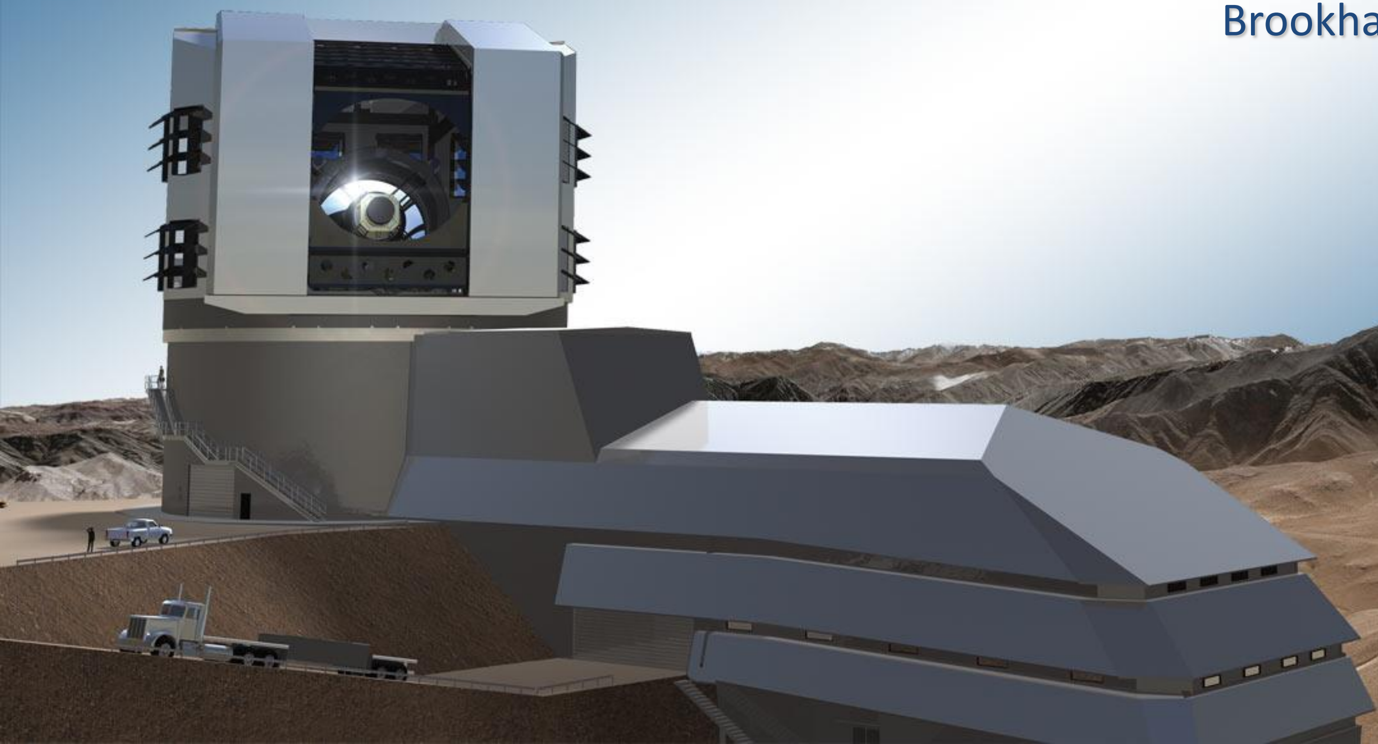
The LSST

Steven Bellavia
Principal Mechanical Engineer, LSST Camera Team
Brookhaven National Laboratory

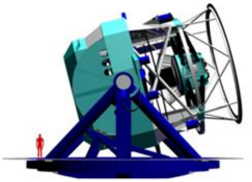
August 8th, 2017

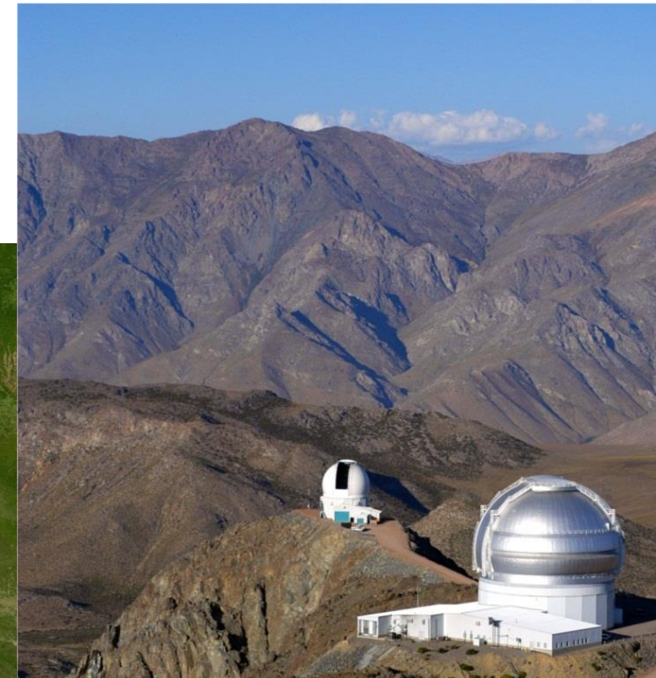


Large Synoptic Survey Telescope

The world's largest survey telescope with the largest digital camera ever built.

LSST Location





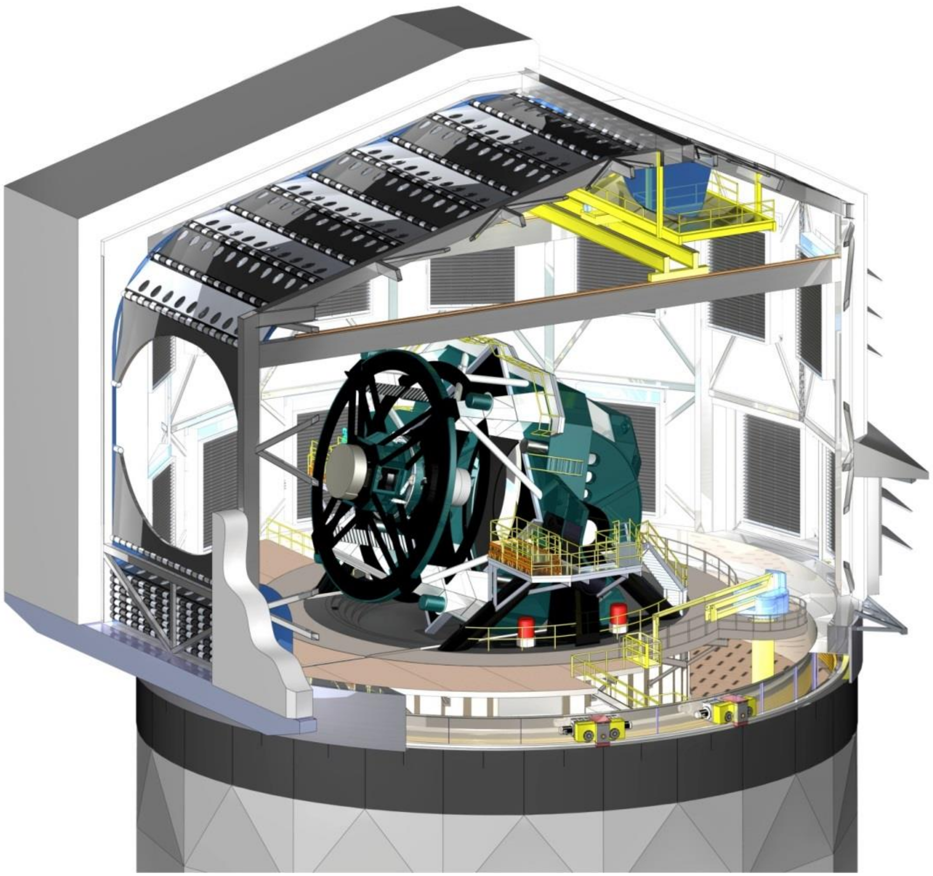
In the
Cerro Pachon
Ridge of Chile'
7000 feet
above sea level

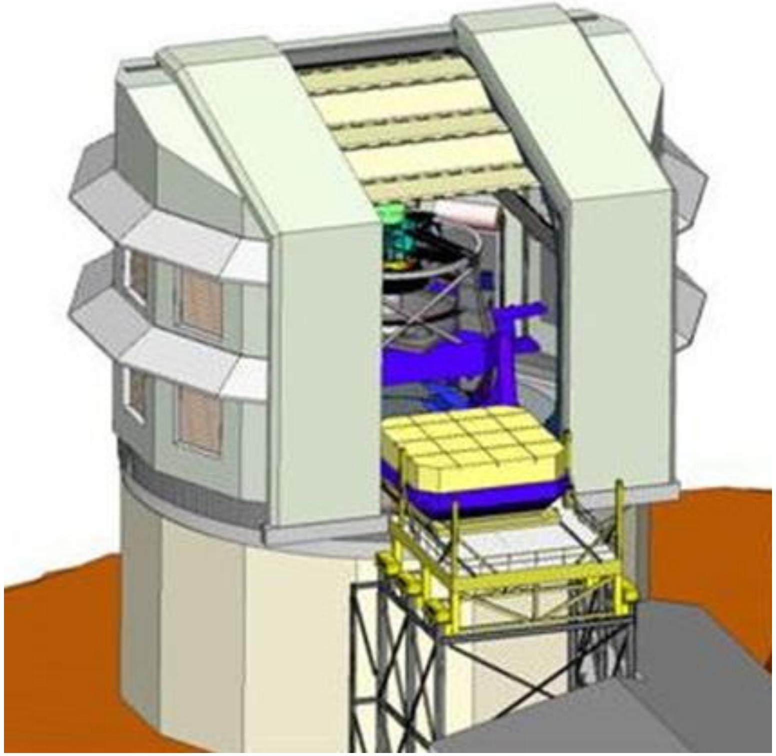
ESO,
Gemini ,
Slooh...

are all in
Chile'

BROOKHAVEN
NATIONAL LABORATORY

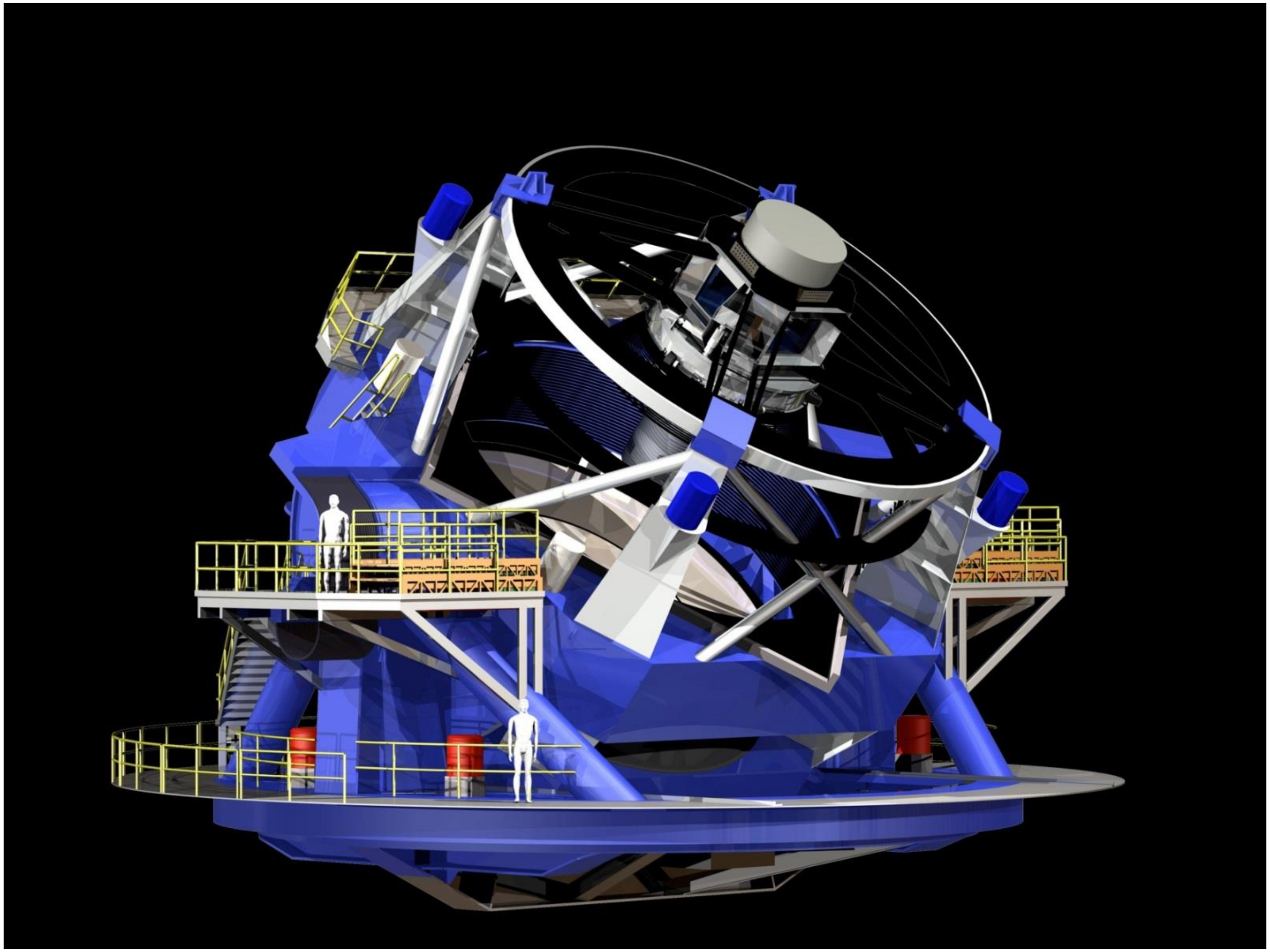
LSST – The Observatory





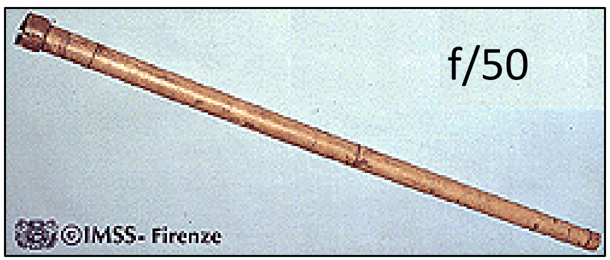
BROOKHAVEN NATIONAL LABORATORY

LSST – The Telescope

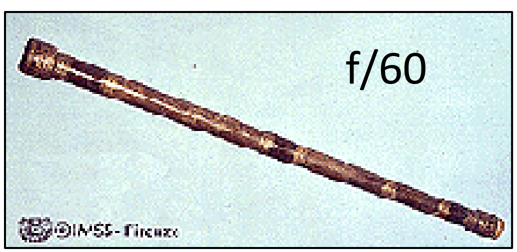


The First Astronomy Telescope

Galileo made and sold many telescopes. These were his two primary scopes

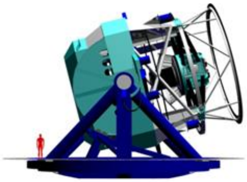


The longer scope had a 26mm aperture, focal length of 1330 and a 14 x magnification (-94mm eyepiece)

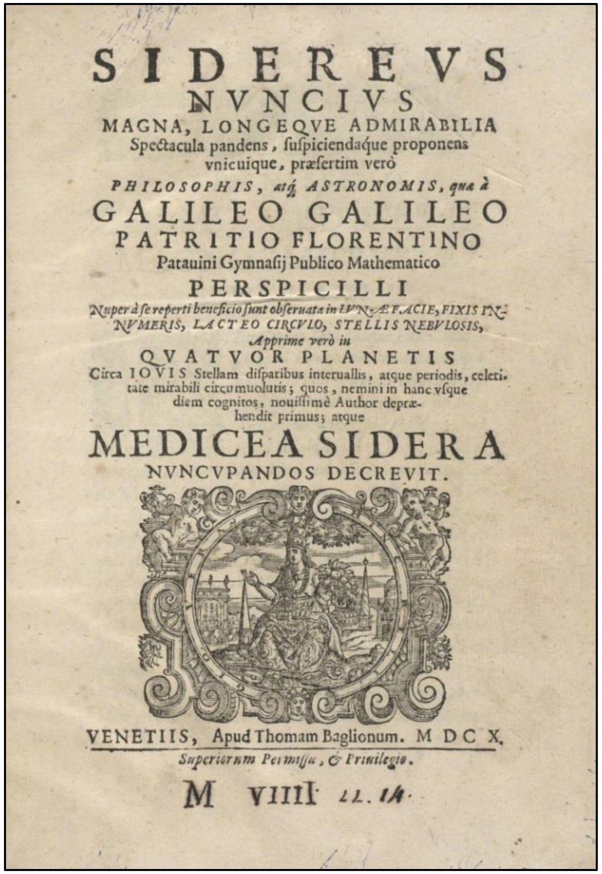


His shorter scope had an aperture of 37mm, but was **stopped down to 16mm**, with a 980 mm focal length and magnified 21X (-47.5mm eyepiece). He used this telescope to discover Jupiter's moons

BROOKHAVEN NATIONAL LABORATORY



Galileo Used an Aperture Stop



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M D C X.
Superiorum Permissu, & Priuilegio.

M VIIII 22.14

Sidereus Nuncius – "Starry Messenger"

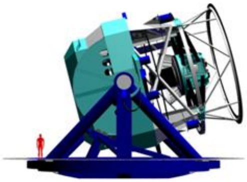
> *It would be better if the convex lens, which is the furthest from the eye, were in part covered, and that the opening which is left uncovered be of an oval shape, because in this manner it would be possible to see objects much more distinctly.*

LSST – The Telescope

Indeed, until the end of 1610 only telescopes made by Galileo were equipped with aperture stops. This is evident from a letter sent by Christopher Clavius (1538 – 1612) to Galileo in December 17, 1610, in which he inquired,

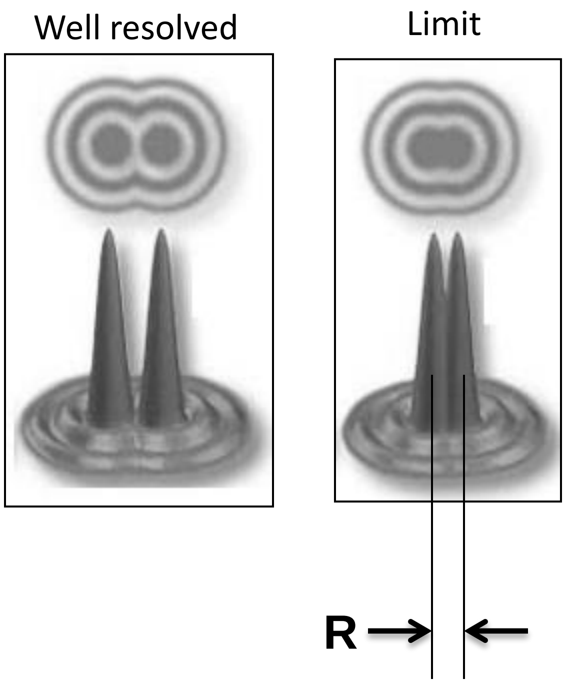
We have seen here in Rome some telescopes which you [Galileo] have sent, which had very large convex lenses covered so that a very small opening is left over. We would like to know what is the purpose for using such large lenses if they were partly covered? Some of us think that these lenses are made so large, so that the entire opening may be exposed at night, in order to better see the stars

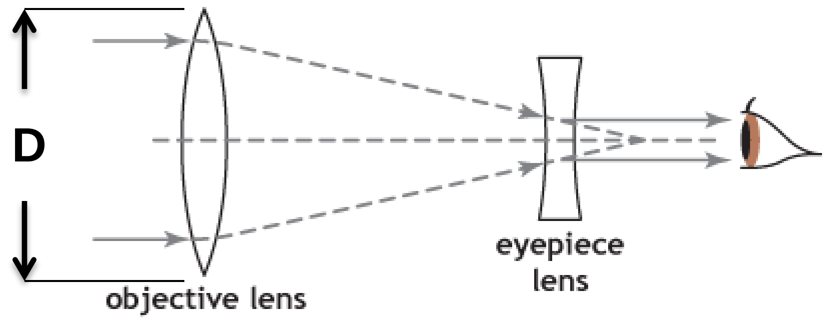
BROOKHAVEN NATIONAL LABORATORY



Resolution

Galileo did not know about Resolution





- Two objects, or features of one object, are said to be *just resolved* when the maximum of the first Airy pattern falls on top of the first minimum of the second Airy pattern.

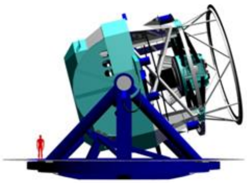
(The **Rayleigh** Criterion).

Spatial resolution, R

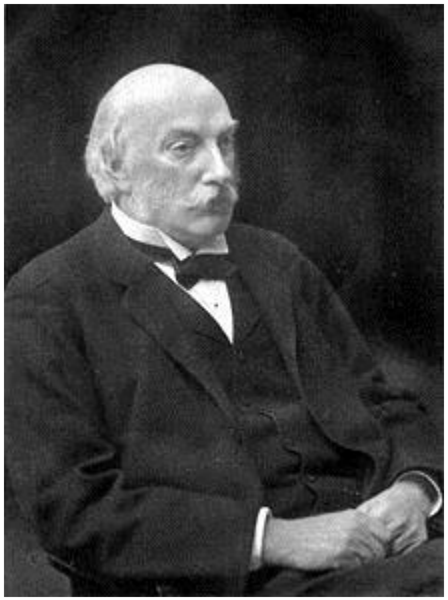
$$R = 1.22\frac{L\lambda}{D}$$

L Is the distance to the object
λ is the wavelength of light
D is lens aperture (diameter)

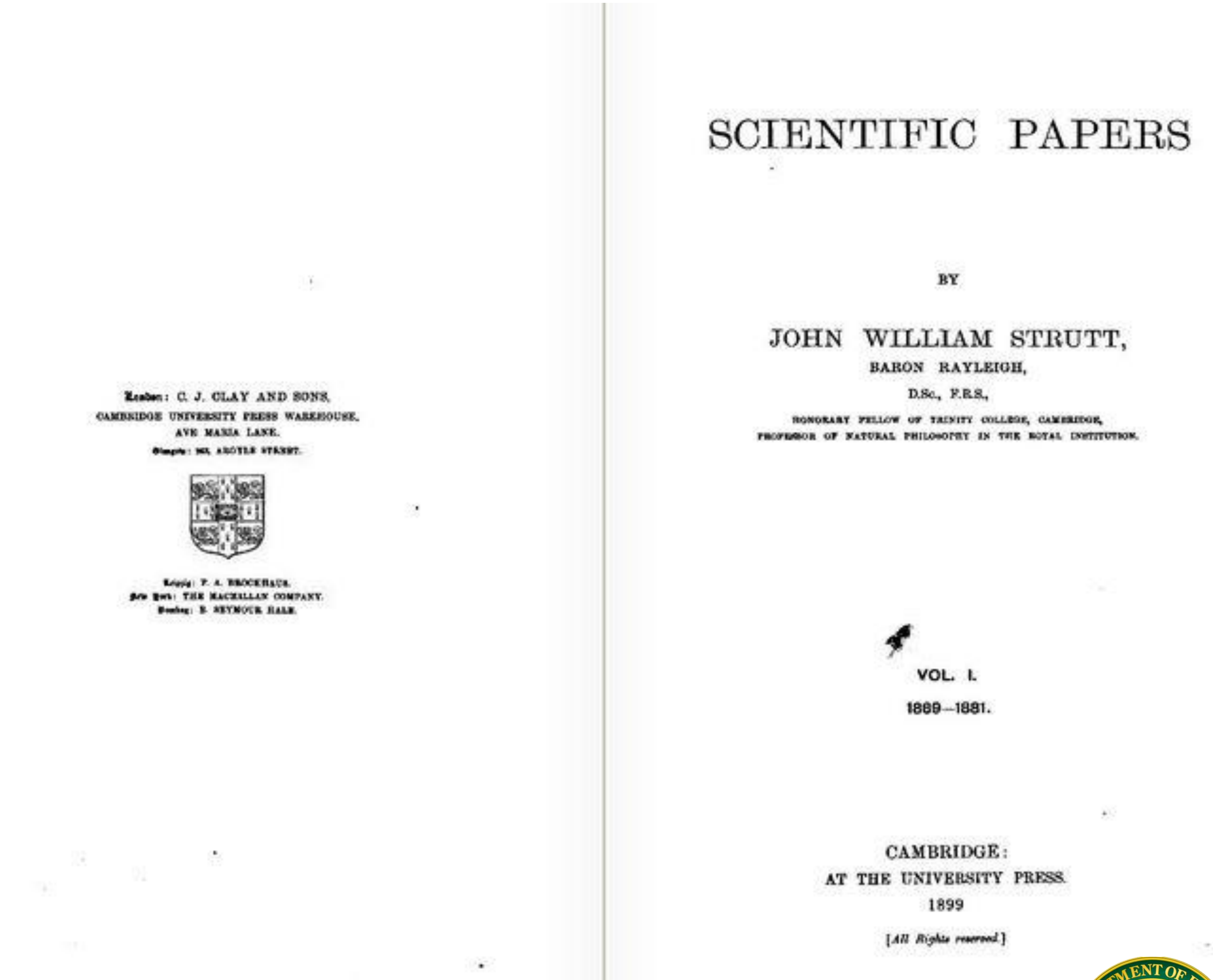
BROOKHAVEN NATIONAL LABORATORY



Rayleigh & Resolution



Lord Rayleigh
John William Strutt
1842 - 1919



London: C. J. CLAY AND SONS,
CAMBRIDGE UNIVERSITY PRESS WAREHOUSE,
AVE MARIA LANE.
Glasgow: 263, ARGYLE STREET.

Leipzig: F. A. BROCKHAUS.
New York: THE MACMILLAN COMPANY.
Bombay: E. SEYMOUR HALE.

SCIENTIFIC PAPERS

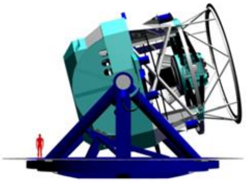
BY

JOHN WILLIAM STRUTT,
BARON RAYLEIGH,
D.Sc., F.R.S.,
HONORARY FELLOW OF TRINITY COLLEGE, CAMBRIDGE,
PROFESSOR OF NATURAL PHILOSOPHY IN THE ROYAL INSTITUTION.

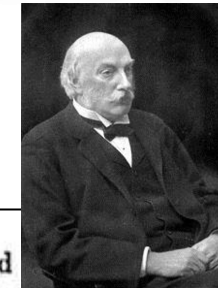
VOL. I.
1869—1881.

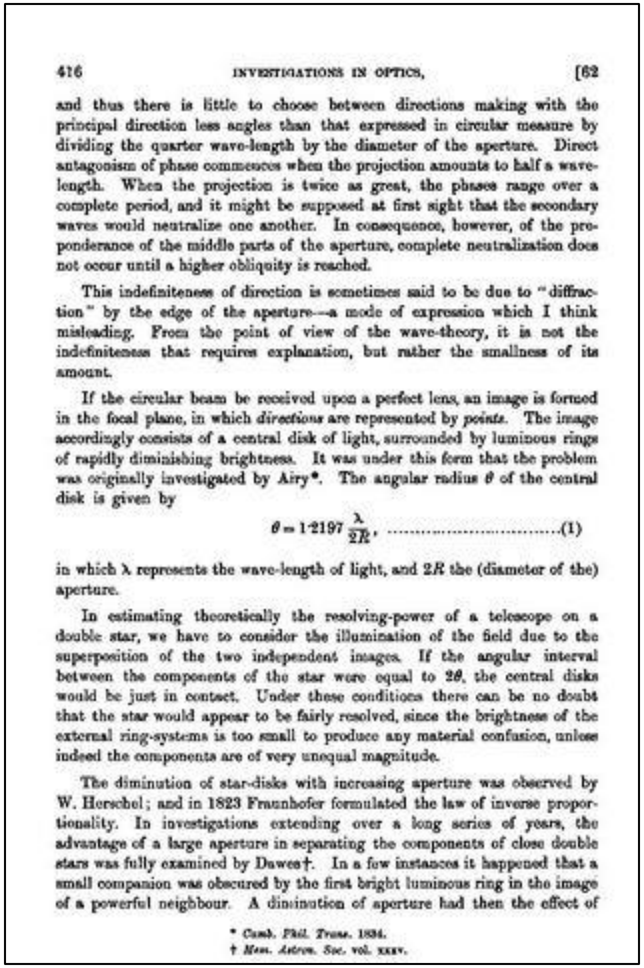
CAMBRIDGE:
AT THE UNIVERSITY PRESS
1899

[All Rights reserved.]



Resolution Criteria





416 INVESTIGATIONS IN OPTICS, [62

and thus there is little to choose between directions making with the principal direction less angles than that expressed in circular measure by dividing the quarter wave-length by the diameter of the aperture. Direct antagonism of phase commences when the projection amounts to half a wave-length. When the projection is twice as great, the phases range over a complete period, and it might be supposed at first sight that the secondary waves would neutralize one another. In consequence, however, of the preponderance of the middle parts of the aperture, complete neutralization does not occur until a higher obliquity is reached.

This indefiniteness of direction is sometimes said to be due to "diffraction" by the edge of the aperture—a mode of expression which I think misleading. From the point of view of the wave-theory, it is not the indefiniteness that requires explanation, but rather the smallness of its amount.

If the circular beam be received upon a perfect lens, an image is formed in the focal plane, in which *directions* are represented by *points*. The image accordingly consists of a central disk of light, surrounded by luminous rings of rapidly diminishing brightness. It was under this form that the problem was originally investigated by Airy*. The angular radius θ of the central disk is given by

$$\theta = 1{\cdot}2197\,\frac{\lambda}{2R}, \qquad \text{(1)}$$

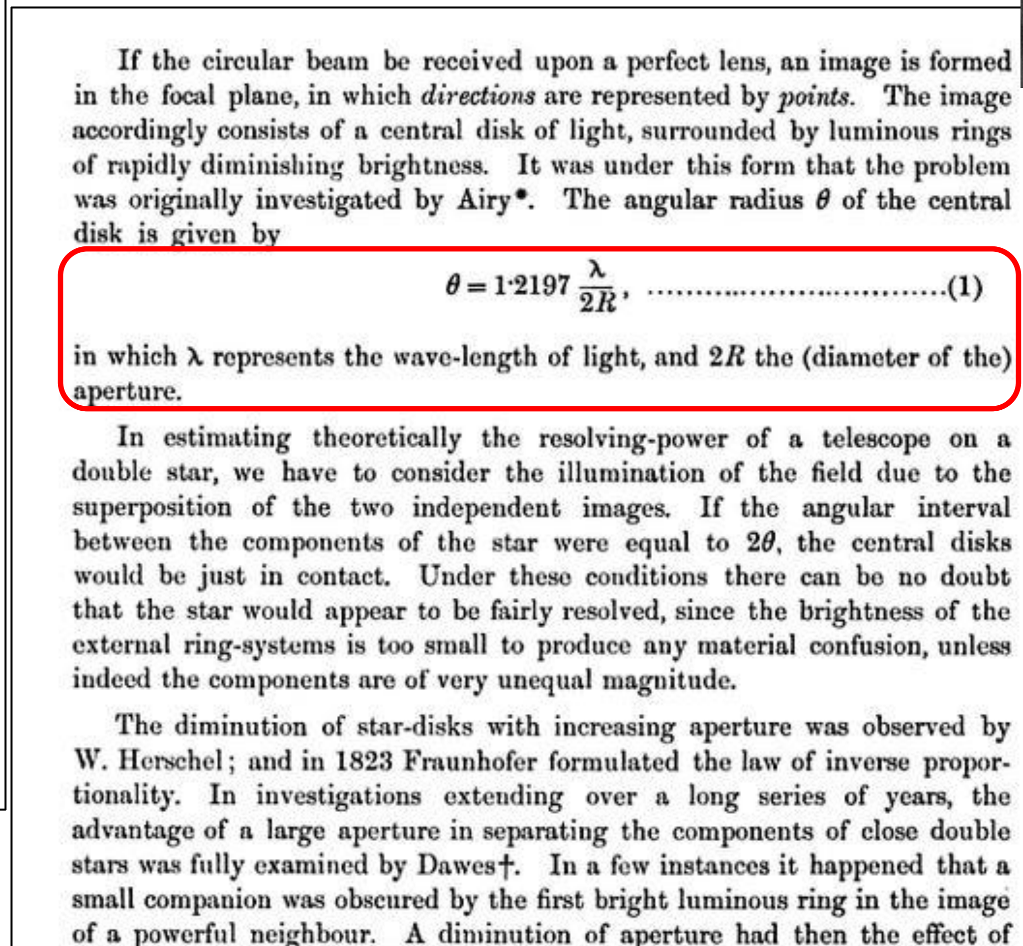
in which λ represents the wave-length of light, and $2R$ the (diameter of the) aperture.

In estimating theoretically the resolving-power of a telescope on a double star, we have to consider the illumination of the field due to the superposition of the two independent images. If the angular interval between the components of the star were equal to 2θ, the central disks would be just in contact. Under these conditions there can be no doubt that the star would appear to be fairly resolved, since the brightness of the external ring-systems is too small to produce any material confusion, unless indeed the components are of very unequal magnitude.

The diminution of star-disks with increasing aperture was observed by W. Herschel; and in 1823 Fraunhofer formulated the law of inverse proportionality. In investigations extending over a long series of years, the advantage of a large aperture in separating the components of close double stars was fully examined by Dawes†. In a few instances it happened that a small companion was obscured by the first bright luminous ring in the image of a powerful neighbour. A diminution of aperture had then the effect of

* Camb. Phil. Trans. 1834.
† Mem. Astron. Soc. vol. xxxv.

Page 416 of 3,702



If the circular beam be received upon a perfect lens, an image is formed in the focal plane, in which *directions* are represented by *points*. The image accordingly consists of a central disk of light, surrounded by luminous rings of rapidly diminishing brightness. It was under this form that the problem was originally investigated by Airy*. The angular radius θ of the central disk is given by

$$\theta = 1{\cdot}2197\,\frac{\lambda}{2R}, \qquad \text{(1)}$$

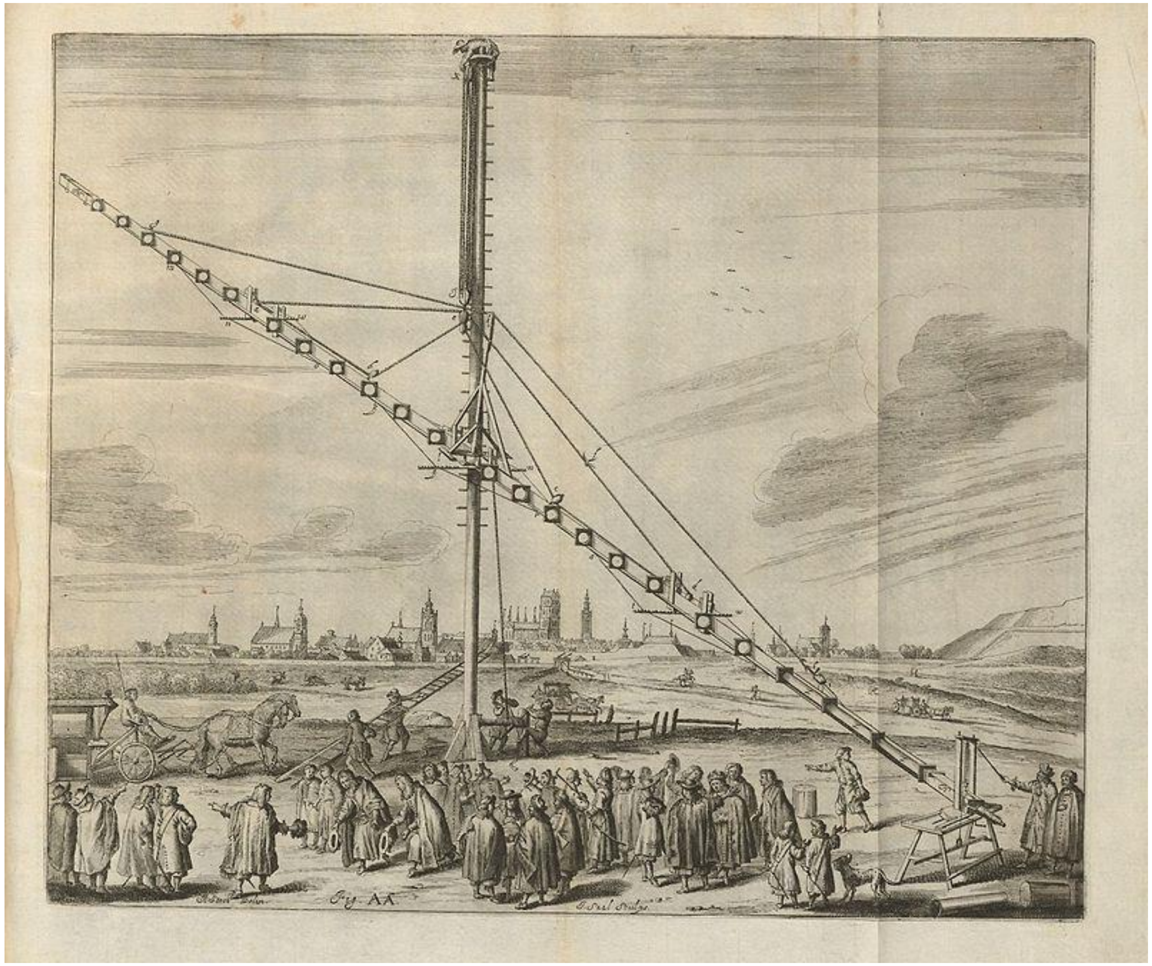
in which λ represents the wave-length of light, and $2R$ the (diameter of the) aperture.

In estimating theoretically the resolving-power of a telescope on a double star, we have to consider the illumination of the field due to the superposition of the two independent images. If the angular interval between the components of the star were equal to 2θ, the central disks would be just in contact. Under these conditions there can be no doubt that the star would appear to be fairly resolved, since the brightness of the external ring-systems is too small to produce any material confusion, unless indeed the components are of very unequal magnitude.

The diminution of star-disks with increasing aperture was observed by W. Herschel; and in 1823 Fraunhofer formulated the law of inverse proportionality. In investigations extending over a long series of years, the advantage of a large aperture in separating the components of close double stars was fully examined by Dawes†. In a few instances it happened that a small companion was obscured by the first bright luminous ring in the image of a powerful neighbour. A diminution of aperture had then the effect of

BROOKHAVEN NATIONAL LABORATORY

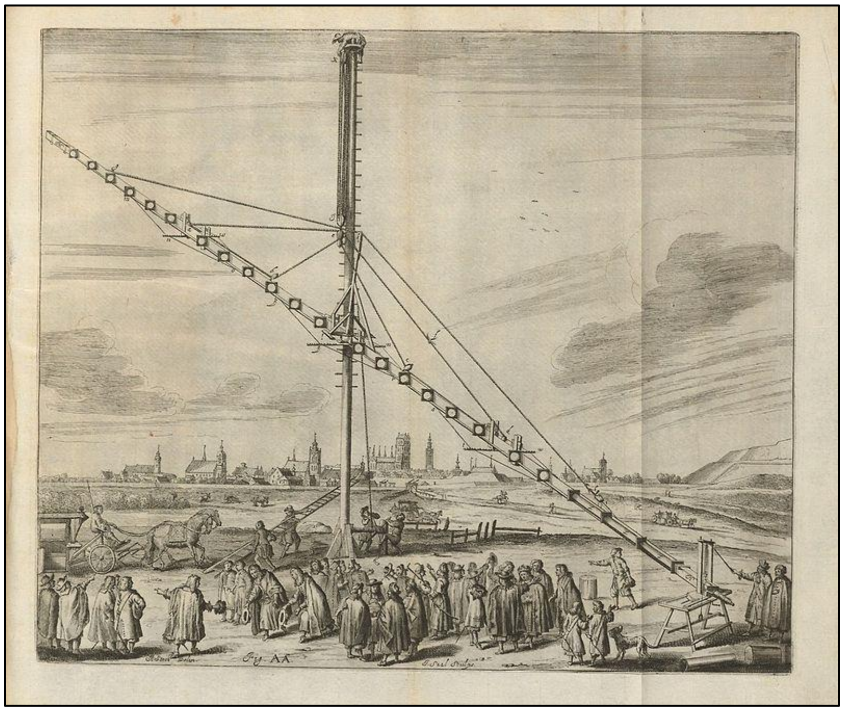
Telescopes Before Rayleigh



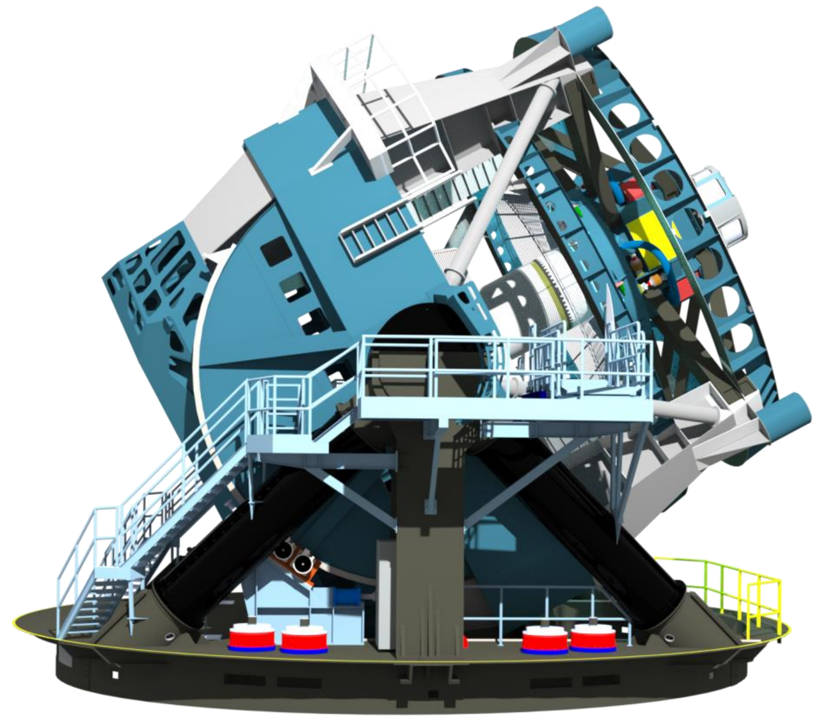
Johannes Hevelius' 8-inch aperture, 150 foot focal length telescope. (f/225) built in 1673

BROOKHAVEN NATIONAL LABORATORY

That Was Then, This is Now

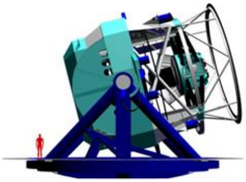


Hevelius 0.2m x 50m telescope
1673



LSST 8.4m x 10m telescope
2020

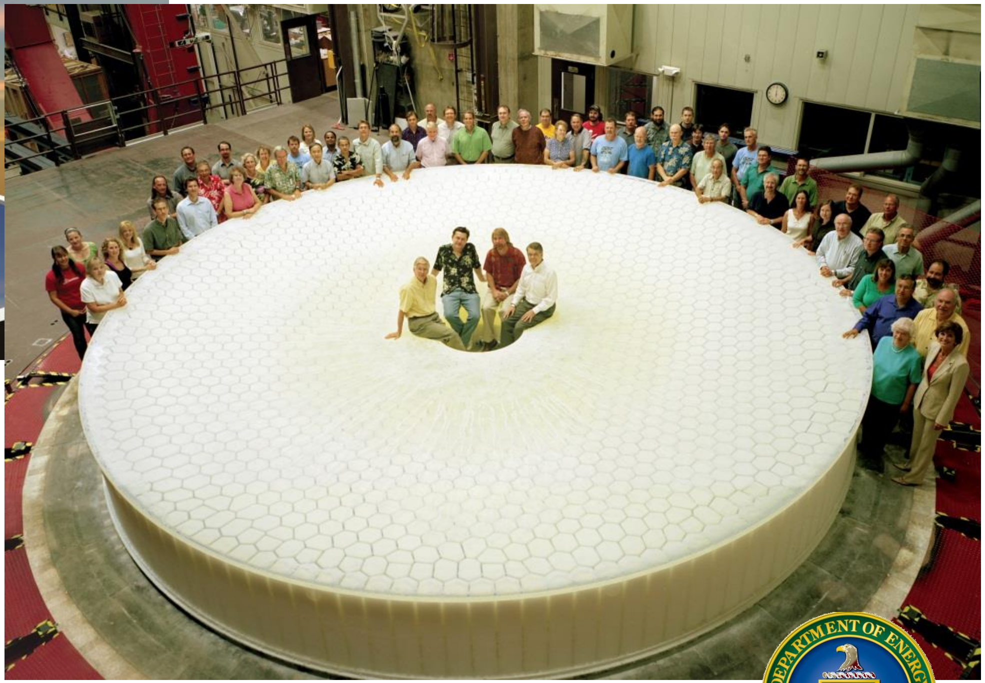
BROOKHAVEN
NATIONAL LABORATORY



LSST – Optics

3 mirrors, 3 lenses

8.4 meter primary mirror



A unique folded system, where the primary and tertiary mirror are made from one mirror (Under the U of Az football stadium)

BROOKHAVEN NATIONAL LABORATORY

LSST – Optics

Aluminum silicate cores bolted down with silicon carbide nuts and bolts.
Then the cores are loaded with 23.5 tons of Ohara E6 low expansion glass

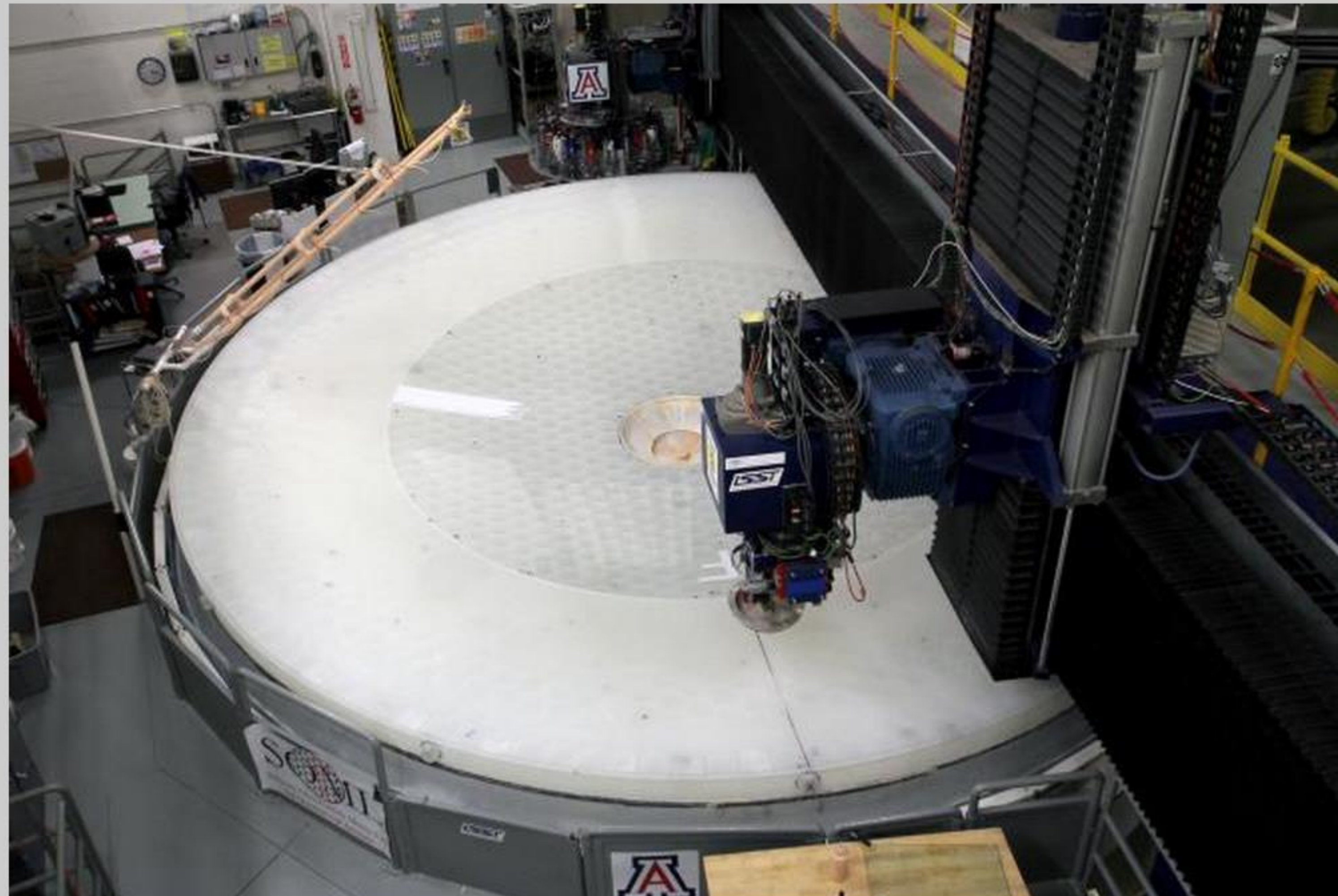
BROOKHAVEN NATIONAL LABORATORY

LSST – Optics

Credit: Ray Bertram / Steward Observatory

Shown here are pieces of Ohara E6 low expansion glass being loaded into the furnace mold. The loading process will take two days to complete and requires 51,900 pounds of glass.

LSST – Optics

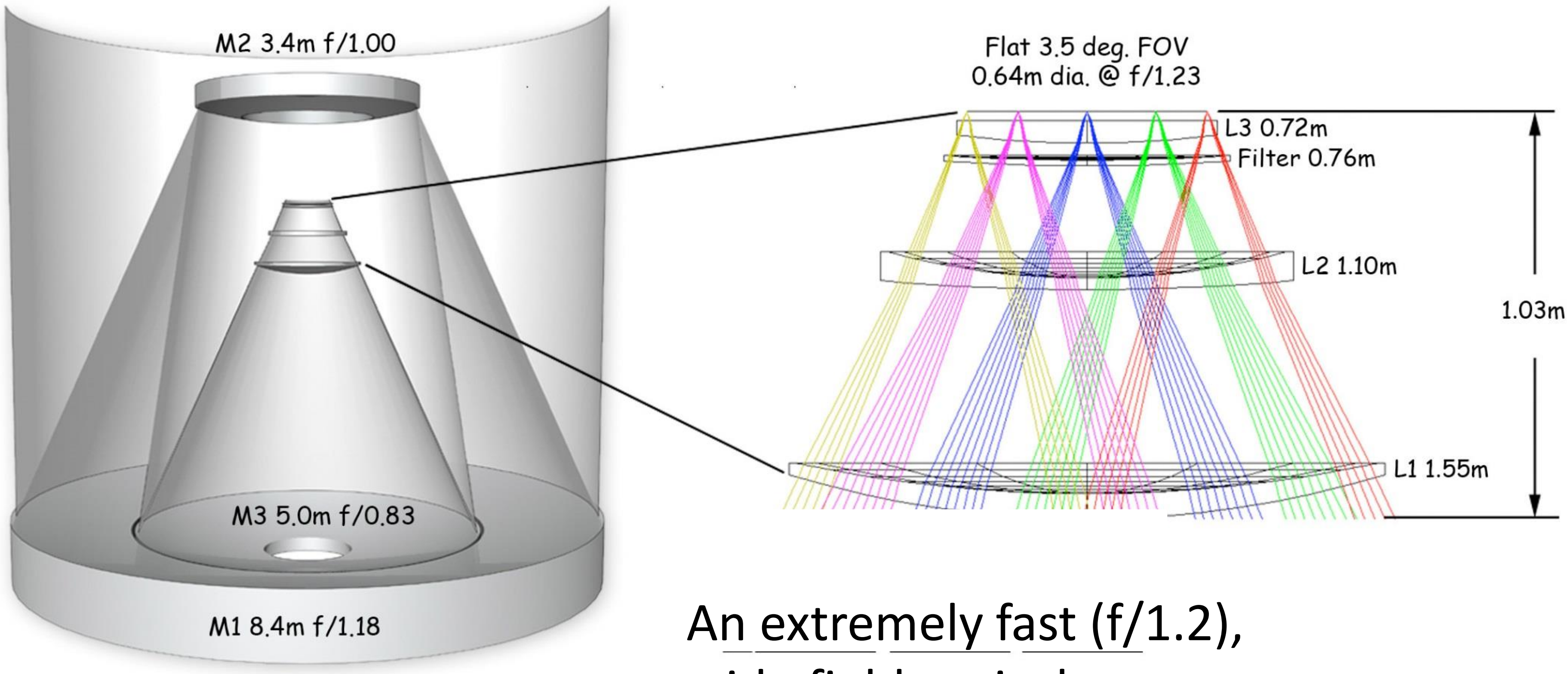


Credit: E. Acosta / LSST Corporation

[illegible]ique LSST M1/M3 mirror surfaces are nearing perfection. Both mirror surfaces are being carefully polished and optically tested with completion anticipated by the end of December 2013. 12/9/2013

BROOKHAVEN
NATIONAL LABORATORY

LSST – Optics



An extremely fast (f/1.2), wide field optical system. Allows 3.5 degree field of view. (10 square degrees)

BROOKHAVEN
NATIONAL LABORATORY

LSST Imaging System

Optical system with filters and camera

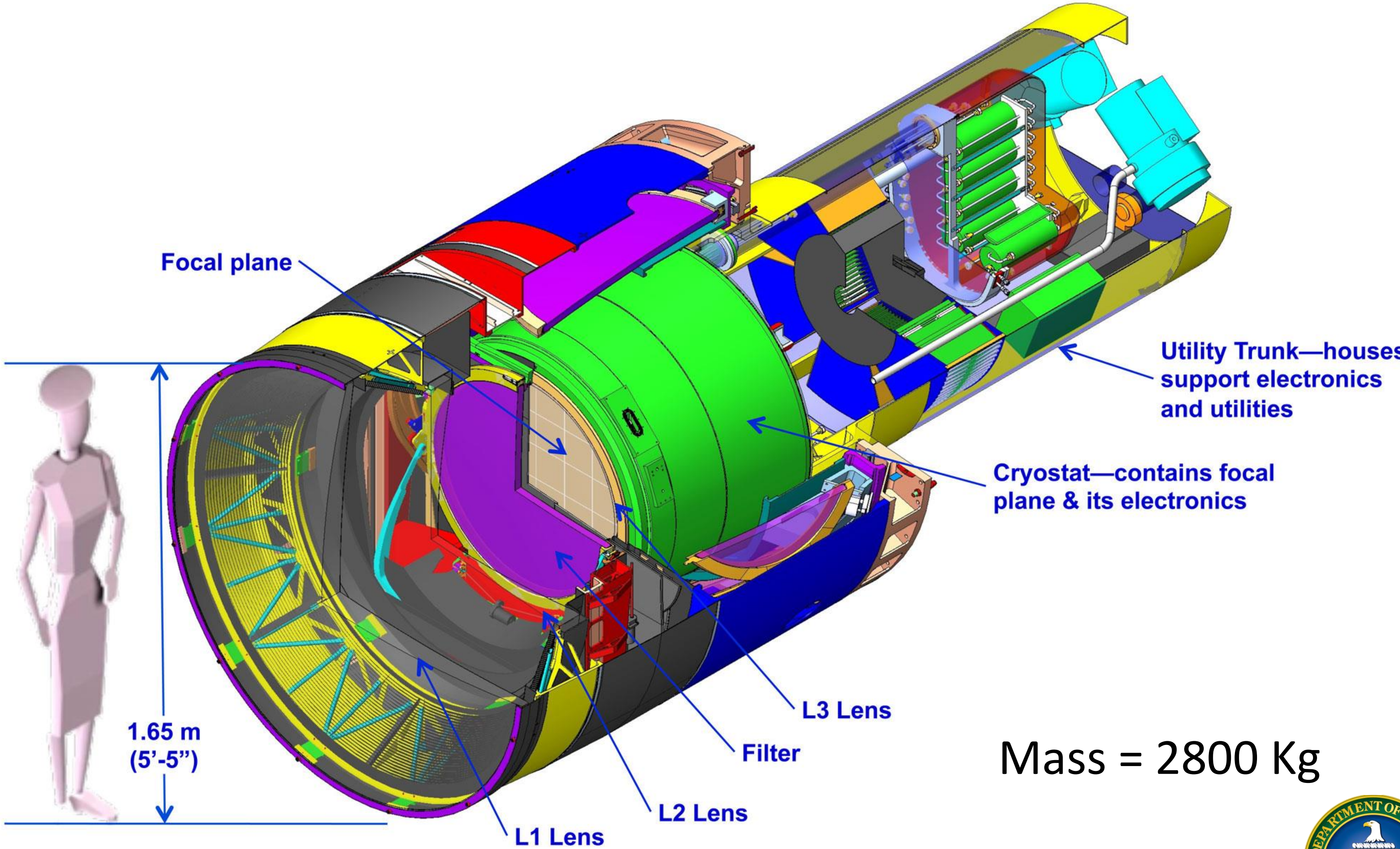
BROOKHAVEN NATIONAL LABORATORY

LSST – The Camera

3.2 Giga-Pixel Camera, to photograph 3.5 degrees of sky

BROOKHAVEN
NATIONAL LABORATORY

LSST – The Camera

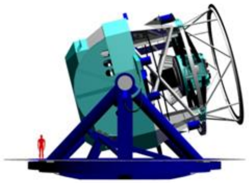


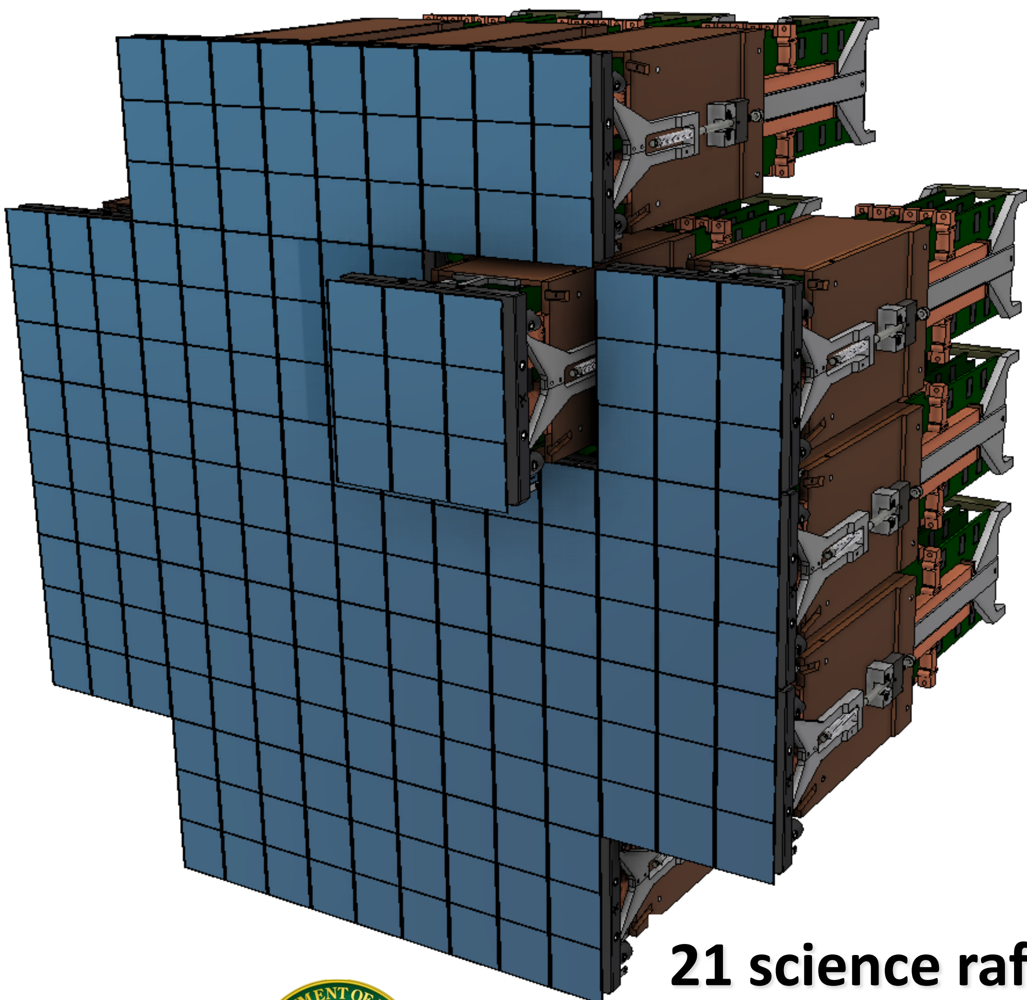
Camera ¾ Section

Mass = 2800 Kg

BROOKHAVEN NATIONAL LABORATORY

LSST Imaging Plane





21 “rafts”

9 CCDs per raft

3 CCDs per board

Focal plane: –100C

Boards: –40C

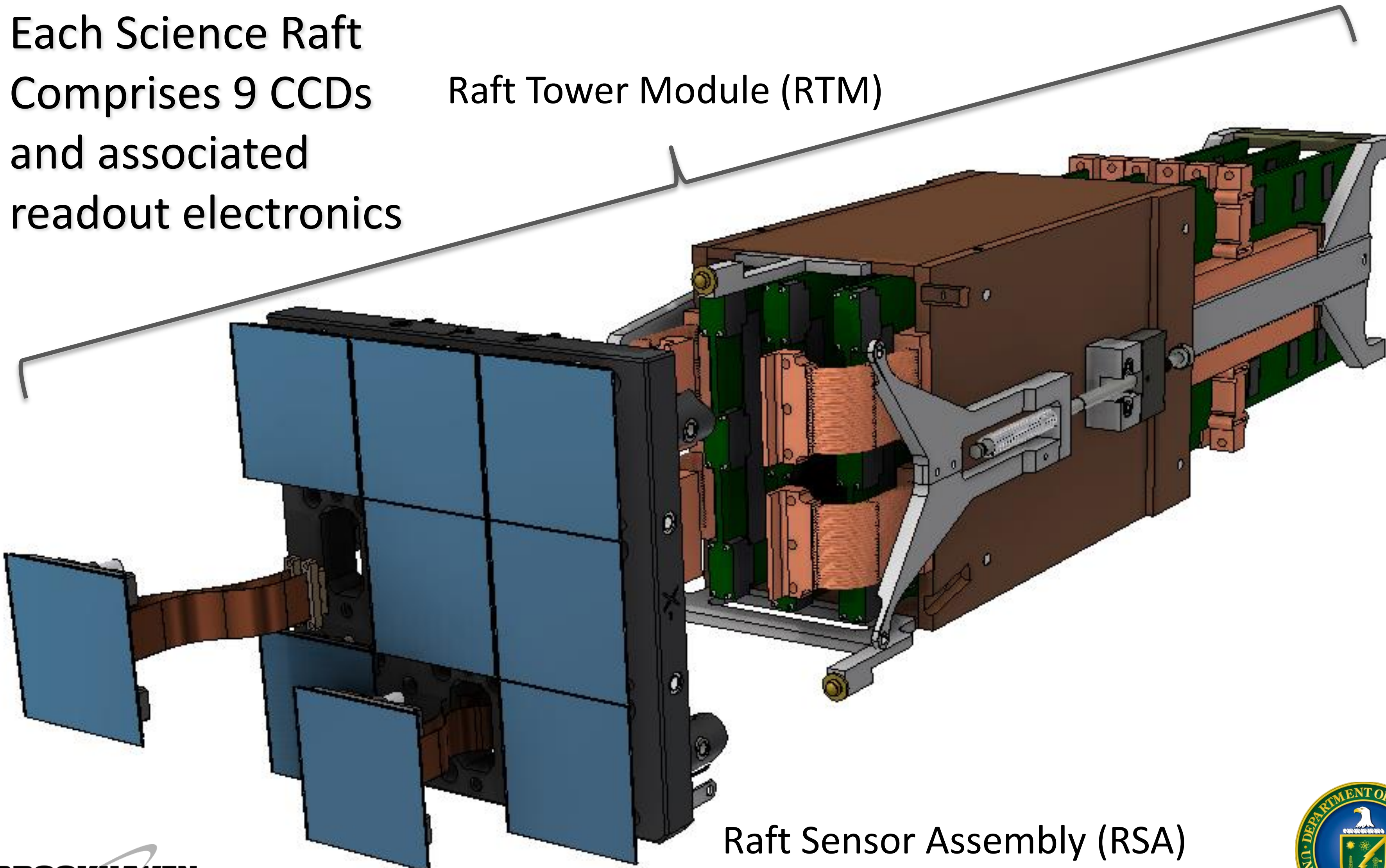
21 science rafts, 189 4K x 4K CCDs

(guider/WFS corner rafts not shown)

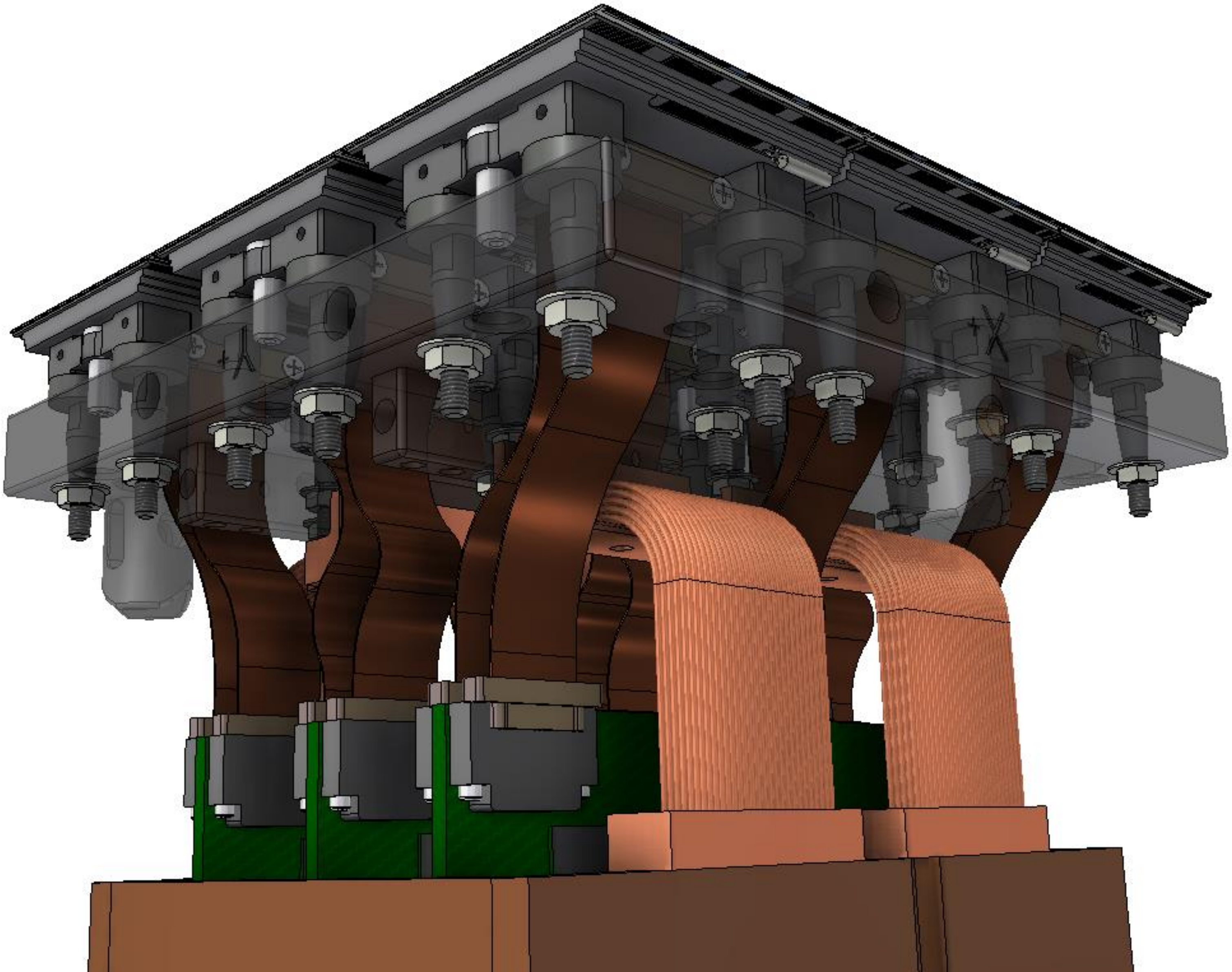
S. Bellavia 21 May 2013

LSST Science raft

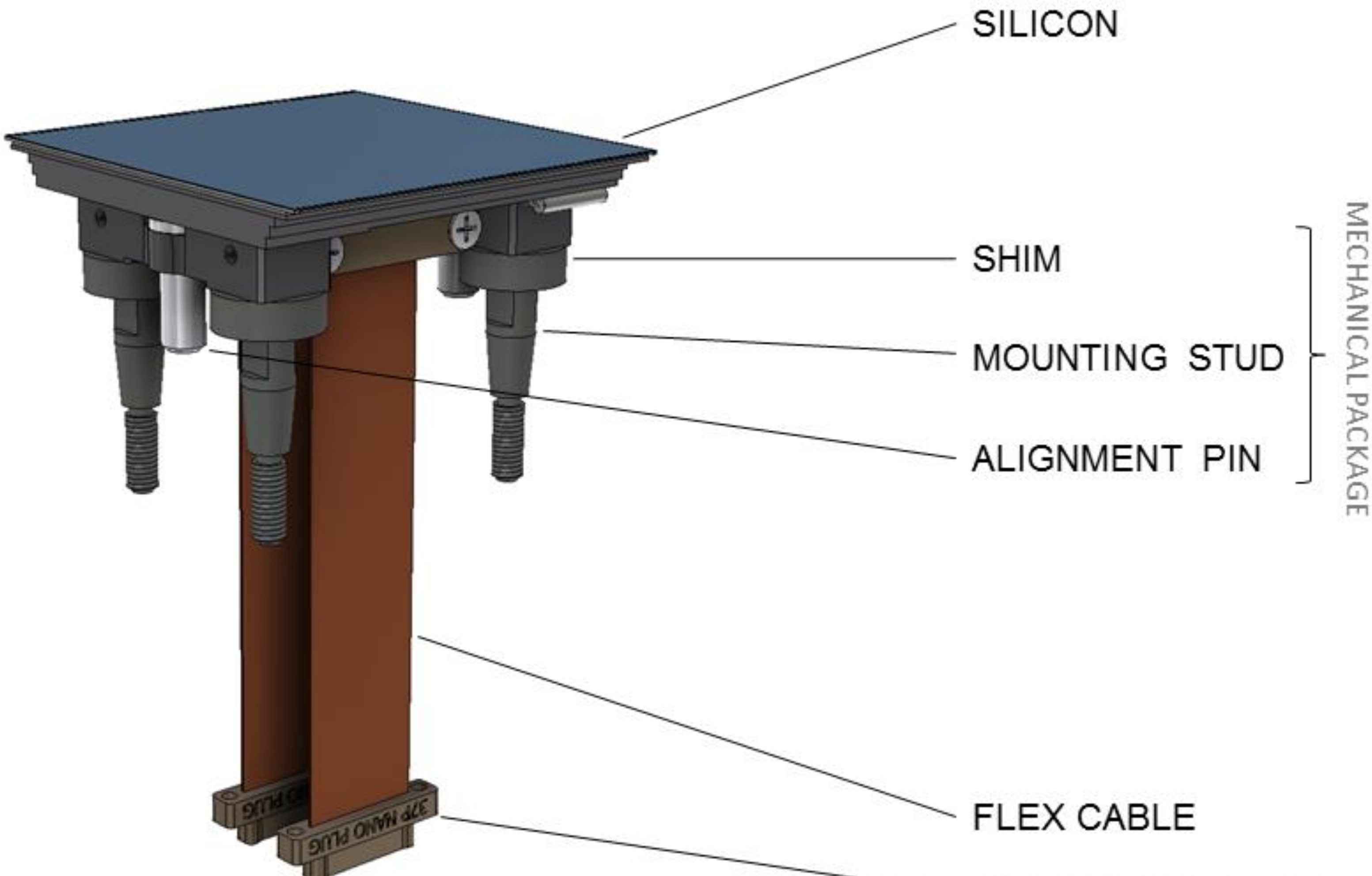
Each Science Raft Comprises 9 CCDs and associated readout electronics



Raft Sensor Assembly (RSA)

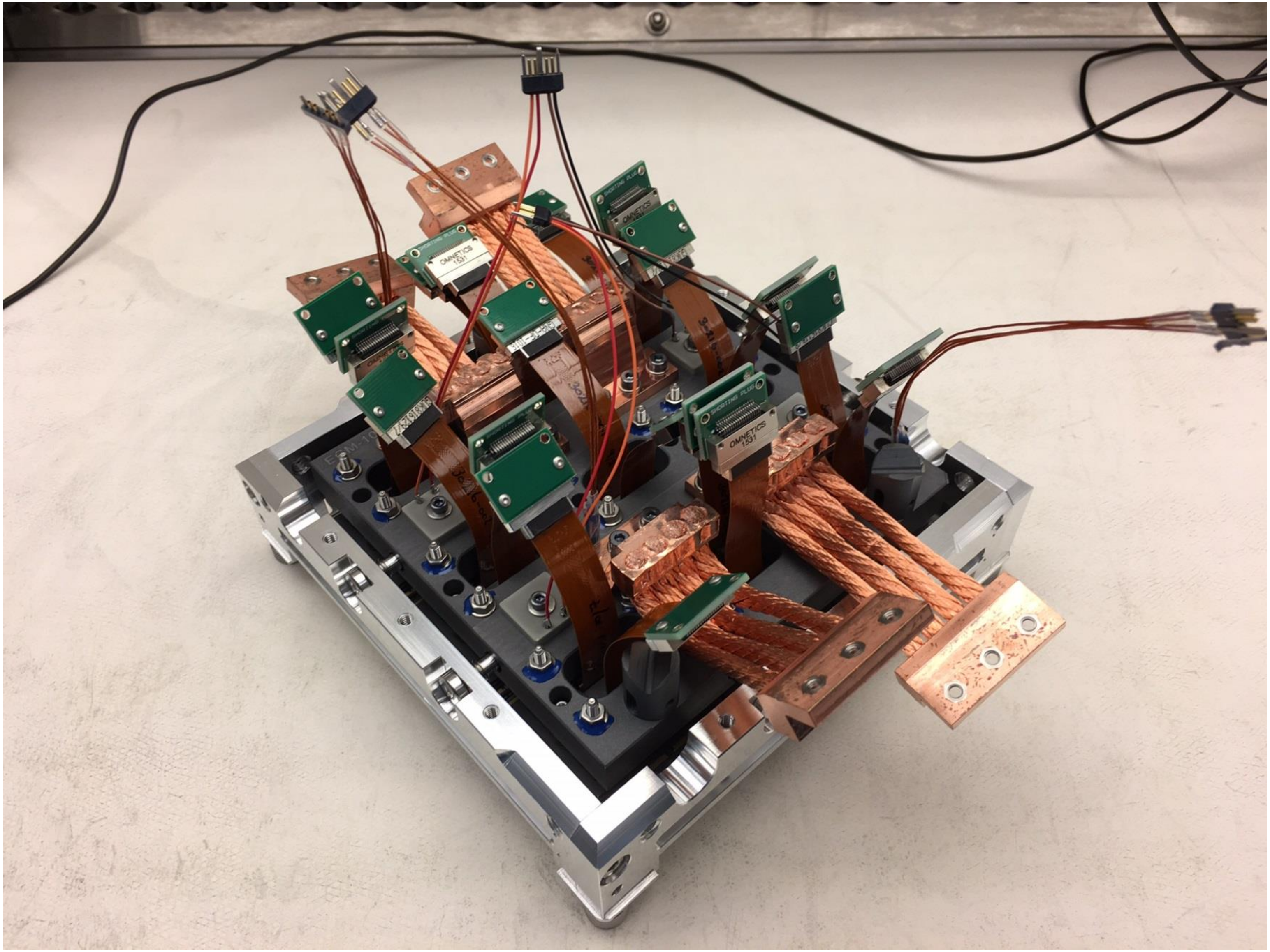


CCD Imaging Sensor

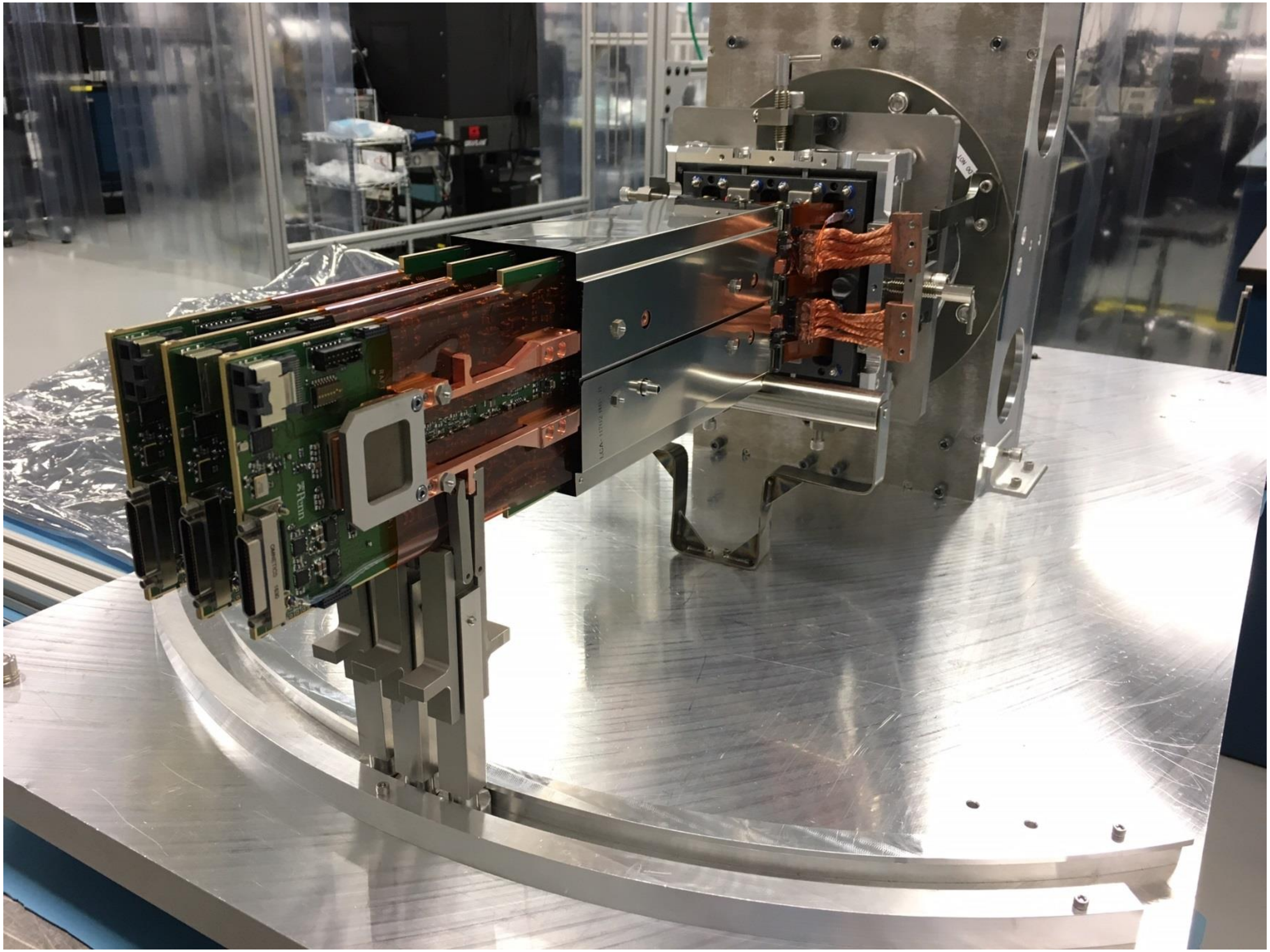


BROOKHAVEN
NATIONAL LABORATORY

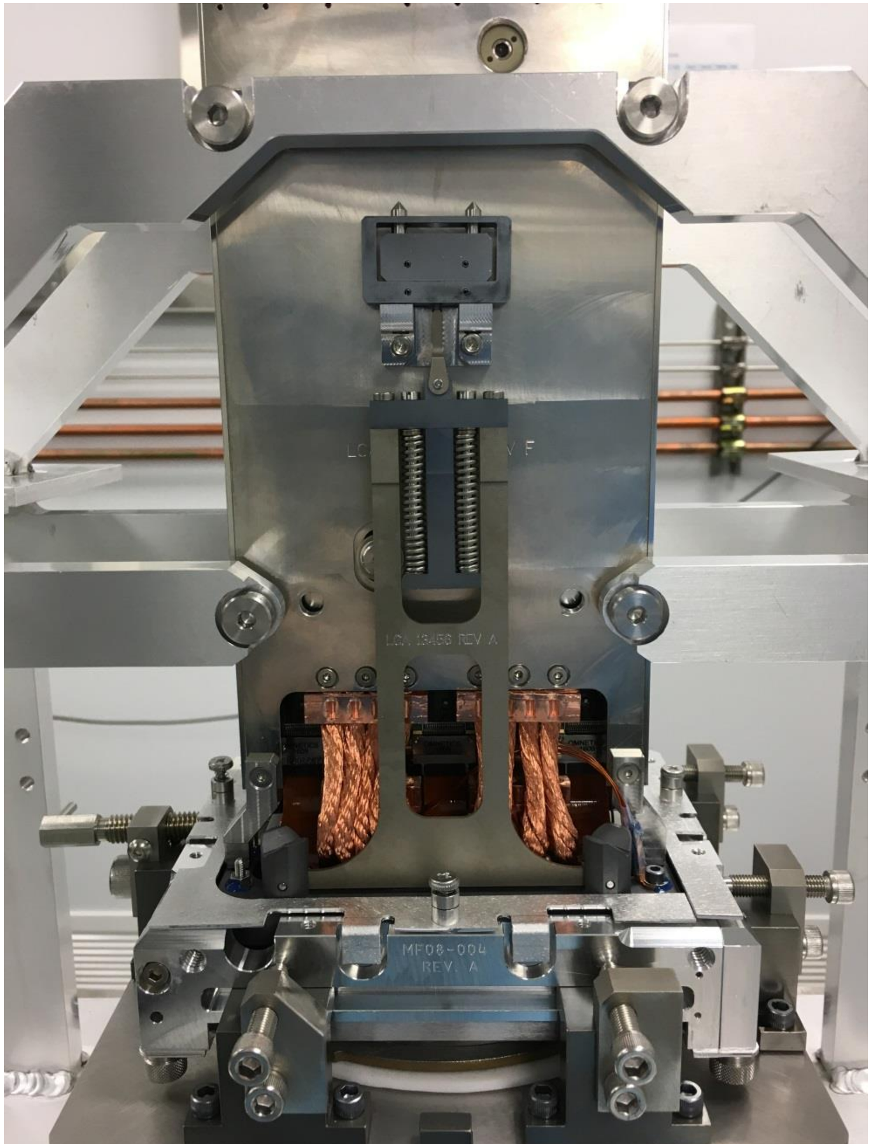
LSST RSA

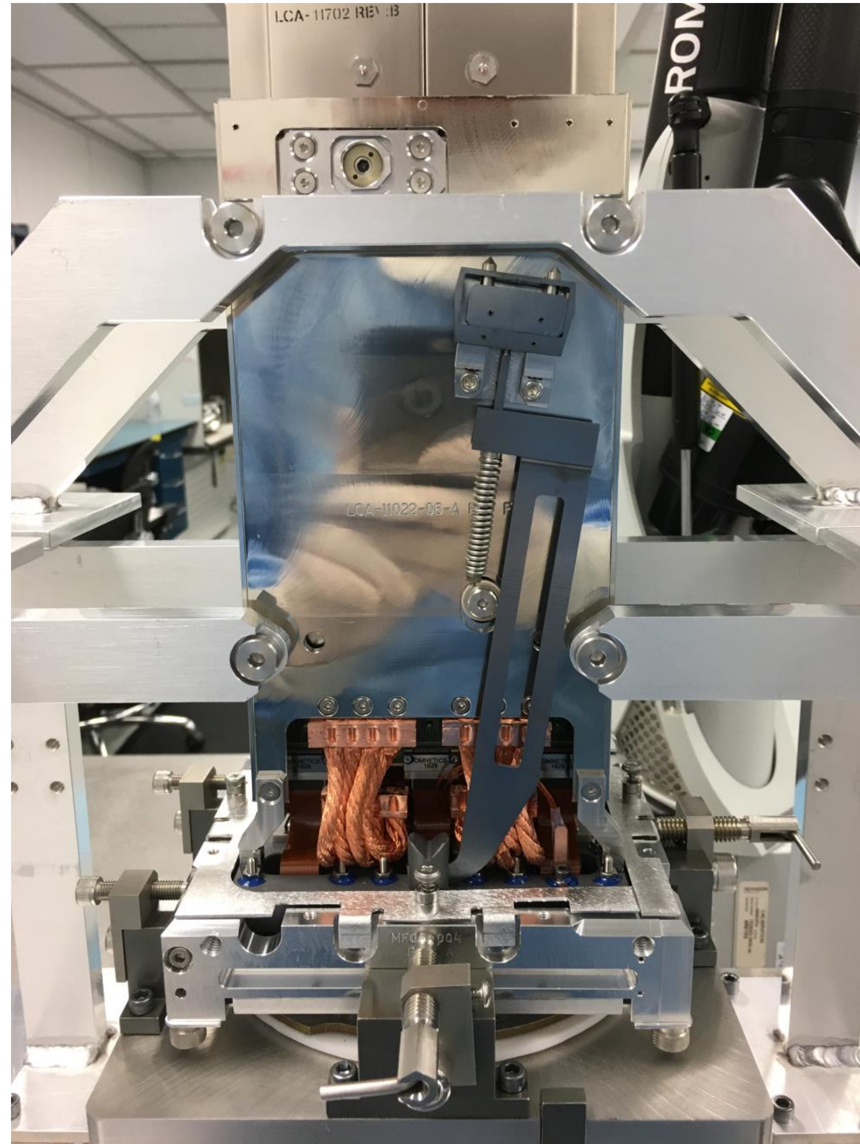


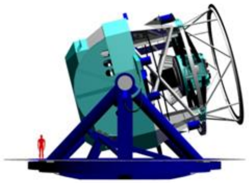
LSST RTM



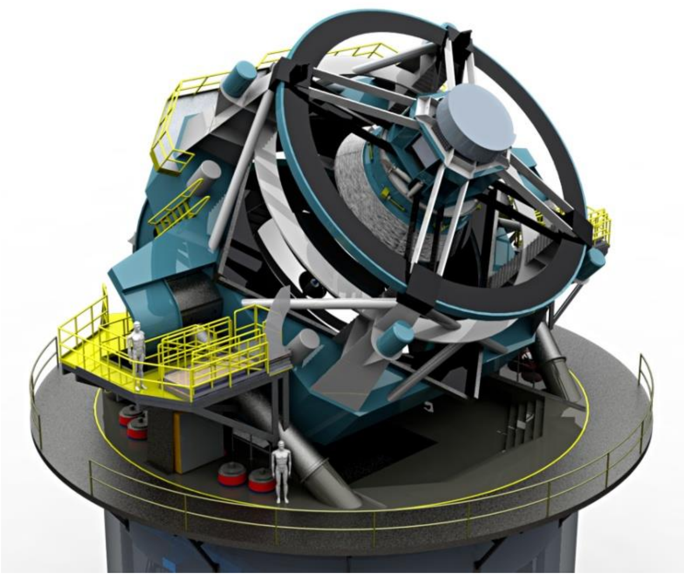
LSST RTM





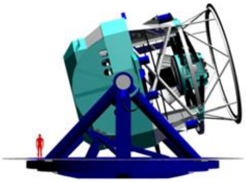


LSST - Performance



- It will be the Largest Survey Telescope in the world
- It will have the Largest Digital Camera in the World
- Will take a full photo of the night sky every 3 nights. If you wanted to see each photo in full resolution you would need 3,839 17-inch computer monitors!
- 1 GByte/sec, 20-30 TBytes/night
- There will be more data than scientists to analyze it – public distribution / citizen science.

X 3,839



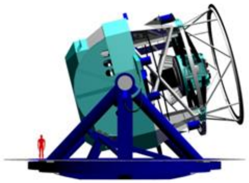
LSST Performance Details

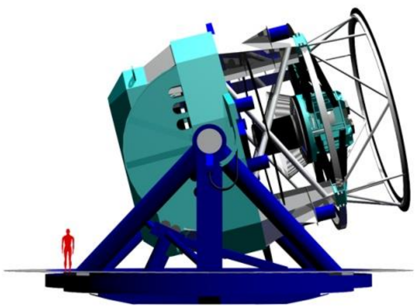
- Three Mirror Anastigmat (TMA) optical design.
    - 8.4 meter primary, 6.5 meter effective aperture
    - 3.4 meter diameter secondary
    - 5 m tertiary is being fabricated in same substrate as primary mirror
    - three-element refractive corrector
    - f/1.2 beam delivered to camera
    - 9.6 square degree field (on science imaging pixels)
    - optics deliver < 0.2 arcsec FWHM spot diagram,
    - 6 filters: u-g-r-i-z-y: 320 nm to 1050 nm

- 3.0 Gpixel camera
    - 10 micron pixels, 0.2 arcsec/pixel
    - Pair of 15 second exposures (to avoid trailing of solar system objects)
        - 12 GBytes per image (as floating point numbers), 20 TBytes/night.

- 24th magnitude limit for a single exposure
- Over ten years, 850 visits for each patch of sky, allows stacking to 27th magnitude, over 18,000 square degrees.

LSST vs. other scopes





LSST

Aperture:
8.4 m

Field of View:
3.5° x 3.5°

Etendue:
300 deg^2m^2

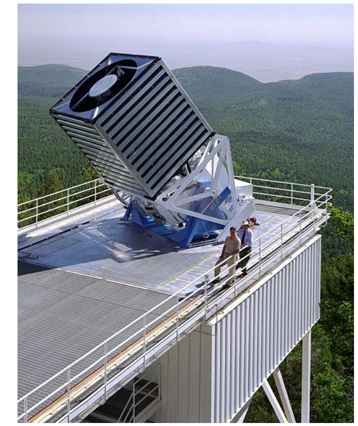
Keck*

(*Not a fair comparison)

Aperture:
9.96 m

Field of View:
.03° x .13°

Etendue:
.025 deg^2m^2



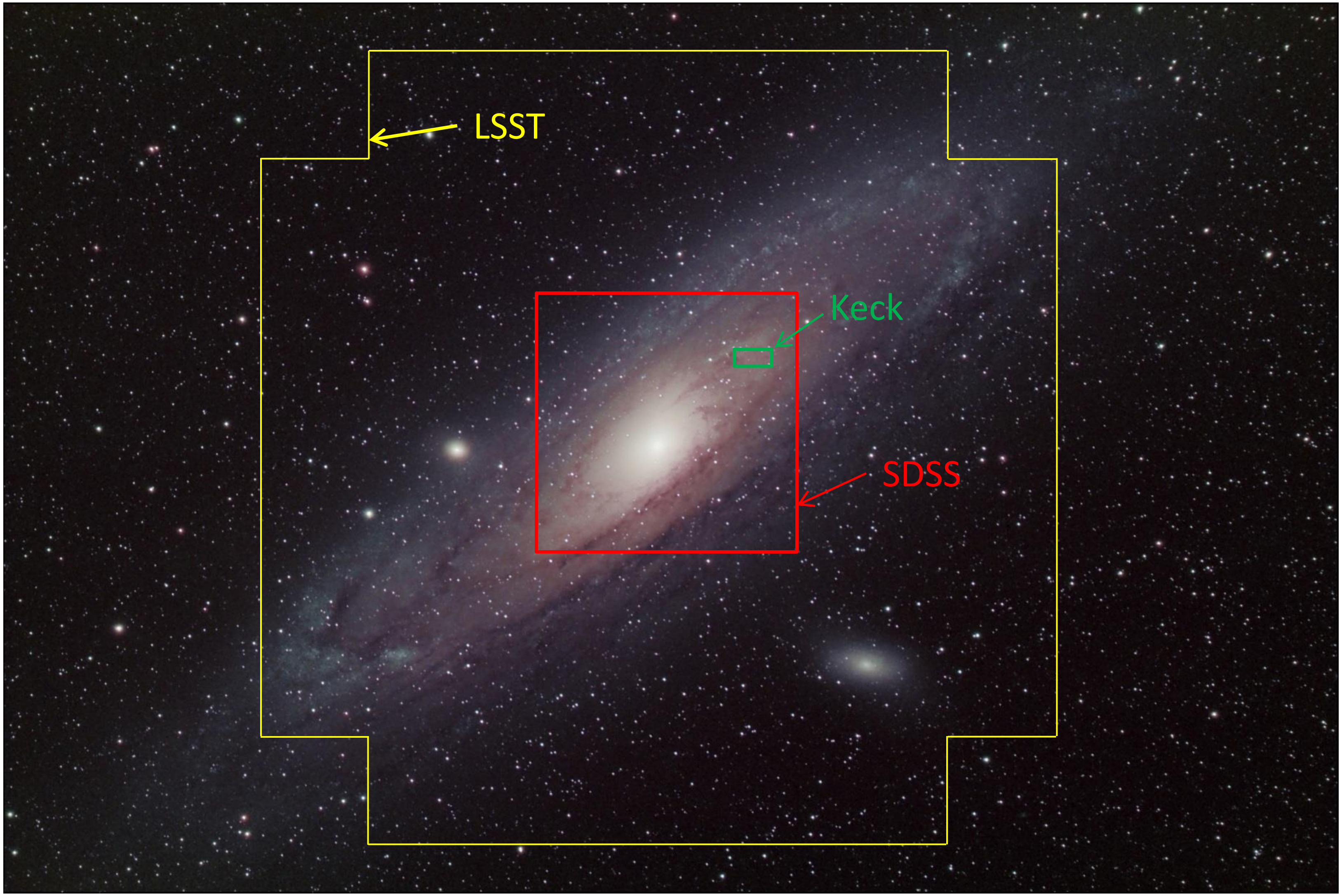
SDSS

Aperture:
2.5 m

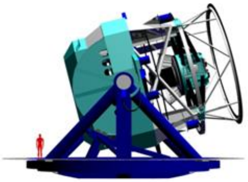
Field of View:
1.12 ° x 1.34°

Etendue:
7.4 deg^2m^2

LSST vs other scopes



Andromeda Galaxy Photo by S. Bellavia

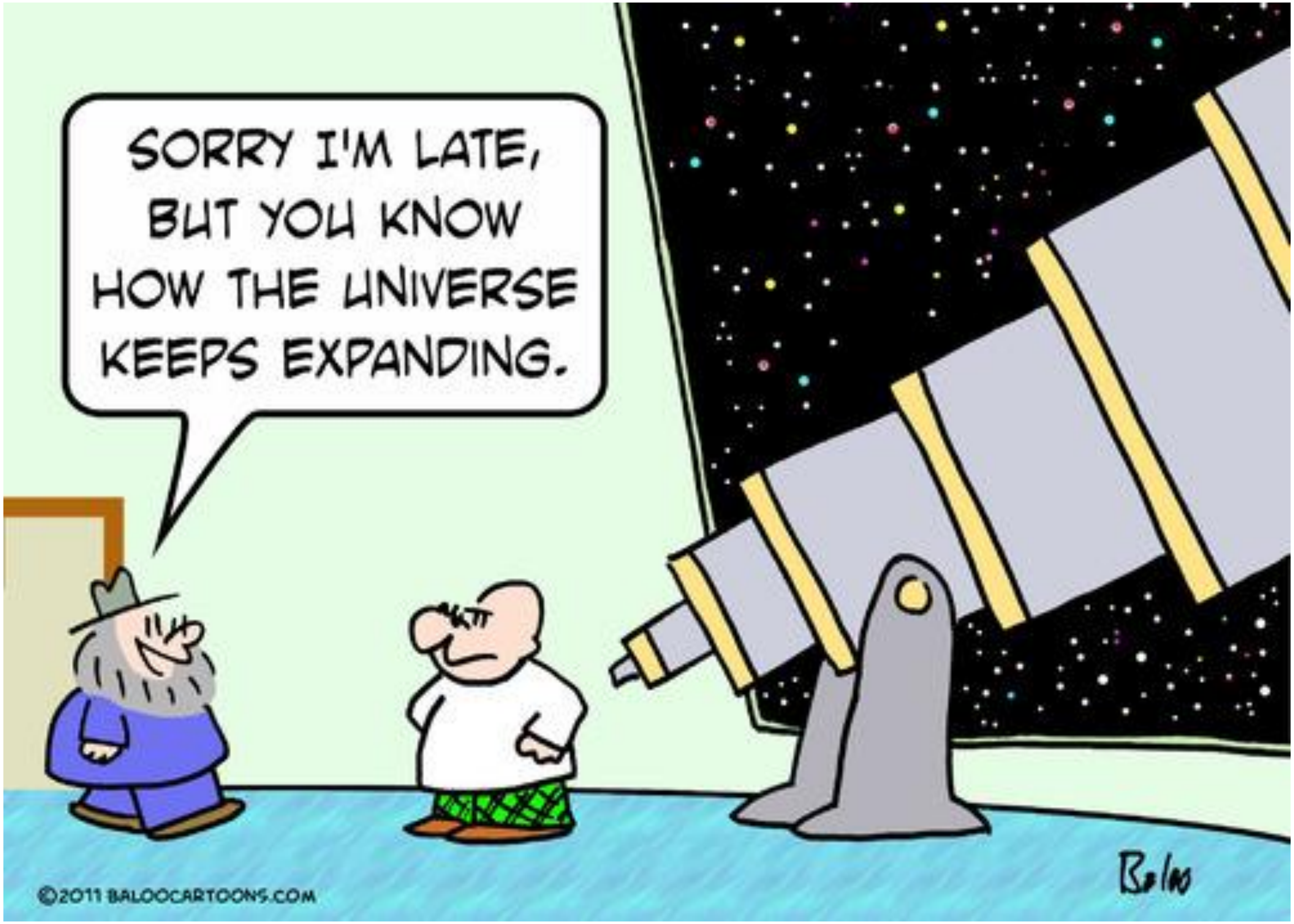


LSST Science Goals

- Dark Matter
- Dark Energy
- Supernovae
- Mapping our own Milky Way galaxy
- Near Earth Objects

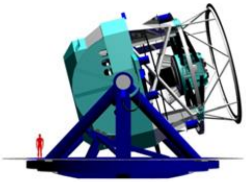
BROOKHAVEN NATIONAL LABORATORY

Dark Energy – Dark Matter

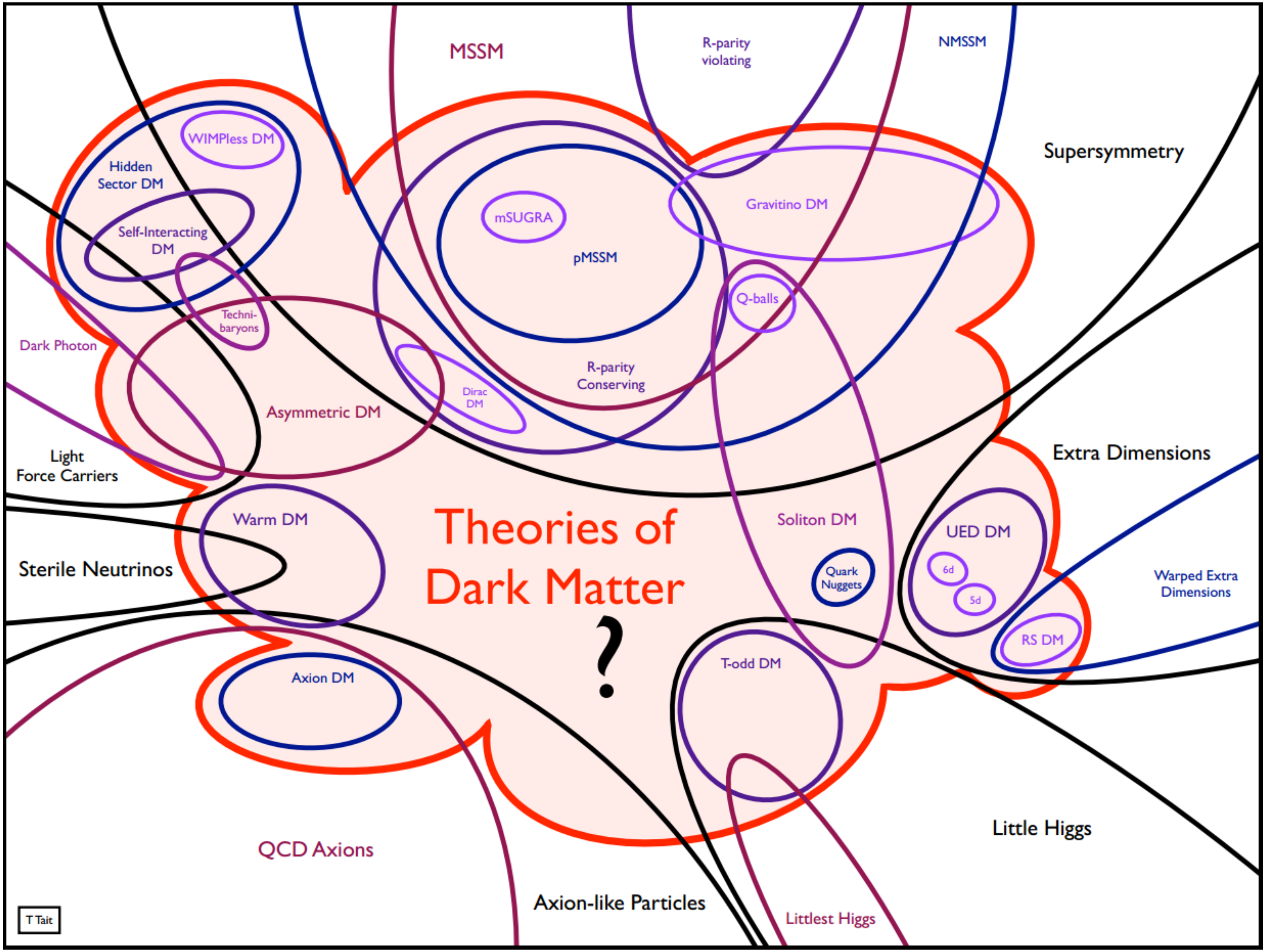


Dark Matter

?



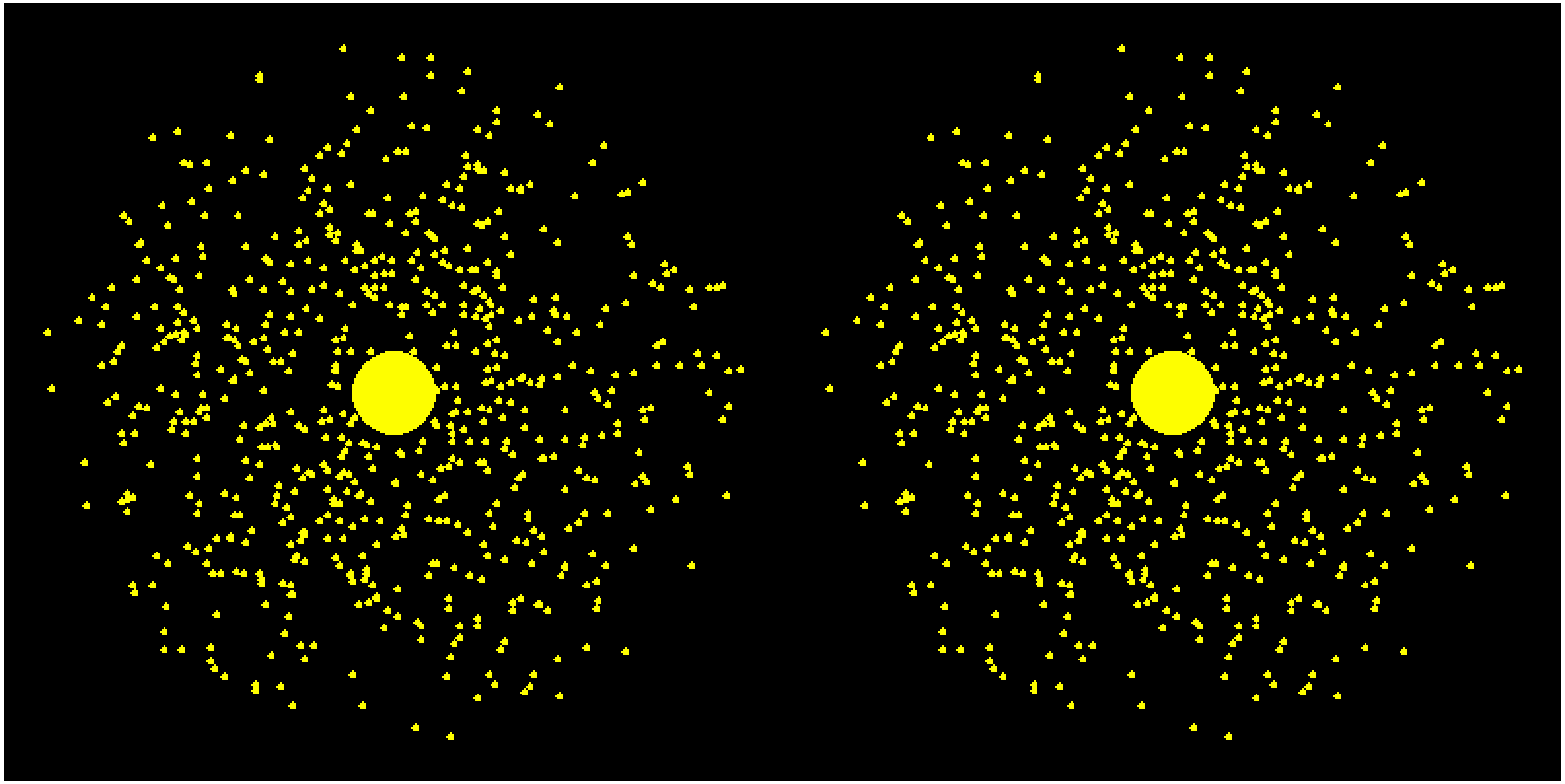
Dark Matter



Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Asymmetric DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dirac DM
R-parity Conserving
Light Force Carriers
Extra Dimensions
Warm DM
Sterile Neutrinos
Soliton DM
Quark Nuggets
UED DM
6d
5d
RS DM
Warped Extra Dimensions
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

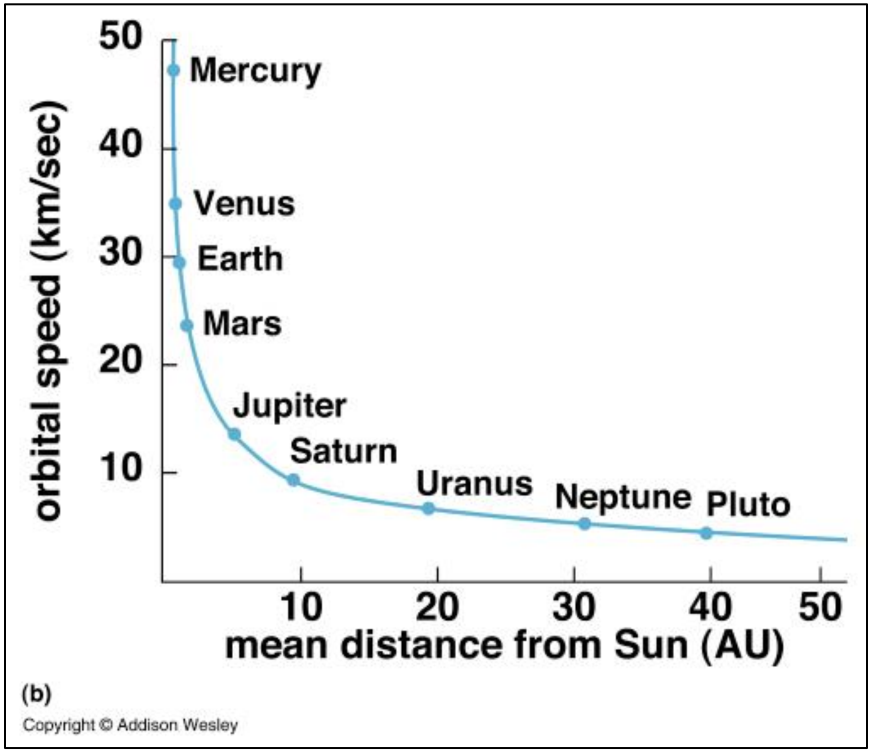
Dark Matter

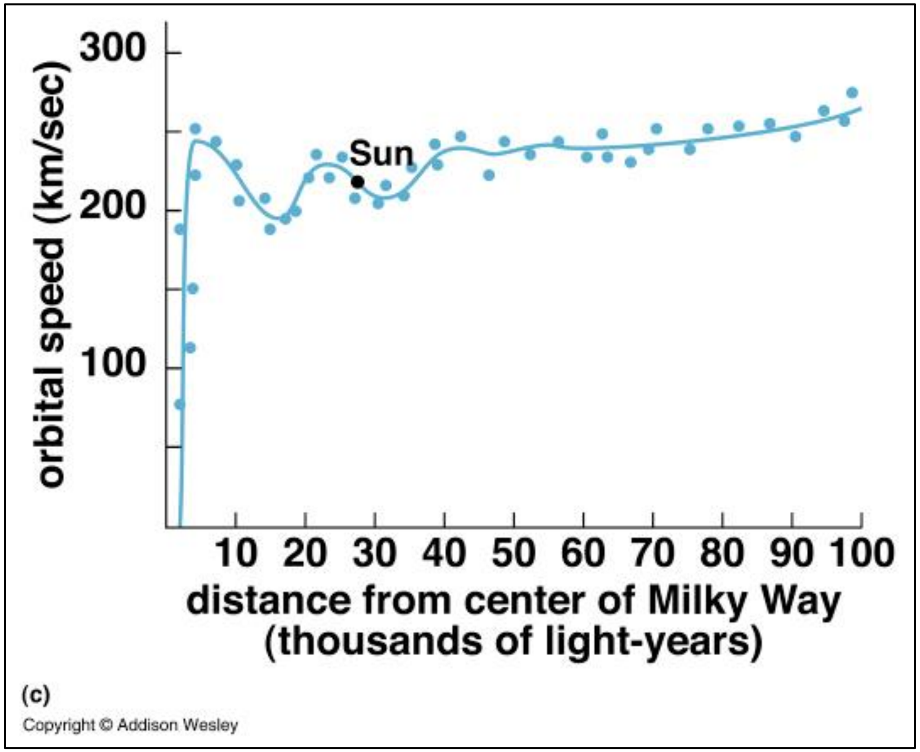
Dark Matter



We find that galaxies do not rotate as if all their mass were in the visible stars (as in the animation on the left), but instead rotate at almost a constant rate no matter the distance from their centers (as in the animation on the right).

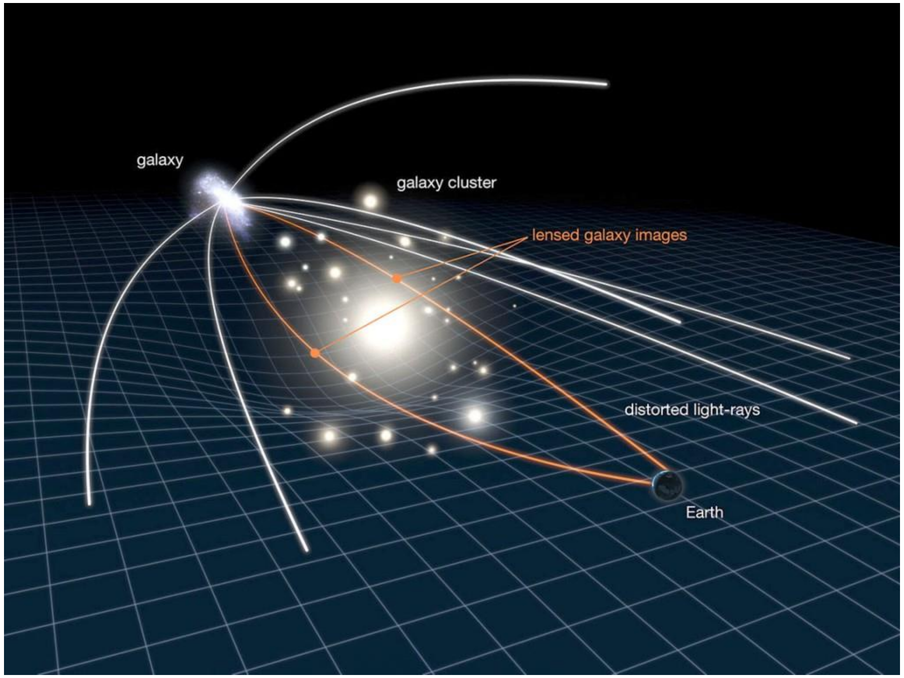
Dark Matter

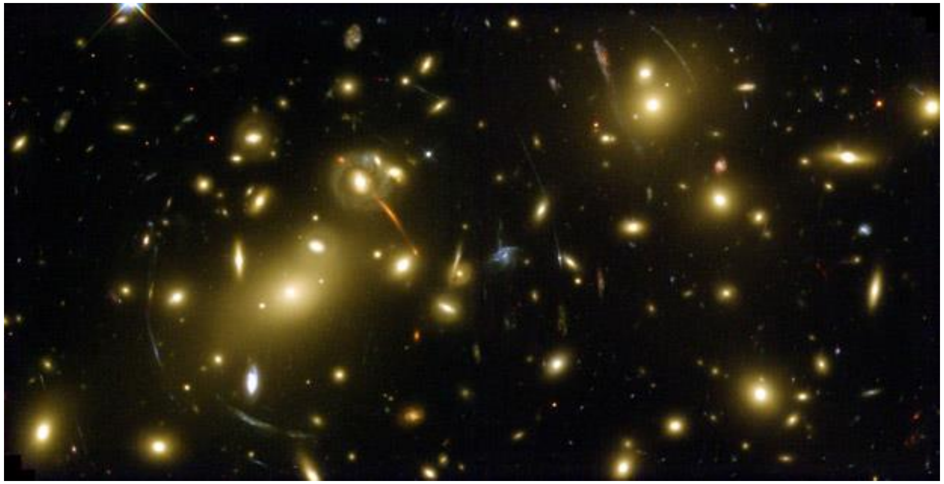




If the mass followed the "normal" matter -- stars and gas -- the rotation speed would drop per Kepler's Laws. Instead, the rotation curve is nearly flat with increasing radius. Evidently there are huge amounts of unseen "dark" matter in the outer parts of the galaxy that add gravitational field beyond that just from the center, causing the stars and gas to orbit faster. (Figures from The Essential Cosmic Perspective, by Bennett et al.)

Lensing due to "Bright" Matter

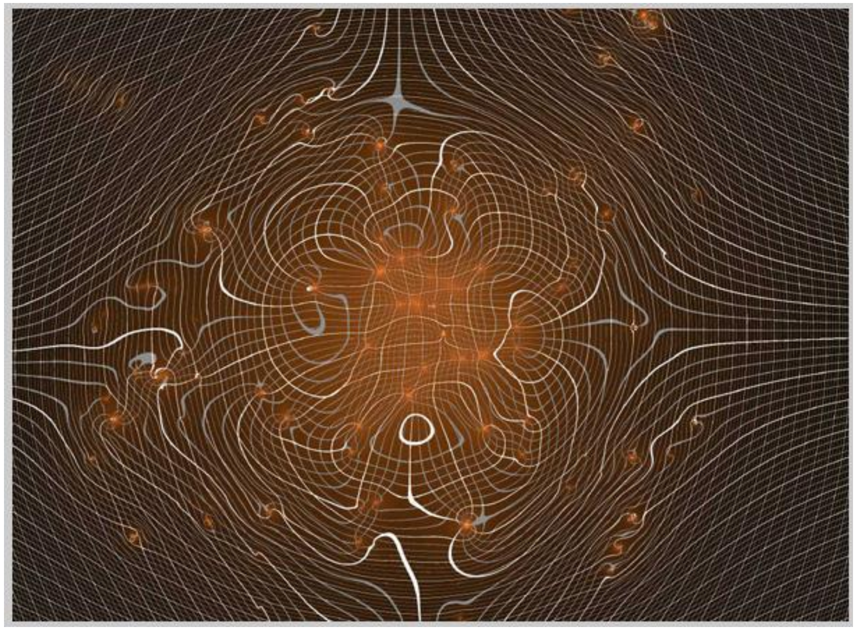




Strong gravitational lensing caused by galaxy cluster Abell 2218 in Draco (Hubble Photo)

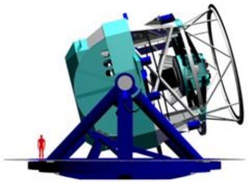
Lensing due to Dark Matter

Galaxy Cluster CL2004



Galaxy Cluster CL2004 with gravitationally distorted graph overlaid. Weak lensing inverted to yield a model for mass distribution of dark matter.

BROOKHAVEN
NATIONAL LABORATORY



Dark Energy

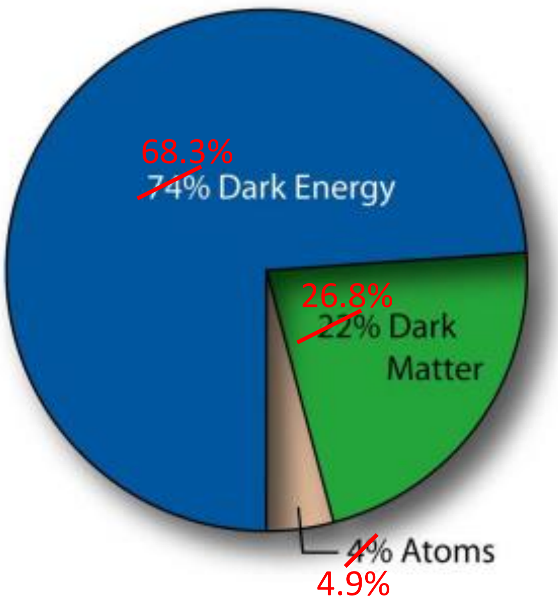
?

Dark Energy

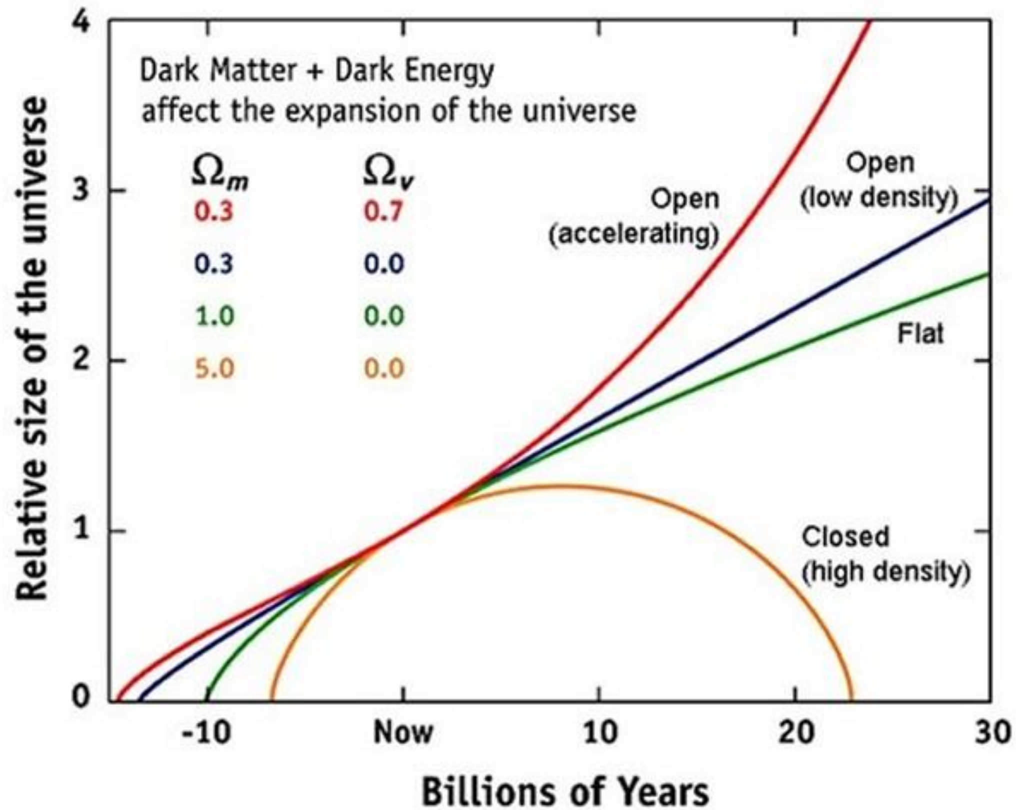
Once an object is set into motion, it cannot gain speed.
This violates conservation of energy

$$(\tfrac{1}{2}\,mv^2)_i = (\tfrac{1}{2}\,mv^2)_f$$

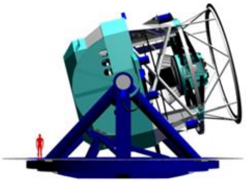
Dark Energy



Planck data, 03-21-2013



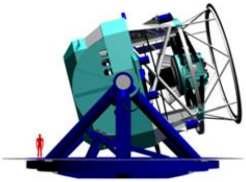
LSST will take "snapshots" of mass clusters at different cosmic times (distances) to record the history of the Hubble expansion. This will be combined with Supernovae as well as the distribution of dark matter .



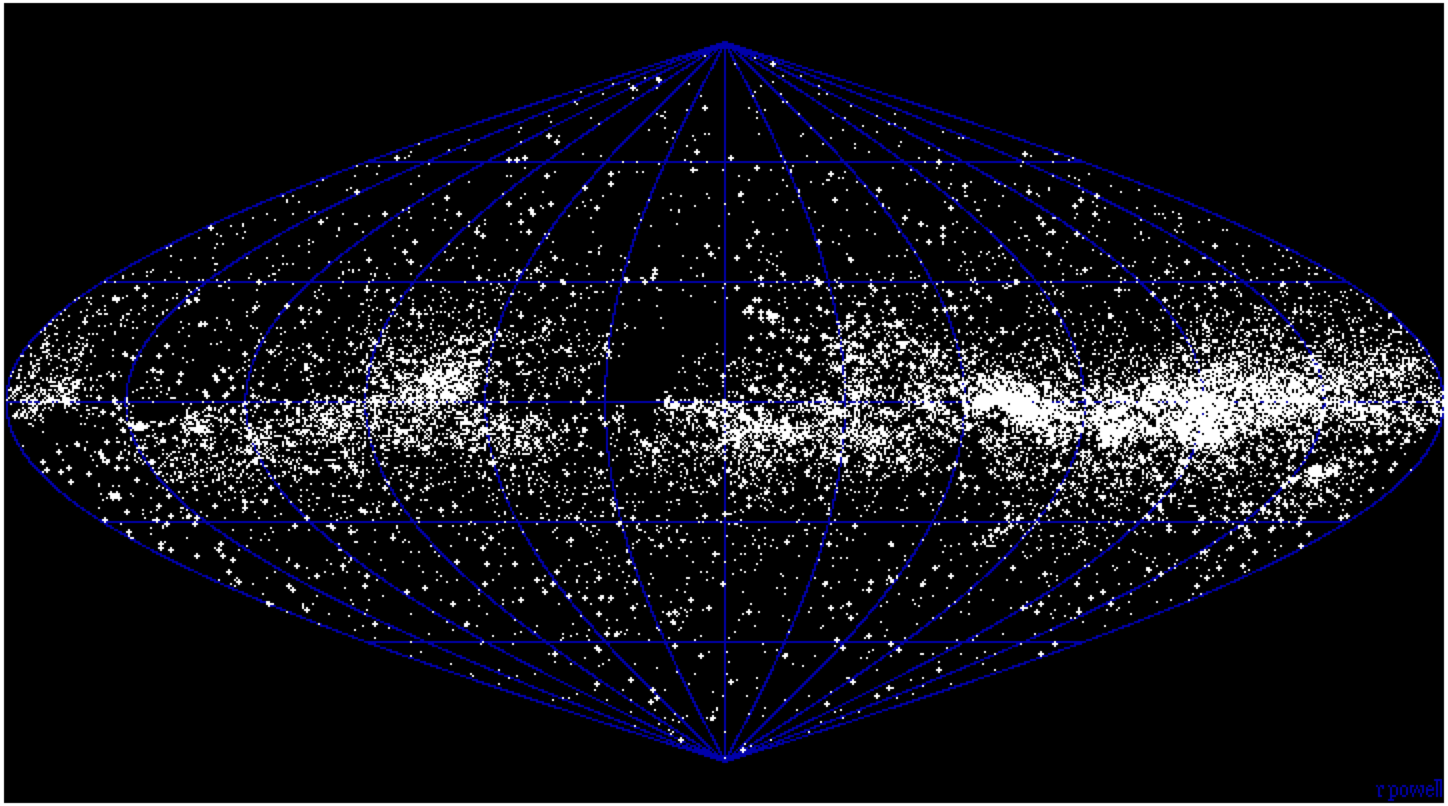
Supernovae

Photo of Supernova SN2014J by S. Bellavia

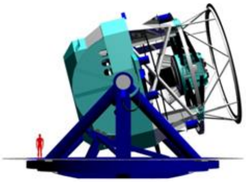
LSST will detect and image supernovae for rapid identification and allow other specialized observatories to gather information at the critical early stages of these stellar explosions. Hubble expansion data will also be collected from these.



Mapping the Milky Way



LSST will detect about 10 billion stars, with sufficient signal-to-noise ratio to enable accurate light curve, geometric parallax, and proper motion measurements for about a billion of these stars.

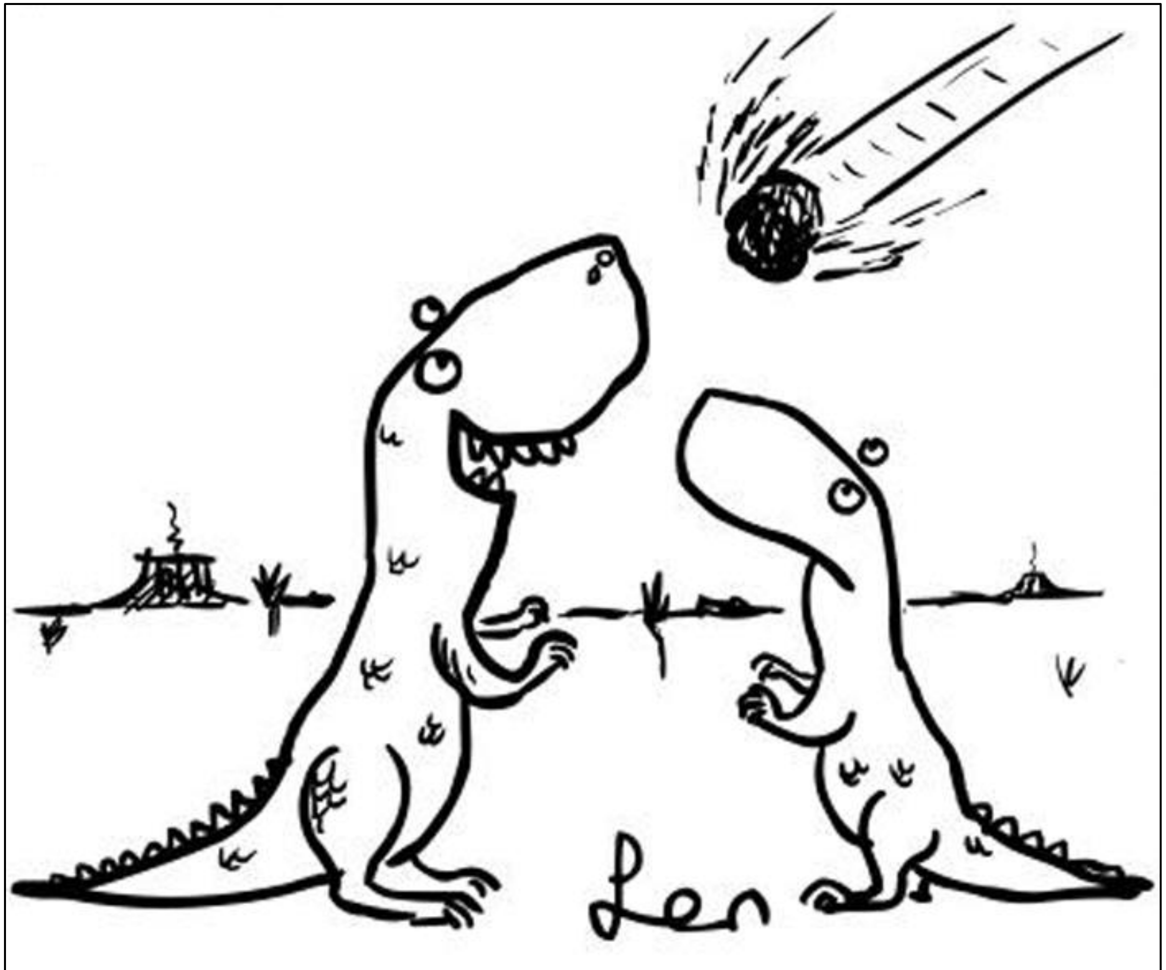


Near Earth Objects

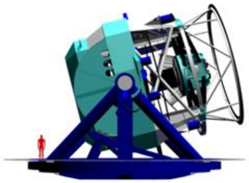
1998: Congress mandates discovery of 90 percent of all NEO's >1,000 meters in diameter by 2008 (Spaceguard Survey)
2005: Congress mandates 90 percent of all near-Earth objects >140 meters diameter discovered by 2020 (George E. Brown NEO Survey Act)

LSST will image numerous asteroids and comets and their changing position with time to identify potential threats to our planet.

Near Earth Objects



"Ooh, look! A shooting star.
Make a wish."



Who Pays for all this?

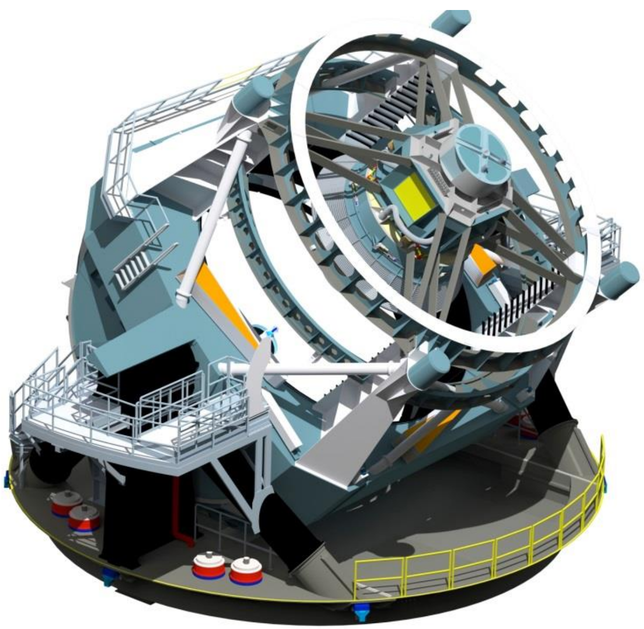
Private Funding For Optics (Charles Simonyi, Bill Gates and many more)

Telescope and Site Preparation

+

Camera, Shutter, Filters, Corrector

Image Analysis Software
Database Implementation



Multiple Science Goals from Same Image Stream

Questions ?