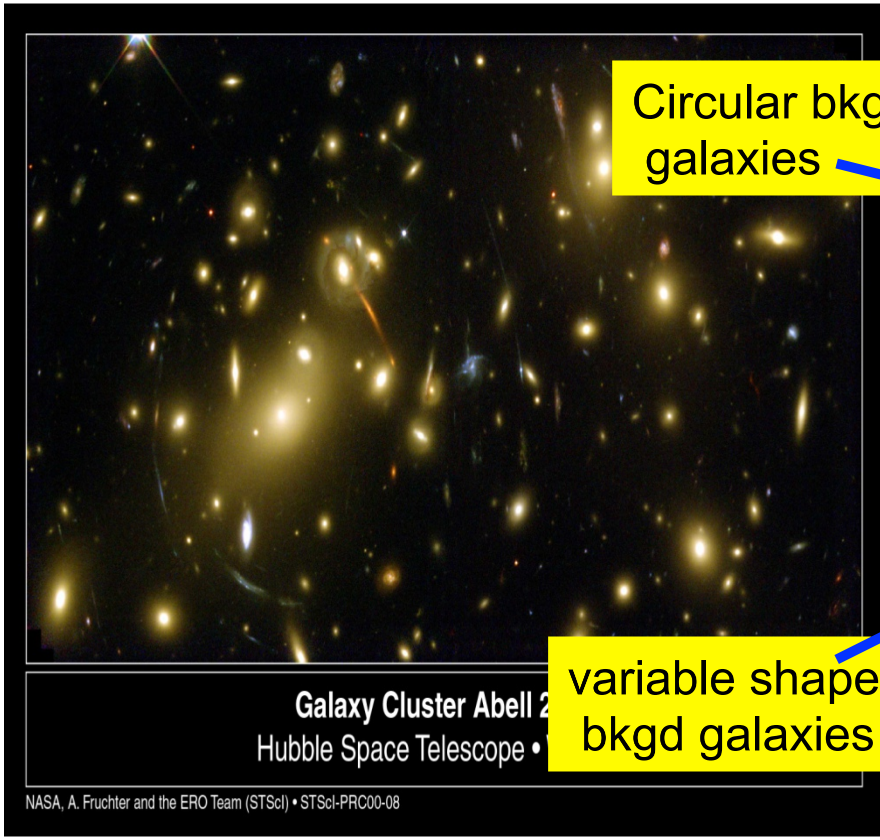
Telegraphie des Deutschen Reichs.

Berlin, Haupt-Telegraphenamt

three pairs australia tahiti eclipse plates measured by campbell 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 +

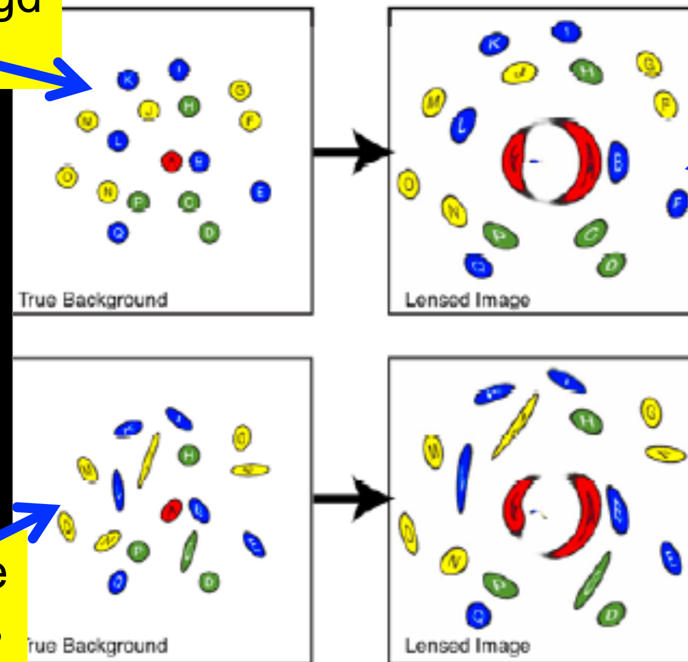
Extended objects are sheared

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



Circular bkgd galaxies

variable shape bkgd galaxies



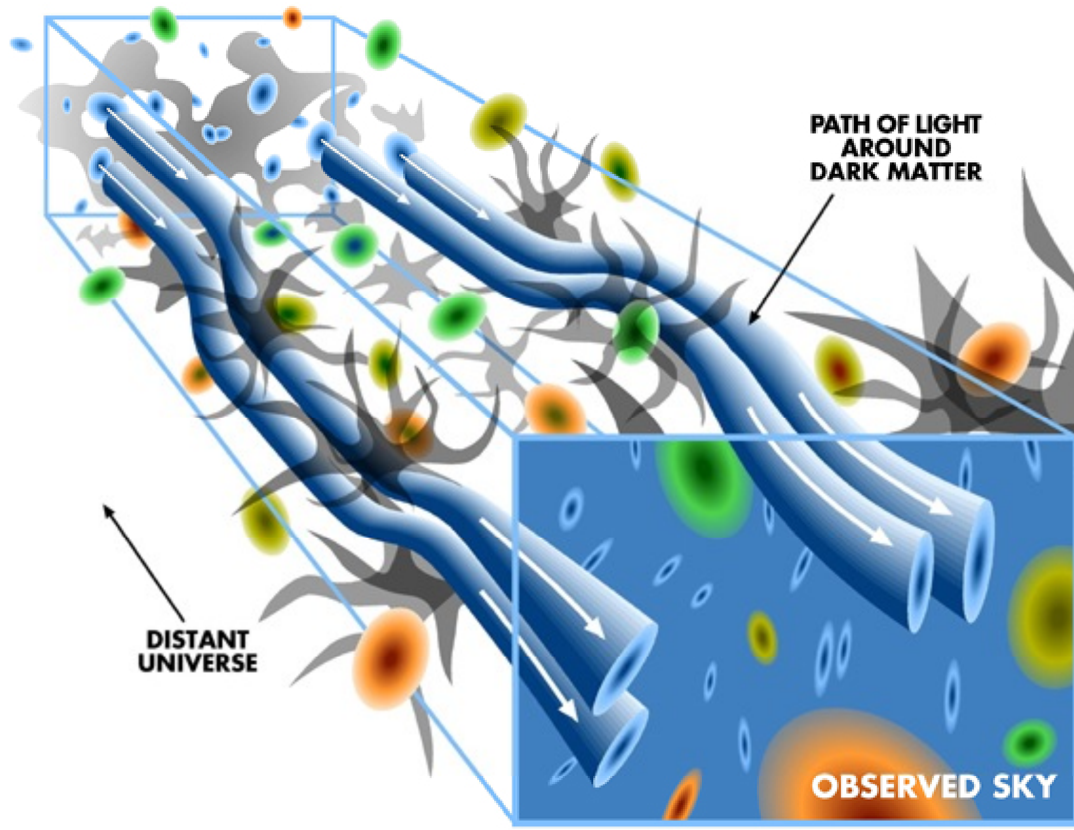
what is observed

Weak Lensing shear pattern less obvious but detectable statistically

Strong lensing requires alignment, rare, readily visible
Weak lensing, does not require alignment, common, detectable only statistically

Cosmic Shear

- **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.**
- **A given galaxy image is both displaced and sheared.**
- **The effect is detectable only statistically. *The shearing of neighboring galaxies is correlated, because their light follows similar paths on the way to earth.***



Tyson et al 2002

- Massively exaggerated

Cosmic shear: ~ 0.01

e.g. circular galaxy → ellipse with a/b ~ 1.01

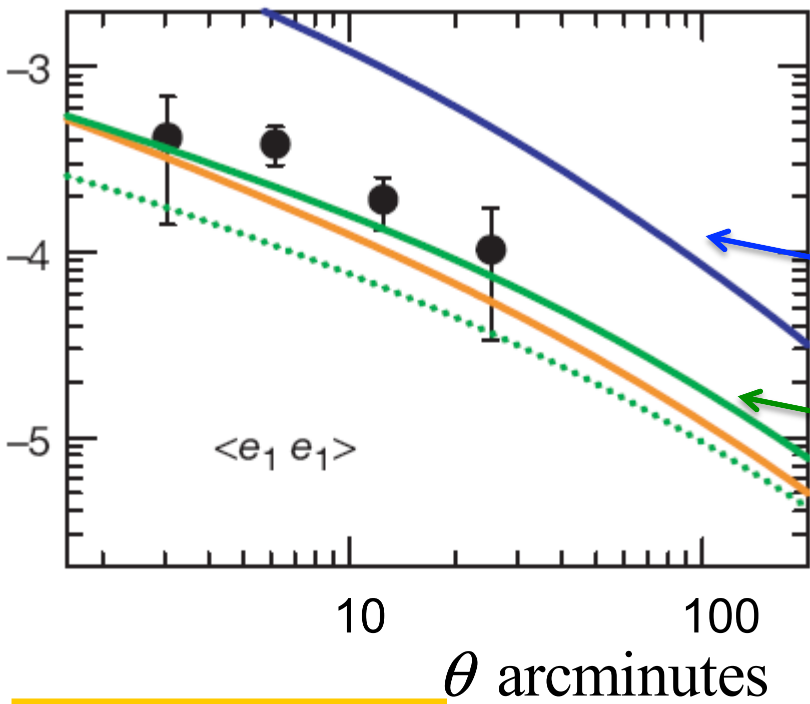
1^{st} Detections of Cosmic Shear (2000-2003)

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

Whitman 2000
145,000 galaxies
~1 degree

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

Log ellipticity correlation



No dark energy
Means more structure
& more shear

Ω(DE) =0.67

Universe at ½
critical density

Green dash
galaxies
are x2 closer

More recent surveys
CFHTLens (2013)
4.2 million galaxies
~154 sq degree

SDSS (2011)
4.7million galaxies
~275 sq degree

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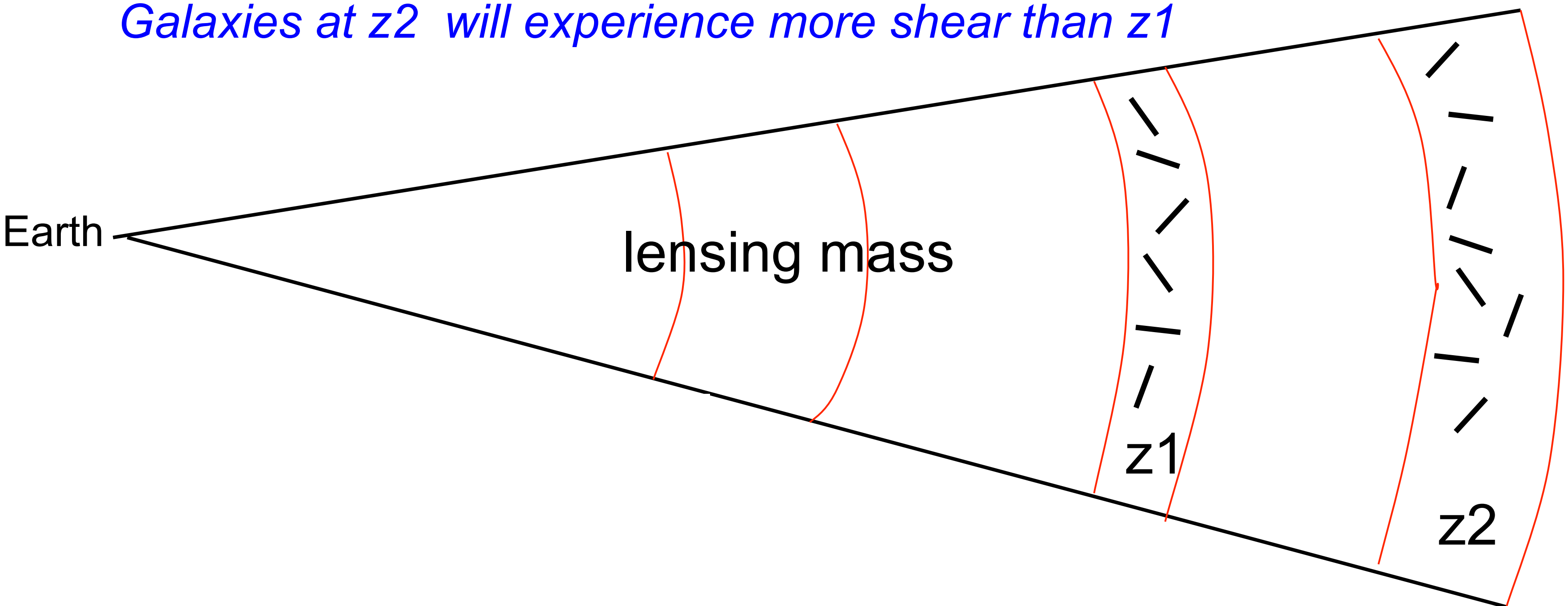
Lensing tomography

As statistics grow measurement of comic shear as a function of redshift becomes possible

Galaxies at z2 will experience more shear than z1

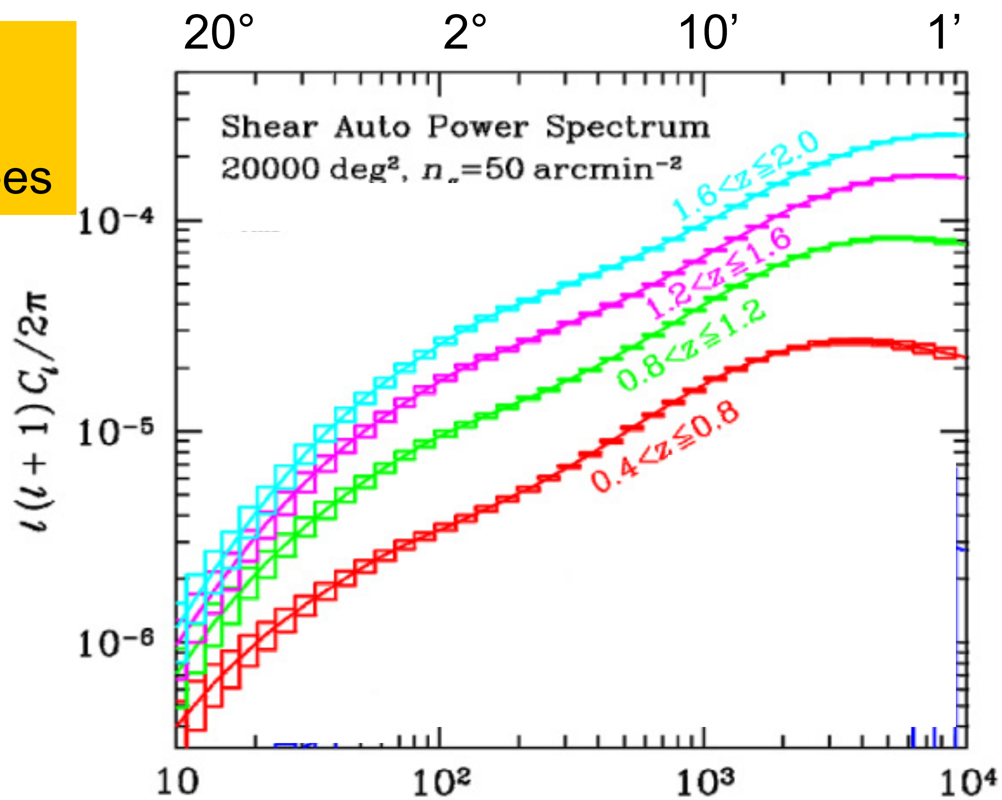


CFHTLensS(2013)
4.2 million galaxies
~154 sq degree

LSST and Cosmic Shear

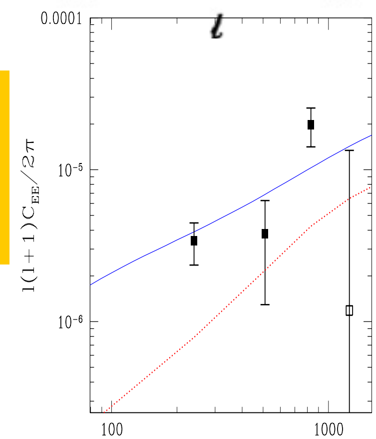
CFHTLens (2013)
4.2 million galaxies
~154 sq degree

LSST
4 billion galaxies
18,000 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**

SDSS (2011)
4.7E6 galaxies
~275 sq degree



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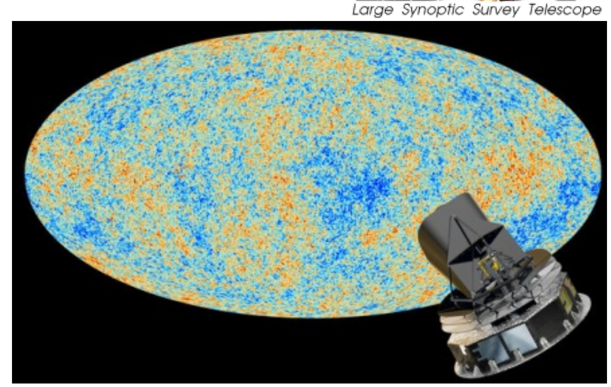
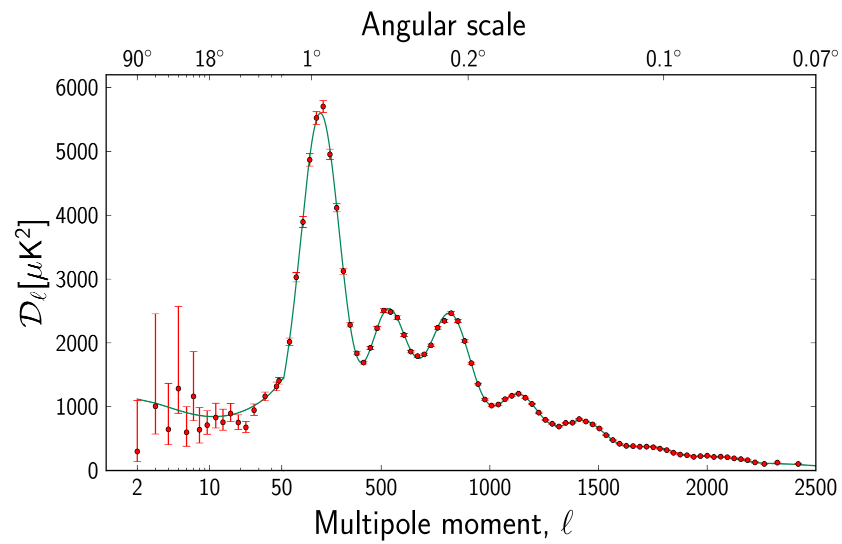
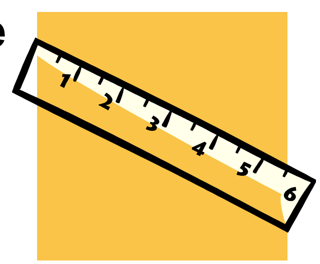
Baryon Acoustic Oscillations



- **Prior to the formation of atoms 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 sound speed, .**



- **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.**

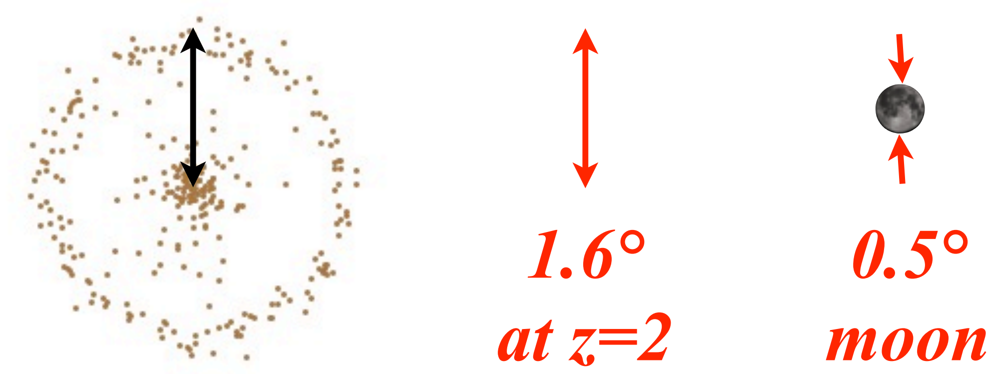


These acoustic waves are visible as the peaks in the CMB power spectrum.

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.**

r_s ~150 Mpc



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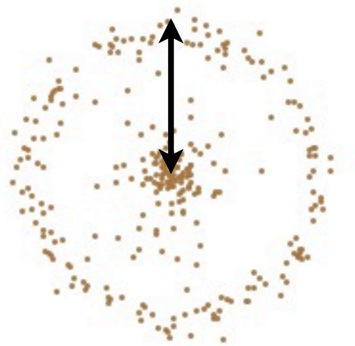
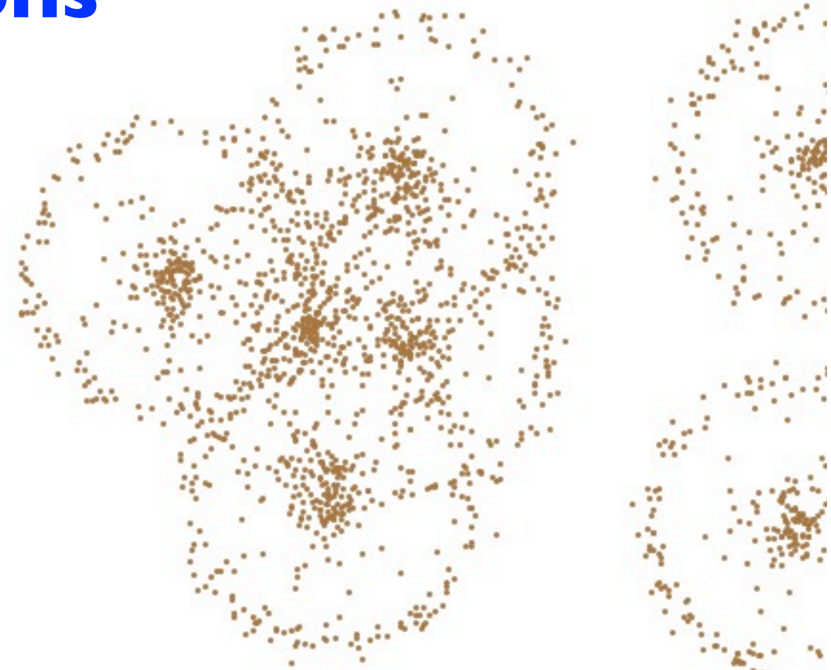
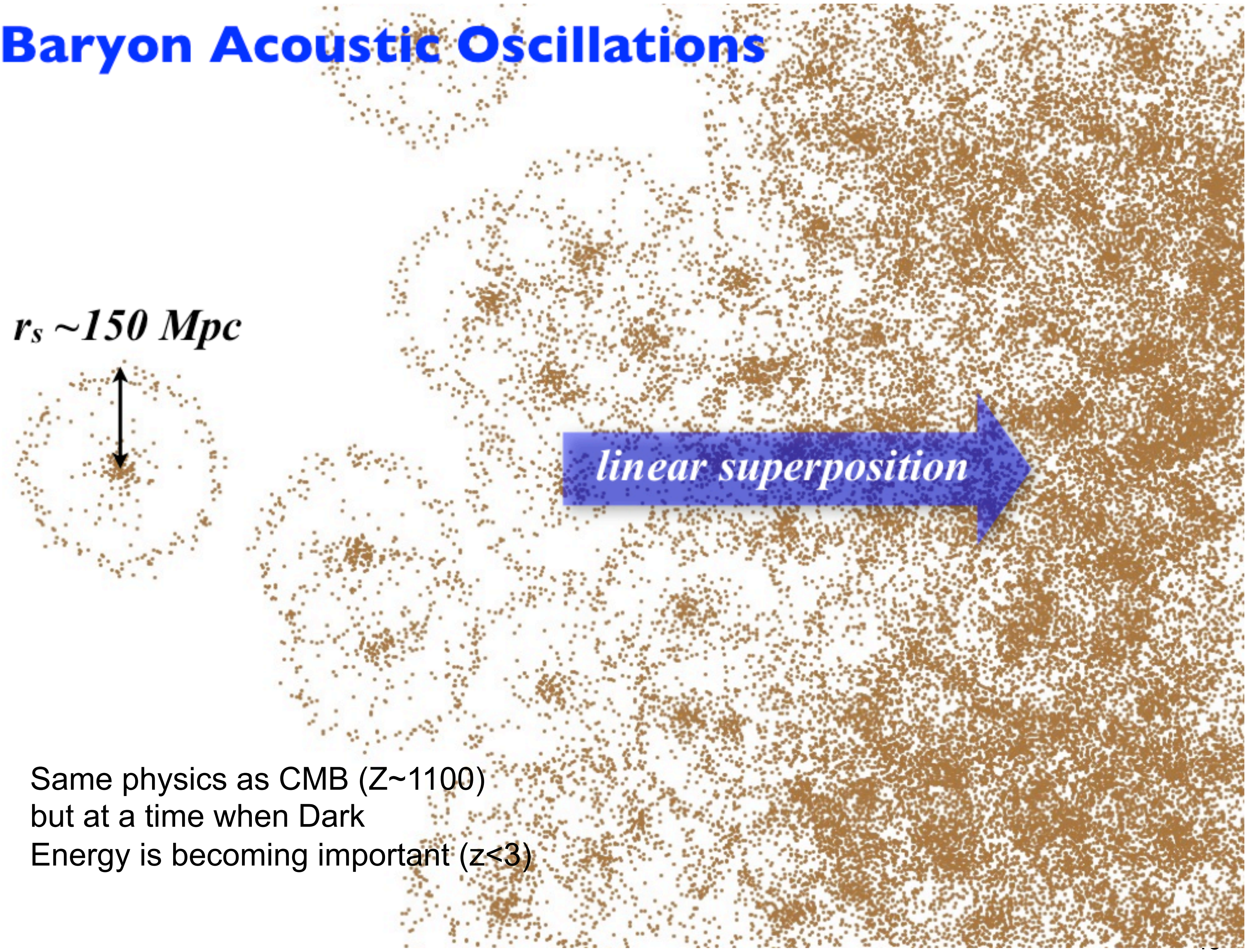
Baryon Acoustic Oscillations

r_s ~150 Mpc



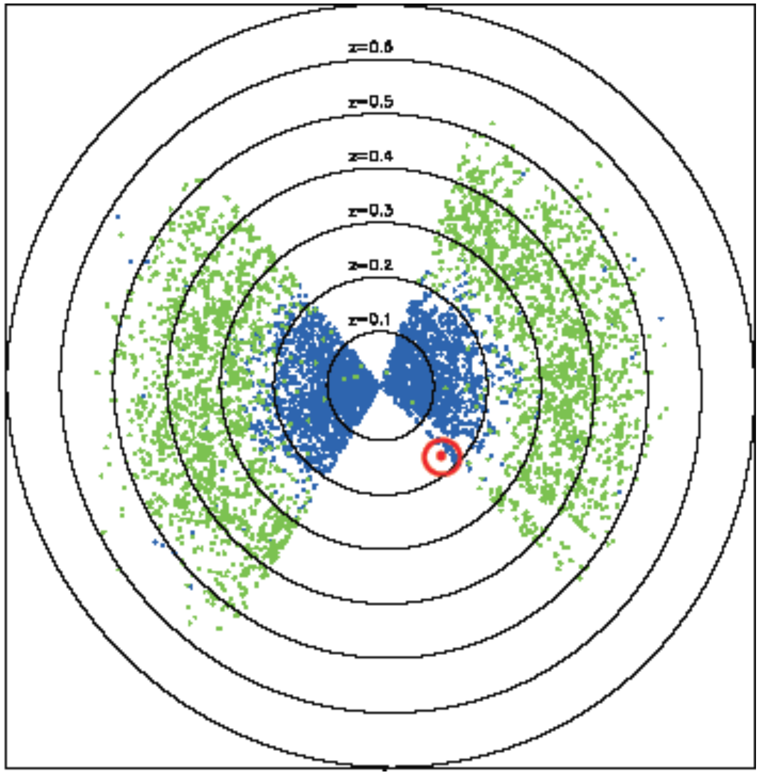


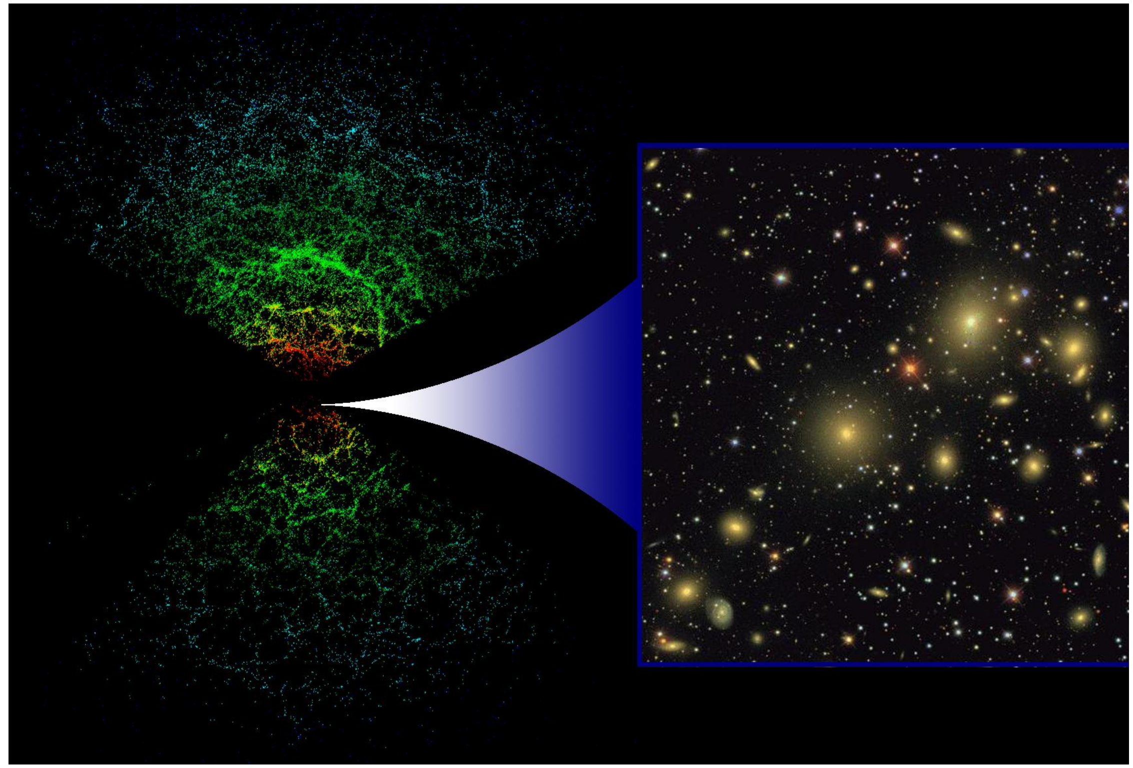
Baryon Acoustic Oscillations

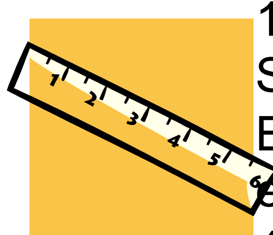


Same physics as CMB (Z~1100)
but at a time when Dark
Energy is becoming important (z<3)

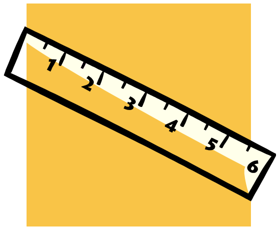
Baryon Acoustic Oscillations SDSS







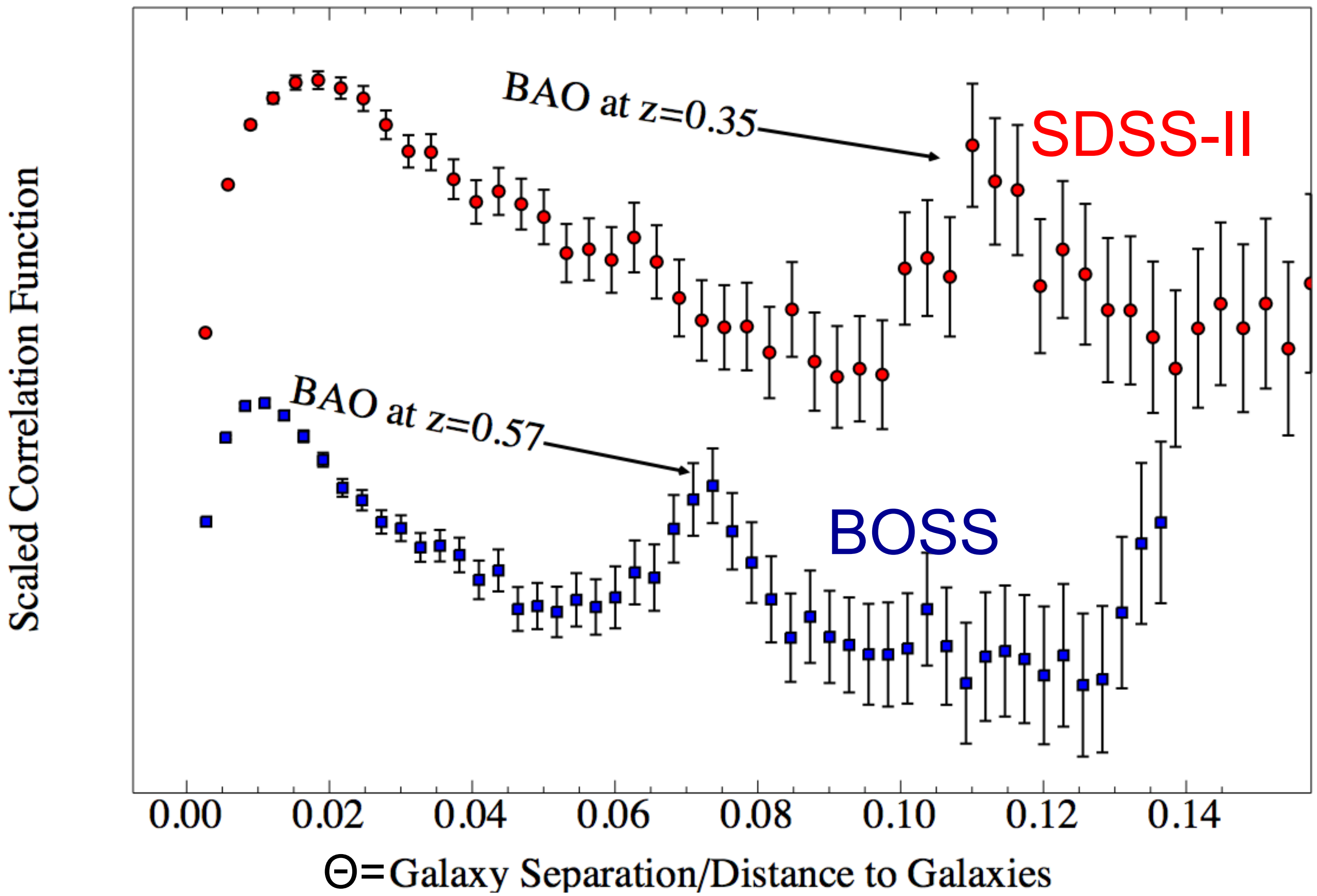
1st observation
SDSS
Eisenstein
et al (2005)
40,000 galaxies
0.16<z<0.47

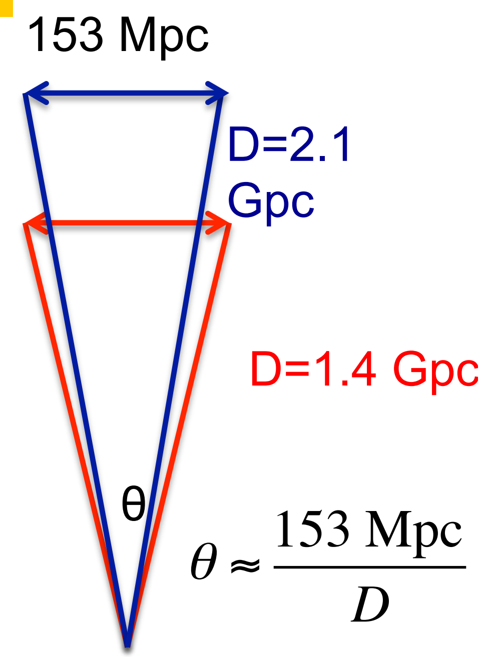


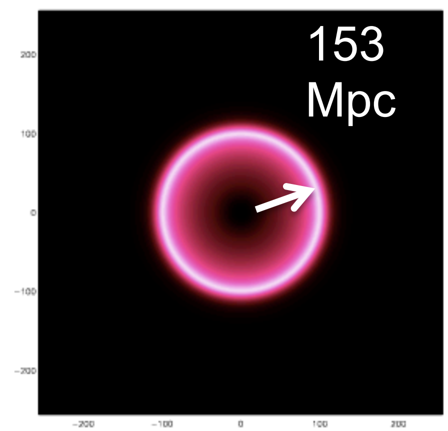
1st observation
SDSS Eisenstein
et al (2005)
40,000 galaxies
$0.16<z<0.47$

BOSS (2013)
1 million galaxies
8,500 deg^2 13 Gpc^3
largest survey to date
z=0.32 & z=0.57

Measure angle θ, do trigonometry to get D(z).







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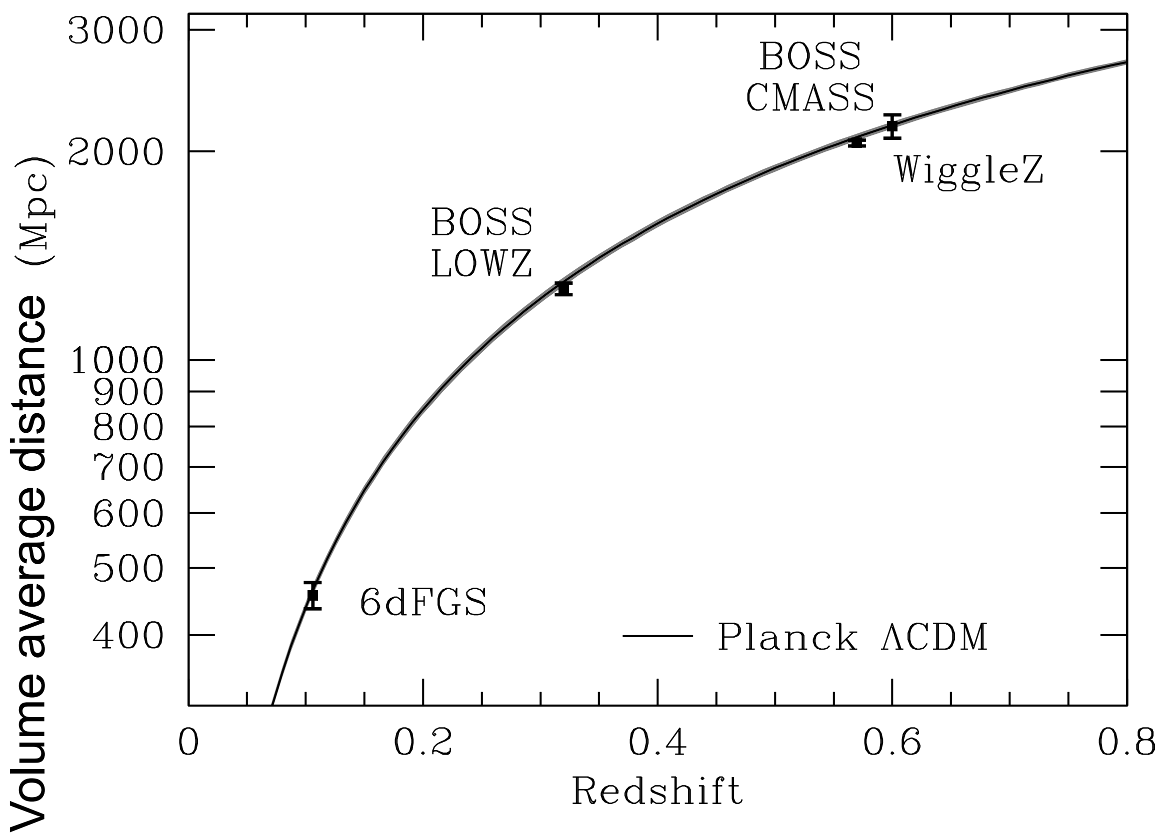
- **How the length scale evolves with redshift is dependent on the Hubble parameter and therefore sensitive to dark energy**



WiggleZ Katzin 2014
BOSS Anderson 2013
6dFGS Beutler 2011

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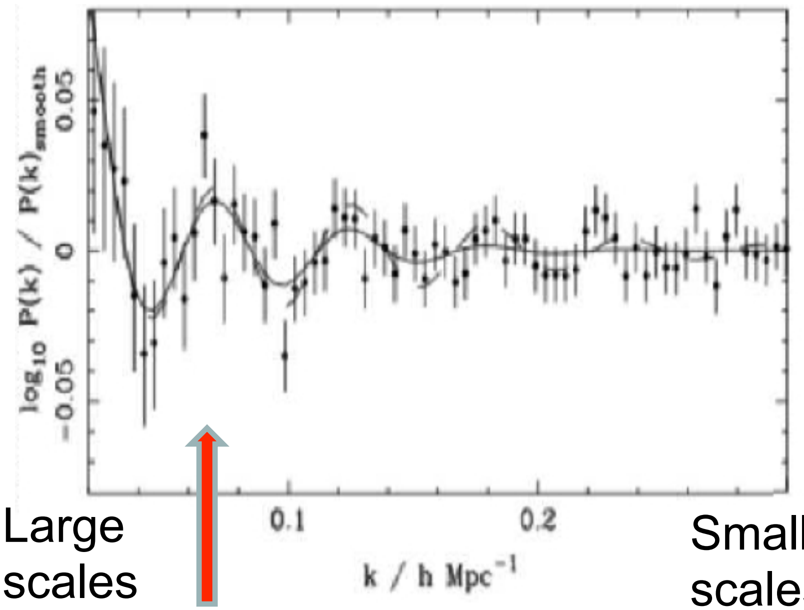
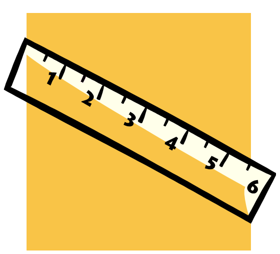
Baryon Acoustic Oscillations and LSST

Compilation of data this time as a power spectrum



Large scales

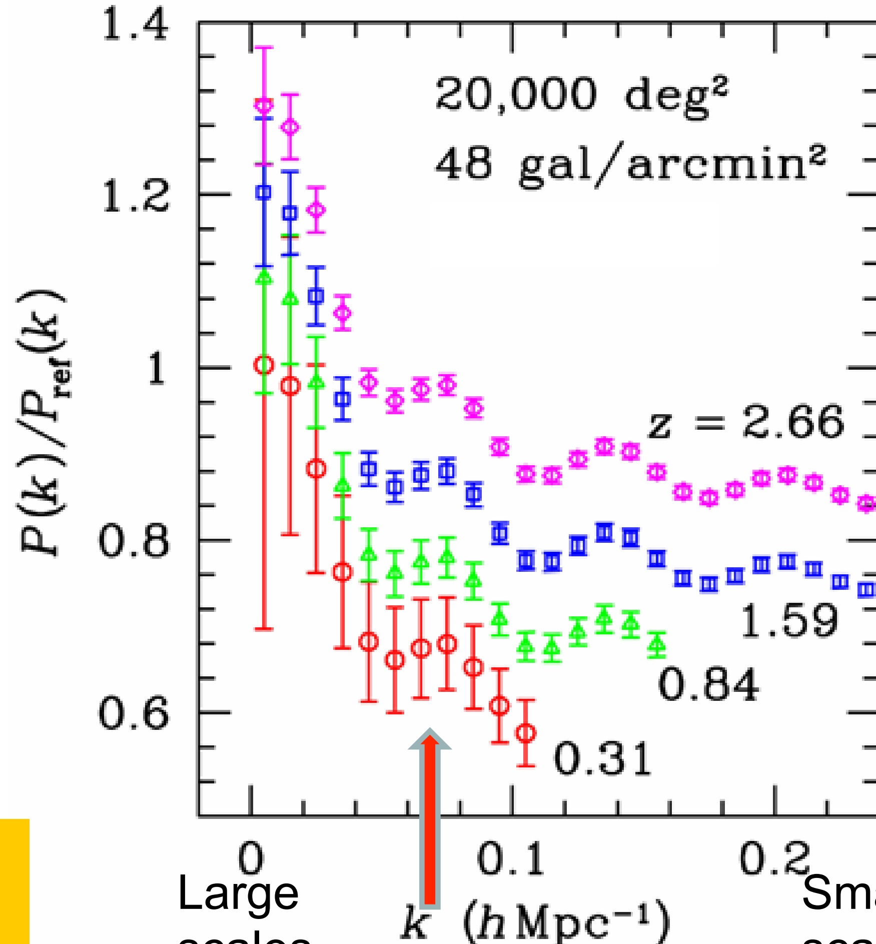
Small scales



BOSS (2013)
1 million galaxies

LSST
3 billion galaxies

I. Shipsey



Large scales

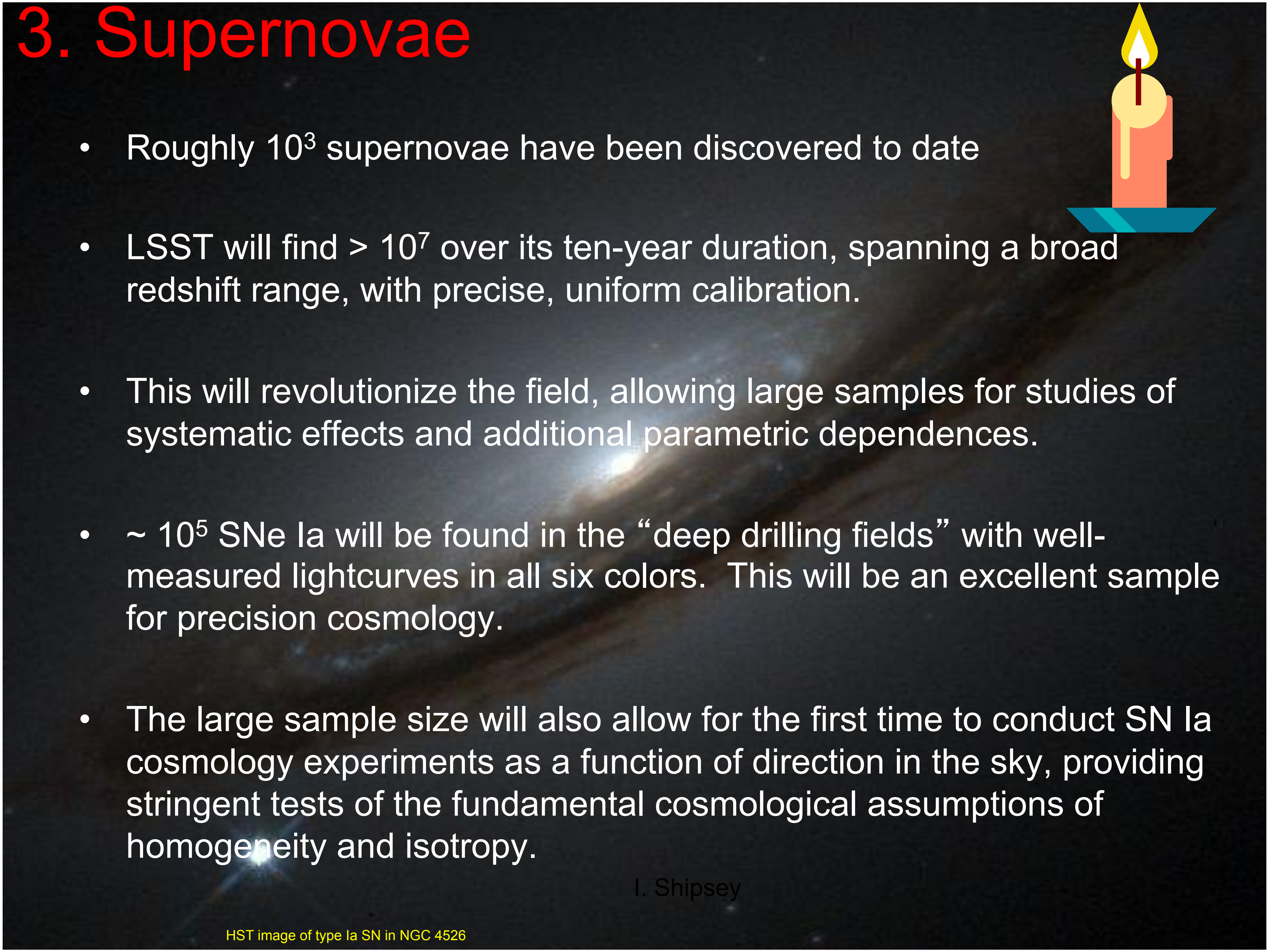
Small scales

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

3. Supernovae

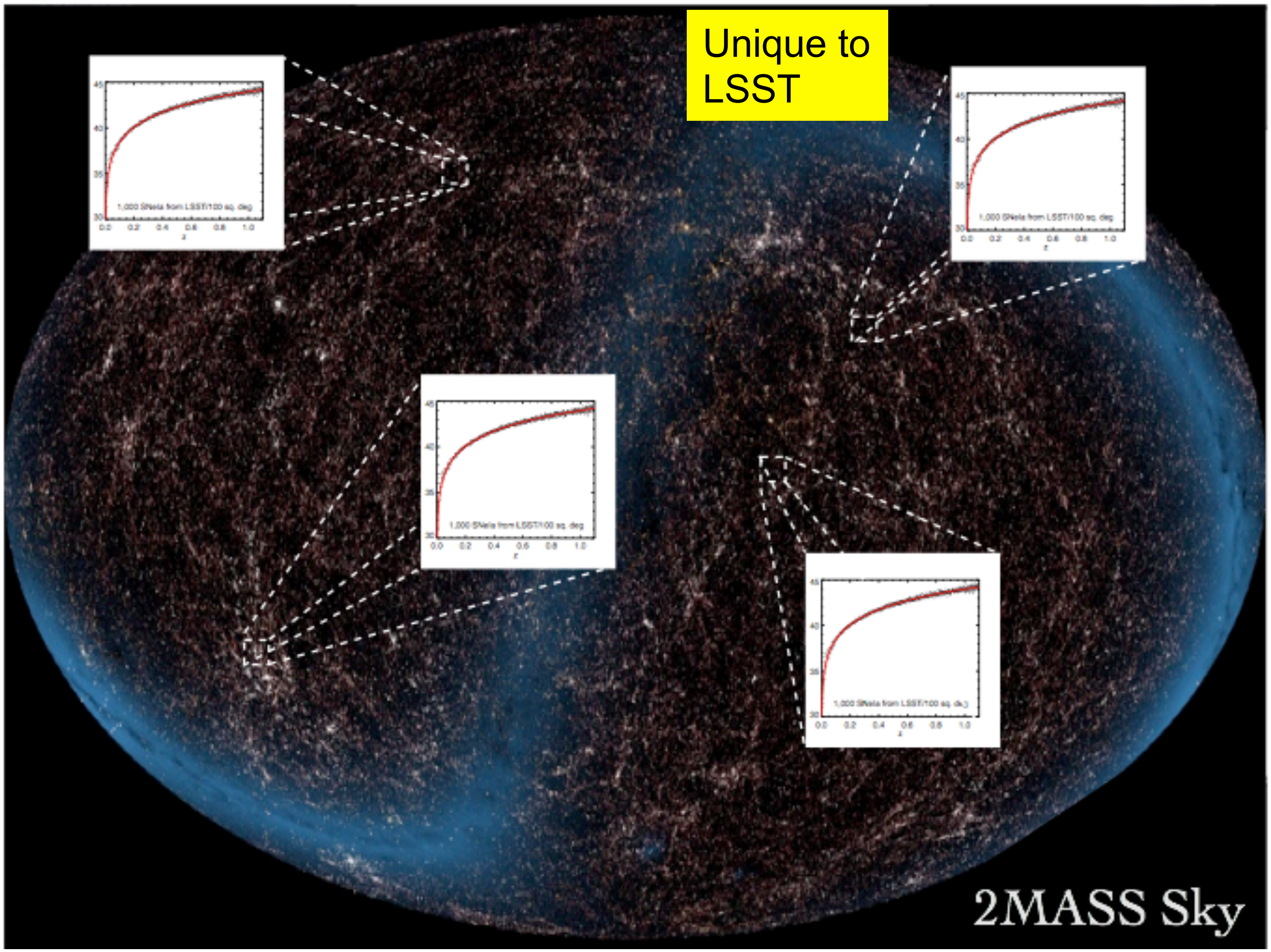
- Roughly 10^3 supernovae have been discovered to date
- LSST will find > 10^7 over its ten-year duration, spanning a broad redshift range, with precise, uniform calibration.
- This will revolutionize the field, allowing large samples for studies of systematic effects and additional parametric dependences.
- ~ 10^5 SNe Ia will be found in the “deep drilling fields” with well-measured lightcurves in all six colors. This will be an excellent sample for precision cosmology.
- The large sample size will also allow for the first time to conduct SN Ia cosmology experiments as a function of direction in the sky, providing stringent tests of the fundamental cosmological assumptions of homogeneity and isotropy.

I. Shipsey



HST image of type Ia SN in NGC 4526

Isotropy of Cosmic Acceleration

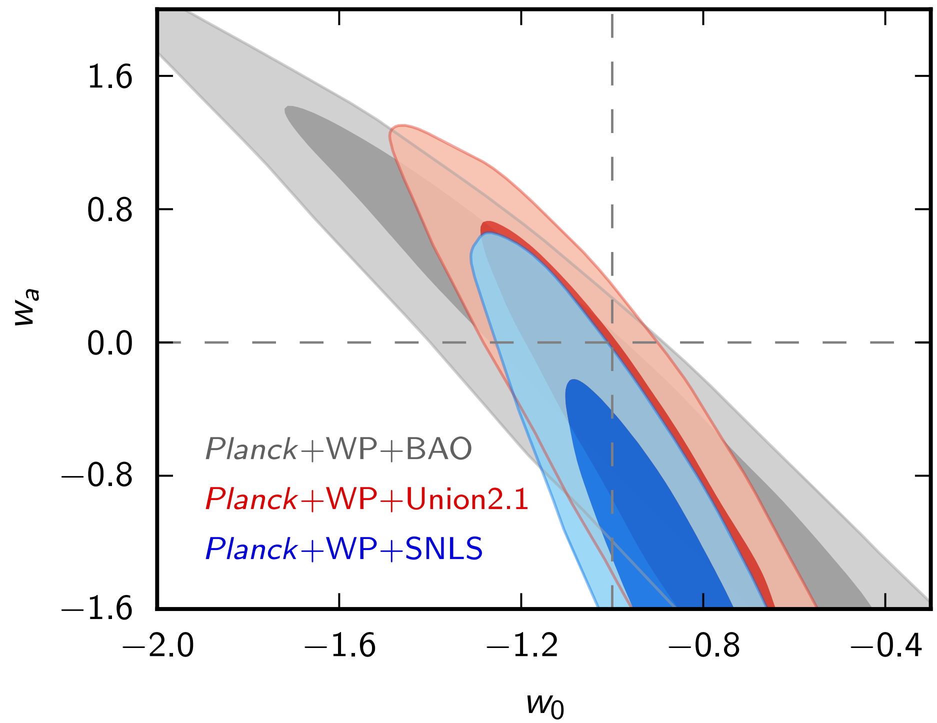


Current constraints on Dark Energy from multiple techniques

$$w = P/\rho$$

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

now evolution



Planck
arXiv:1303.5076v2
December, 2013

Combined:
SN + BAO + CMB

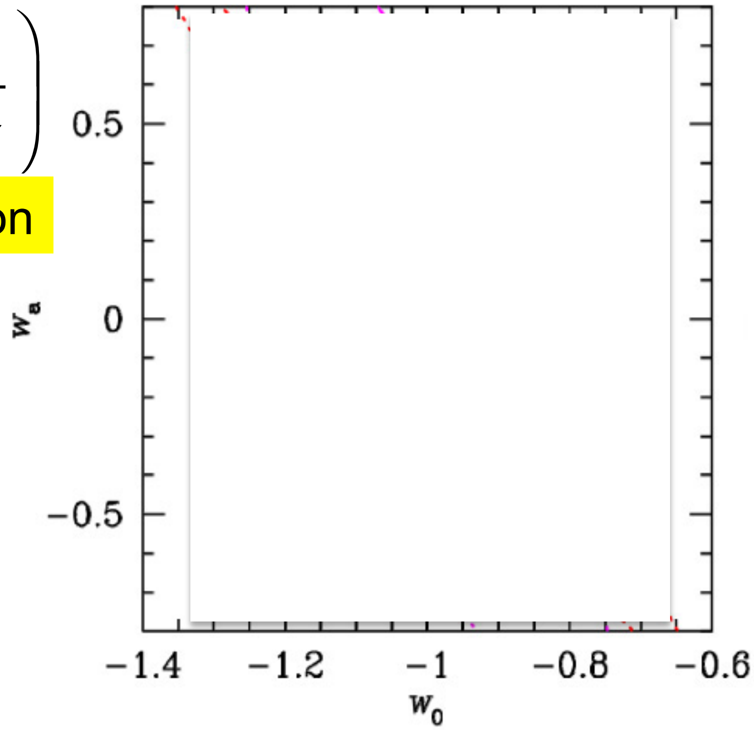
Predicted LSST Constraints on Dark Energy from multiple techniques

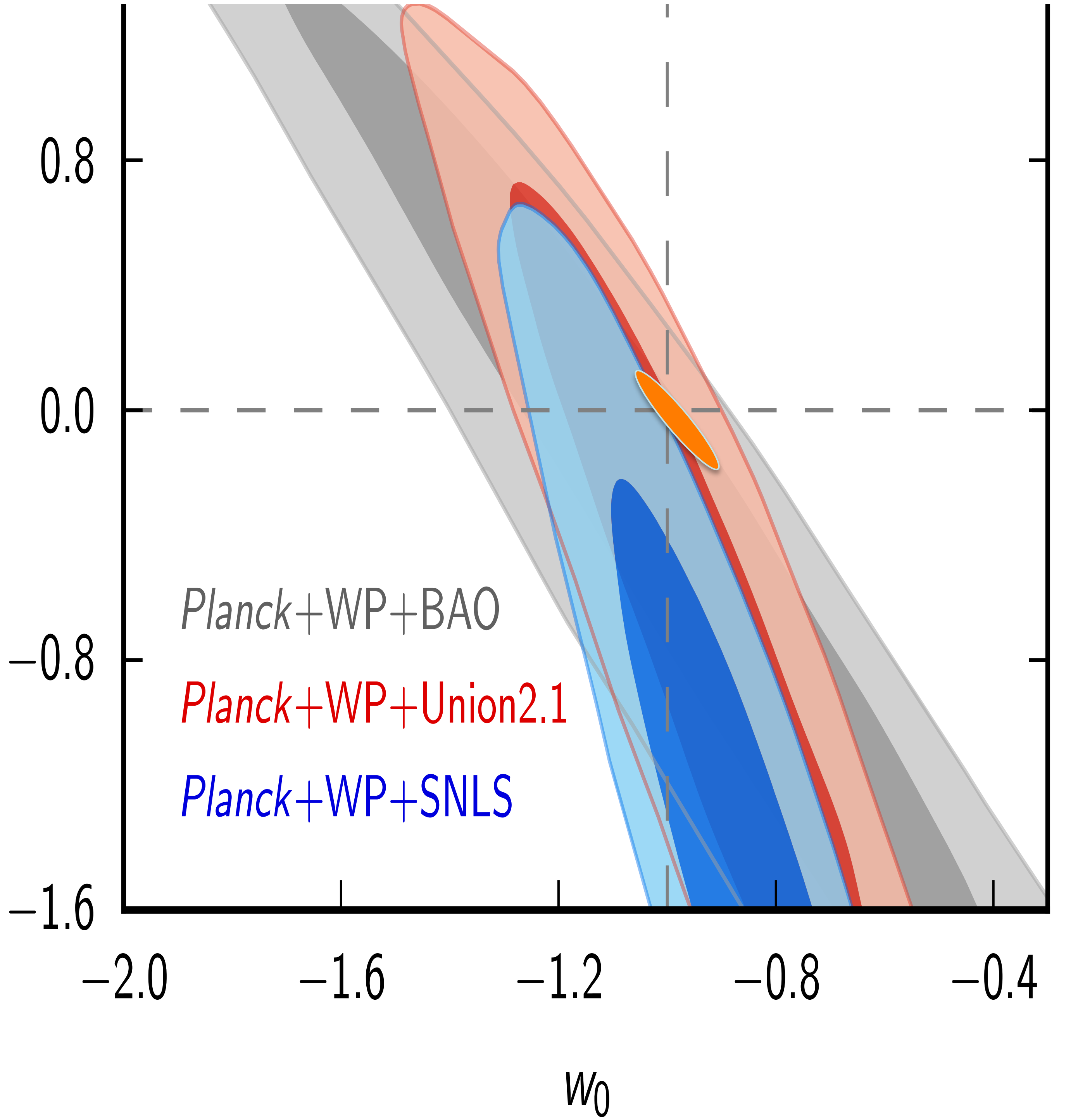
$$w = P/\rho$$

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

now

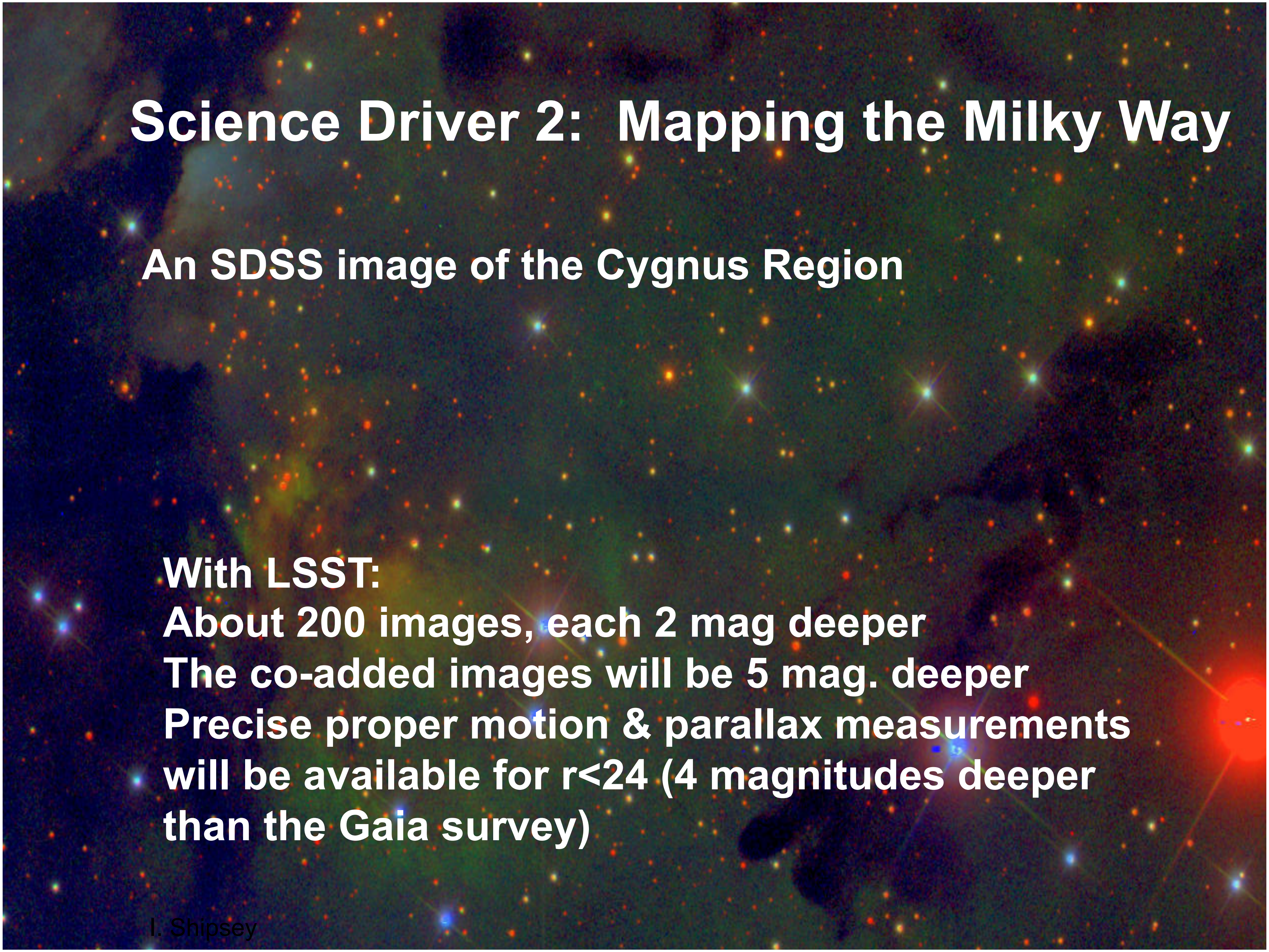
evolution





Present state of knowledge

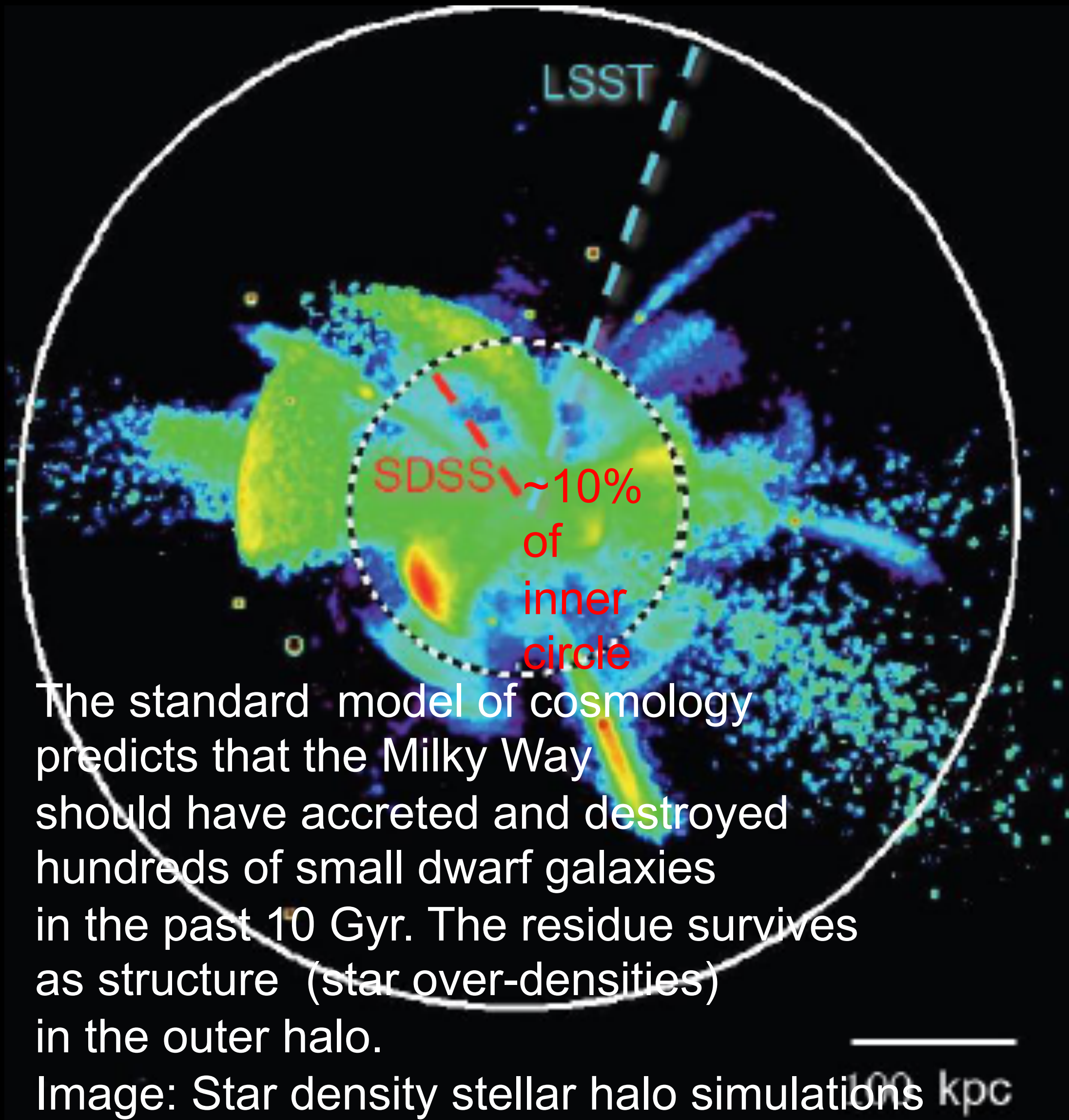
I. Shipsey


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)
I. Shipsey

Stellar Populations

- LSST will individually resolve and detect billions of stars in the Milky Way and neighboring Local Group galaxies,
- Studies of field stars and stellar associations can address a multitude of astrophysical issues associated with star formation and evolution, the assembly of the MW galaxy, and the origin of the chemical elements.
- Key techniques for these investigations include:
  - Construction of color magnitude diagrams
  - Trigonometric parallaxes to establish absolute distances
  - Stellar proper motions to separate associations from background stars and from one another
  - Using RR Lyrae and other variables as “standard candles”
  - Using eclipsing binaries to measure stellar masses

Example: structure of outer milky way



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) in the outer halo.
Image: Star density stellar halo simulations

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

- Inventory of solar system is incomplete
  Estimate 17,000 undetected

- LSST would determine orbits of nearly all NEOs larger than 150m

- Demanding project: requires mapping the sky down to 24th magnitude every few days, individual exposures not to exceed 15 sec

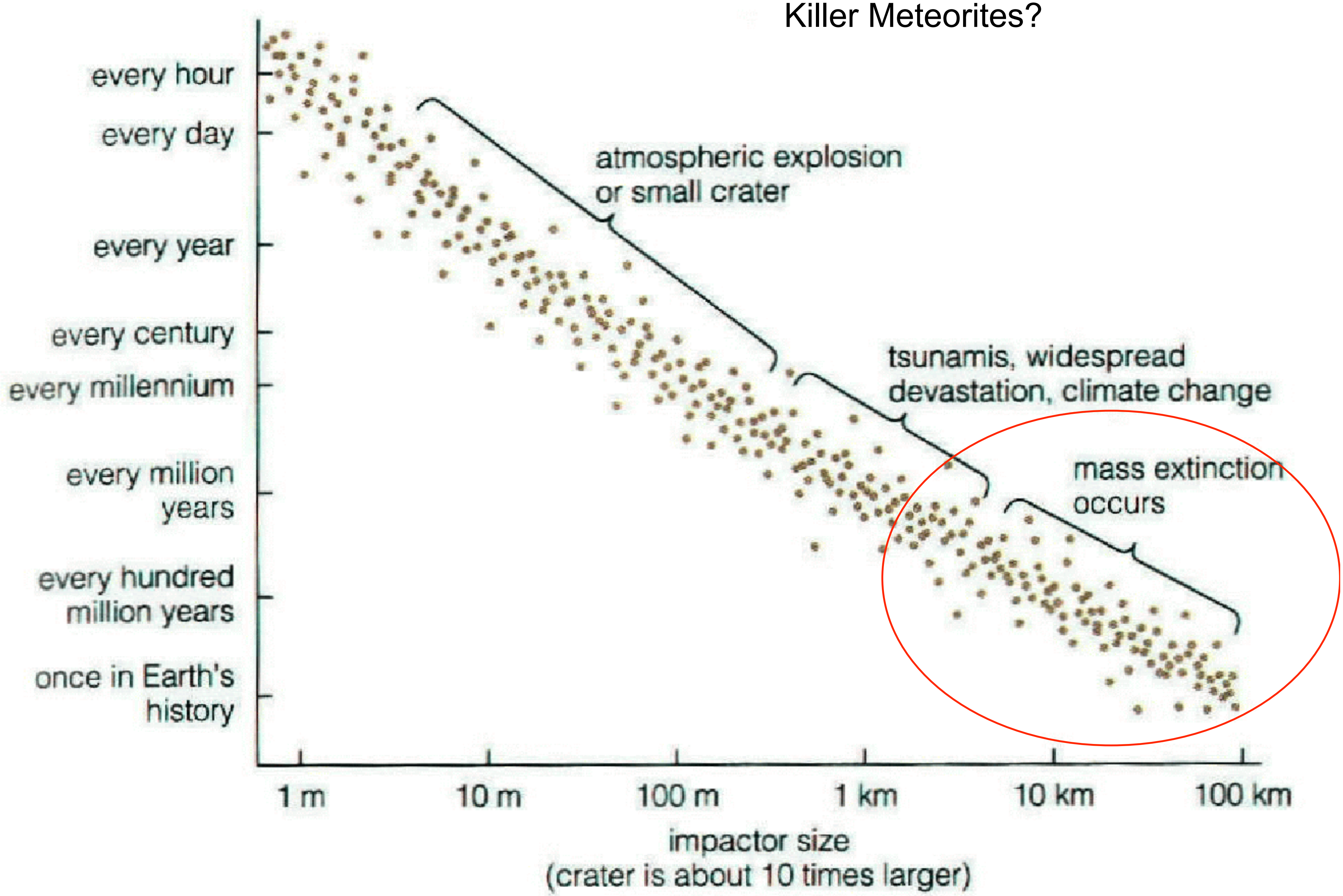
The Sky is Falling

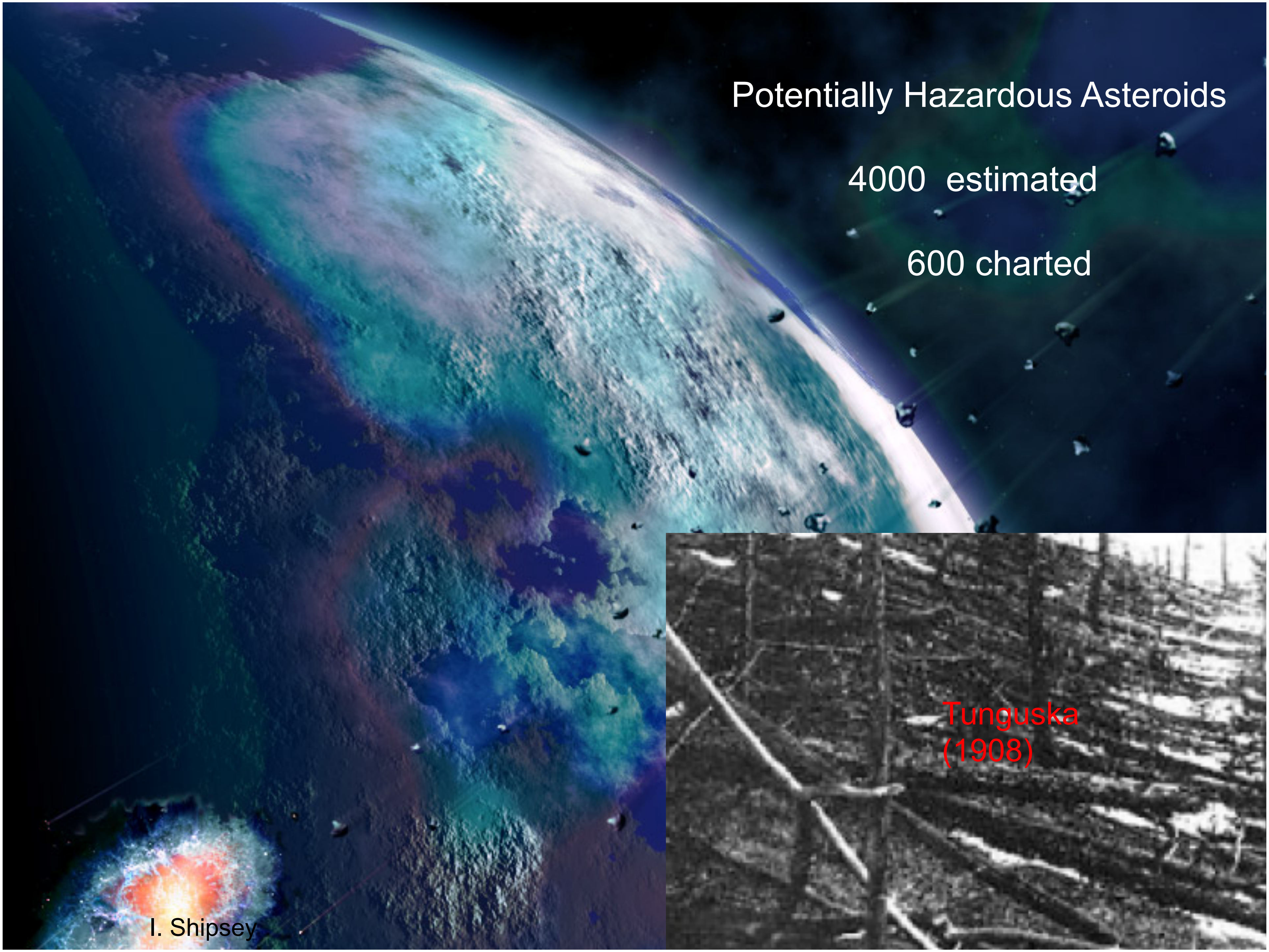
- Meteroids/Fireballs that are golf-ball sized and up
  - Each day, ~ 100 tons of rock burns up in our atmosphere.

- **This fireball witnessed by thousands of people on October 9, 1992 in… guess where?**
  - streaked across sky at 50,000 km/h
  - 1st meteor ever filmed *and then* recovered


THIS CAR WAS STRUCK BY A
METEORITE
ON OCTOBER 9th, 1992 IN PEEKSKILL, N.Y.
SEE METEORITE IN ROOM 153

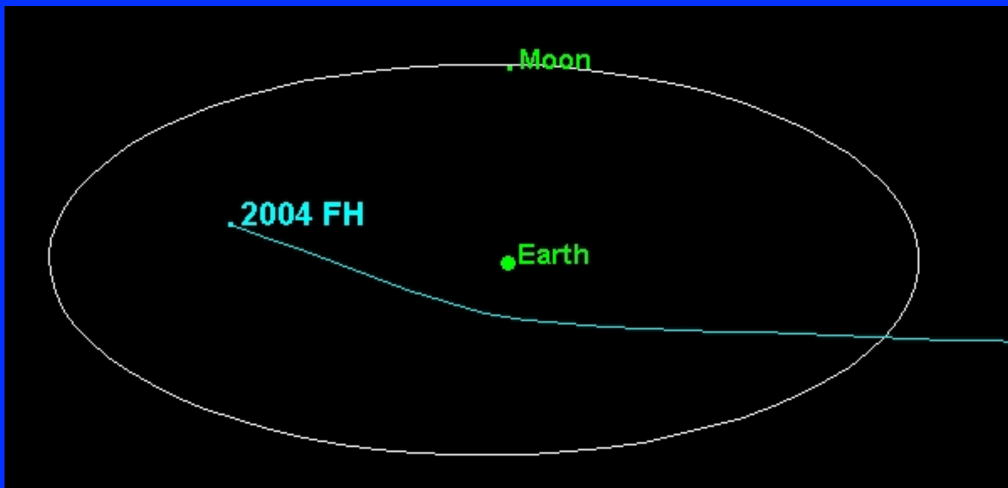
Killer Meteorites?




Potentially Hazardous Asteroids
4000 estimated
600 charted
Tunguska
(1908)
I. Shipsey

Recent Close Calls

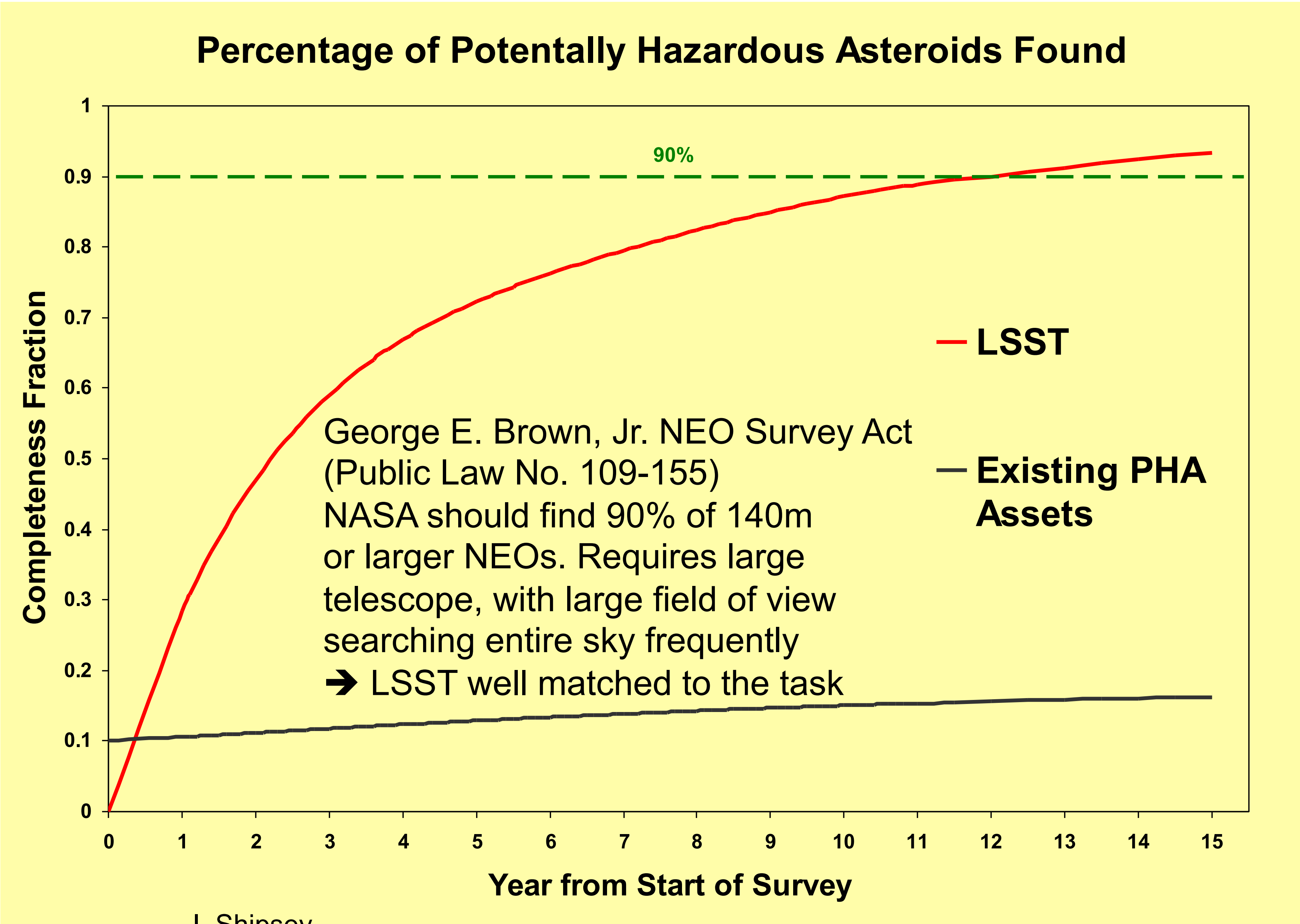
Many near misses are discovered only after the object has missed Earth.



- **March 18, 2004**
  - 100 m asteroid came within 43,000 km of Earth
  - discovered 1 day in advance
- **Similar events happen roughly ev**
  - 500 m diameter asterc 000 km of Earth

Mar 6 2014   2014 EF 0.4 x lunar distance
Mar 6 2014   2012 EC 0.2 x lunar distance
http://neo.jpl.nasa.gov/ca/

Large Synoptic Survey Telescope



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Understanding the formation and evolution of the Solar System

- LSST will detect and determine orbits for millions of small bodies in the Solar System.

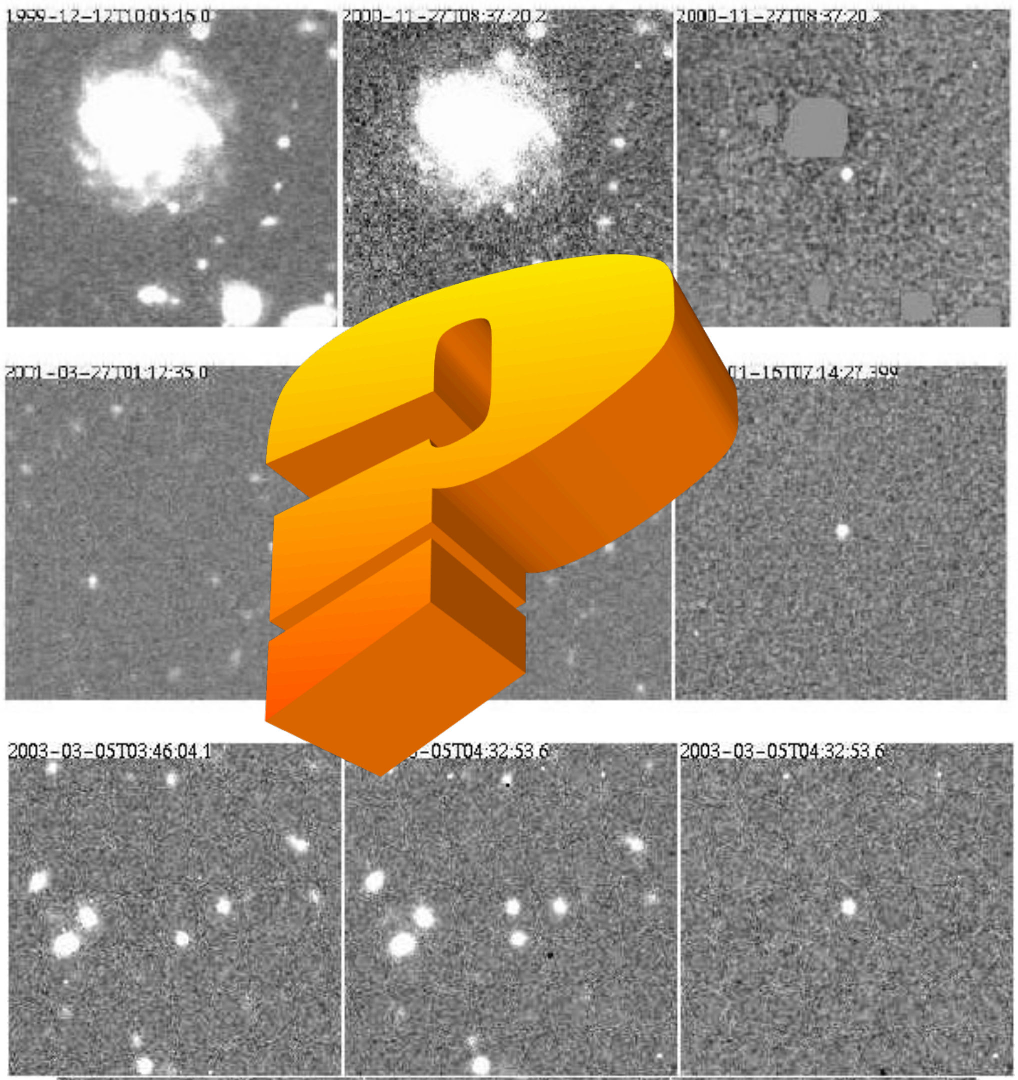
- Classes include:
  - Near Earth Asteroids (NEAs), and their subclass, Potentially Hazardous Asteroids (PHAs), whose orbits can potentially impact the Earth.
  - Main Belt Asteroids (MBAs), lying between the orbits of Mars and Jupiter.
  - Trojans, which are asteroids in 1:1 mean motion resonance with a planet.
  - Trans-Neptunian Objects (TNOs), and their subclass, Classical Kuiper Belt Objects (cKBOs). These occupy a large area of stable orbital space.
  - Jupiter-Family Comets (JFCs), whose orbits are strongly perturbed by Jupiter.
  - Long Period Comets (LPCs), which originate in the Oort Cloud at 10,000 AU.
  - Halley Family Comets (HFCs), which also come from the Oort Cloud, but have shorter periods.
  - Damoclids, a group of asteroids with similar dynamical properties to the HFCs.

- Understanding the origin and behavior of these various systems is crucial for modelling the formation and evolution of the Solar System.

Large Synoptic Survey Telescope

Science Driver 4: Transients & variable objects

(t=0) **(t'>t=0)** **Difference**



Supernova

Optical flashes

Optical flashes

Deep Lens Survey

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

Science Driver 4: Transients and Variable Objects

Recent surveys have shown the power of measuring variability for studying gravitational lensing, searching for supernovae, determining the physical properties of gamma-ray burst sources, probing the structure of active galactic nuclei, studying variable stars, and many other subjects at the forefront of astrophysics .

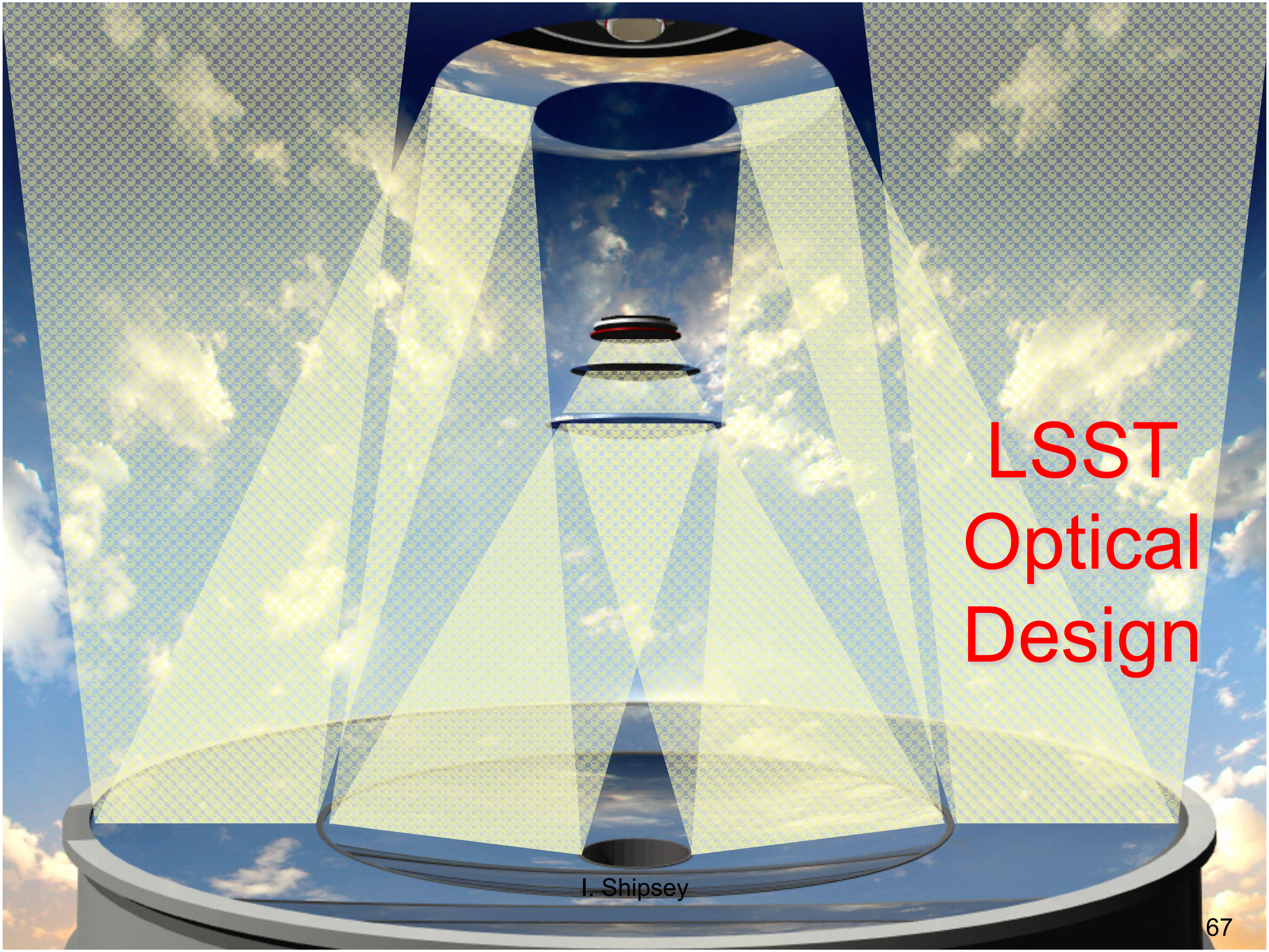
Wide-area, dense temporal coverage to deep limiting magnitudes enables the discovery and analysis of rare and exotic objects such as neutron star and black hole binaries, novae and stellar flares, gamma-ray bursts and X-ray flashes, active galactic nuclei (AGNs), stellar disruptions by black holes, and possibly new classes of transients, such as binary mergers of black holes

LSST: ~10 million cosmic explosions over most of the observable Universe, extending the volume of the parameter space for discovery by x1,000 reaching unprecedented sensitivity. A movie of the universe

Massively Parallel Astrophysics

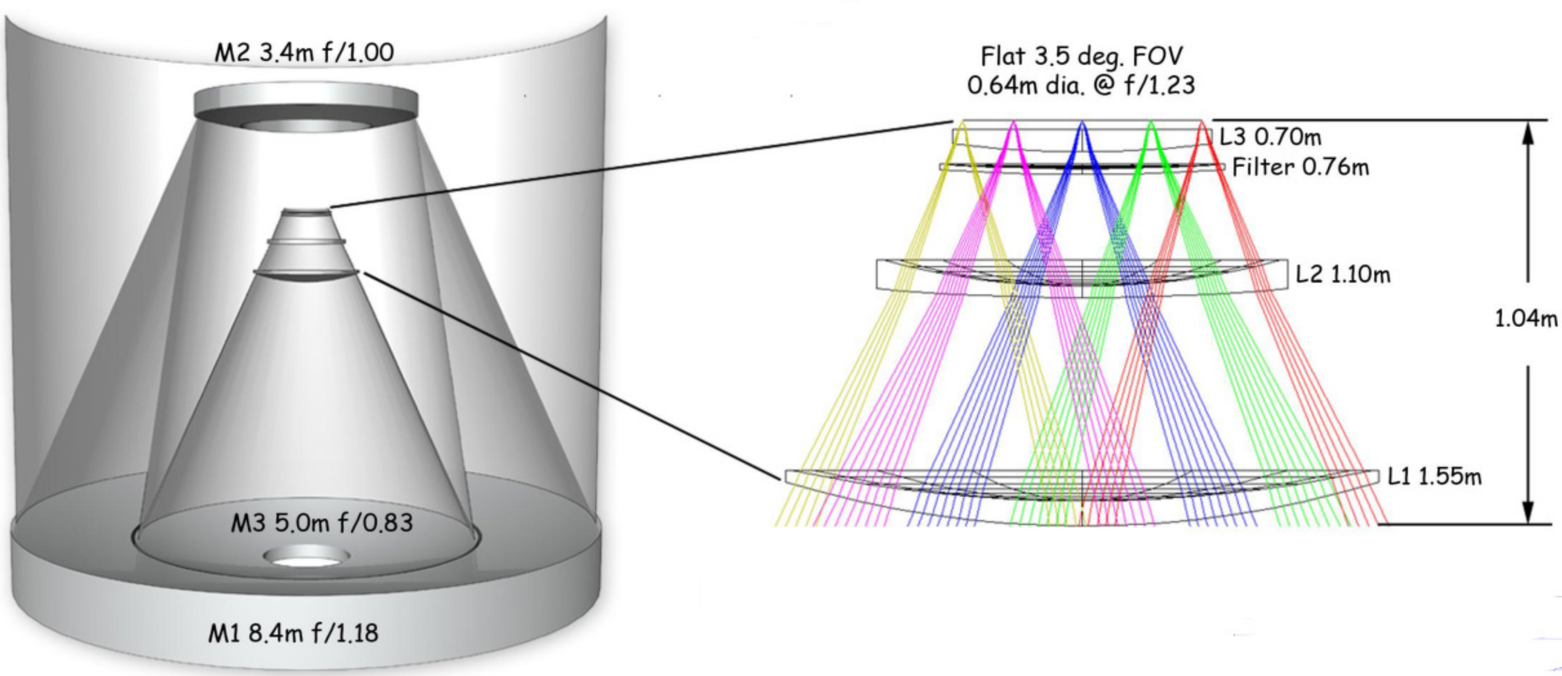
- Dark matter/dark energy via weak lensing
- Dark energy via baryon acoustic oscillations
- Dark energy via supernovae
- Galactic Structure encompassing local group
- Dense astrometry over 18000 sq.deg: rare moving objects
- Gamma Ray Bursts and transients to high redshift
- Gravitational micro-lensing
- Strong galaxy & cluster lensing: physics of dark matter
- Multi-image lensed SN time delays: separate test of cosmology
- Variable stars/galaxies: black hole accretion
- Optical bursters to 25 mag: the unknown
- 5-band 27 mag photometric survey: unprecedented volume
- Solar System Probes: Earth-crossing asteroids, Comets, TNOs
- Planetary transits

All science programs conducted in parallel


LSST
Optical
Design
I. Shipsey

LSST Optical Design

- $f/1.23$ Very short focal length gives wide field of view for given image size
- 3.5 ° FOV over a 64 cm focal plane, Etendue = 319 m^2deg^2
- < 0.20 arcsec FWHM images in six filter bands: 0.3 – 1 μm



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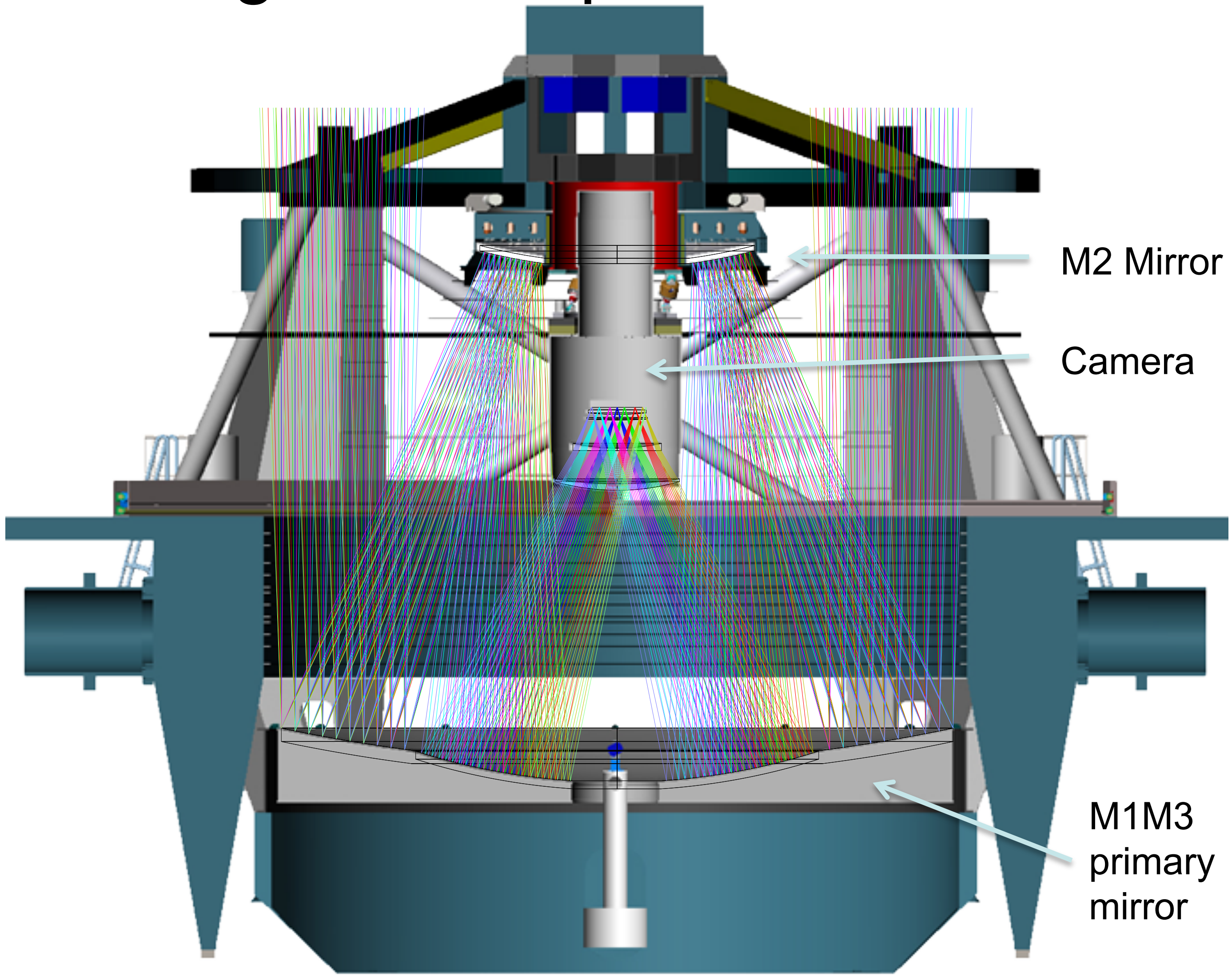
Cross section through telescope and camera



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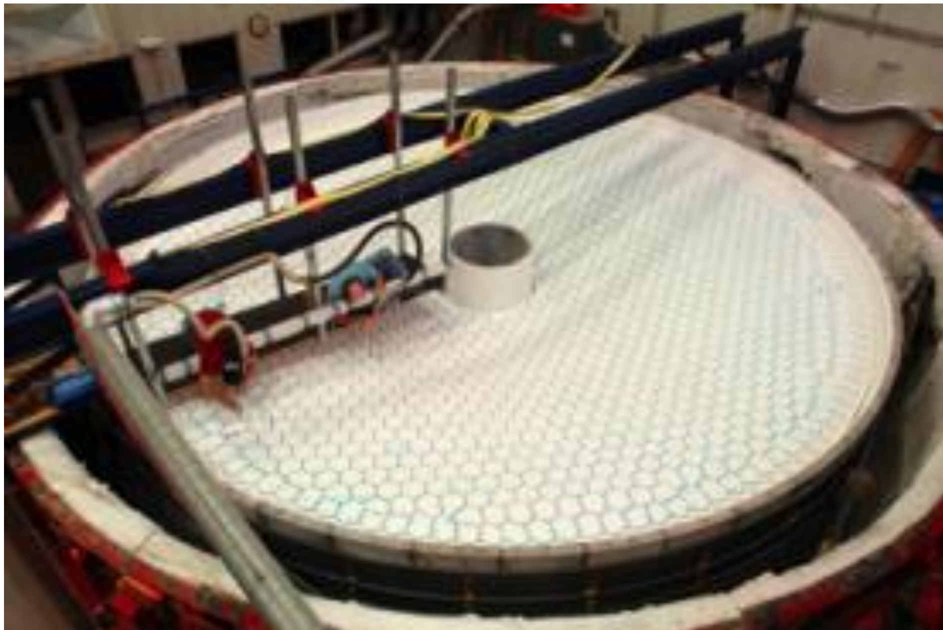
The primary/tertiary mirror is a long lead time item…



Stewart Observatory Mirror
Lab Tucson, AZ

High Fire, March 29 2008

2 September 2008

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

Mirror has been ground,
And polished

Completion :2014

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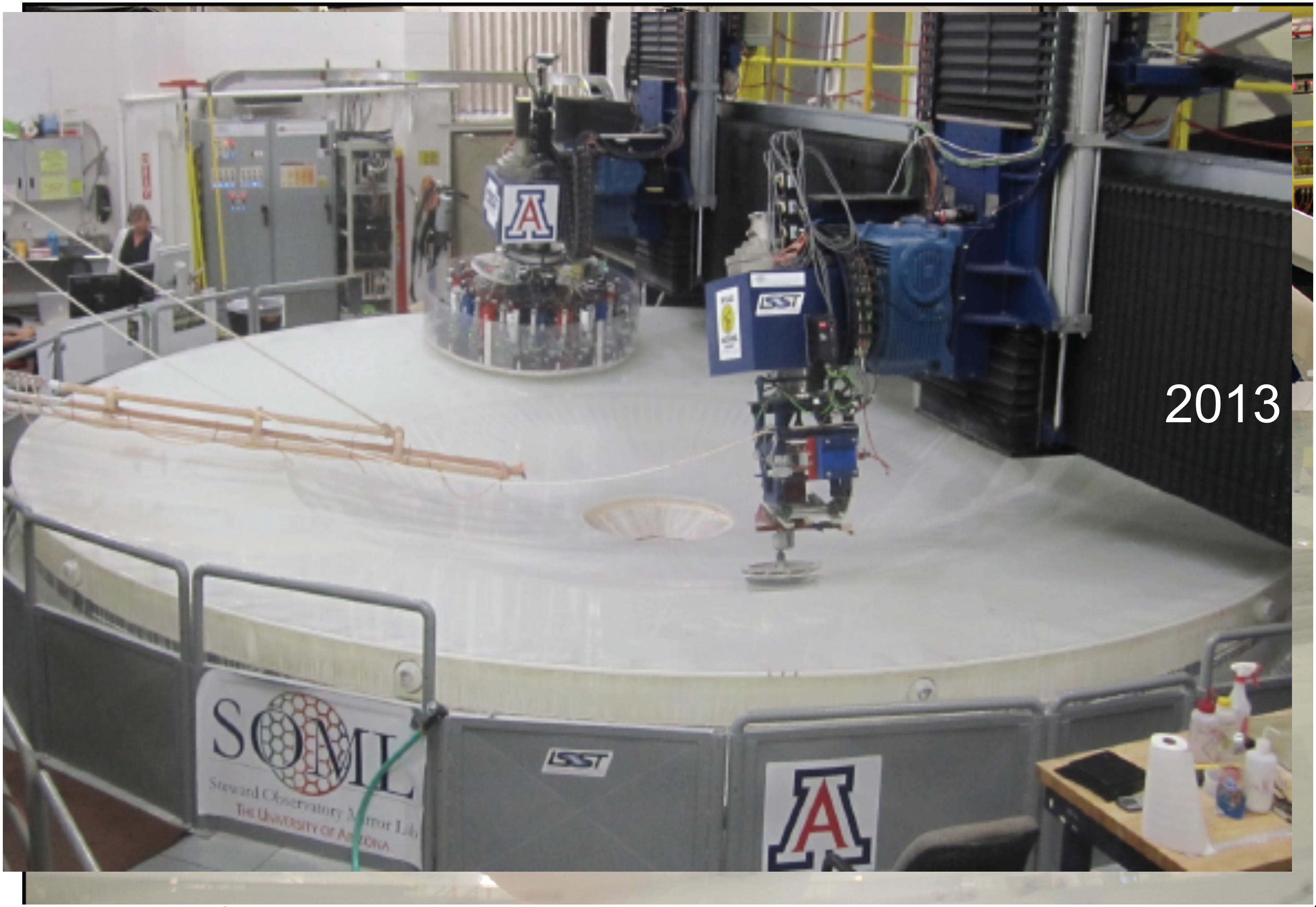
2013
SOML
Steward Observatory Mirror Lab
THE UNIVERSITY OF ARIZONA
LSST

LSST Will be Sited in Central Chile

LSST is located in an NSF compound near SOAR & Gemini

Cerro Pachón, as seen from Tololo, April 9, 2011 (During first ever LSST Board meeting in Chile)

Site and observatory

facility designed to minimalize
atmospheric turbulence
in the vicinity of the dome

After ~4,000 kg of explosives and ~12,500 m^3 of rock removal, Stage I of the El Peñón summit leveling is completed.

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LSST Observing Cadence Set by Science Goals

Pairs of 15 second exposures (*to 24.5 mag*) per visit to a given position in the sky.

Visit the same position again within the hour with another pair of exposures.

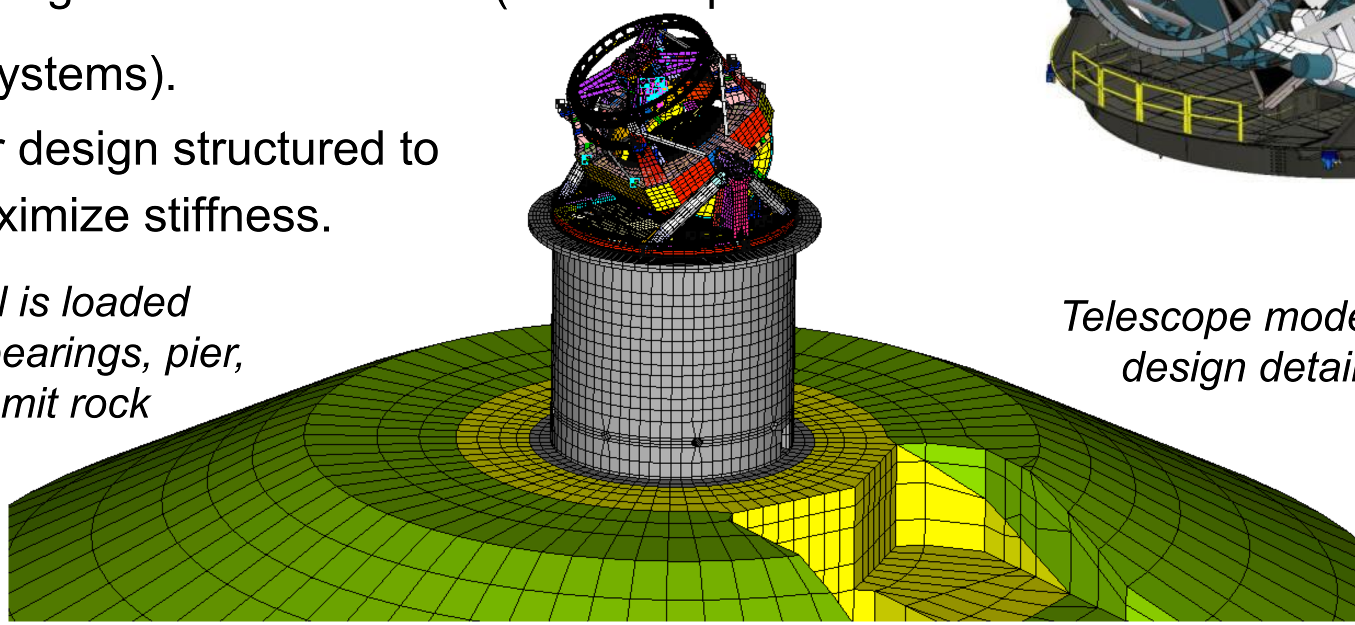
Number of 9.6 sq.deg field-of-view visits per night: 900

Detection of transients announced worldwide within 60 seconds.
Expect 1-2 million alerts per night!

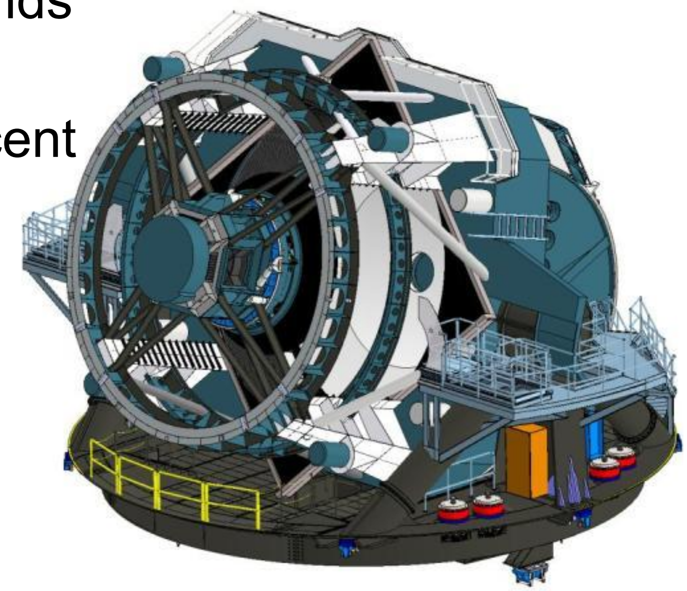
Telescope System Designed to Slew and Settle within 5 seconds

Large Synoptic Survey Telescope

- The high curvature mirrors allow a short, light, stiff , stable and agile telescope employing an alt-azimuth mount
- Points to new positions in the sky every 39 seconds
- Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 seconds
  - Moving Structure 350 tons (60 tons optical systems).
  - Pier design structured to maximize stiffness.



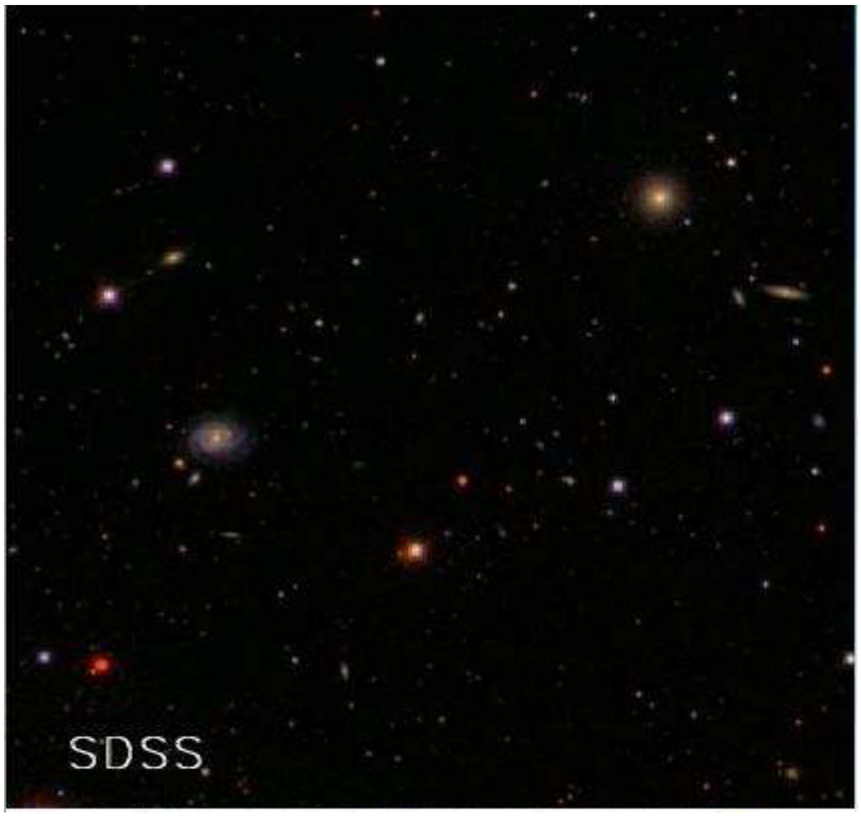
FEA model is loaded structure on bearings, pier, and summit rock

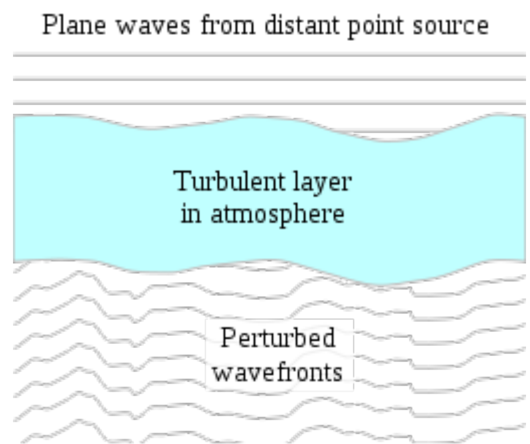


Telescope model with system design details included

Optical Quality at the LSST site

Large Synoptic Survey Telescope



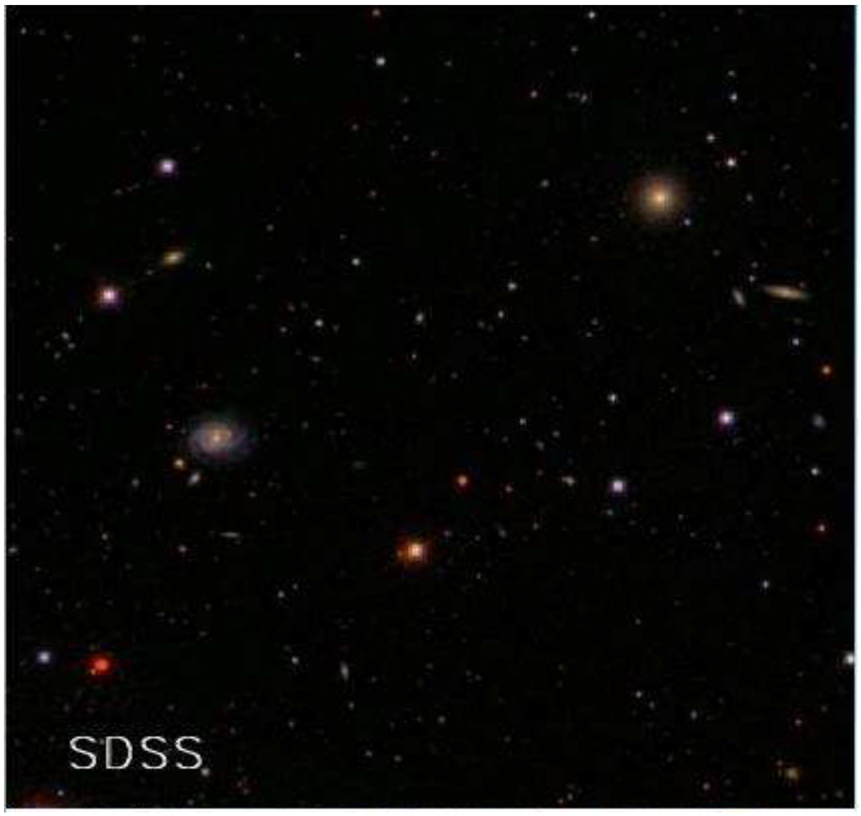


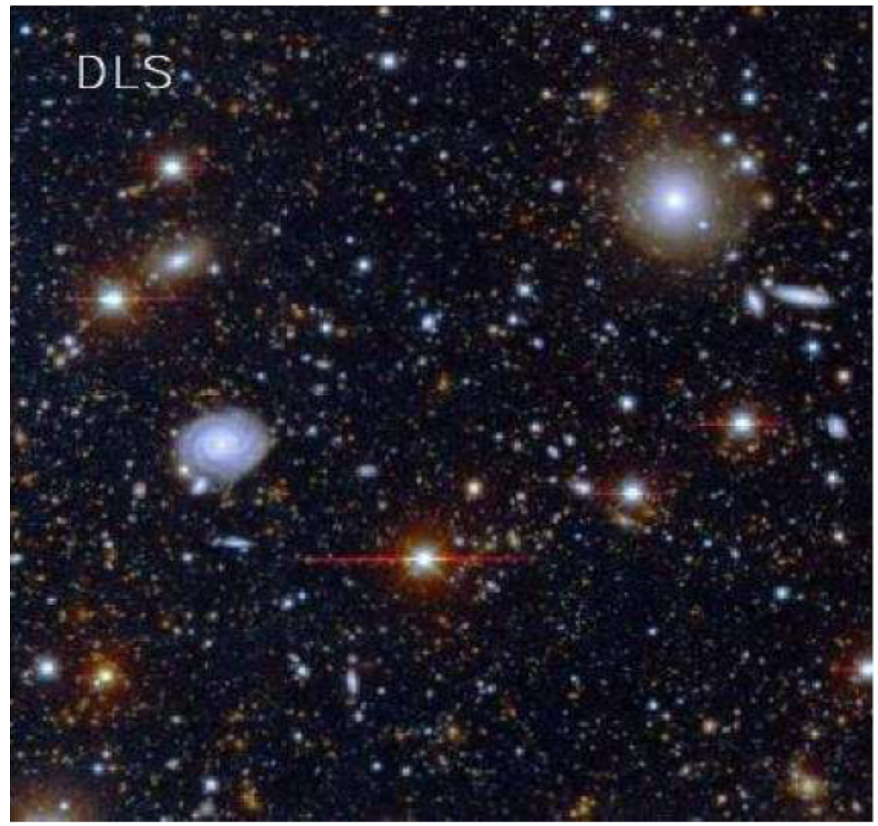
SDSS Apache Point NM, 1.3 arc sec seeing

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 Coaddition is x75 fainter than SDSS)

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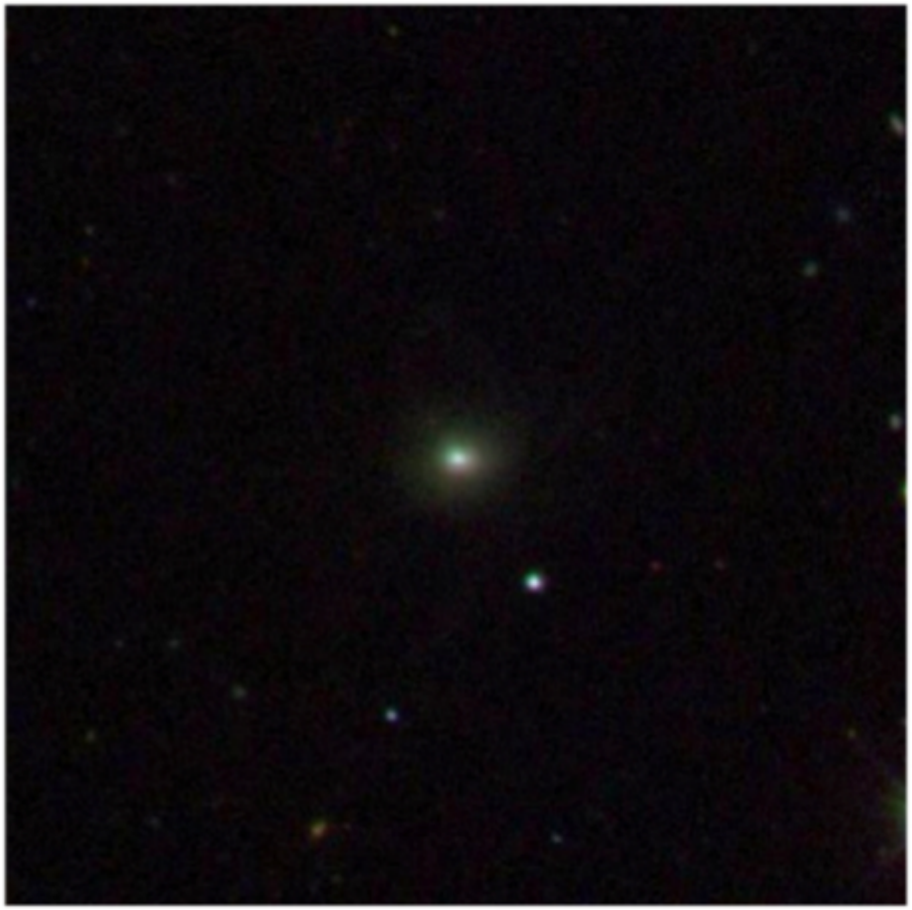
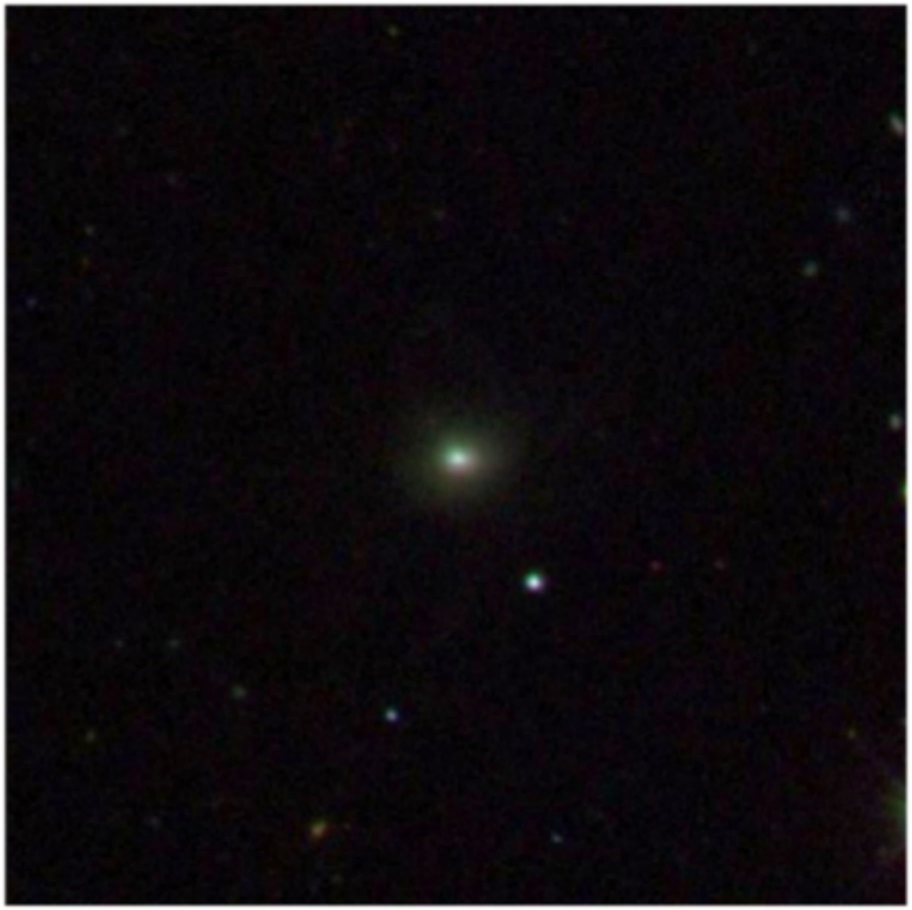
….and for a single galaxy

SDSS



....and for a single galaxy

These two images are of the same galaxy

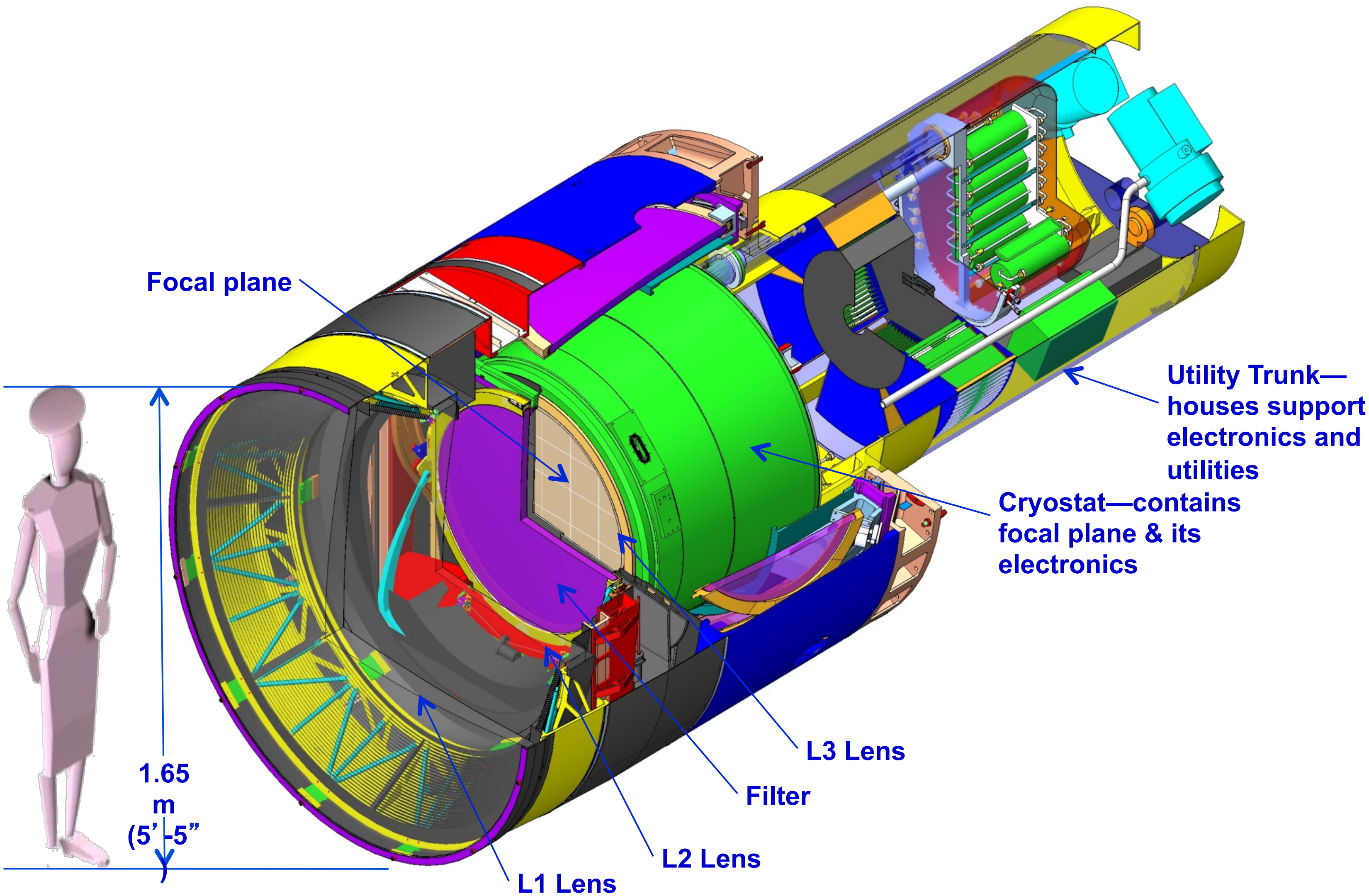


MUSYC

MUSYC is x25 fainter than SDSS but still x X3 less faint than LSST

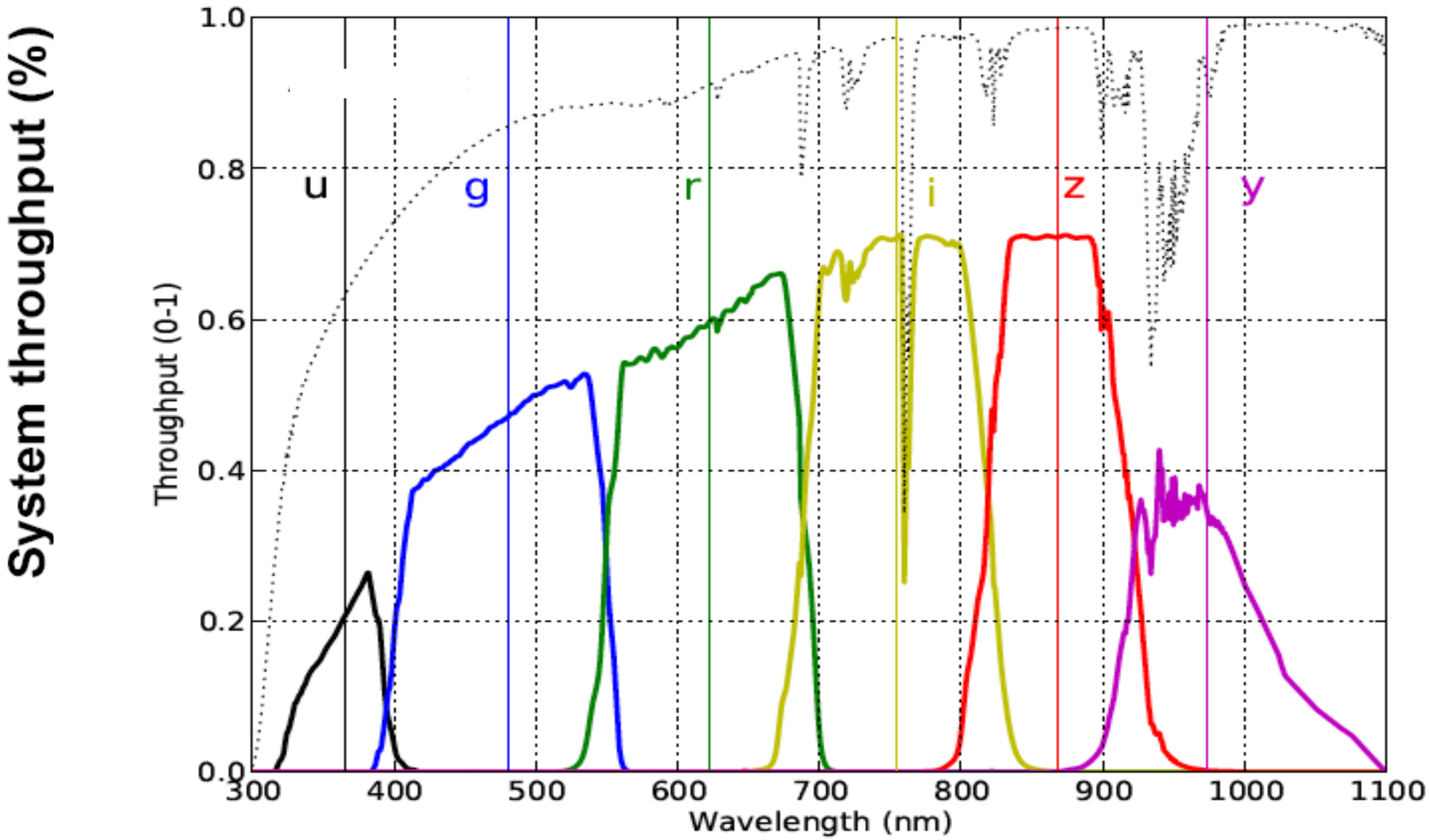
Gawiser et al

3.2 Billion Pixel Camera



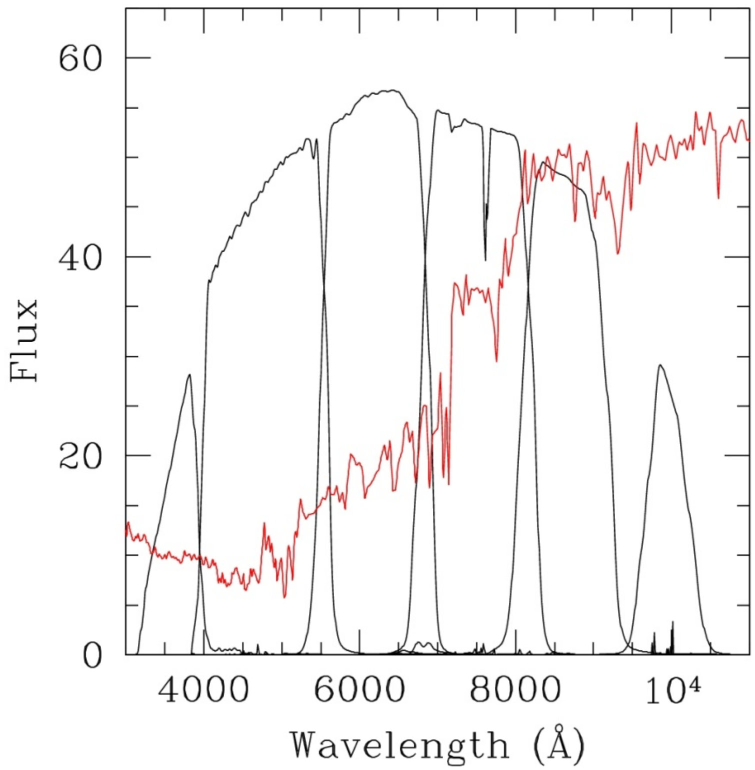
LSST's Six Optical Filter Bands
Determine color and redshift

Transmission- atmosphere, telescope, & detector QE



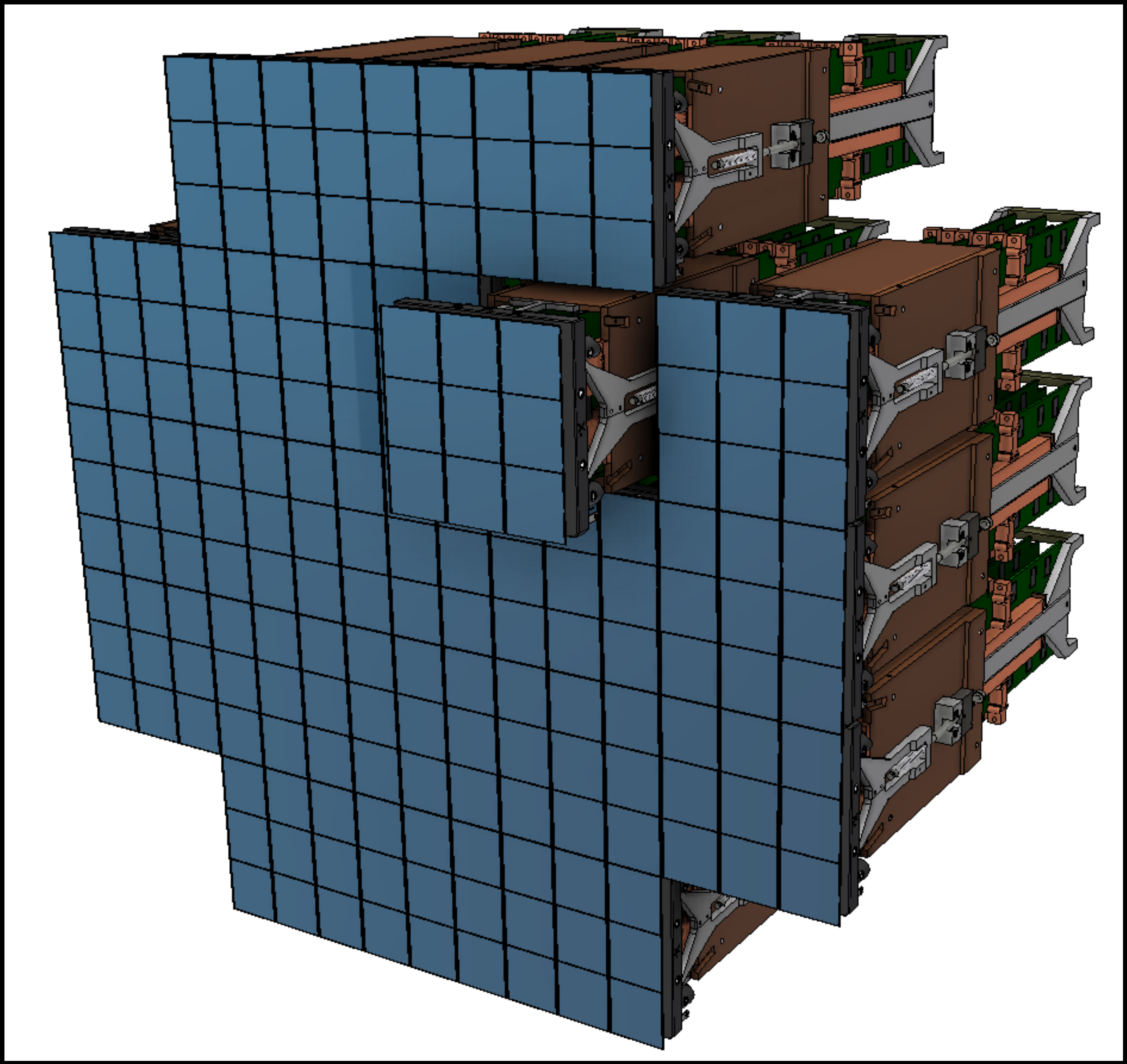
→ Photometric determination of galaxy redshifts

Photometric Redshifts

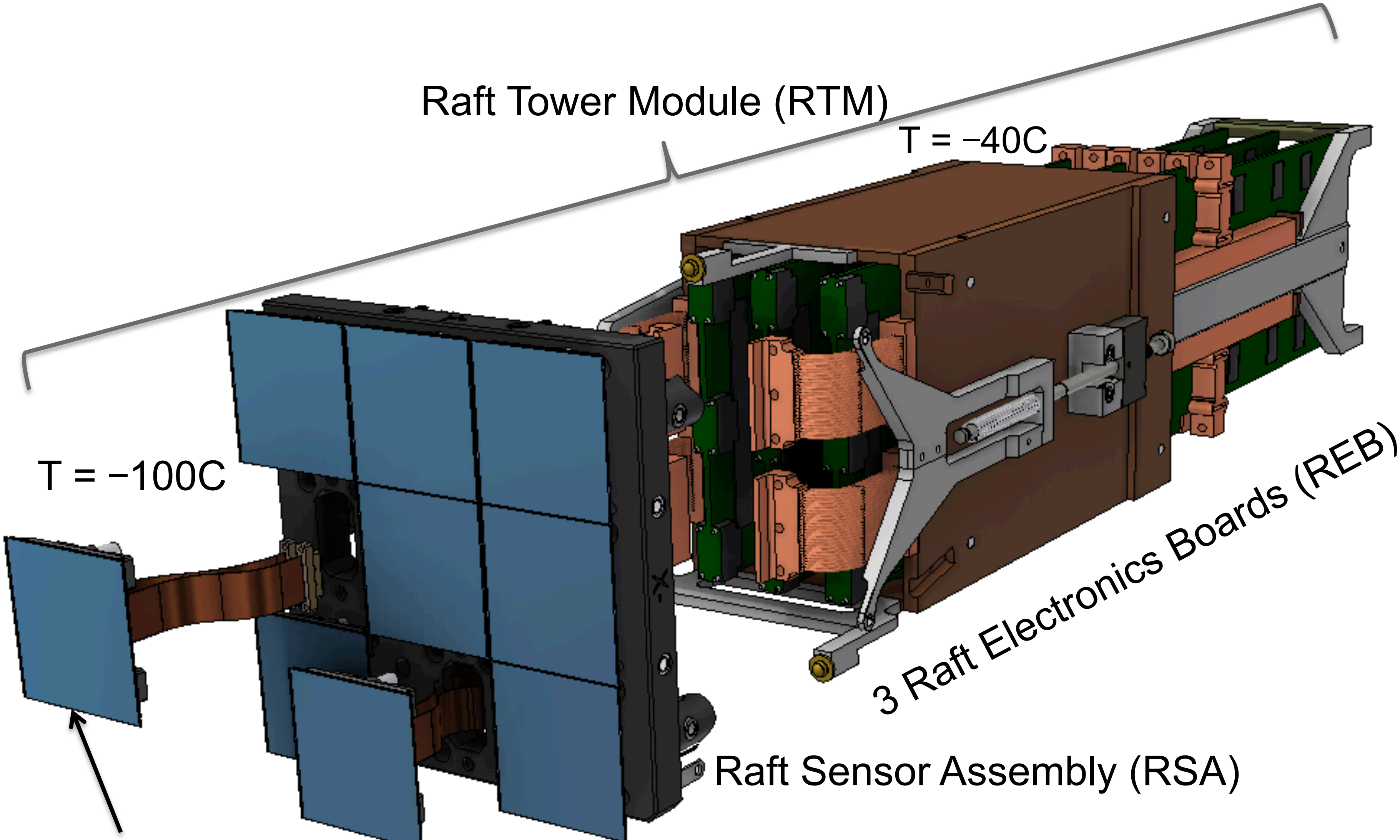


- **Galaxies have distinct spectra, with characteristic features at known rest wavelengths.**
- **Accurate redshifts can be obtained by taking spectra of each galaxy. But this is impractical for the billions of galaxies in LSST cosmic shear and BAO studies.**
- **Instead, the colors of the galaxies are 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**

21 science rafts, 189 4K x 4K CCDs

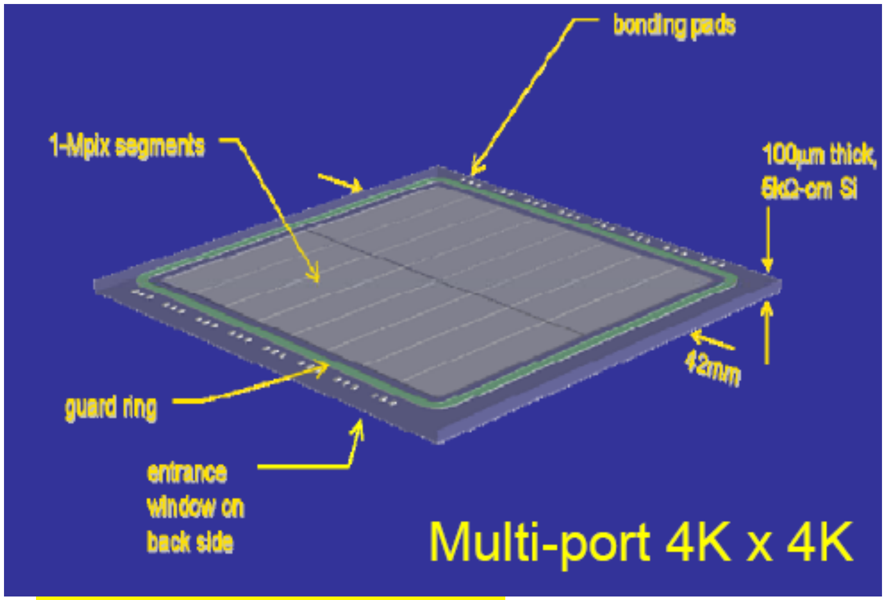


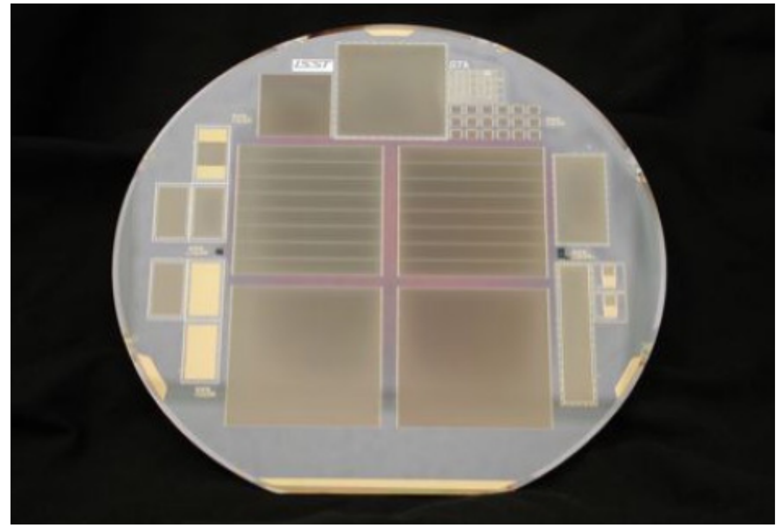
Science Raft Comprises 9 CCDs and associated electronics.



Individual sensor includes mechanical mount and flex cable
Each raft is a standalone 144 Mpix camera

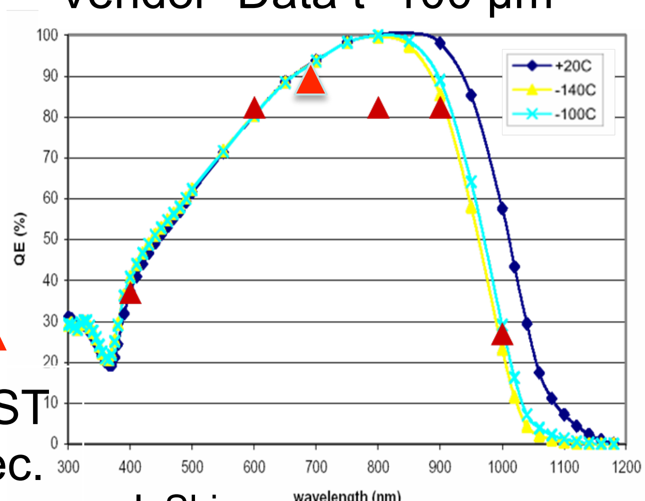
Focal Plane Sensors Quantum Efficiency





Quantum Efficiency

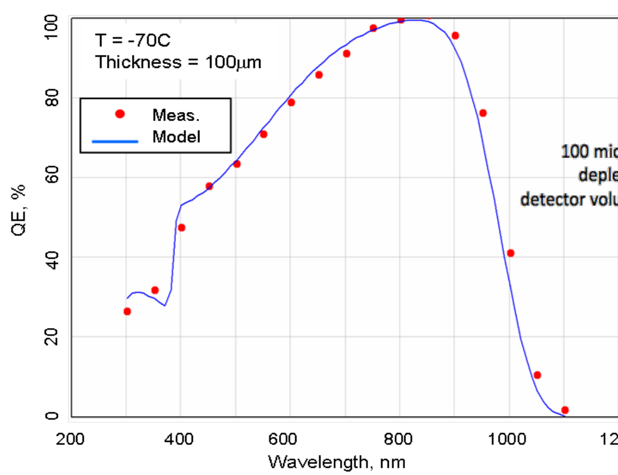
Vendor Data t=100 µm

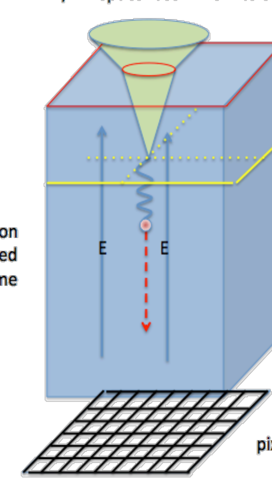


LSST spec.

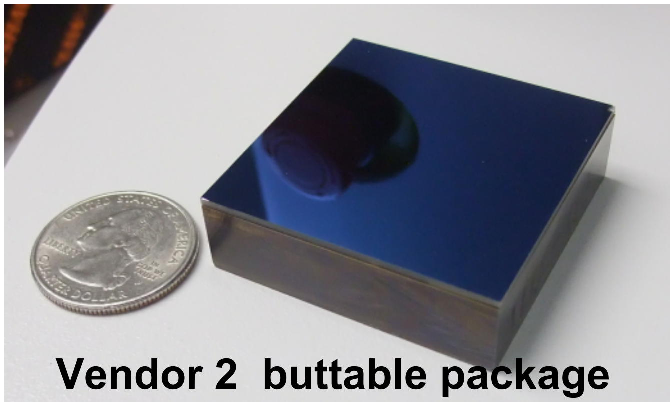
I. Shipsey

LSST (BNL) DATA

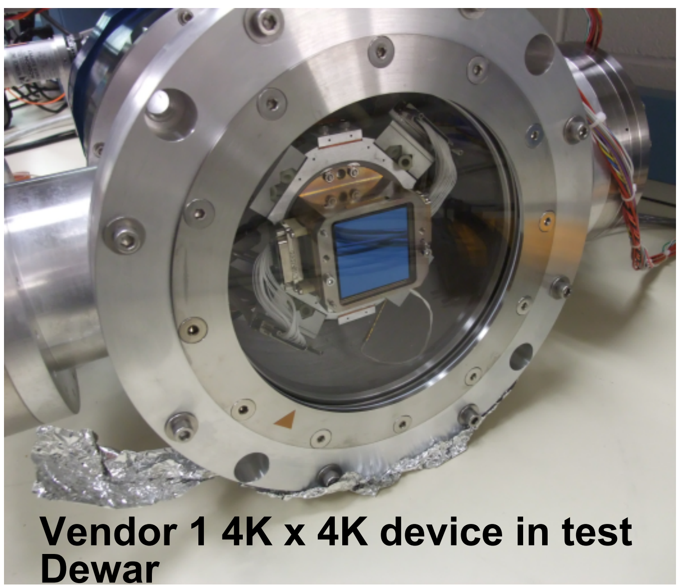




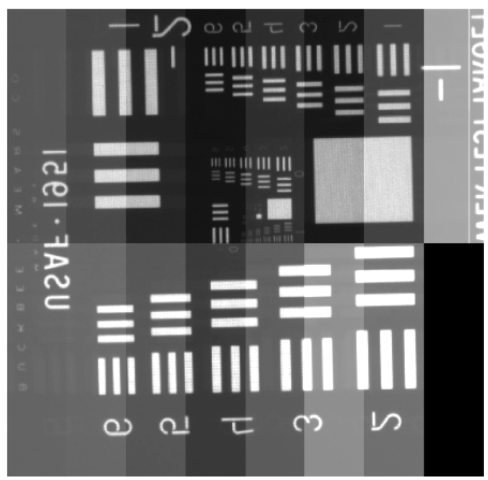
The LSST sensors have been tested on-the sky



Vendor 2 buttable package



Vendor 1 4K x 4K device in test Dewar



**also known as Calypso at Kitt Peak*

Sensors meet Requirements, Procurement is Under Way

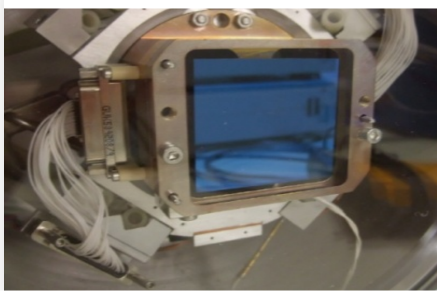
We have shown that we have LSST prototype sensors that meet project requirements.

The LSST sensors passed Final Design Review (FDR) in May 2013, second across this finish line after the primary mirror.

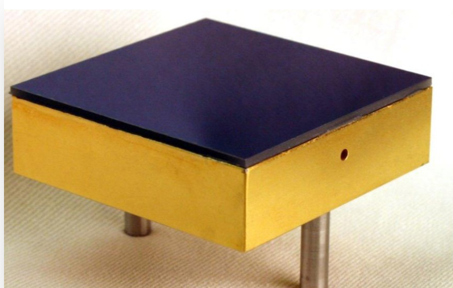
Sensor procurement is now under way, as these are long lead items.

Sensor delivery rate is the critical path pacing item for the LSST camera.

prototype, vendor 1



prototype, vendor 2

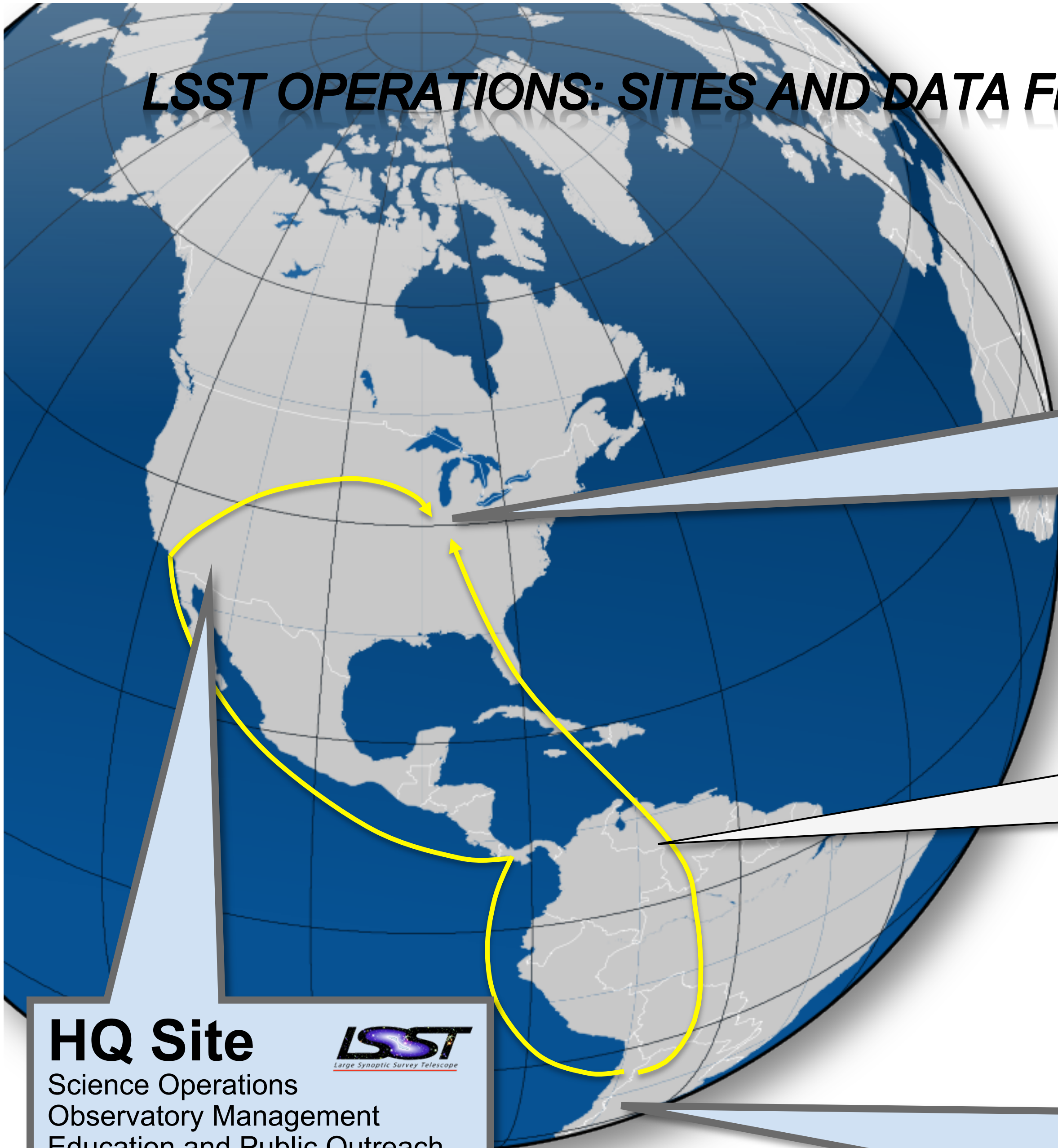


compliance matrix

	Number	Specification	Value	Unit	No. Tested/Passe	Result
ARCHITECTURE	CCD-001	Format	Design Consideration		ALL	-
	CCD-002	Pixel size	Design Consideration		ALL	-
	CCD-003	Segmentation	Design Consideration		ALL	-
	CCD-004	Contiguity	Design Consideration		ALL	-
ELECTRICAL	CCD-006	Read time	2	sec	9/9	tested at 545kpix/s
	CCD-007	Read noise	8	e- rms	6/0	7.8 ±1
					3/3	5.01 ±0.97
	CCD-008	Bloomed full well	175000	e- max	4/4	145000 ±17000
	CCD-009	Nonlinearity	±2	%	2/2	1.00 ±0.3
	CCD-010	Serial CTE	0.999995	-	1/1	0.999997
	CCD-011	Parallel CTE	0.999997		9/9	0.9999994
	CCD-012	Active area and cosmetics	99.5	% of 16.129M pixels	6/6	0.3± 0.3

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

LSST OPERATIONS: SITES AND DATA FLOWS



Archive Site

NCSA

Archive Center

Alert Production
Data Release Production
Calibration Products Production
EPO Infrastructure
Long-term Storage (copy 2)

Data Access Center

Data Access and User Services

Dedicated Long Haul Networks

Two redundant 40 Gbit links from La Serena to Champaign, IL (existing fiber)

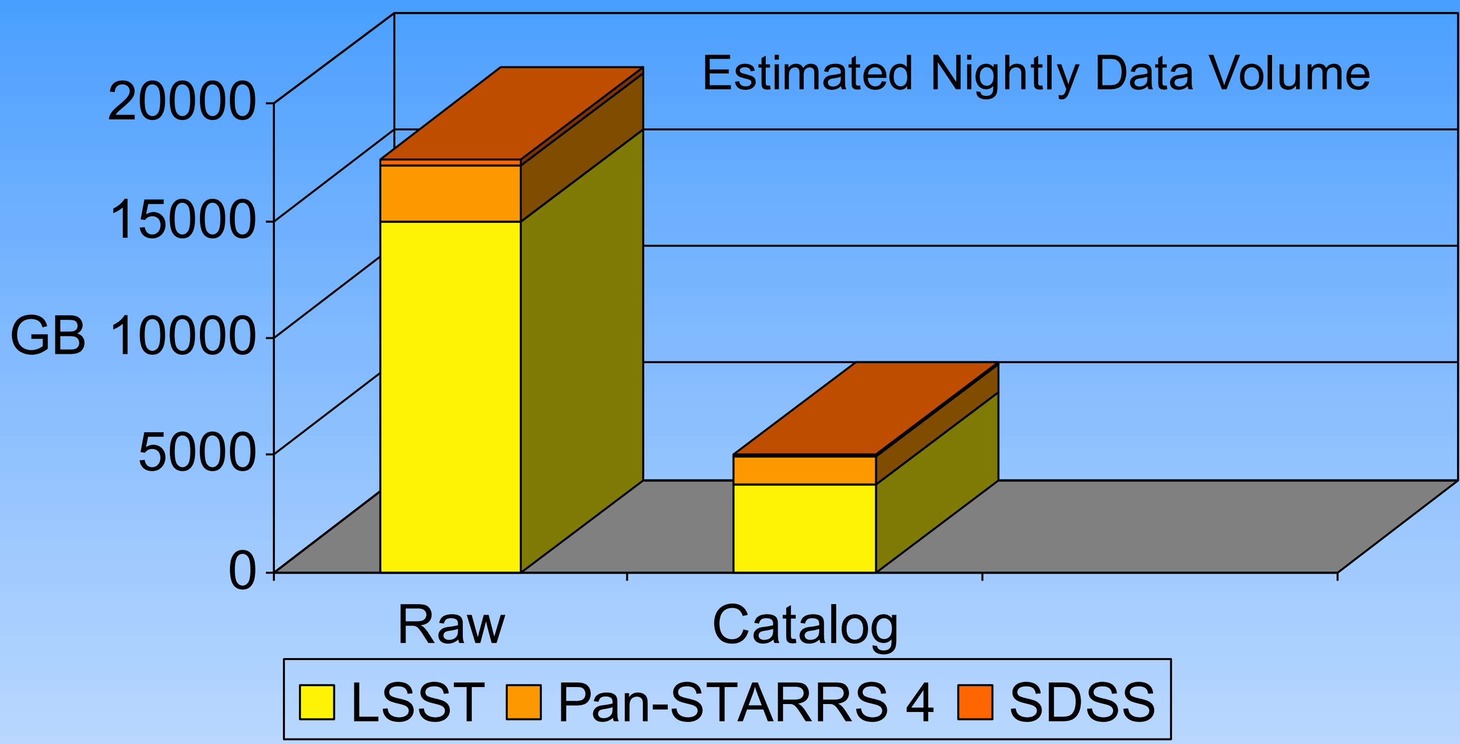
Summit and Base Sites

Telescope and Camera
Data Acquisition
Crosstalk Correction
Long-term storage (copy 1)
Chilean Data Access Center

HQ Site

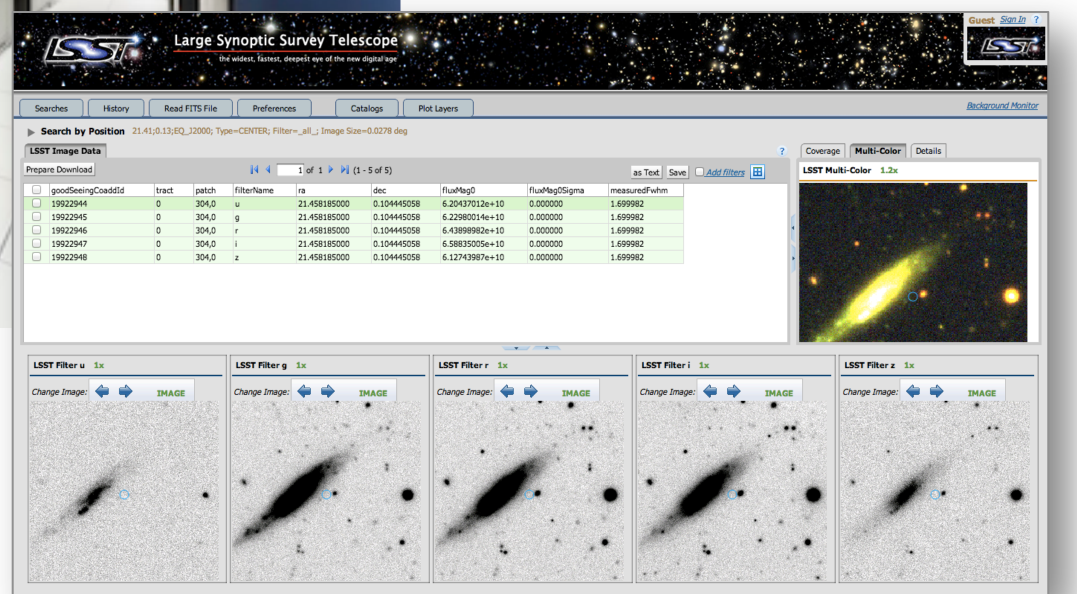
Science Operations
Observatory Management
Education and Public Outreach

Data volumes & rates are unprecedented in astronomy



Ultimate LSST Deliverable: Reduced Data Products

*A petascale supercomputing system at the **LSST Archive** (at NCSA) will process the raw data, generating reduced image products, time-domain alerts, and catalogs.*



***Data Access Centers** in the U.S. and Chile will provide end-user analysis capabilities and serve the data products to LSST users.*

LSST From the User's Perspective

- Images
- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Level1 1
Nightly

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations ("sources"), produced annually, accessible through online databases.
- Deep co-added images.

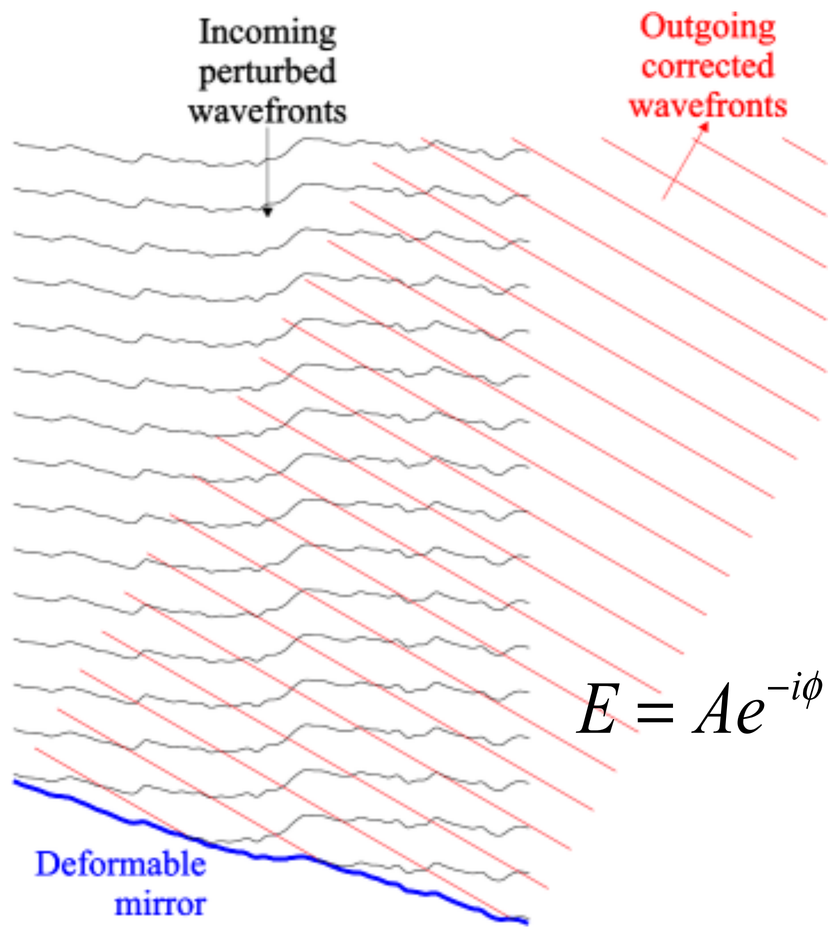
Level 2
Annual

- Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
- Software and Applications Programming Interfaces enabling development of analysis codes.

Level 3

Adaptive Optics and Active Optics

$$E = Ae^{i\phi}$$



$$E = Ae^{-i\phi}$$

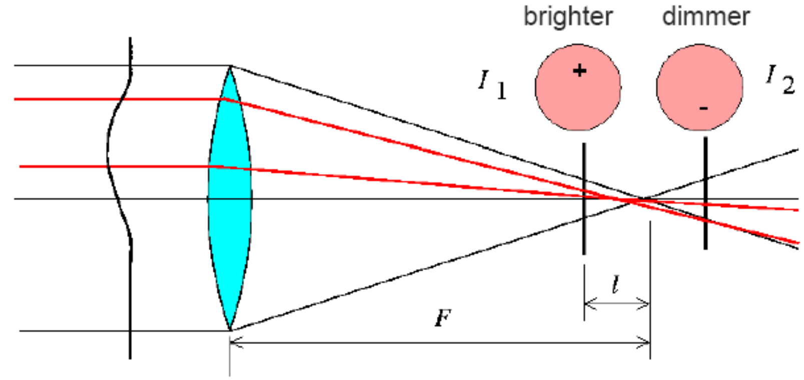
Adaptive Optics (Rapid 50-300Hz)
Limited to a small field of view
(LSST has a big field of view)

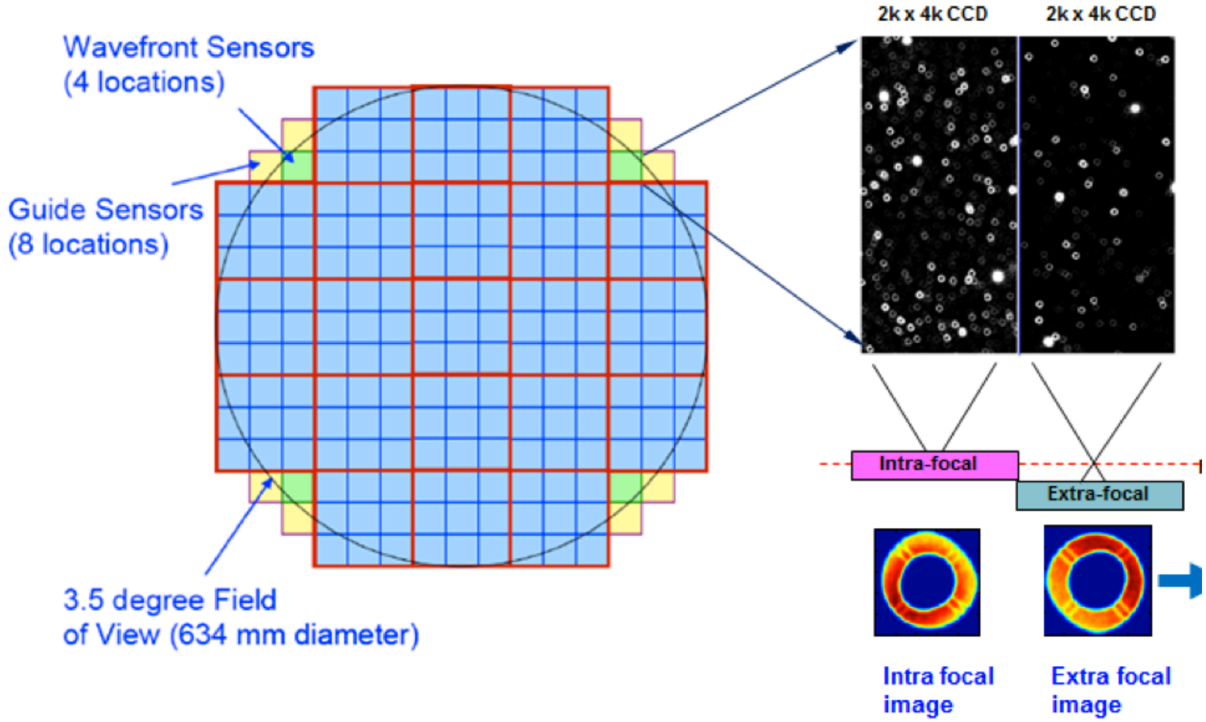
Active Optics (LSST)

* Measure perturbed wavefront to correct distortions in telescope and camera optics
* BUT Long-exposure sampling of wavefront to average atmospheric turbulence
* Telescope optical surfaces are adjustable between exposures to correct for distortions but remain static during each exposure

I. Shipsey

LSST Wavefront Sensing

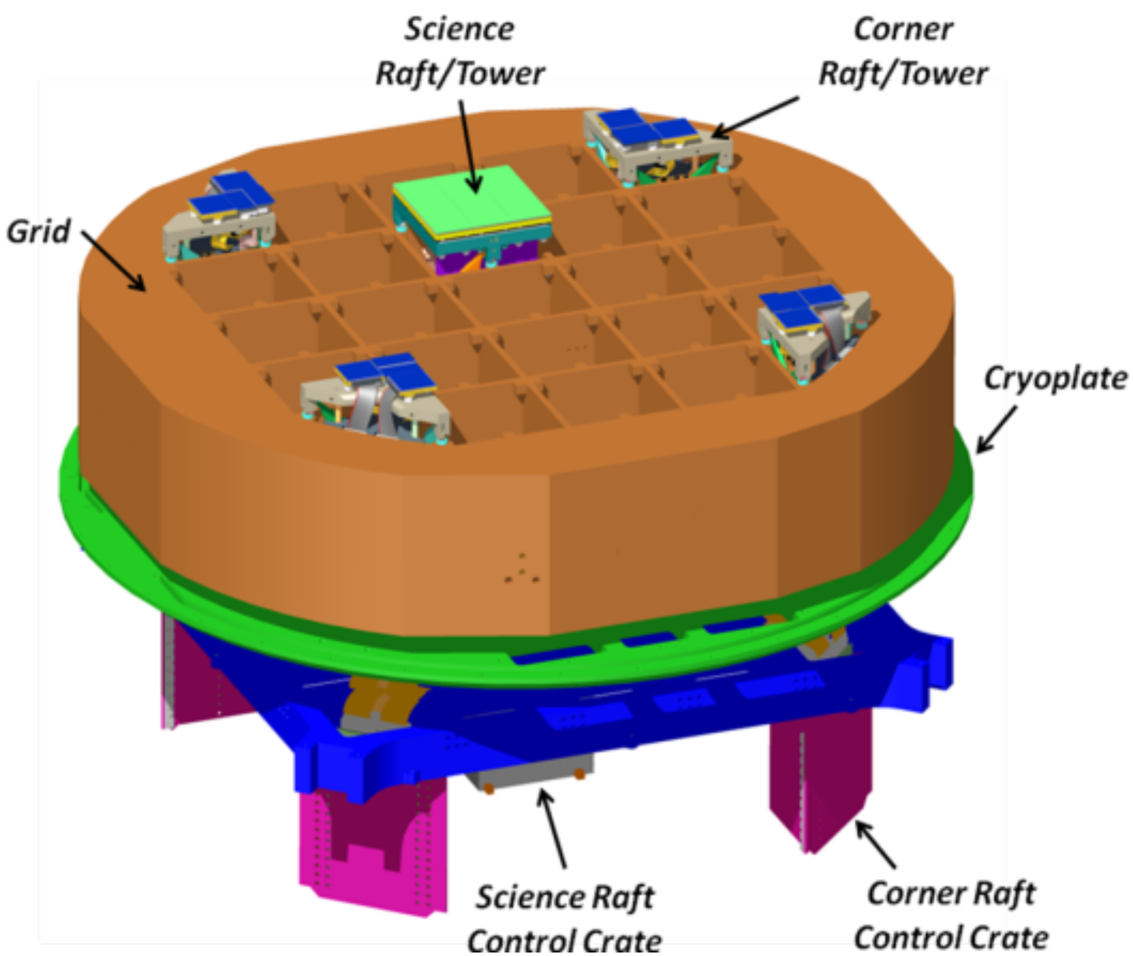




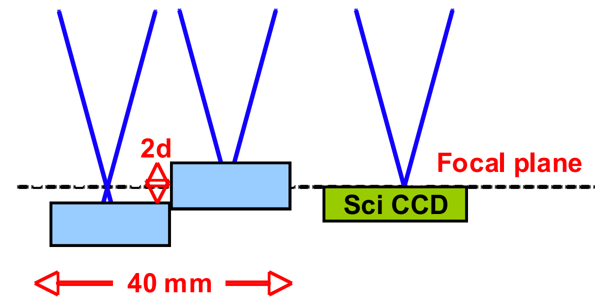
4 split sensors provide wavefront information

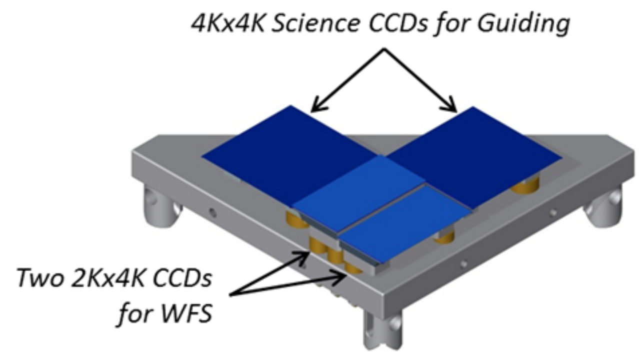
Purdue/NOAO

Wavefront Sensing Corner Rafts of LSST Camera



CCD Curvature Sensor



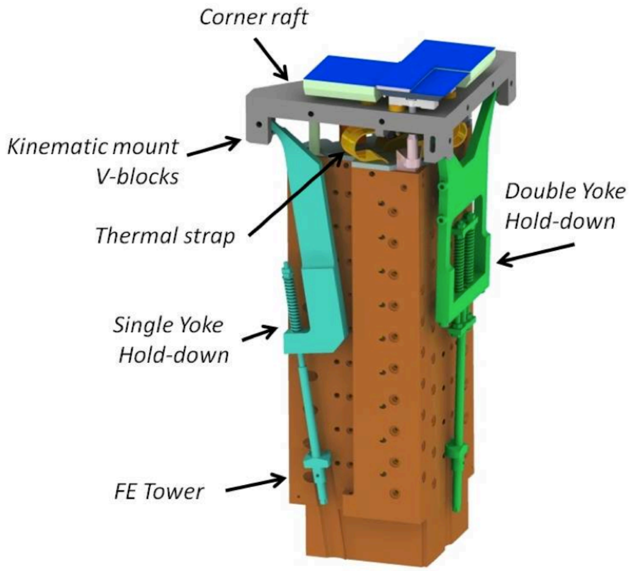


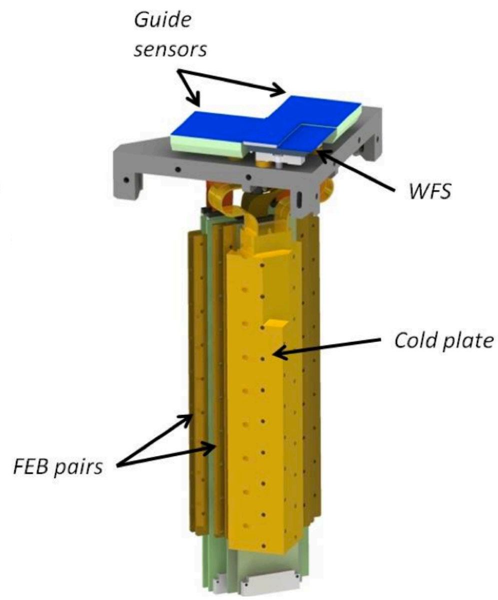
Purdue/NOAO

Corner Raft mechanical & thermal design work

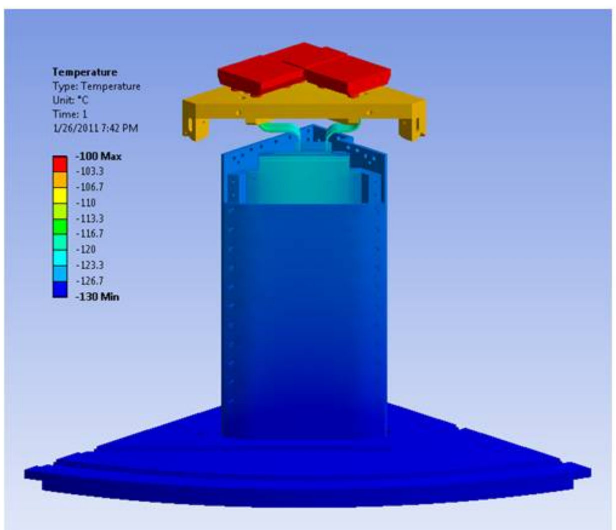
- **Design for accurate and stable mount for sensors and electronics in the Camera**
- **Assembly sequence & insertion tooling**
- **Mechanical & Thermal analysis (FEA & prototype tests)**
- **risk & cost analysis**

Purdue

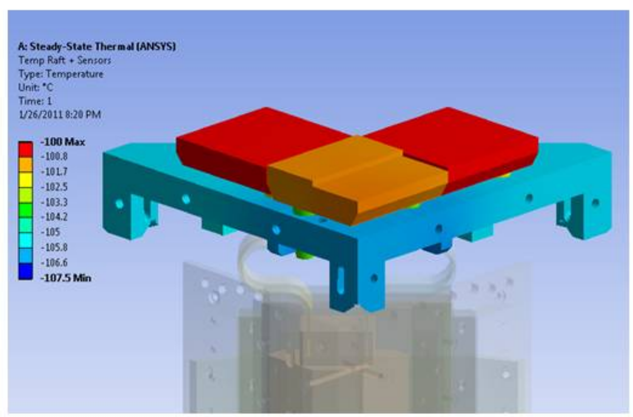




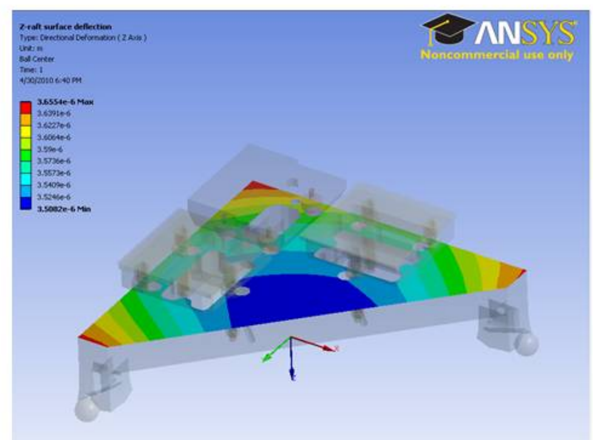
Overall FE model ΔT = 30C



ΔT across Corner Raft + sensors = 7.5C



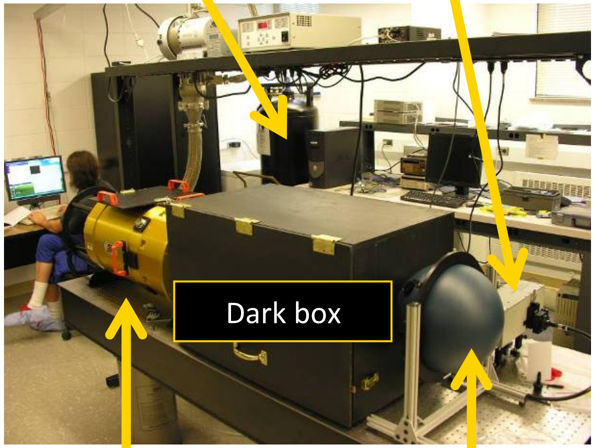
Corner Raft surface deformation <1 micron



Wavefront Reconstruction and Sensor Evaluation Station at Purdue

LN2 storage cylinder

monochrometer



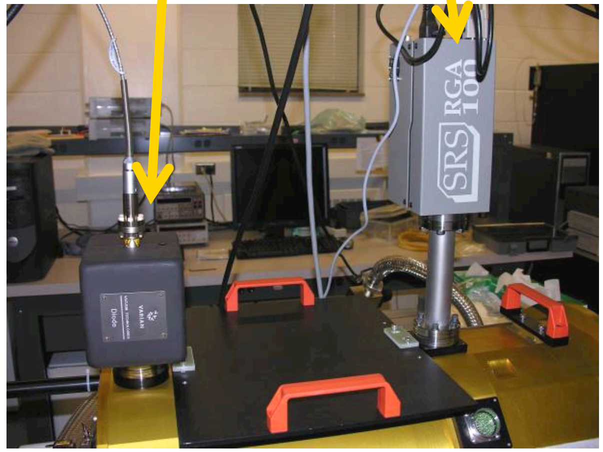
Dark box

Universal Cryogenics Dewar

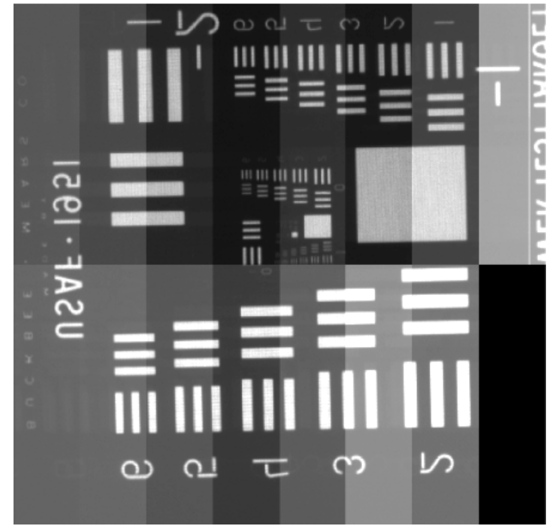
integrating sphere

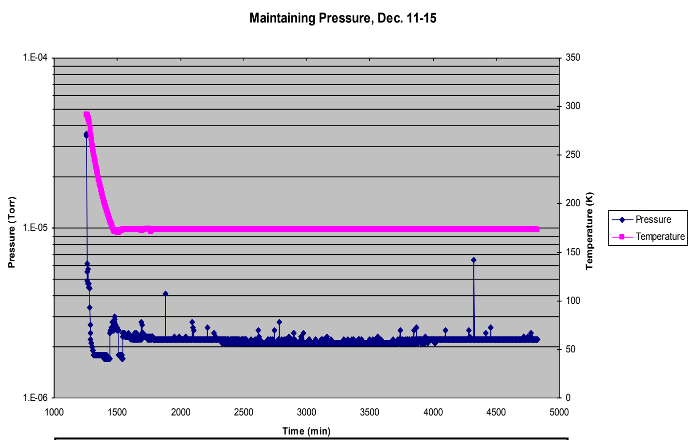
Ion Pump

RGA

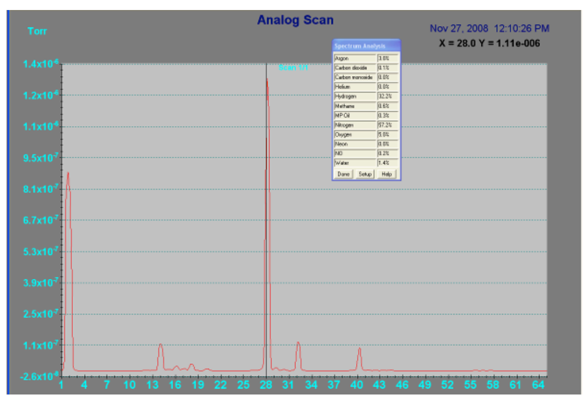


EXview HAD CDD Air Force target image





Pressure and temperature curve
LN2 + turbo + ion pumps



RGA scan

Status – all operational

- Cryostat (LN2 cooling + vacuum system)
- X-ray (Fe55) source
- Optical flat-field source
- Monochrometer
- Electronic shutter
- Camera lens + motion control

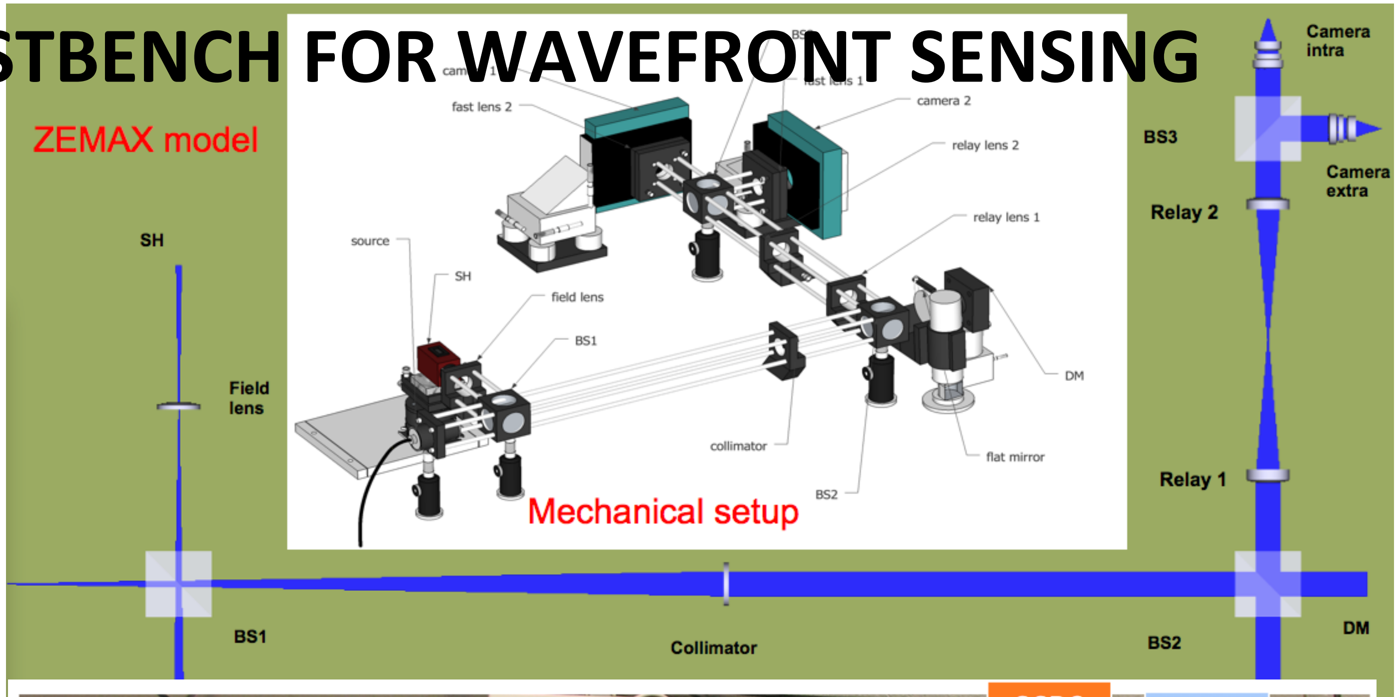
Purdue

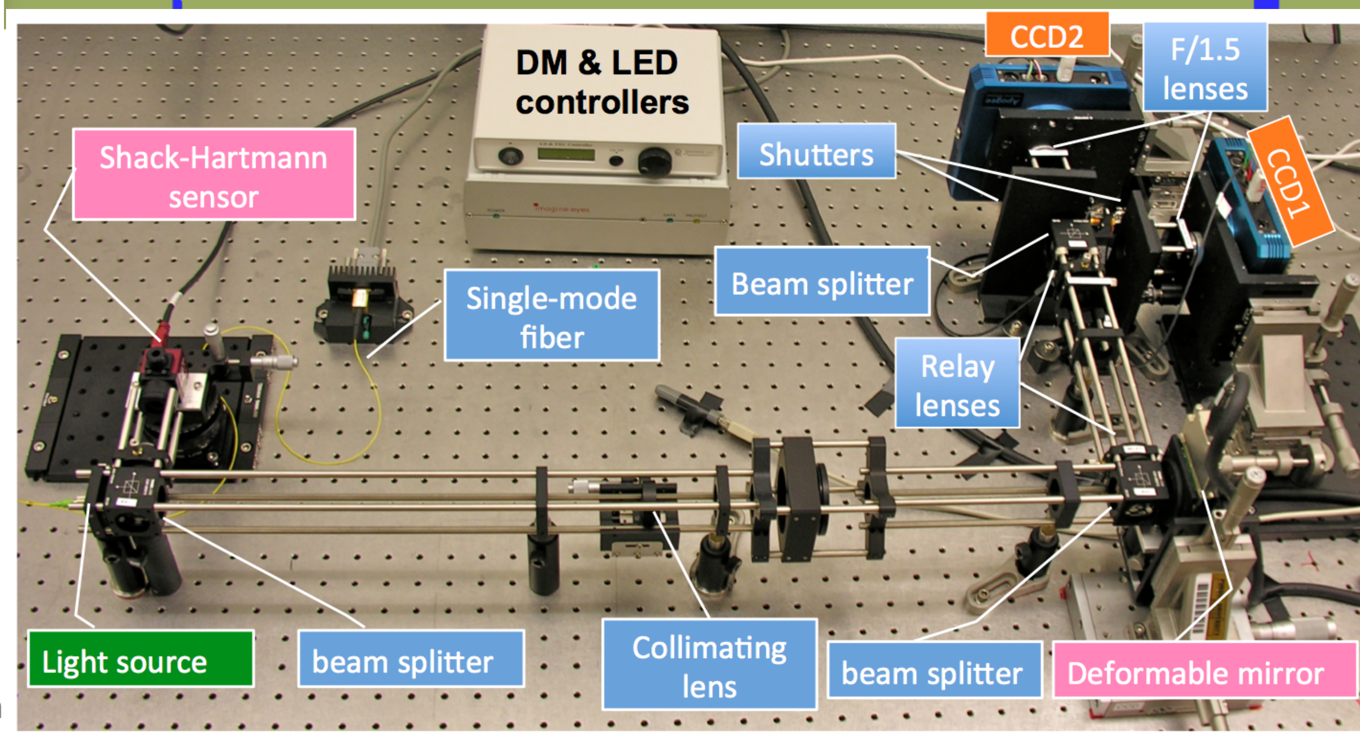
Initially configured for tests using single sensors for wavefront and guider studies.

The test station will be expanded to accommodate tests of a full Corner Raft/ Tower which will be fabricated @ Purdue

I. Shipsey

TESTBENCH FOR WAVEFRONT SENSING

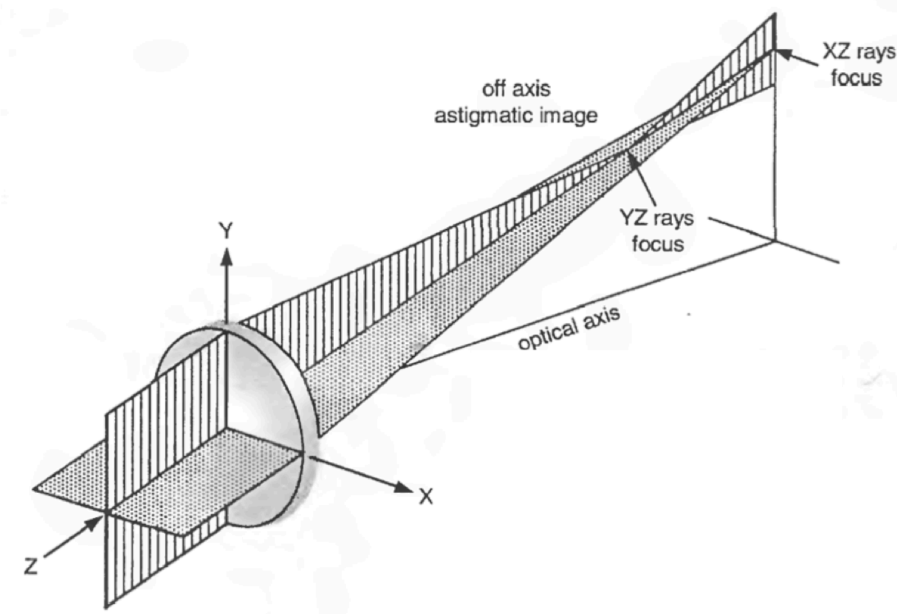




Purdue

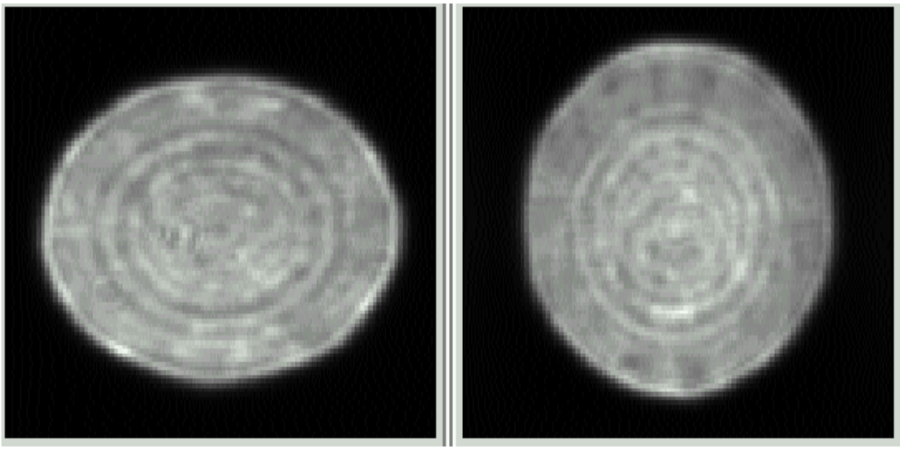
When 2um of x-axis astigmatism is dialed in to simulate a 2 micron distortion of the LSST primary mirror

Example

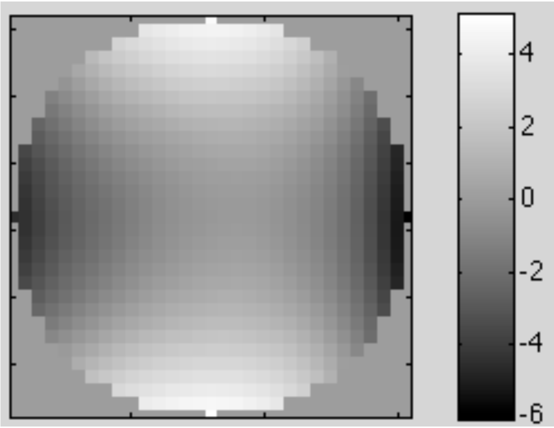


Intra-focal image
Z = -1mm

Extra-focal image
Z = +1mm



The two CCD images are used to Reconstruct the perturbed Wavefront . Fit it to get→



Unit: um

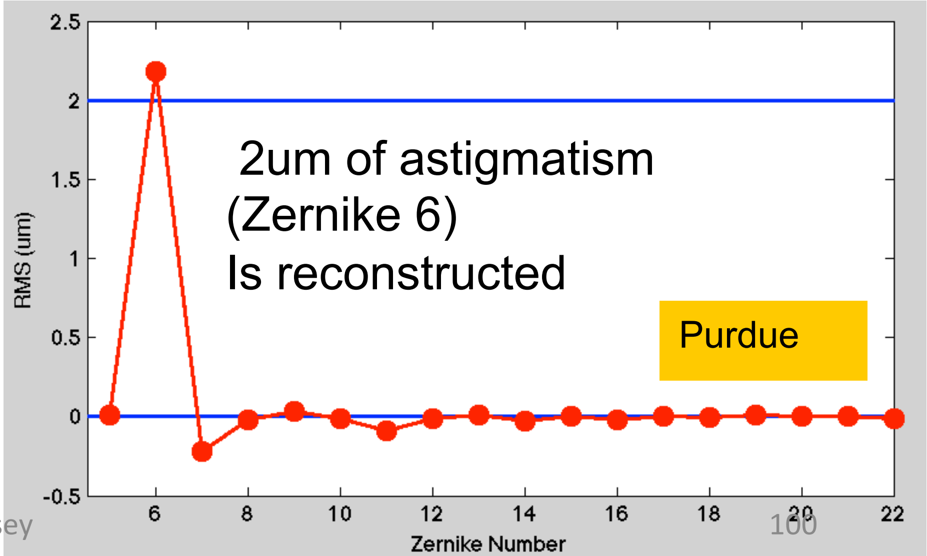
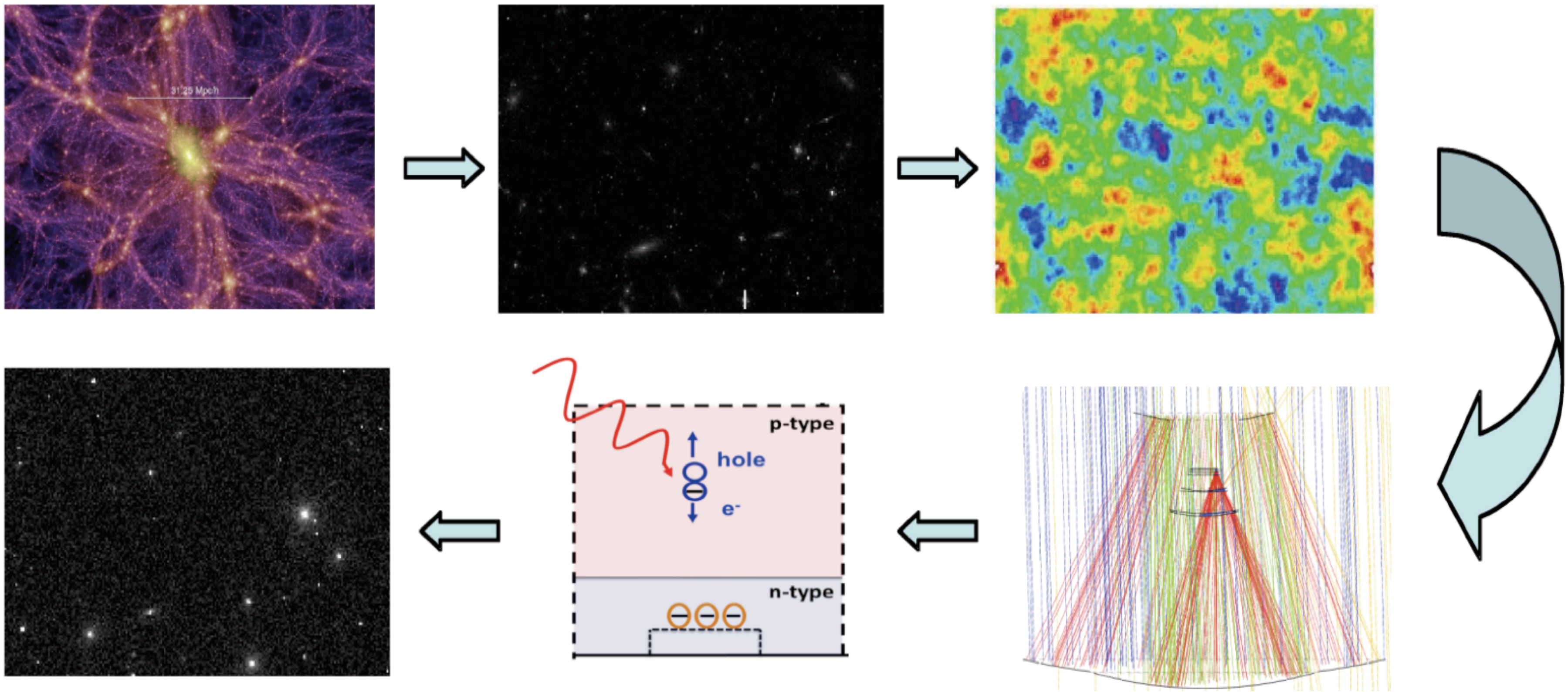


Image Simulation: Implementing a simulated sky

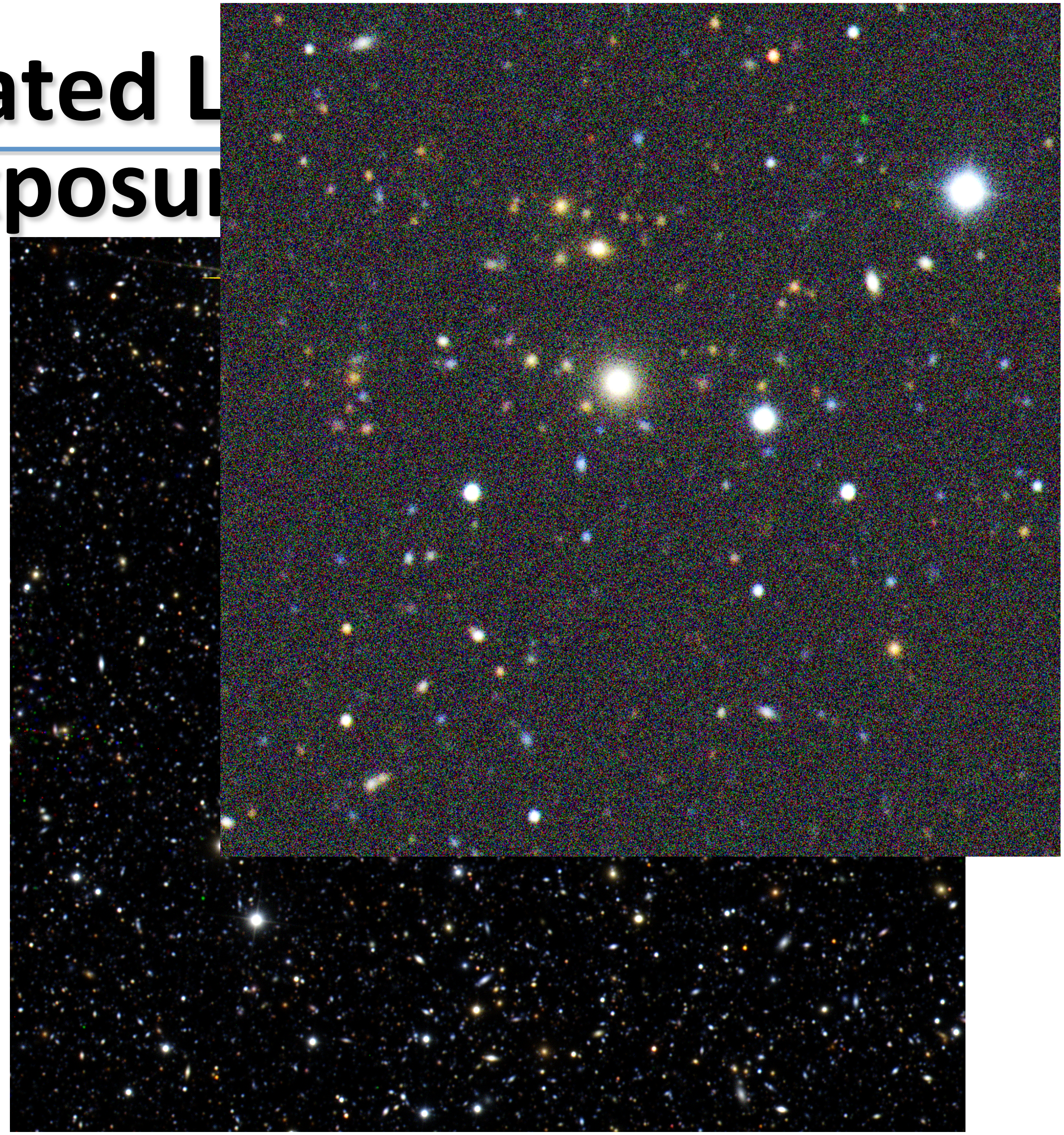


Following the photon flow…


Optics
+Tracking
+Diffraction
+Detector Misalignments & Perturbations
+Lens Misalignments
+Mirror Misalignments Perturbations, & Micro-roughness
+Detector
+High Altitude Atmosphere
+Mid Altitude Atmosphere
+Low Altitude Atmosphere
+Pixelization
20 x 20 pixels
+Saturation & Blooming

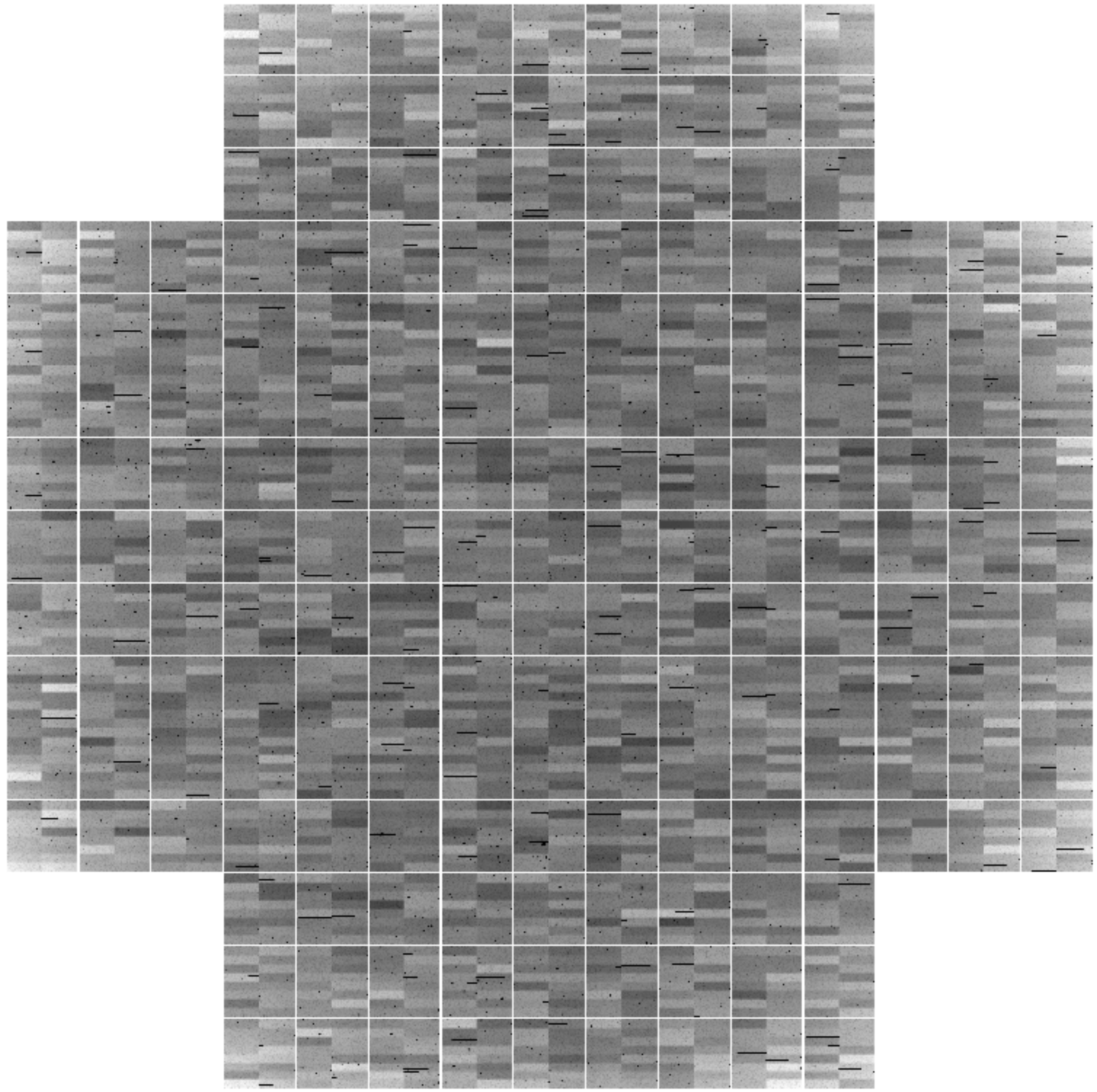
Simulated L
(one exposu

Three filter (gri) composite image of about 6’ on a side, (1800 pixels)
Area is 1/5 of a CCD
Or 10^{-3} of a single LSST image
Representing $5X\ 10^{-10}$ of the LSST data.
A single 15-sec exposure.



Simulation of full LSST focal plane

Simulation at the scale of LSST with the same cadence & similar Systematics Is a powerful Probe of Physics reach & survey design



LSST operations simulator

LSST Operations are determined by a special simulation program including real weather data, seeing, twilight, sky background (lunar), time to slew, overall survey coverage + and depth already achieved ➔ ranking algorithm for next observation (constantly updated) results in the visits per patch of sky (color coded at right) for each of the six filters for 10 year survey at right

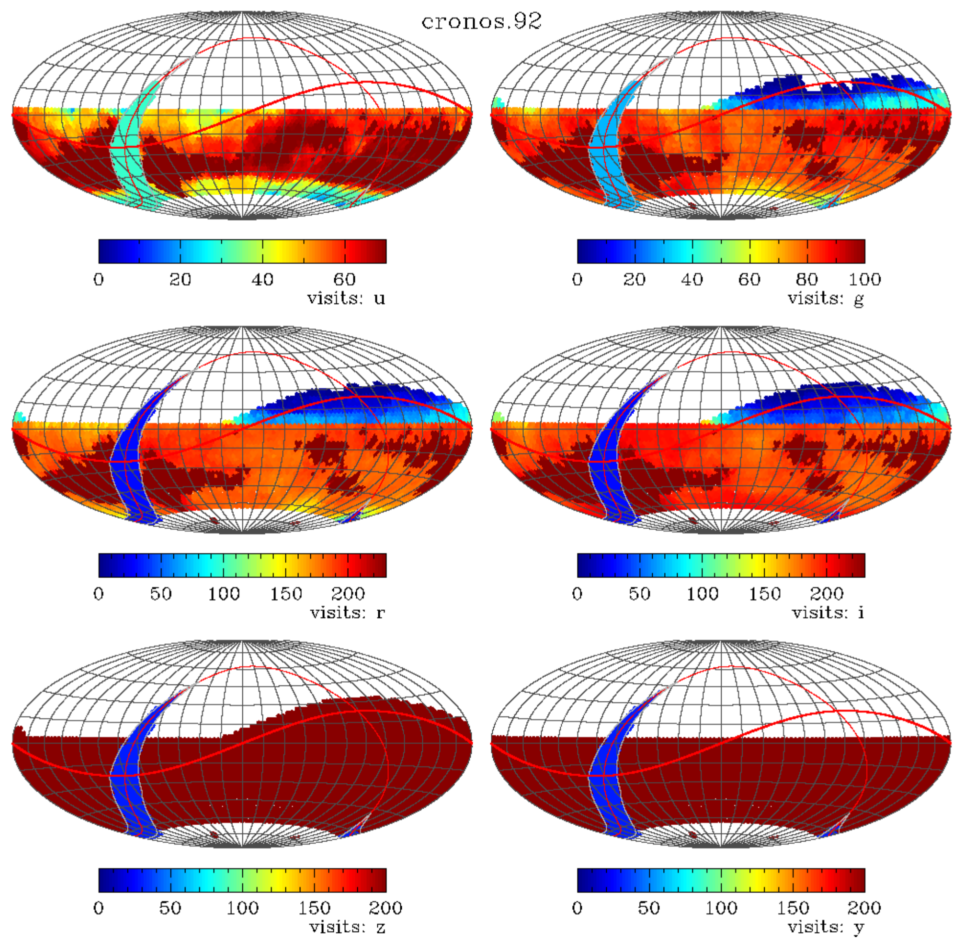
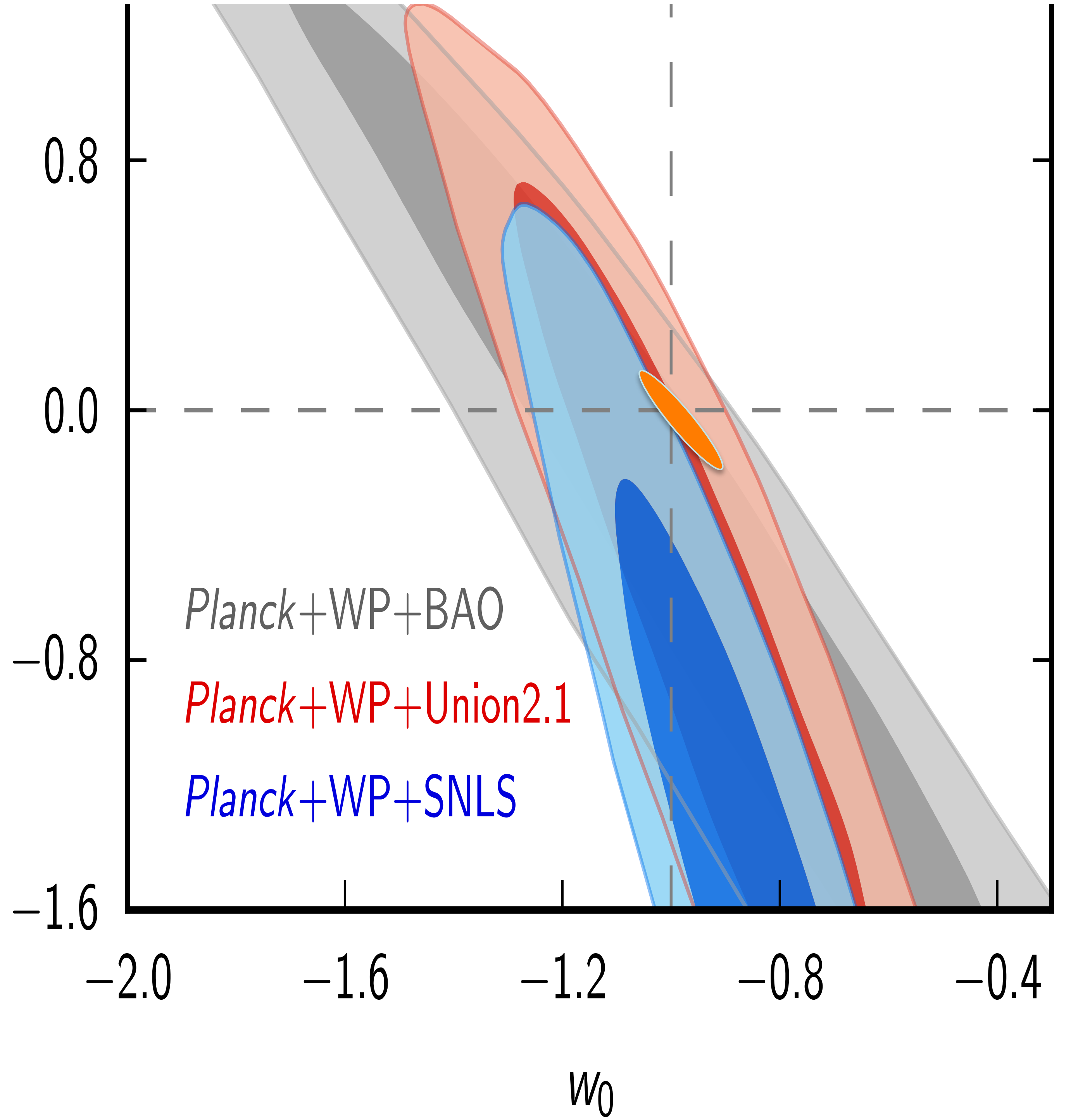


Figure : Visits numbers per field for the 10 year simulated survey

I. Shipsey

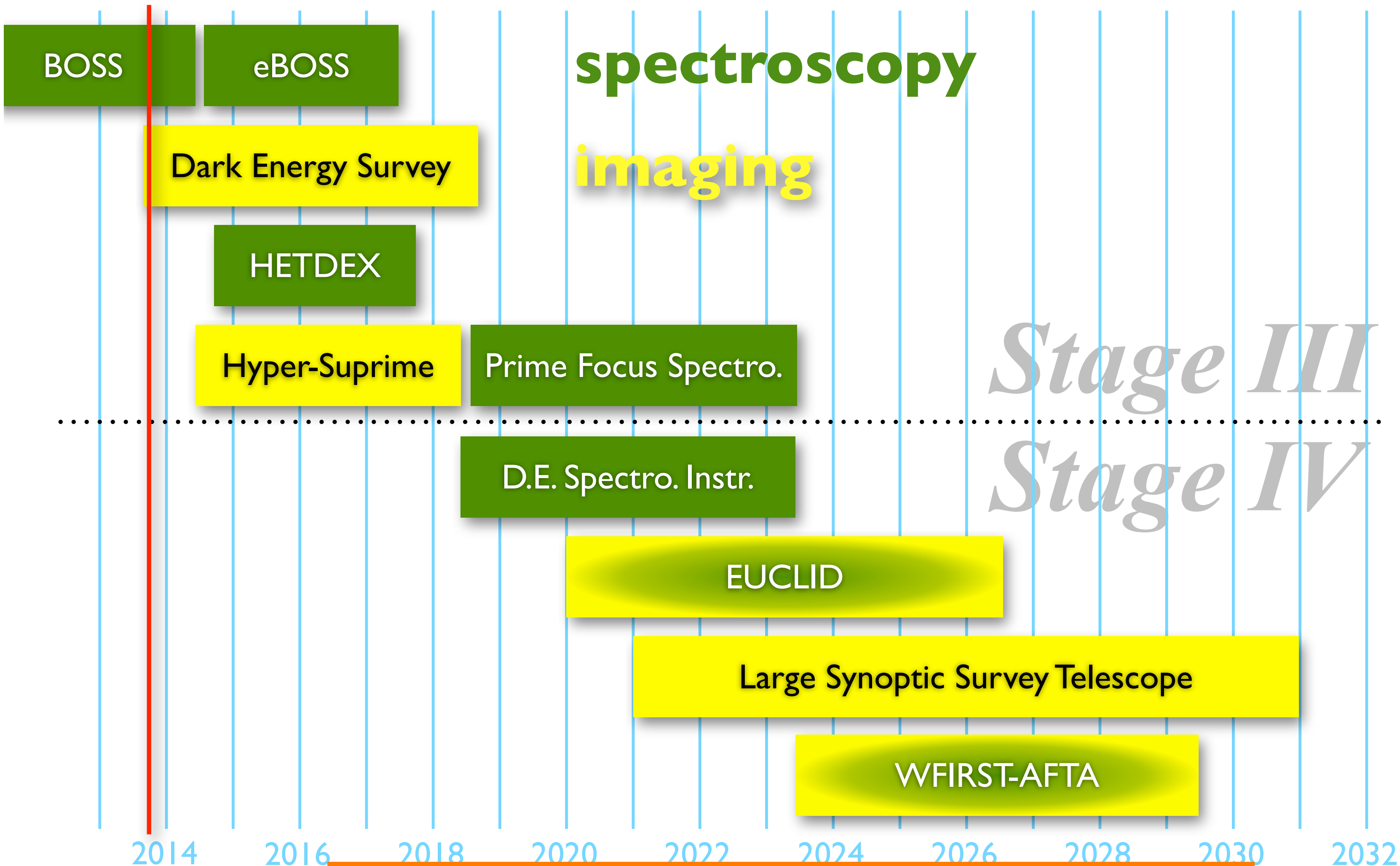
Predicted L
fr



Present state
of knowledge

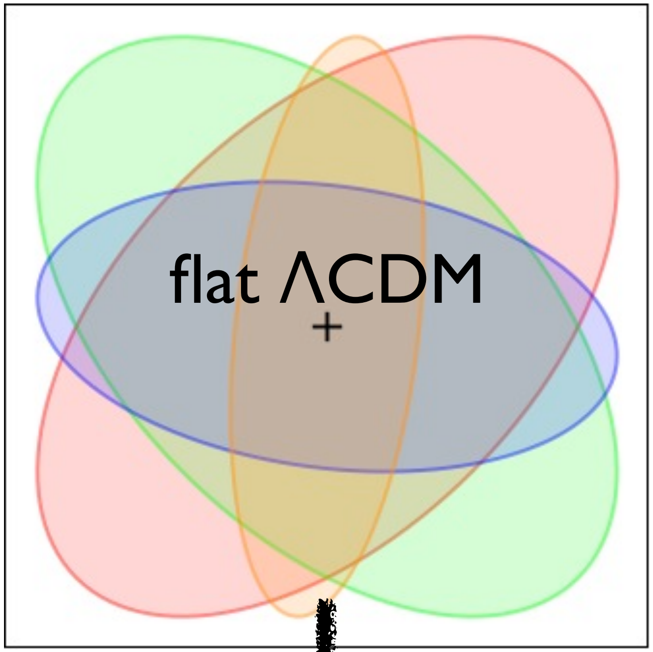
I. Ships

The dark energy facilities roadmap



High degree of complementary between missions

I. Shipsey



Stage III

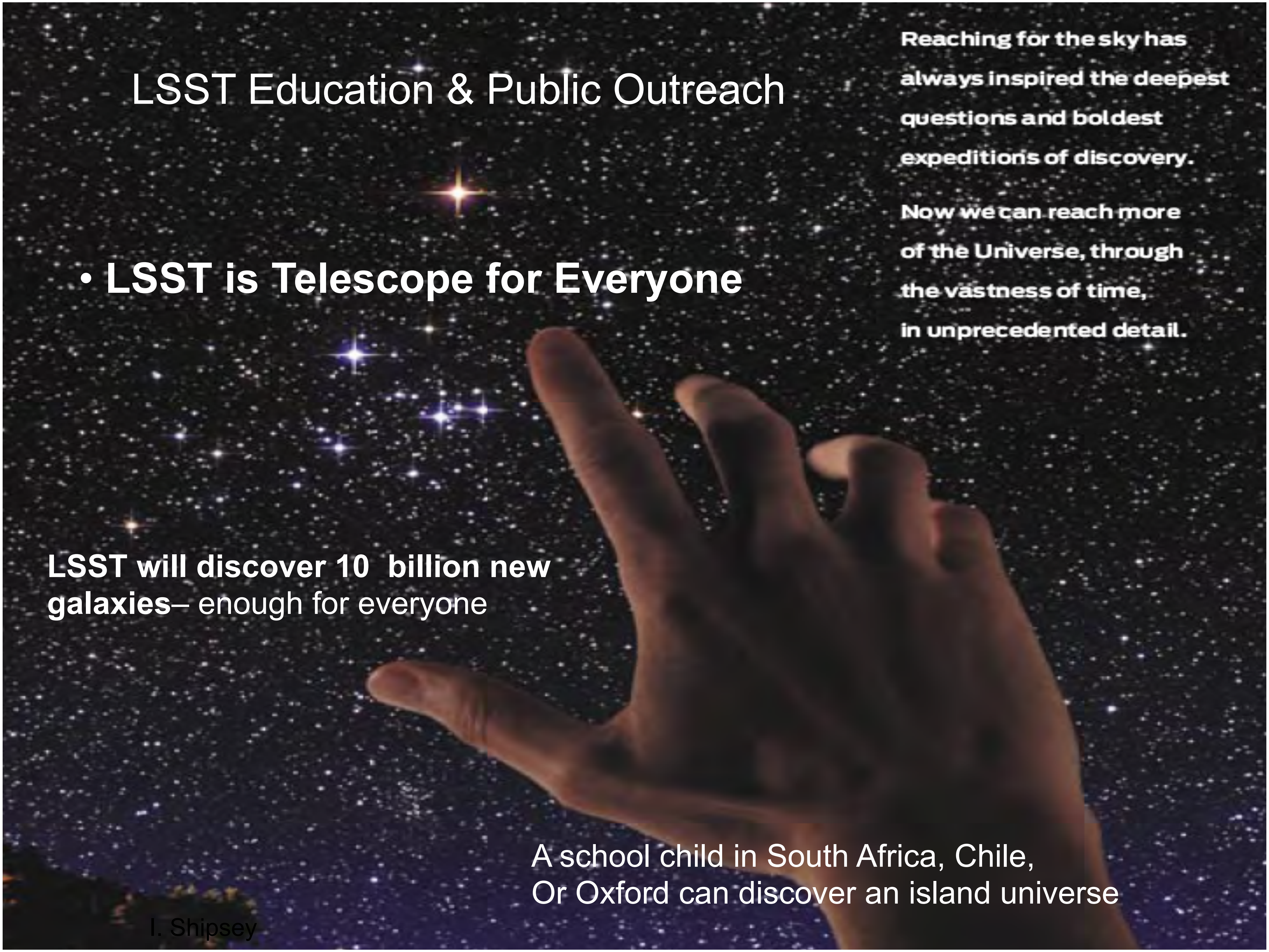
LSST
& other stage IV
experiments

LSST Outreach Data will be used in classrooms, science museums, and online

Classroom Emphasis on:

- Data-enabled research experiences
- Citizen Science
- College classes
- Collaboration through Social Networking

ZOONIVERSE
REAL SCIENCE ONLINE



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.

- **LSST is Telescope for Everyone**

LSST will discover 10 billion new galaxies– enough for everyone

A school child in South Africa, Chile,
Or Oxford can discover an island universe

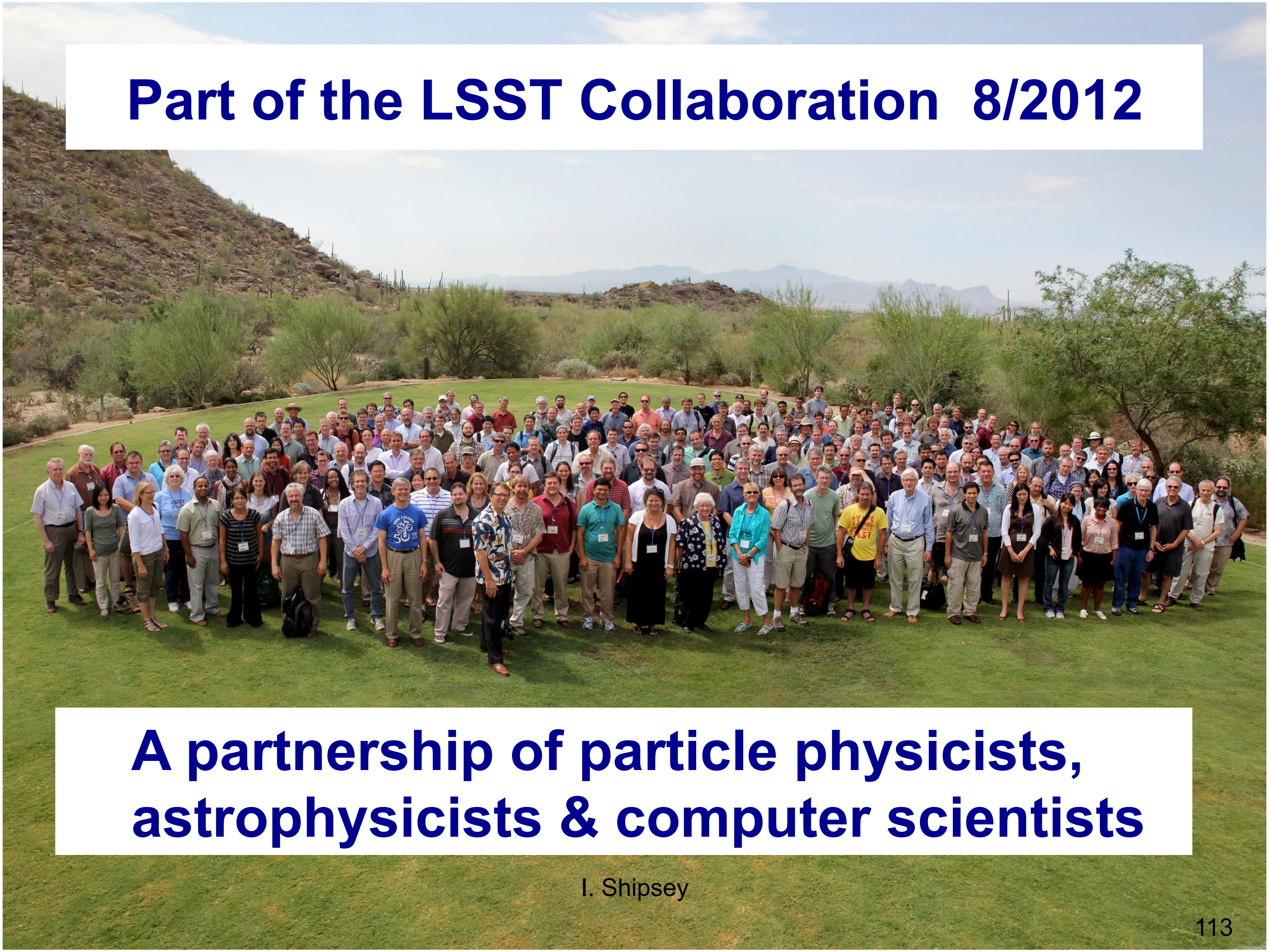
I. Shipsey

LSST Institutions

- The University of Arizona
- University of Washington
- National Optical Astronomy Observatory
- Research Corporation for Science Advancement
- Adler Planetarium
- Brookhaven National Laboratory (BNL)
- California Institute of Technology
- Carnegie Mellon University
- Chile
- Cornell University
- Drexel University
- Fermi National Accelerator Laboratory
- George Mason University
- Google, Inc.
- Harvard-Smithsonian Center for Astrophysics
- Institut de Physique Nucléaire et de Physique des Particules (IN2P3)
- Johns Hopkins University
- Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) - Stanford University
- Las Cumbres Observatory Global Telescope Network, Inc.
- Lawrence Livermore National Laboratory (LLNL)
- Los Alamos National Laboratory (LANL)
- Northwestern University
- Princeton University
- Purdue University
- Rutgers University
- SLAC National Accelerator Laboratory
- Space Telescope Science Institute
- Texas A & M University
- The Pennsylvania State University
- University of California at Davis
- University of California at Irvine
- University of Illinois at Urbana-Champaign
- University of Michigan
- University of Oxford
- University of Pennsylvania
- University of Pittsburgh
- Vanderbilt University

…LSST is growing other UK groups are in the process of joining as are many others from around the globe

Part of the LSST Collaboration 8/2012



A partnership of particle physicists, astrophysicists & computer scientists

Summary

- The Project Team is ready for a construction start in July 2014 to build the system to survey, store, process and serve the data starting in 2022

Acknowledgment

Sarah Bridle, Andy Connolly, Daniel Calabrese, Zelijko Ivezic, Mario Juric, Iain Goodenow, Steve Kahn, Jeff Kantor, Victor Krabbendam, David Kirby, Rob McKercher, Paul O'Connor Chris Stubbs, Jon Thaler, Tony Tyson, Sidney Woolf

The LSST Collaboration

At Purdue: Kirk Arndt, Mike Focosi, Bo Xin, Enver Alagoz, John Peterson
+ many undergraduates