The Dark Energy Survey

Donna Kubik NIU April 27, 2010

2000 objects

- About 2000 celestial objects are visible to the naked eye
  - The Sun
  - Moon
  - 5 planets
  - Bright stars

Hundreds of millions of objects

- Yet astronomers have cataloged literally hundreds of millions of celestial objects!

Hubble Deep Field

What limits how much the naked eye can see?

– Small aperture

– Short integration time

– Narrow bandwidth

How have astronomers overcome the limitations imposed by the human eye?

– Telescopes

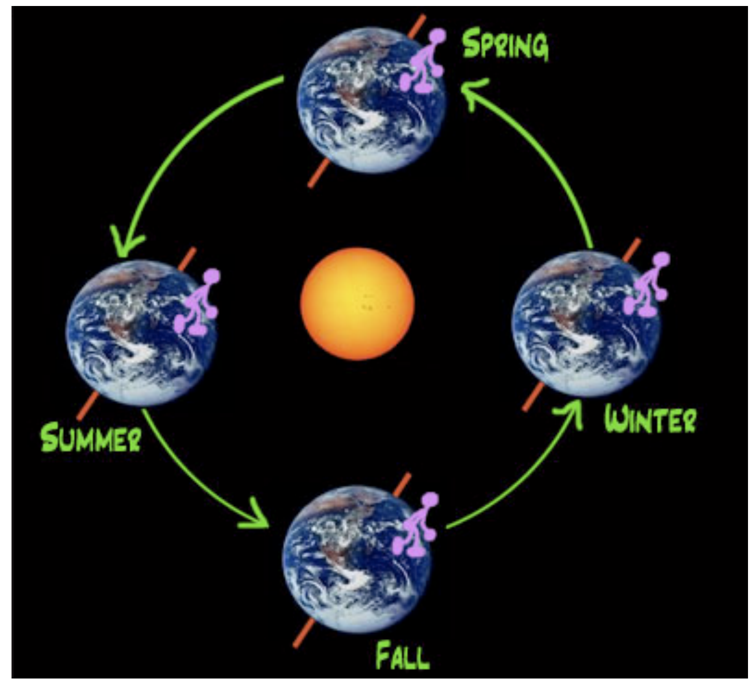
– Cameras

– Telescopes and cameras that can detect colors beyond those the eye can see

We’ve learned that we are on a wilder ride than any at Six Flags Great America…..

The Earth spins on its axis…

…*while* it orbits the Sun, like a crazy Tilt-a-Whirl!



The Sun orbits the center of the Milky Way

- The Sun has orbited the center of the Milky Way Galaxy more than 20 times during its 5 billion year lifetime!

And the Milky Way is only one of an estimated 50 billion galaxies…

Hubble Deep Field in the Northern sky, in the direction of Ursa Major

…which are all moving away from each other!

Hubble Deep Field in the Northern sky, in the direction of Ursa Major

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Hubble Deep Field in the Northern sky, in the direction of Ursa Major

…which are all moving away from each other!

Hubble Deep Field in the Northern sky, in the direction of Ursa Major

Edwin Hubble discovered all galaxies are moving away from each other.

Until 1998,
most astronomers assumed that gravity will take over, and the rate at which galaxies are moving away from each other would slow down…

However, in 1998 it was learned that the Universe will expand forever, and faster and faster!

We've learned that we are on a wilder ride than any at Great America…..

The ride is not going to stop and it's not slowing down!

What keeps the ride going?

Dark Energy.

Dark Energy Survey
(DES)

- Goal: Learn why the universe seems to be expanding *faster* and *faster*.

- Build a new 500 Megapixel camera, the Dark Energy Camera (DECam) and wide field corrector to be used on the 4-meter Blanco telescope at Cerro Tololo Inter-American Observatory in Chile.

DES requirements

DES combines 4 probes of Dark Energy

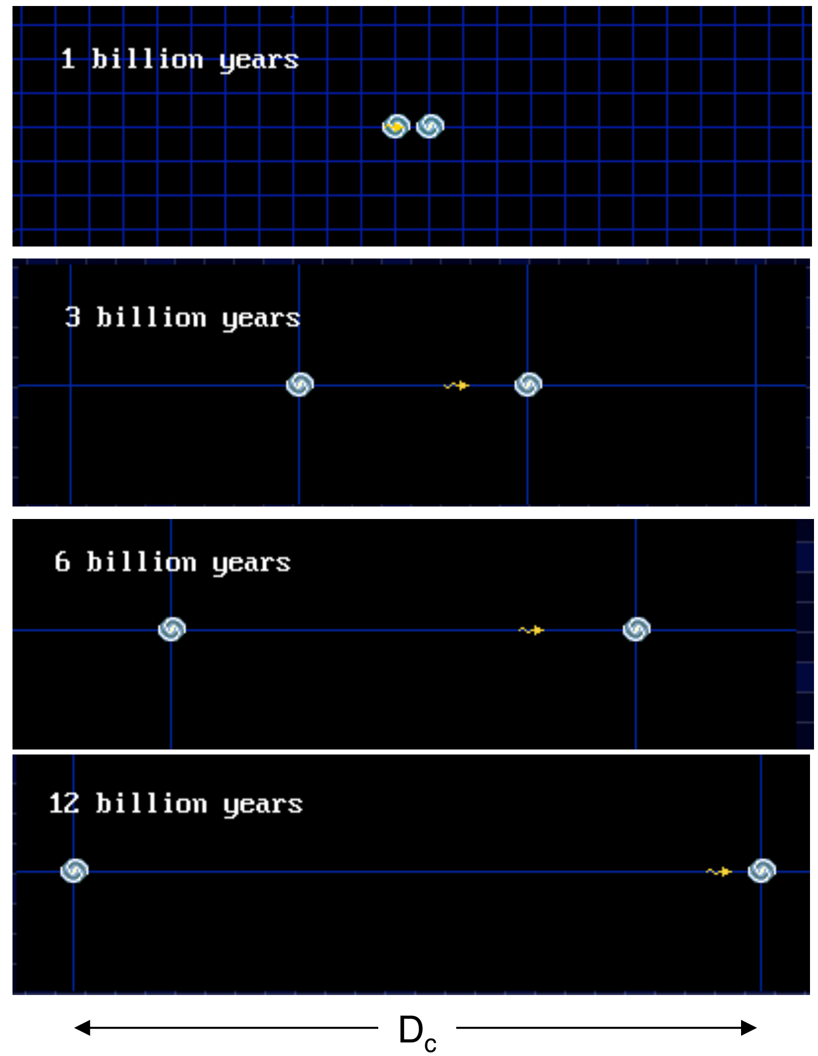
- Weak Gravitational Lensing
  Shapes of ~300 million source galaxies
- Galaxy Cluster Counts
  ~100,000 galaxy clusters to $z > 1$
- Baryon Acoustic Oscillations
  Clustering of ~300 million galaxies to $z = 1$ and above
- Type Ia Supernovae
  ~3000 Type Ia SNe to $z \sim 1$

Blanco telescope

How far is z=1?

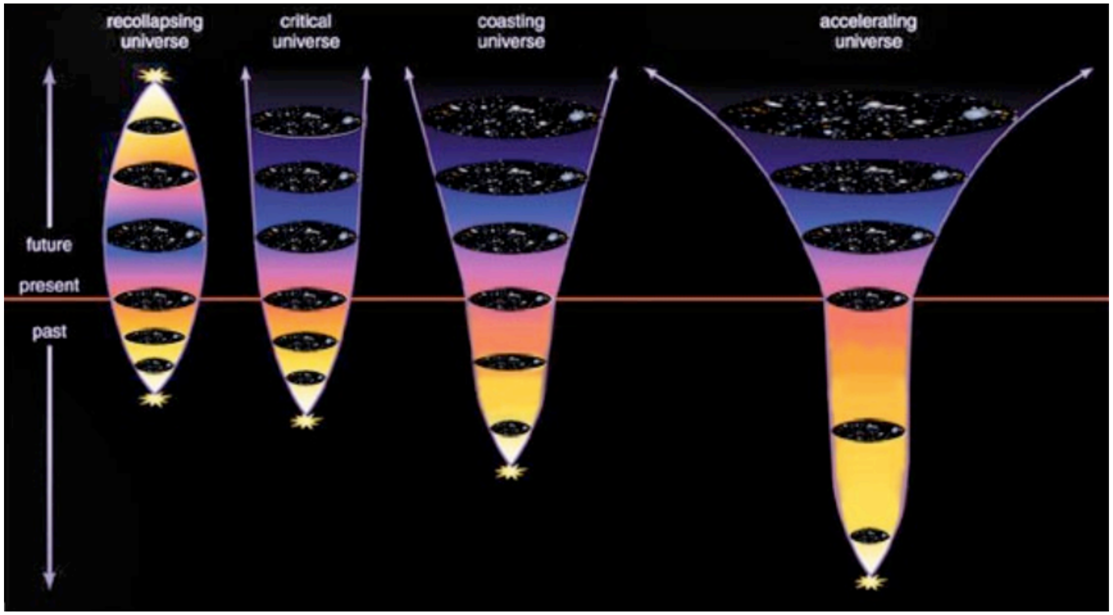
- “DES will count ~100,000 galaxy clusters to z > 1"
- What that really means is:
- "There are 100,000 clusters between us and a comoving distance, D_c, of 3317.3 Mpc. that are bright enough for DES to detect."
- The comoving distance is the distance to the object NOW (or at the time of the observation).

1 Parsec (pc) = 3.26163626 light year



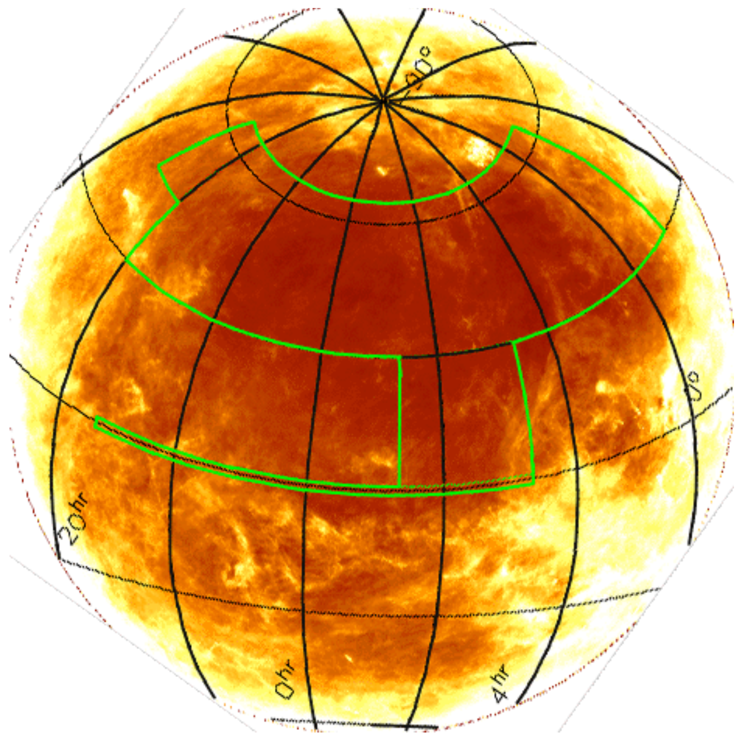
How does the survey work?

- The supernovae will give us an independent measure of expansion with a new dataset, similar to what other surveys have done but out to a larger distance.
- How the density of galaxies varies with distance will also tell us how the universe has changed over time and thus whether the expansion we see has been constant over that time.



How does the survey work?

- Take data for about 100 nights each year for 5 years
  - The survey area is visible from Oct-Feb
- Obtain about 300 images per night
- 100 seconds + 17 second readout time
  - This is driven by the desire for 8 tilings/ observing season: to observe the survey area 8 times/season.
- Send data to NCSA (National Center for Supercomputing Applications) at University of Illinois for processing
- Raw dataset: ~150,000 images
- Processed dataset: > 1 petabyte of data



DES survey area is outlined in green

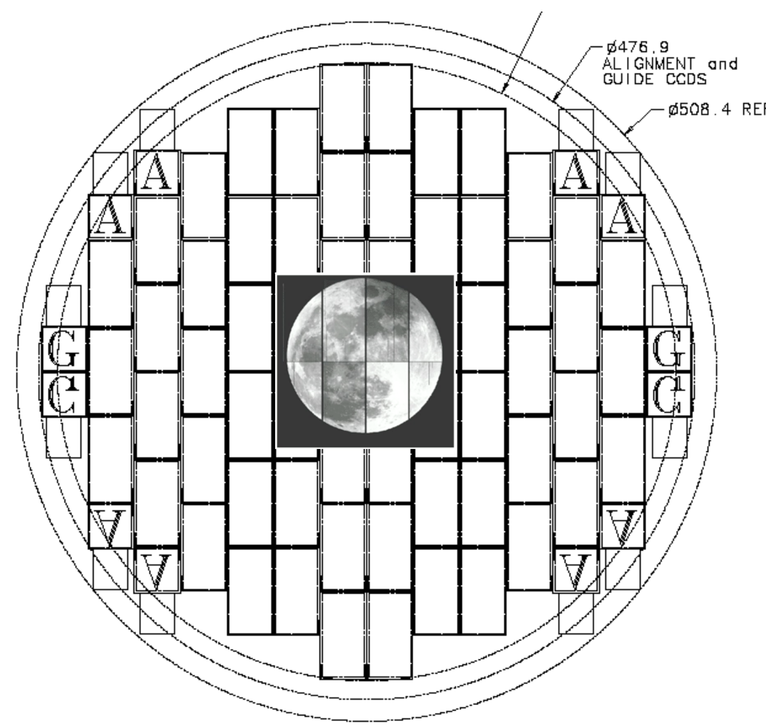
How will the data get from the telescope on the mountain in Chile to the data archive and processing center at NCSA at UIUC?

- It's network the whole way.
- Wireless from the mountain to La Serena and cable thereafter.
- The entryway to the US is through Miami.
- Need to average ~36 Mbps over 18 hour period to return a typical DES night.
- There are hopes to have something more like 100 Mbps.

DES requirements

- For a sky survey, need wide field optics
  - Convert the Blanco to a 3 square degree field of view.
- For a deeper (z>1) survey, need red-sensitive CCDs
  - Use LBNL thick, high-resistivity CCDs
  - By making the CCD thicker, it is easier to detect a red light.

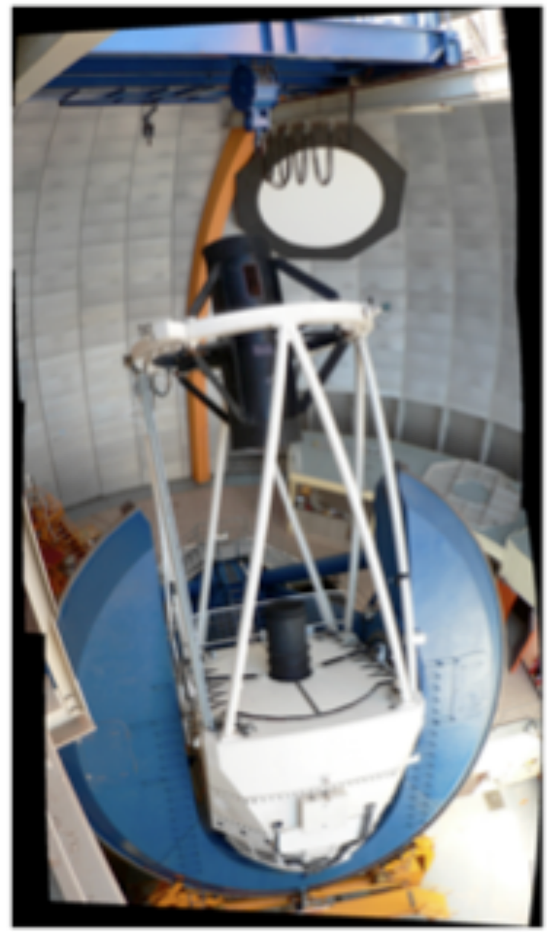
DECam Focal Plane



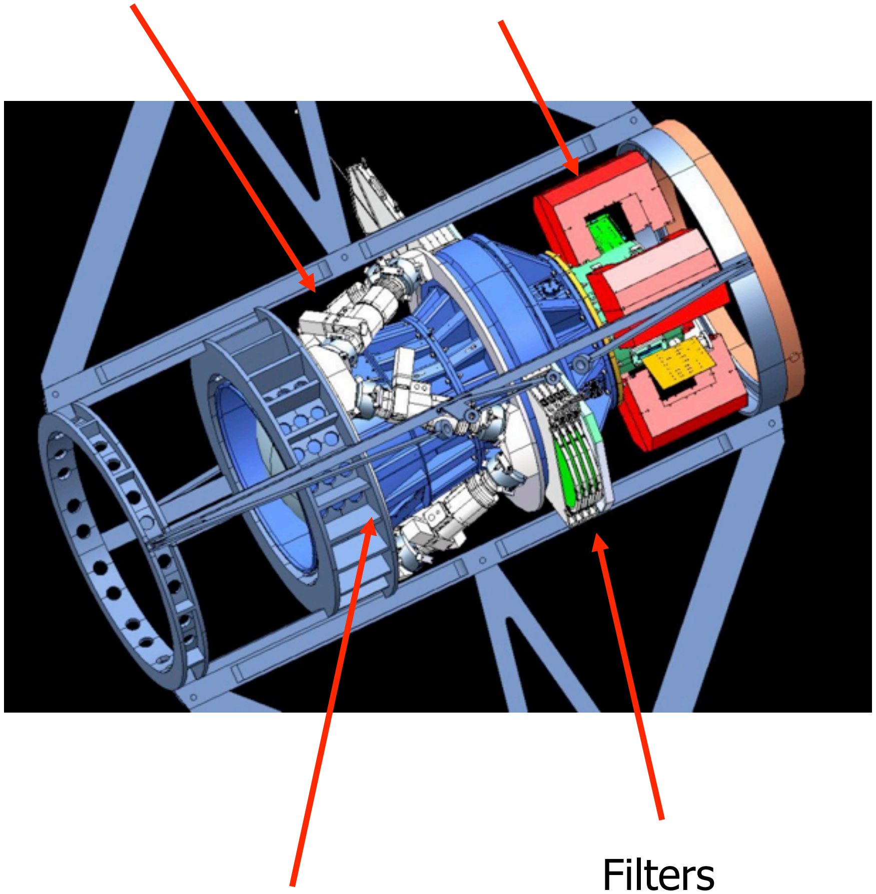
62 2kx4k Image CCDs: 520 MPix
8 2kx2k focus, alignment CCDs
4 2kx2k guide CCDs

New optics + New CCDs = DECam

- The DECam instrument will replace the entire prime focus cage of the Blanco.

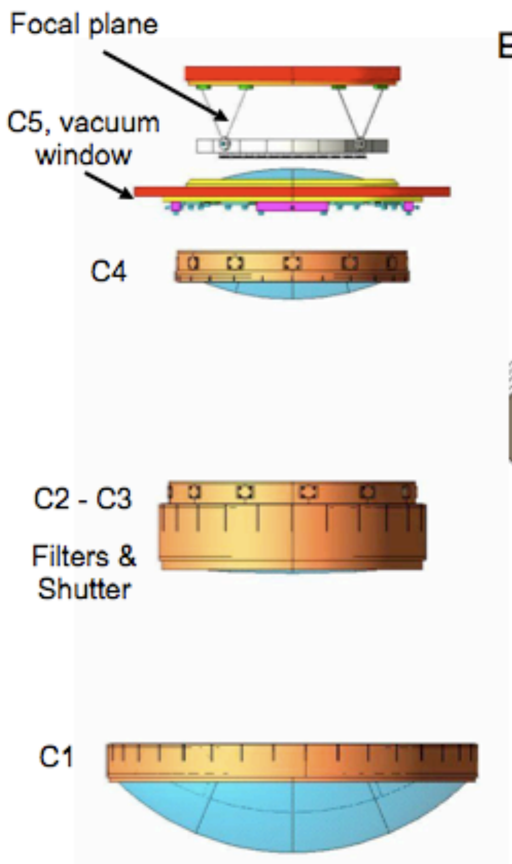


New optics + New CCDs = DECam

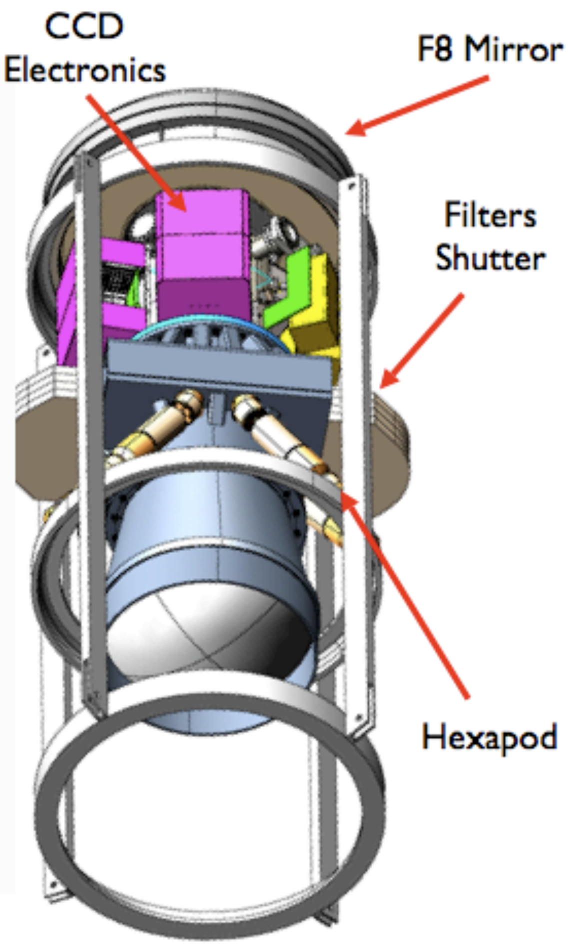


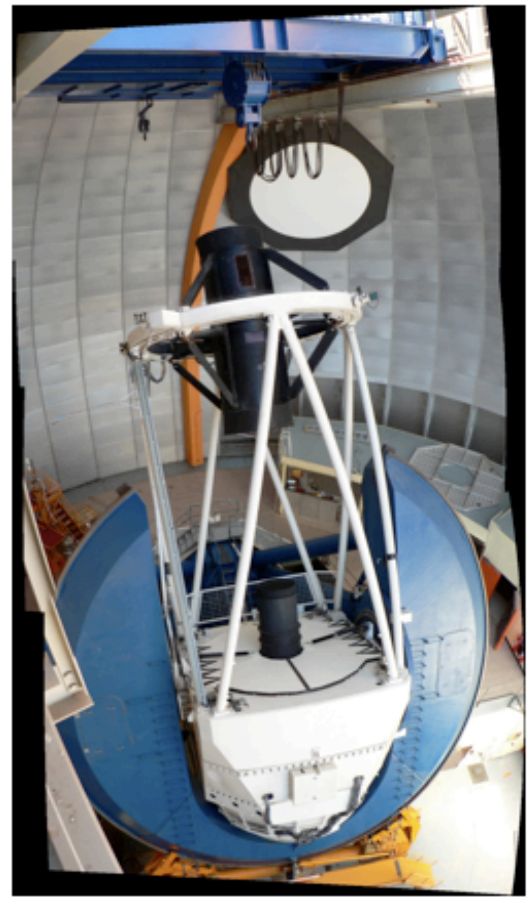
- The major components
  - 520 megapixel CCD camera
  - Low noise read-out system
  - Combination shutter-filter system
  - Wide field optical corrector (3 square degree field of view)
  - Hexapod to provide adjustability

New wide-field optics for Blanco telescope

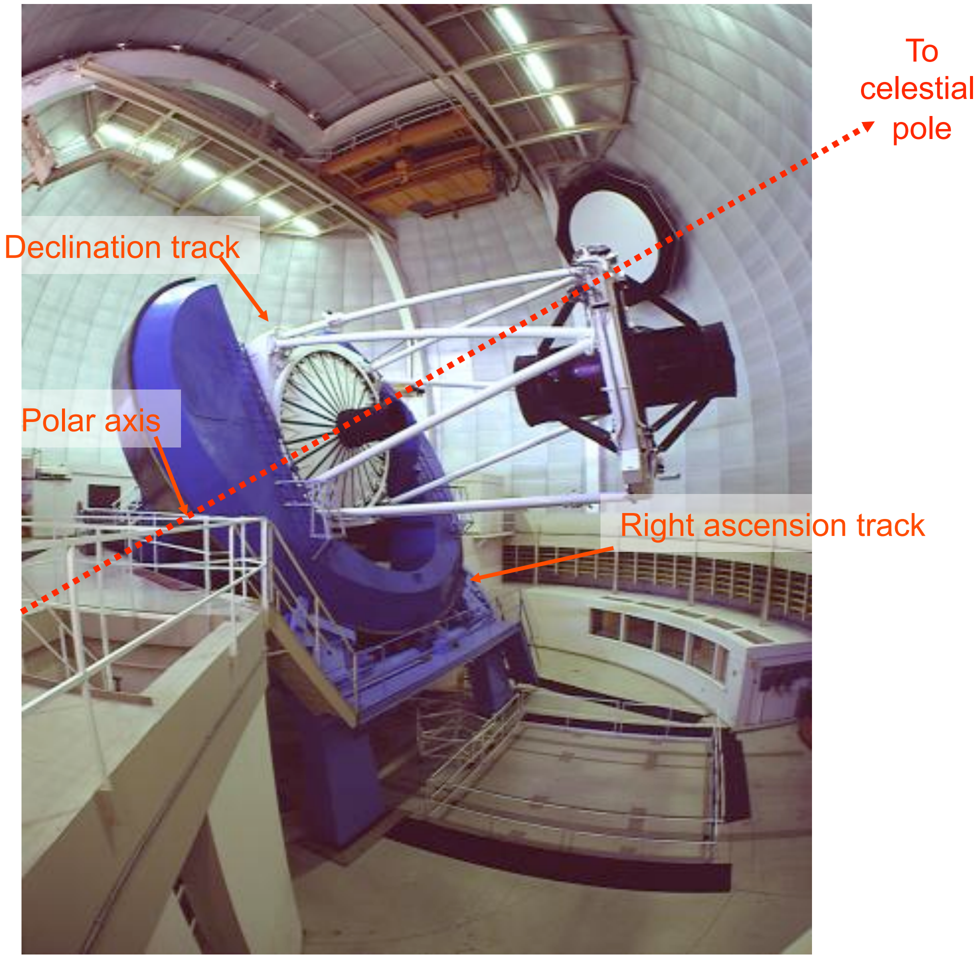


2.2 degrees, ~1 meter





Equatorial mount



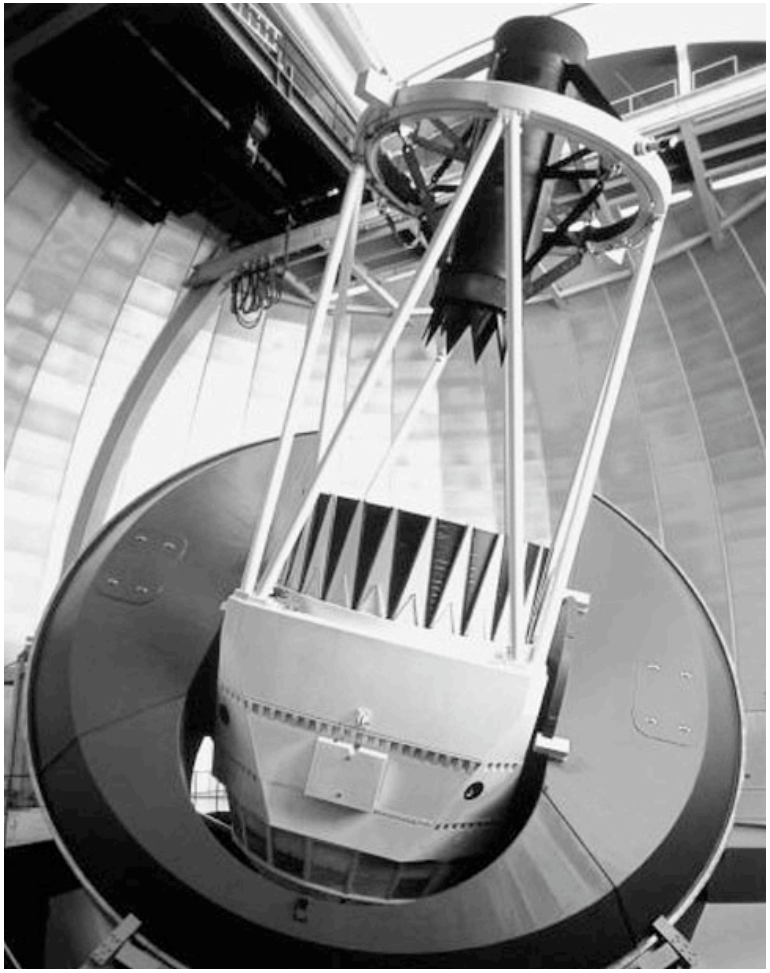
Blanco 4-meter telescope

1/24 scale desktop model of the Blanco

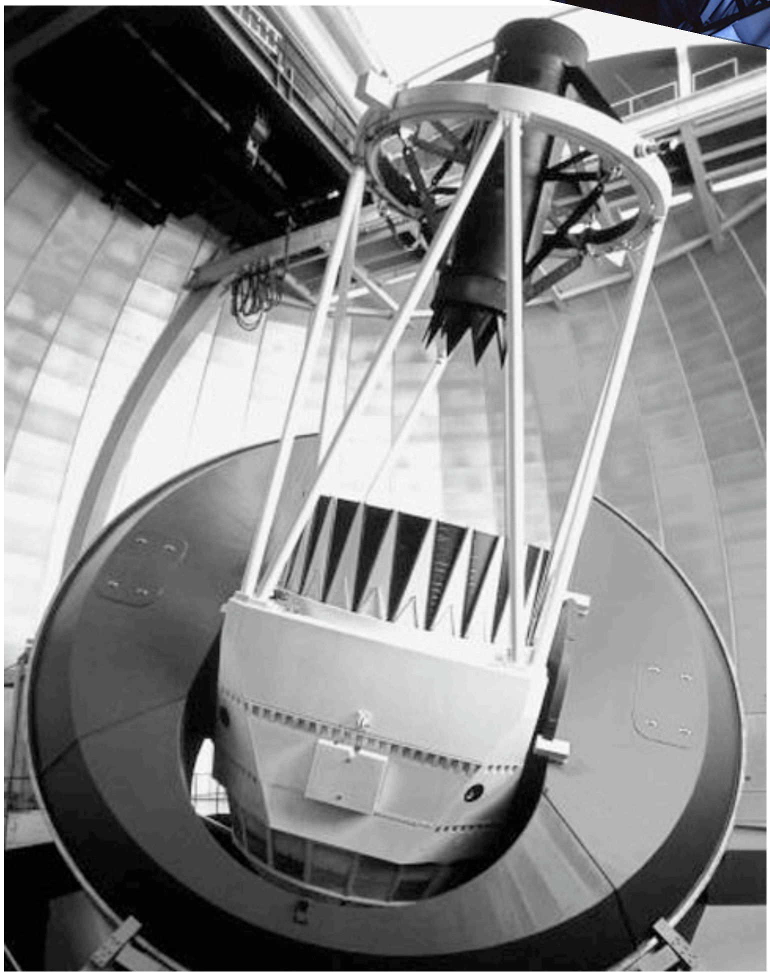
Why use the Blanco telescope?

- The reason DECam is going on the Blanco is that NOAO offered, through a public announcement of opportunity, 30% of the Blanco time in exchange for a new instrument.

- No such offer was available for other telescopes.



Why use the Blanco telescope?



- The Blanco is also ideally suited to getting a new prime focus instrument because it was built to handle a large load at the top end.

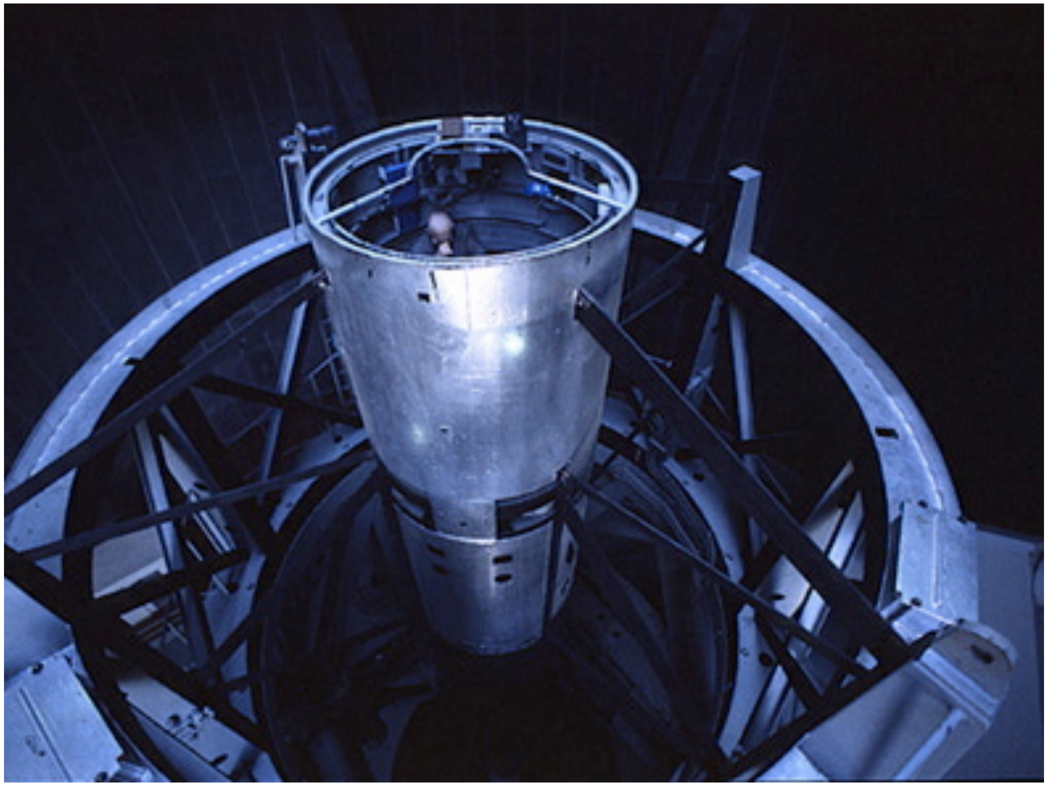
- When it was built, people rode in the cage and took pictures on glass photographic plates.

- Now, DECam will be taking pictures of roughly the same size with CCDs.

Example of observing from a prime focus cage

- *“Each time you go up, you carry a lot of paper. You carry some photographic plates in a tiny little box, and you carry a whole set of dreams of what the object you're going to work on is going to turn out to be.”*
- *Voice of Jesse Greenstein, Cal Tech astronomer*
- *Picture is of prime focus cage of 200” Palomar telescope*

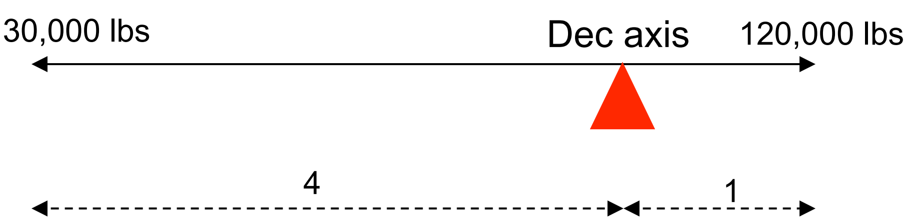
Example of observing from a prime focus cage



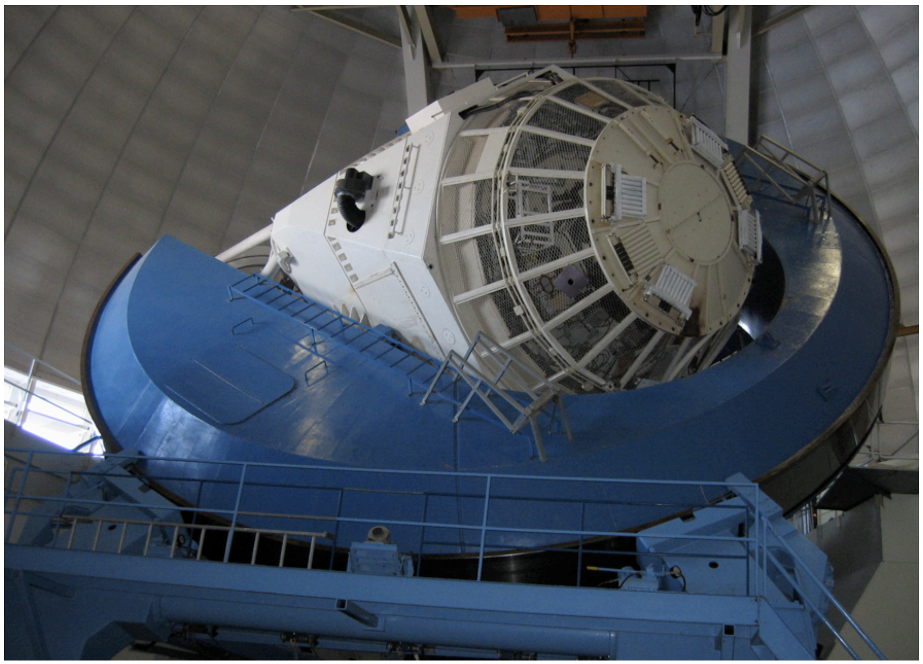
- *"Working a night in the small cage high above the primary mirror, feeling closer to the stars than the earth, remains an exhilarating and unforgettable experience."*
- *Voice of Jesse Greenstein, Cal Tech astronomer*
- *Picture is of prime focus cage of 200" Palomar telescope*

How much does DECam weigh?

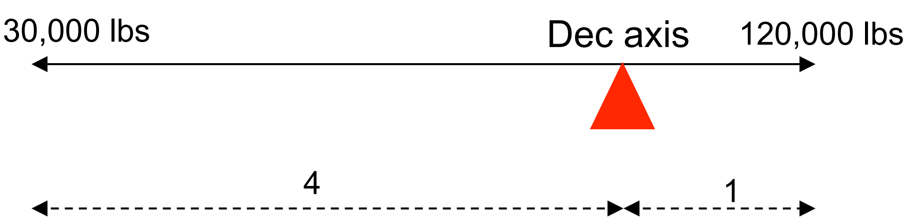
- The total weight of the upper structure is about 30,000 pounds.
- DECam weighs about 7,500 pounds.
  - DECam = corrector + imager + filter changer + shutter.
- The rest of the upper structure weighs about 22,500 pounds.
  - This includes the upper Surrier truss, outer ring, flip ring, fins, and prime focus cage



How much does DECam weigh?



- The lower structure is comprised of the primary mirror, mirror cell, ring girder, and Cassegrain cage.
- The total weight of the lower structure is about 120,000 pounds.



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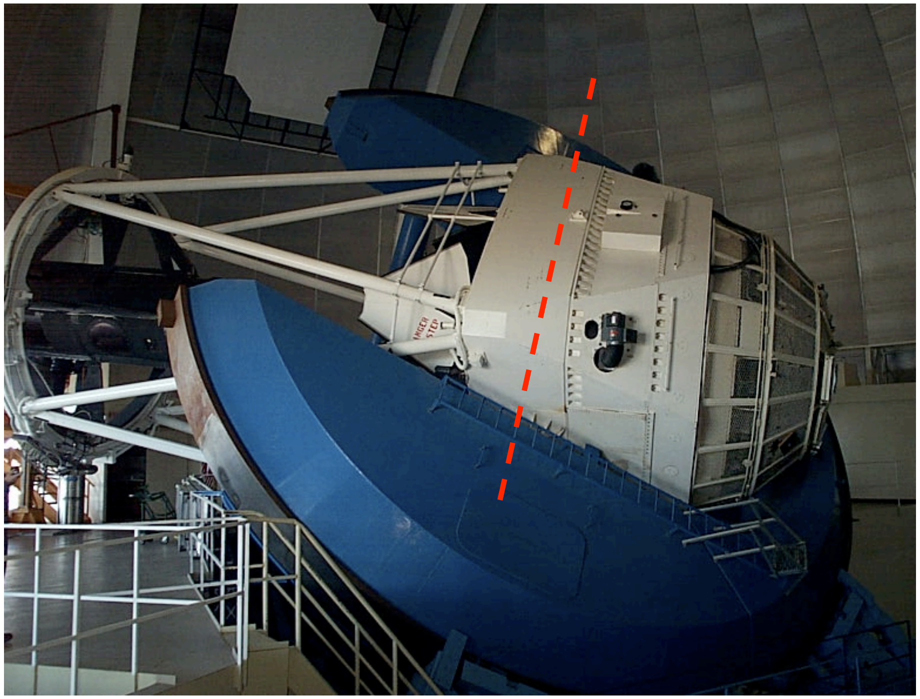
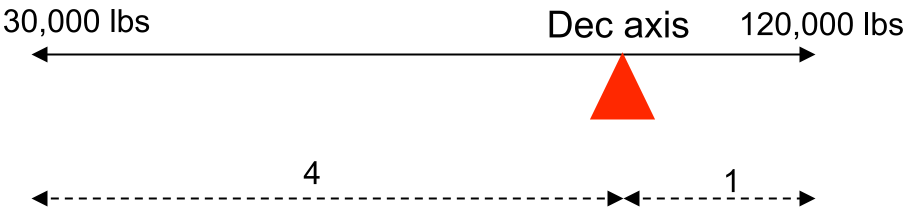


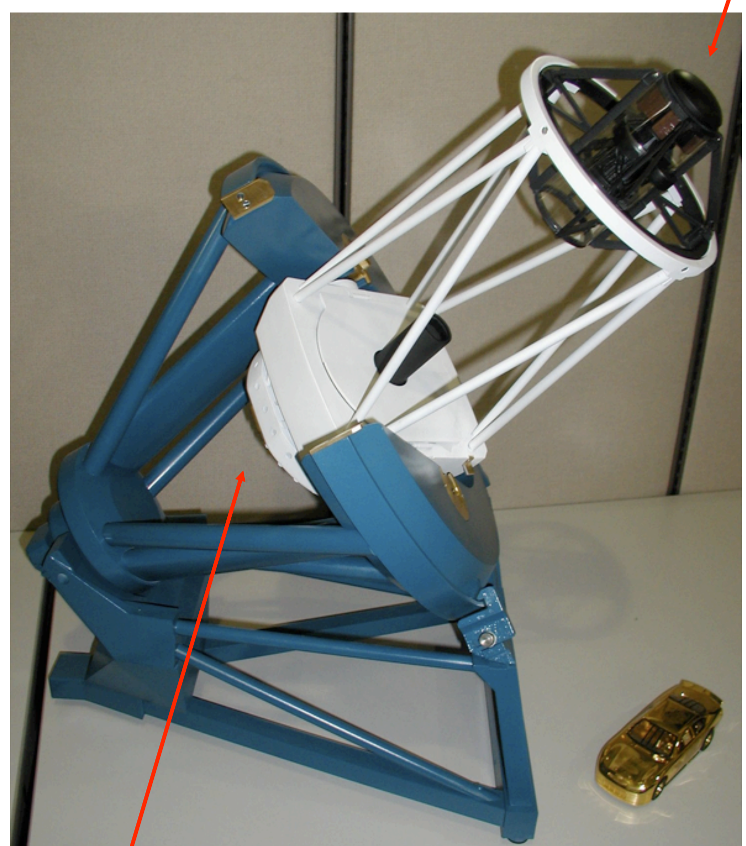


- The weight above the declination axis must be balanced by the weight at the opposite end of the 4:1 lever arm system.

$$(m_{upper}g) \times r_{upper} = (m_{lower}g) \times r_{lower}$$
$$30{,}000lbs \times 4 = 120{,}000lbs \times 1$$

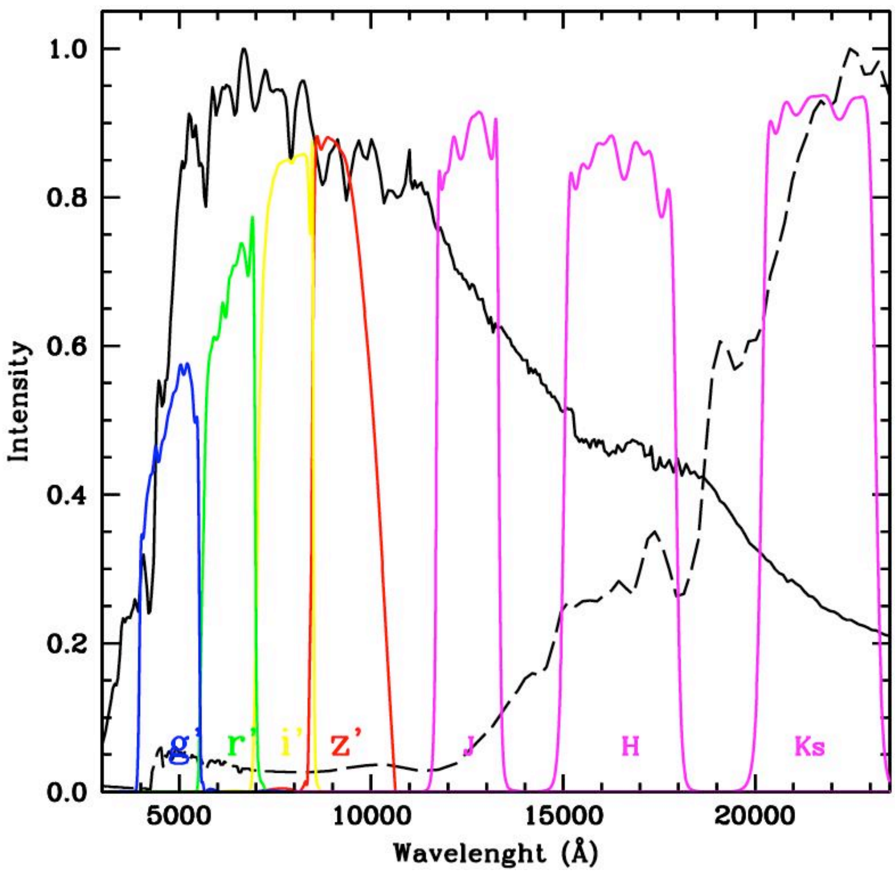
Telescope usage

- DES is comprised of two multiband surveys
  - 5000 deg^2 *g, r, i, z, Y*
  - 40 deg^2 repeat (SNe)
- DECam will be used to perform the Dark Energy Survey with 30% of the telescope time over a 5 year period
- During the remainder of the time, and after the survey, DECam will be available as a community instrument.
- DECam is located at the f/2.7 prime focus of the Blanco telescope.
- Some users may prefer to use other cameras and instruments located at the Cassegrain focus, so provision must be made to install a secondary (f/8) mirror in front of DECam.



Photometric redshifts

- The 5000 square degree area of DES will be surveyed twice per year per filter.
- The galaxy catalog will reach 24th magnitude and have photometric redshifts out to z~1.3
- The survey overlaps the Sunyaev-Zeldovich cluster survey of the South Pole Telescope and the infrared survey of the Vista Hemisphere Survey, which uses the Visual and Infrared Survey Telescope for Astronomy (VISTA)
- Information from VISTA's longer wavelength observations will improve the photometric redshifts.



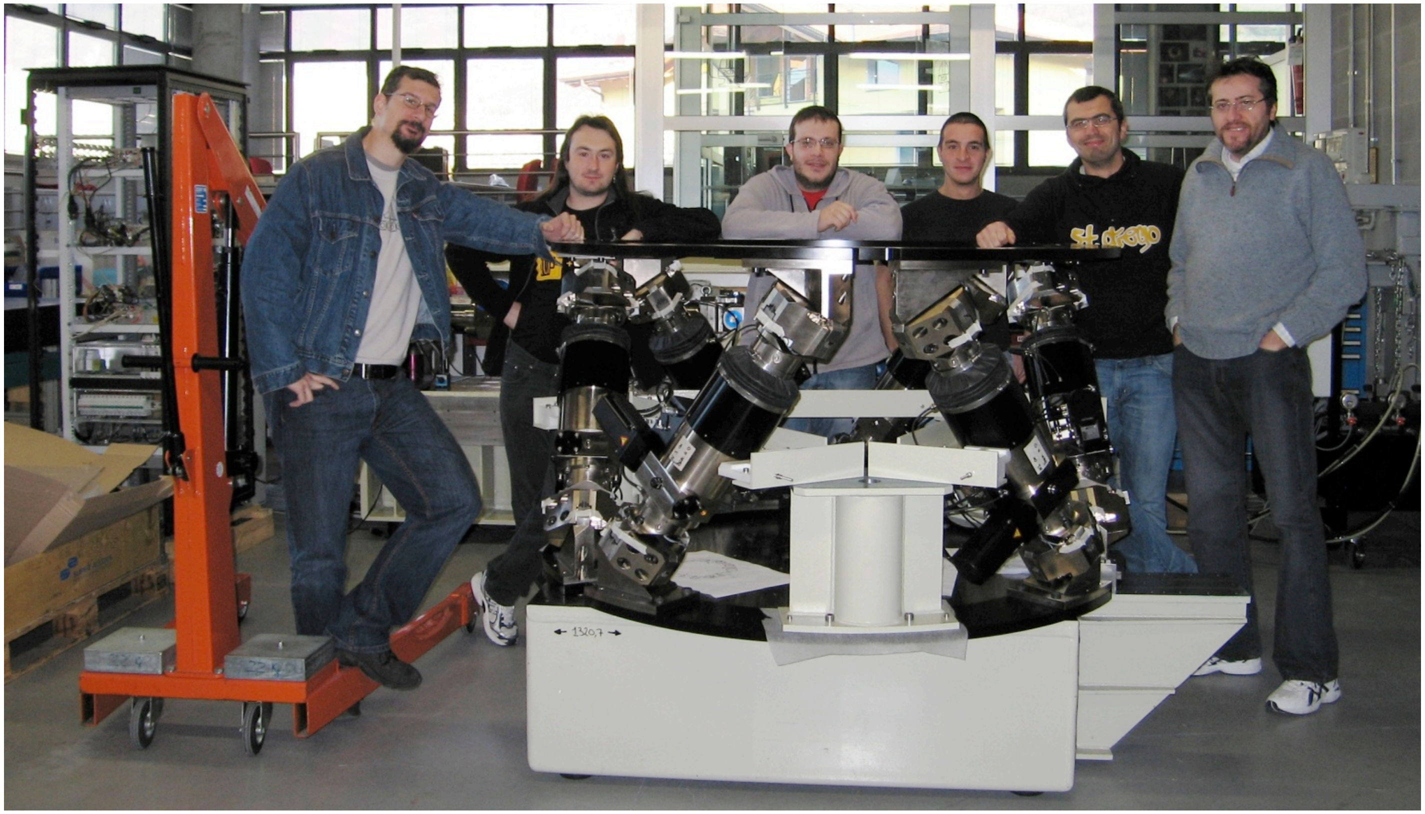
Why isn't adaptive optics used?

- The large field of view (3 square degrees) of DES makes adaptive optics especially challenging and costly.
- Good location minimizes bad seeing:
  - Elevation: 2123 meters
  - The median seeing of 0.9 arc sec is sufficient for the proposed science
- Maintain focus & alignment using the hexapod. (Shown on next slide)
- The telescope's thermal environment was improved by installation of large ventilation doors & ventilation subsystems

Elevation: 2123 meters

Focusing the telescope

- The hexapod positions camera to 1 micron



What limits how much the naked eye can see?

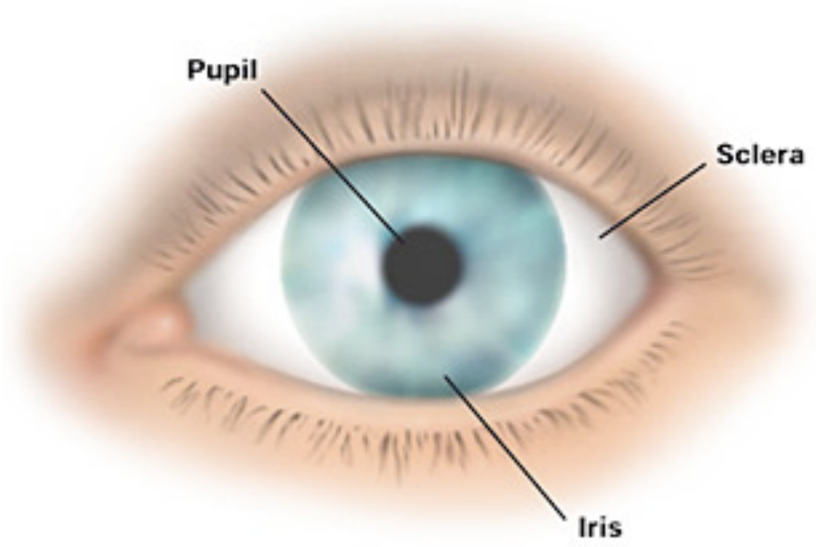
- Small aperture
- Short integration time
- Narrow bandwidth

How have astronomers overcome the limitations imposed by the human eye?

- Telescopes
- Cameras
- Telescopes and cameras that can detect colors beyond those the eye can see

The Eye

- The pupil is the opening in the center of the iris.
- The size of the pupil determines the amount of light that enters the eye.
- The pupil size ranges from only 3-8 millimeters.
- The small size of the pupil limits the amount of light that can enter the eye, maing it difficult to see faint or very distant astronomical objects.

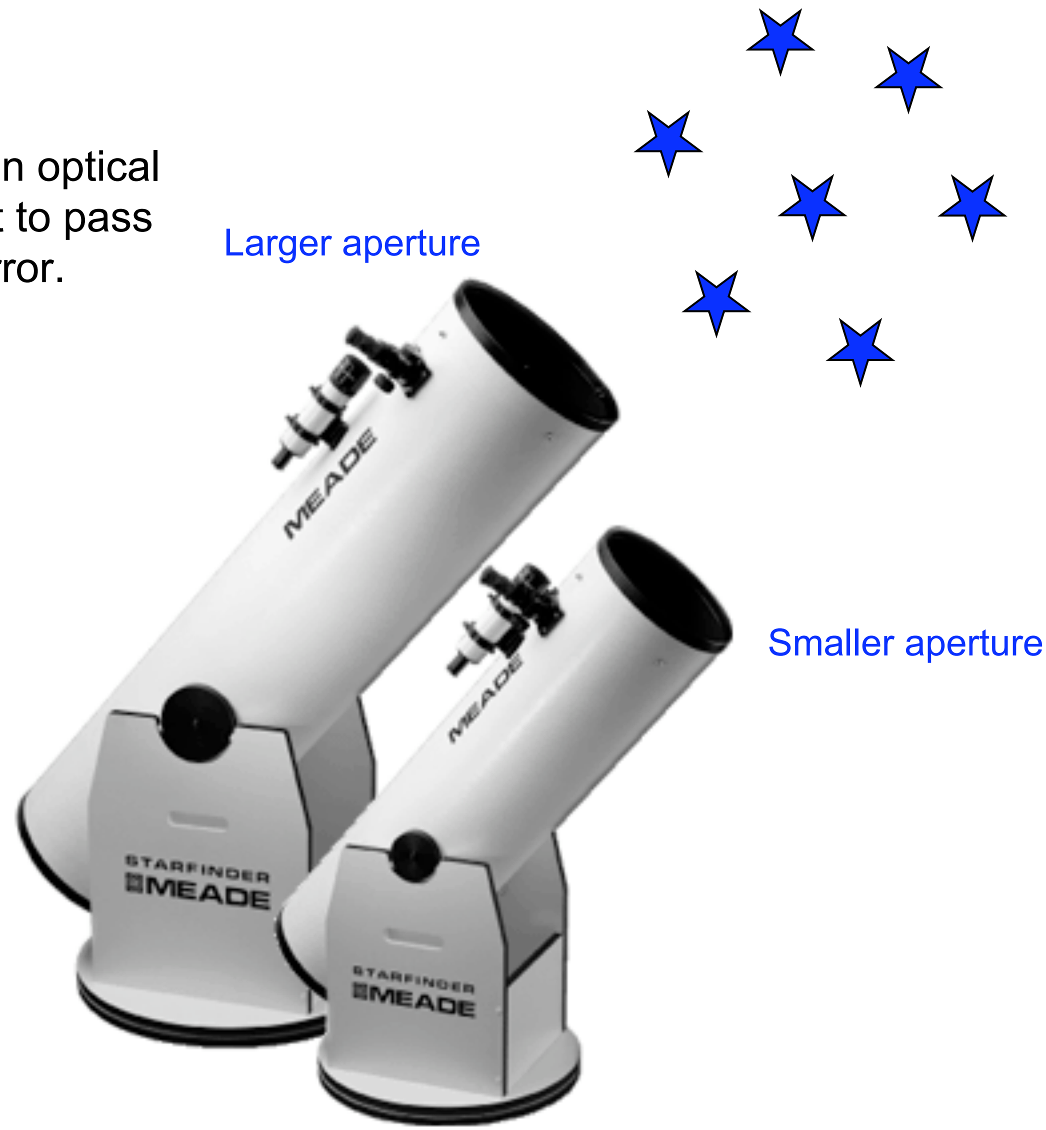


400 years ago: 1608

- The main purpose of a telescope is to gather as much light as possible and funnel it into your eye.
- Based on the telescope invented in the Netherlands in 1608, Galileo made a telescope with a 37 millimeter diameter aperture.

Aperture

- Aperture is the opening in an optical instrument that permits light to pass through a lens or onto a mirror.



400 years ago: 1608

- The light gathering power (LGP) of a telescope is proportional to the *area* of the aperture:

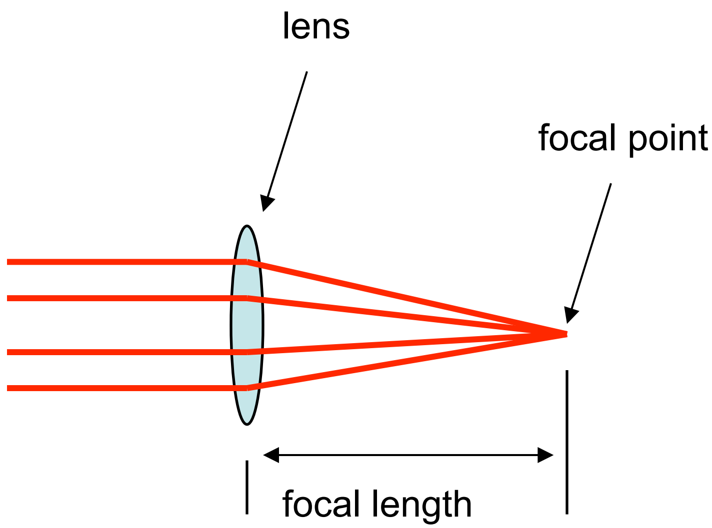
$$Area = \pi(radius)^2$$

- Therefore the light gathering power of Galileo's telescope was about 55 times that of the eye:

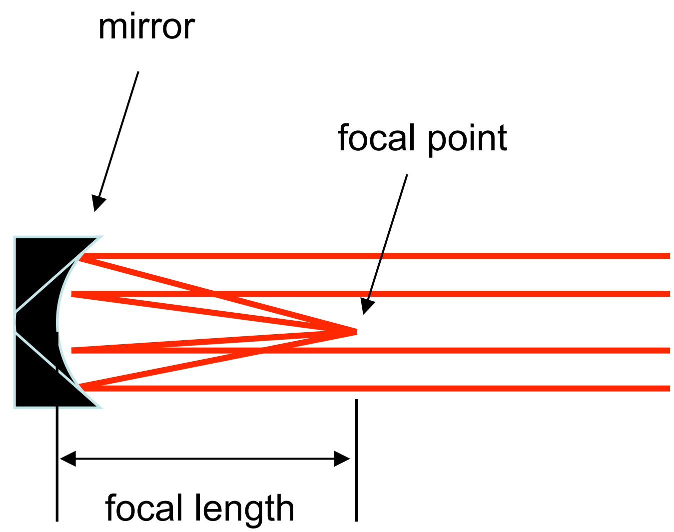
$$\frac{LGP_{Galileo's\ telescope}}{LGP_{eye}} = \frac{\pi(37mm/2)^2}{\pi(5mm/2)^2} \cong 55$$

Diameter = 37mm

Classes of optical telescopes: Reflectors and refractors



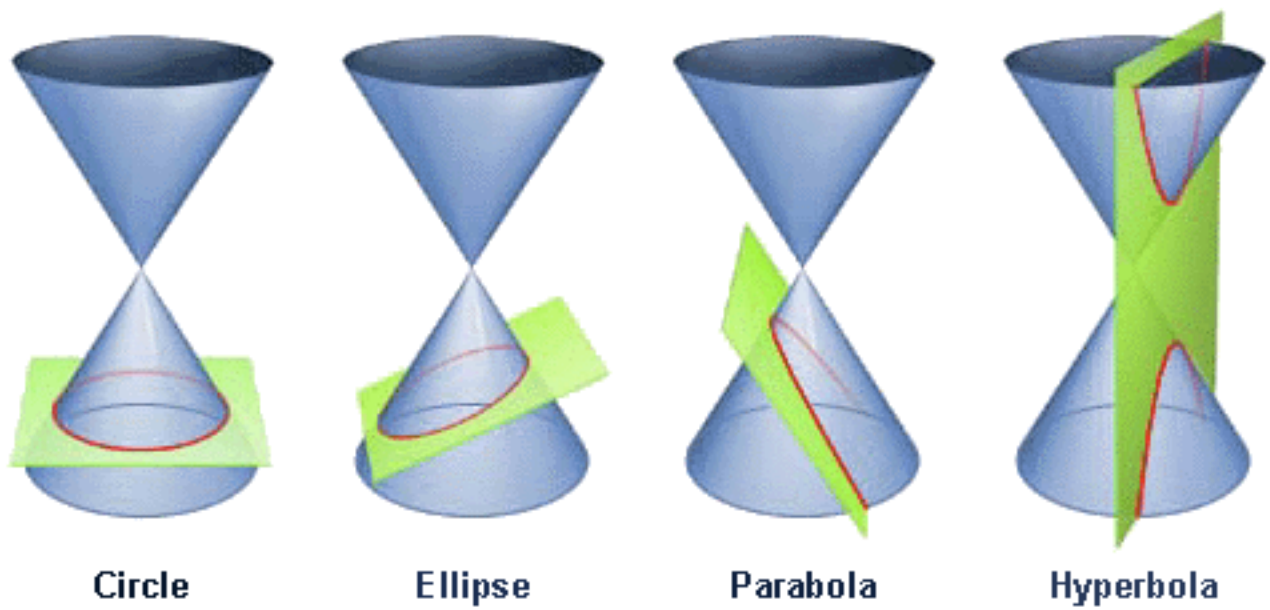
Refractors use lenses



Reflectors use mirrors

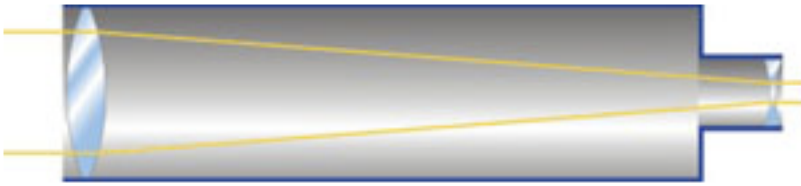
Classes of lens and mirror shapes: Conic sections

- Spherical (circular), parabolic, hyperbolic, and ellipsoidal describe the shape of a lens or mirror.



Refracting telescopes

- Galileo’s telescope was a refractor that used a spherical lens.
- The images he saw were imperfect because of aberrations caused by the spherical lens.



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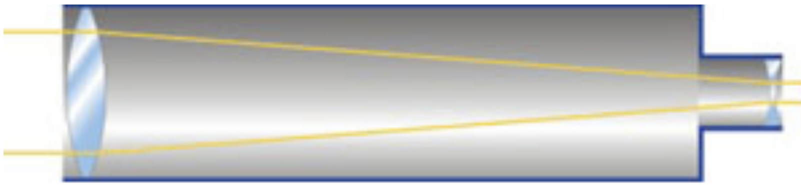
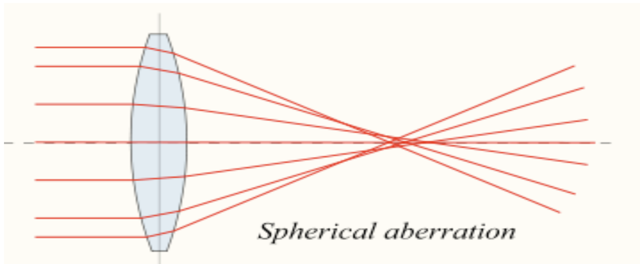
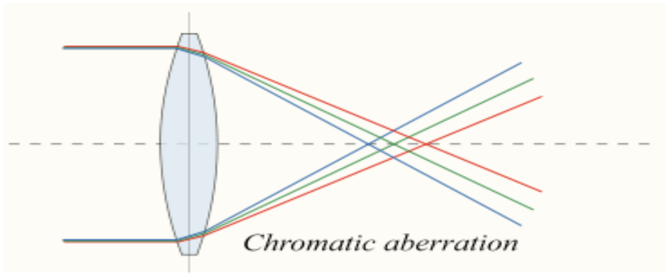


- The images he saw were imperfect because of aberrations caused by the spherical lens.

- Spherical aberration occurs because the spherical shape of the primary lens causes light at different distances from the optical axis to be focused at different distances.

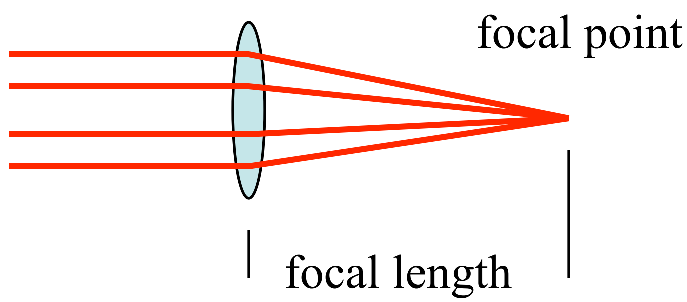


- Chromatic (color) aberration occurs because the index of refraction of a lens is a function of wavelength.

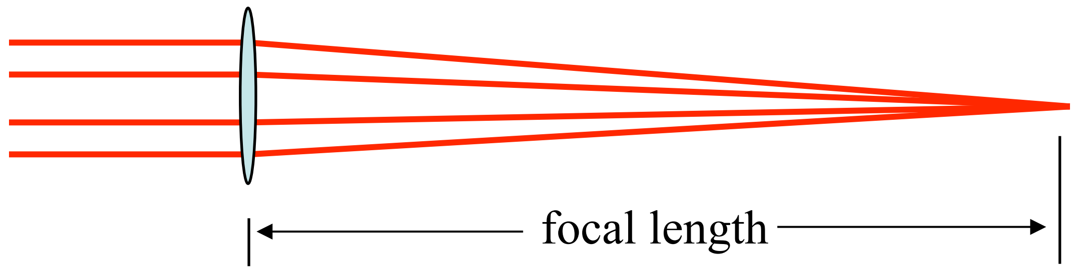


Refracting telescopes

- Try to make spherical lens very thin so its spherical surface approximates a parabola.



- But that results in a very long focal length



Refracting telescopes

- Could get rid of spherical aberration by grinding a parabolic surface.
  - But spherically shaped lenses are much easier to make.

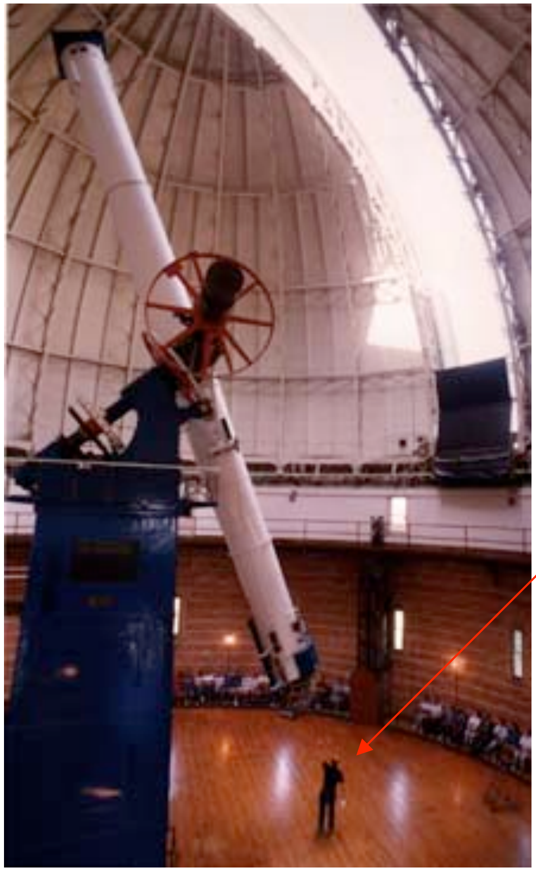
- Spherical surfaces are easier to make for a couple of reasons.

  - Spherical surfaces are easier to test - you can put an interferometer on them with a simple optical test set up (single lens- test at centre of curvature) - Aspheric surfaces need a more complicated test set up (null lens system - have multiple elements)

  - It is also easier to lap spherical surfaces (if you have a spherical surface and spherical lap then is it relatively easy to polish the surface)

Refracting telescopes

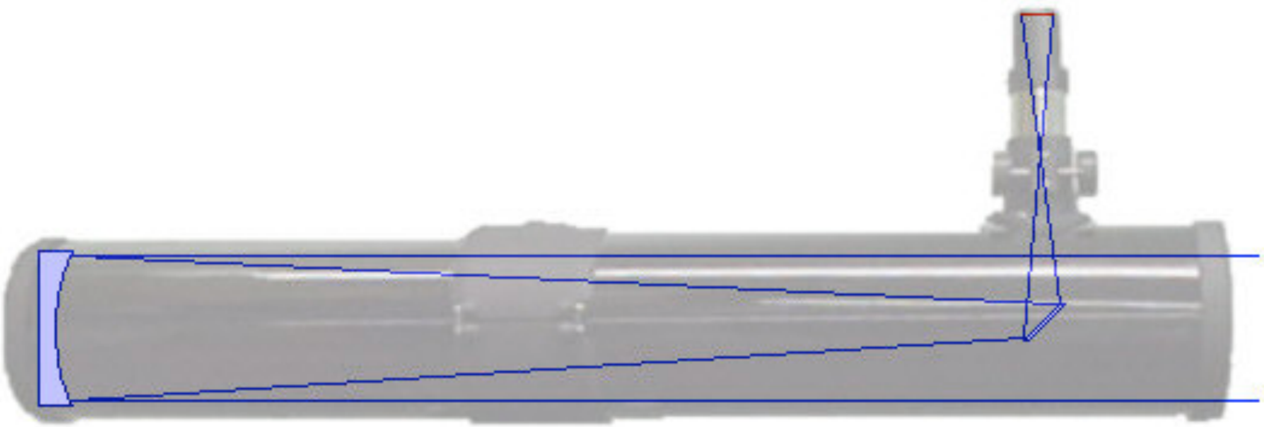
- The world's largest refracting telescope is 19.3 meters (~63 feet) long!
- The ultimate size of refractors is limited by
  - Flexures imposed by the weight of the lenses
  - Absorption of light by massive lenses
  - Unwanted refractions by large lenses



Yerkes
Williams Bay, WI

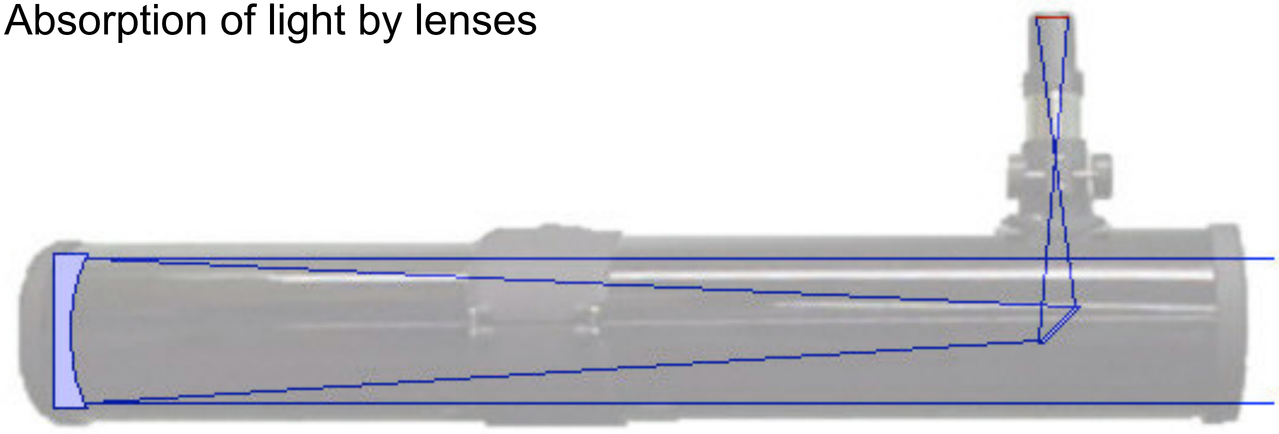
Mirrors to the rescue!

- Newton replaced the lens with a mirror to eliminate chromatic aberration of lenses.



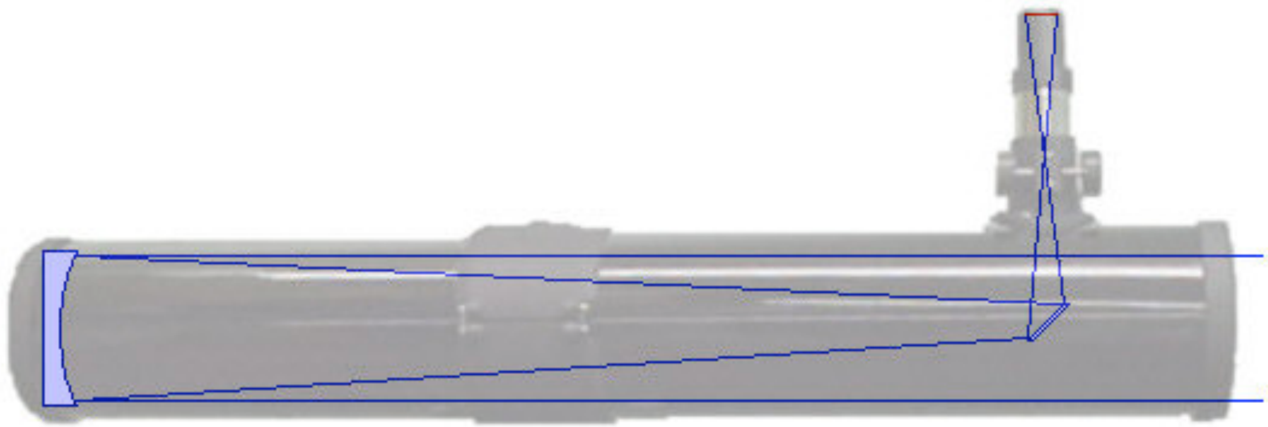
Mirrors to the rescue!

- Mirrors overcome 4 of the 5 problems of refractors:
  - Chromatic aberration
  - Flexure from heavy lenses
  - Unwanted refractions
  - Absorption of light by lenses



Mirrors to the rescue!

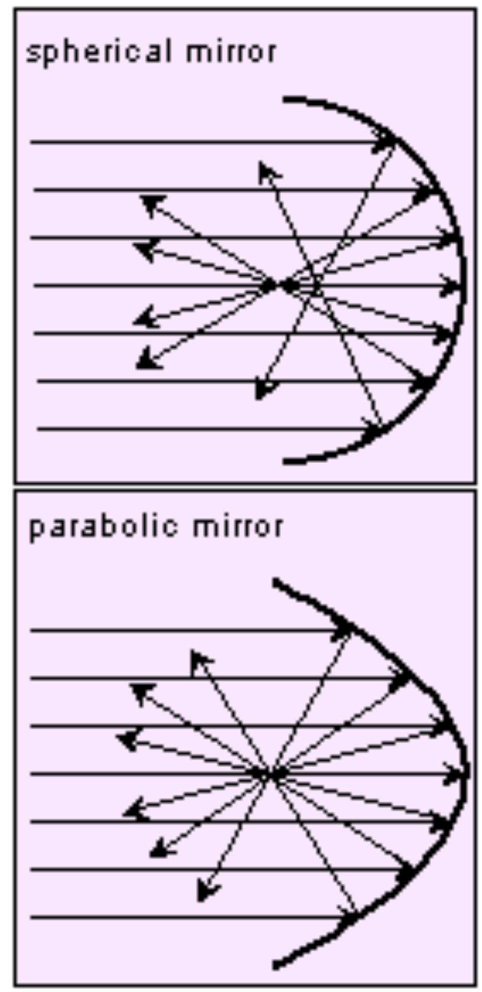
- But mirrors can still have spherical aberration.



One solution

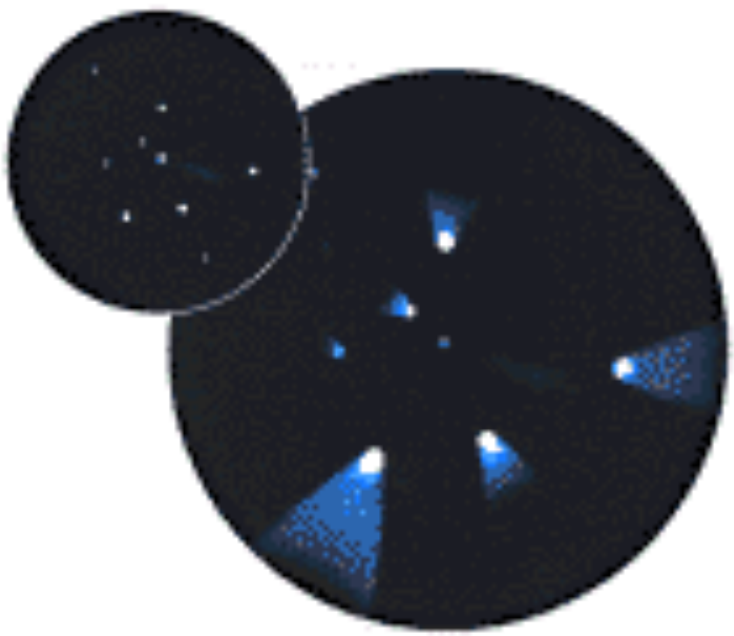
- Use a parabolic mirror instead of a spherical mirror.

- With a perfect parabolic mirror, all rays are focussed to the same point, so there is no spherical aberration.



Coma

- However, a parabolic mirror creates coma (coma = comet-like).

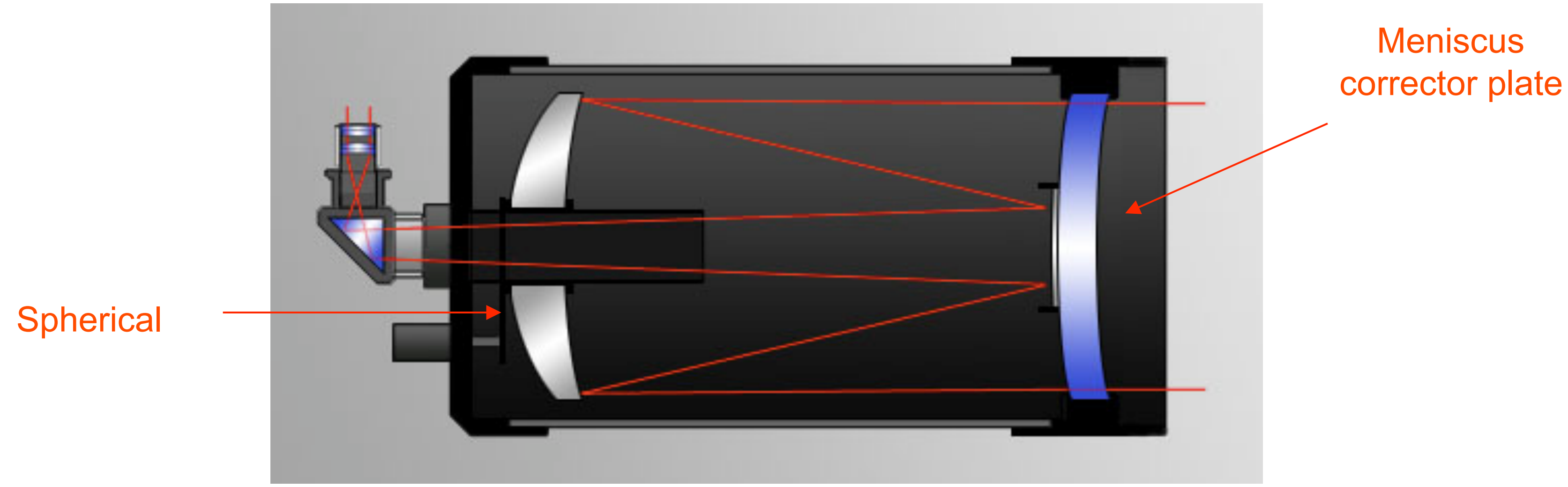


Another solution: Schmidt-Cassegrain

- Uses a spherical mirror (instead of parabolic) to minimize coma
- Uses Schmidt corrector plate to correct for spherical aberration.

Another solution: Maksutov-Cassegrain (Mak)

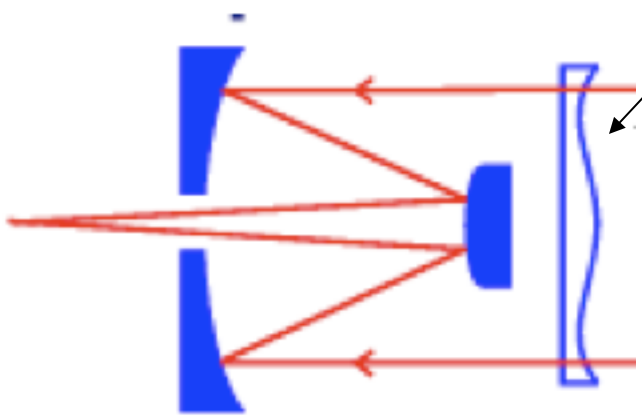
- Still use a spherical mirror to minimize coma.
- Maks use a less-expensive meniscus corrector, a highly curved spherical lens, to correct for spherical aberration.



Correctors

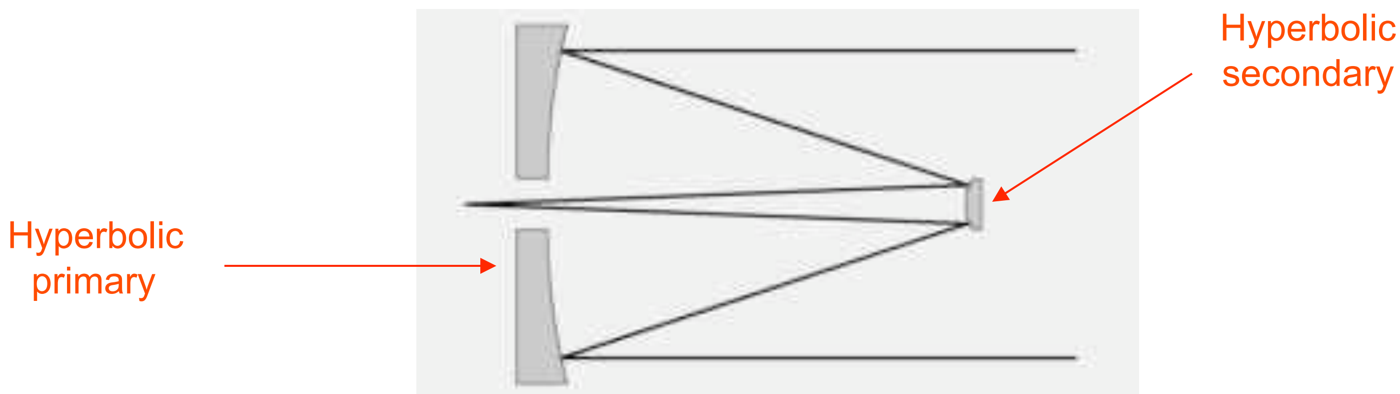
- Since correctors are lenses, don't they reintroduce chromatic aberration, the thing we were getting rid of by using mirrors?

- The amount of chromatic aberration is small and can be minimized by careful design of the shape, as the location of the "dip" in the Schmidt corrector plate and the thickness of the Mak correctors.



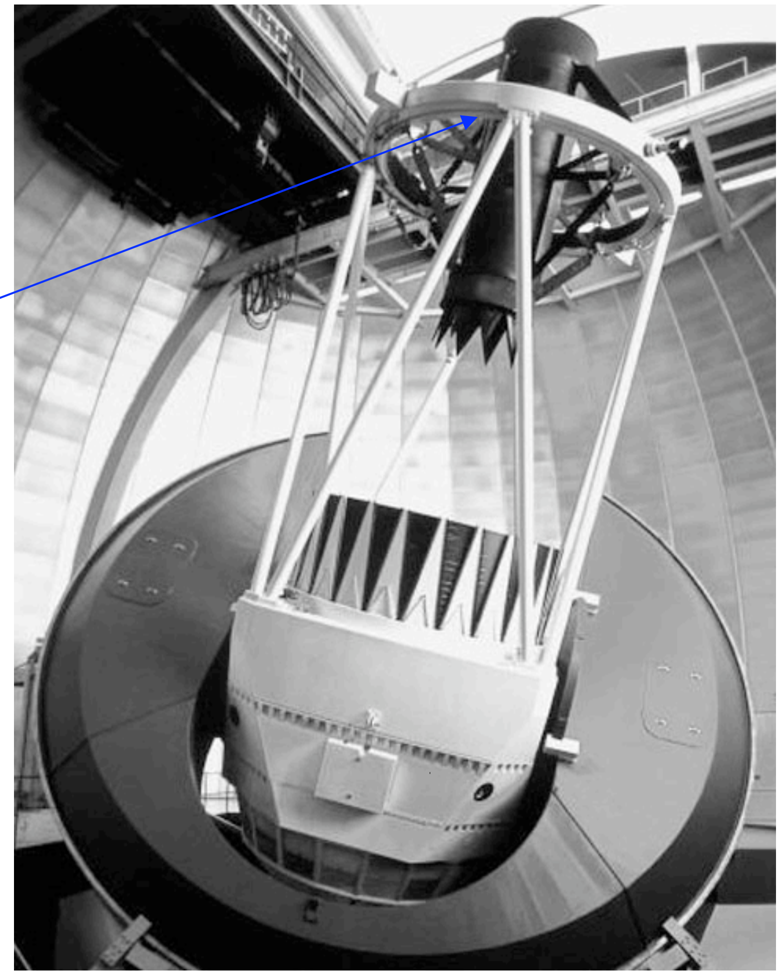
Another solution: Ritchey-Chretien

- Many professional telescopes, including the Hubble Space Telescope, are of the Ritchey-Chretien (RCT) design.
- The RCT telescope is designed to eliminate coma as well as spherical aberration, thus providing a relatively large field of view.
- It has a hyperbolic primary mirror and a hyperbolic secondary mirror.



Professional telescopes also have correcting lenses

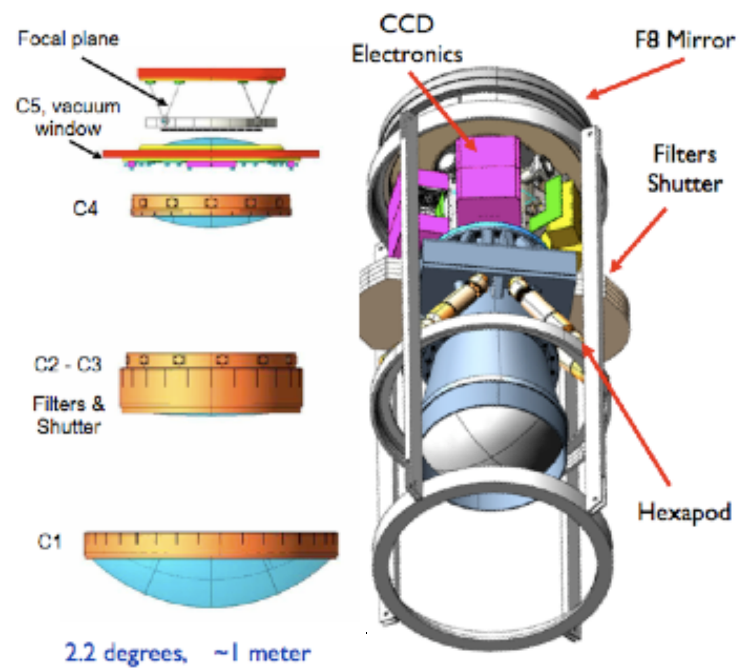
- Although the Blanco telescope has a hyperbolic primary, which helps eliminate spherical aberration and coma, the Dark Energy Survey requires such a large field of view (2.2 degrees) that a corrector is needed.



Blanco Telescope

Professional telescopes also have correcting lenses

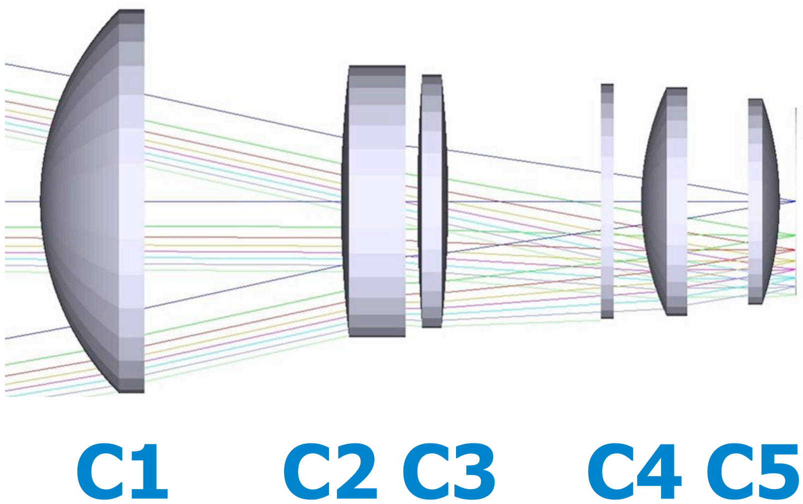
- Conventional two mirror designs are generally optimized to give a good image over a small field of view (~30 arcmin).
- They suffer mainly from coma if you have a wide field.
- The Schmidt can give a large reasonably aberration-free field of view but the Schmidt corrector plates can't be made larger than about 1.5 meter diameter, limiting the collecting area.
- Maksutovs have a similar problem



Blanco corrector

Professional telescopes also have correcting lenses

- The DECam corrector is comprised of 5 lenses, each uniquely shaped to correct for a variety of aberrations.
- Classically 3 corrector elements is a minimum.
- Corrections for all aberrations are folded into all the elements.
- Each element does not have one, unique function (for example, they can't be separated out so "simply" as C1 corrects for coma, C2 for astigmatism, etc)



Blanco corrector

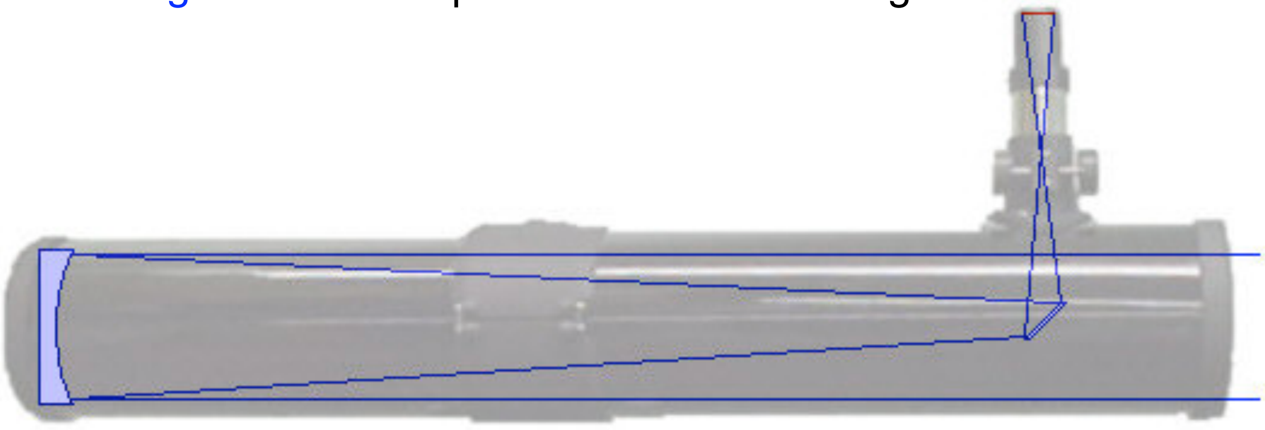
Professional telescopes also have correcting lenses

- The DECam corrector consists of 5 fused silica lenses
- The last element serves as the window of the CCD vacuum vessel, so it is very close to the CCDs.
- High-potassium glass like BK7 cannot be used, because β rays from the decay of ^{40}K produced near the surface of the glass can strike the CCD.
- Lens fabrication is in progress.
- The blanks were completed in Jan. 2008 and the lenses are now being ground and polished at SESO in France.

Blanco blank

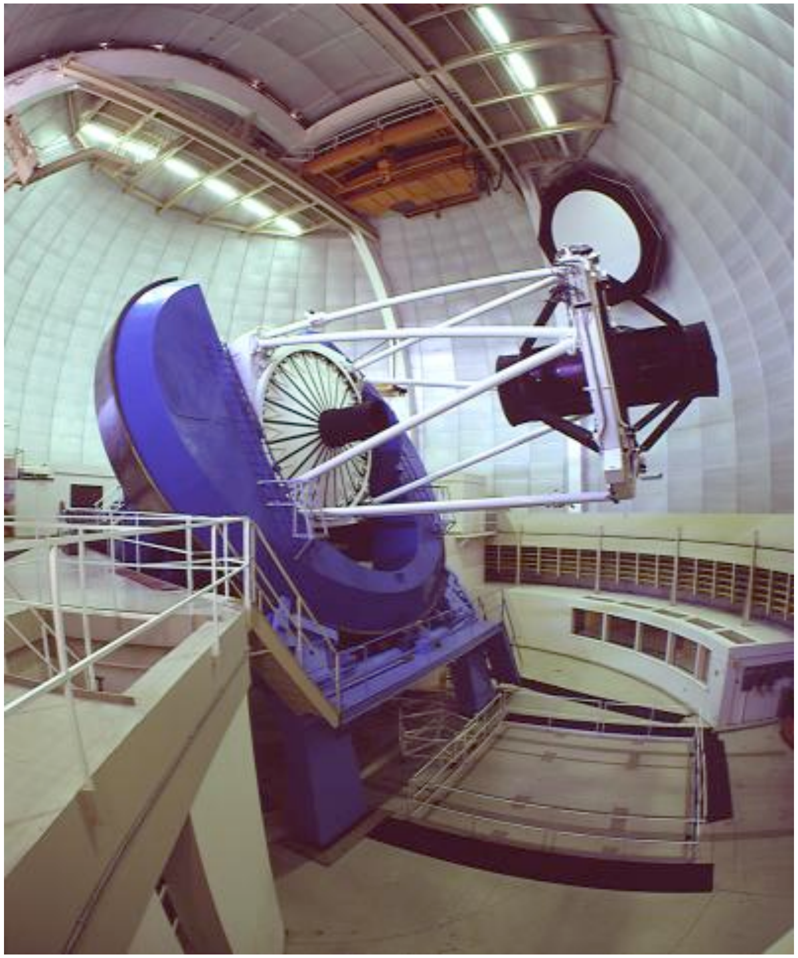
Mirrors to the rescue?

- But reflectors present a new problem:
  - The secondary mirror of a reflector blocks some incoming light.
  - Prevents about 10% of light from reaching the primary mirror.
  - This problem is addressed by constructing primary mirrors with sufficiently large area to compensate to the loss of light.



Professional telescope mirrors are huge

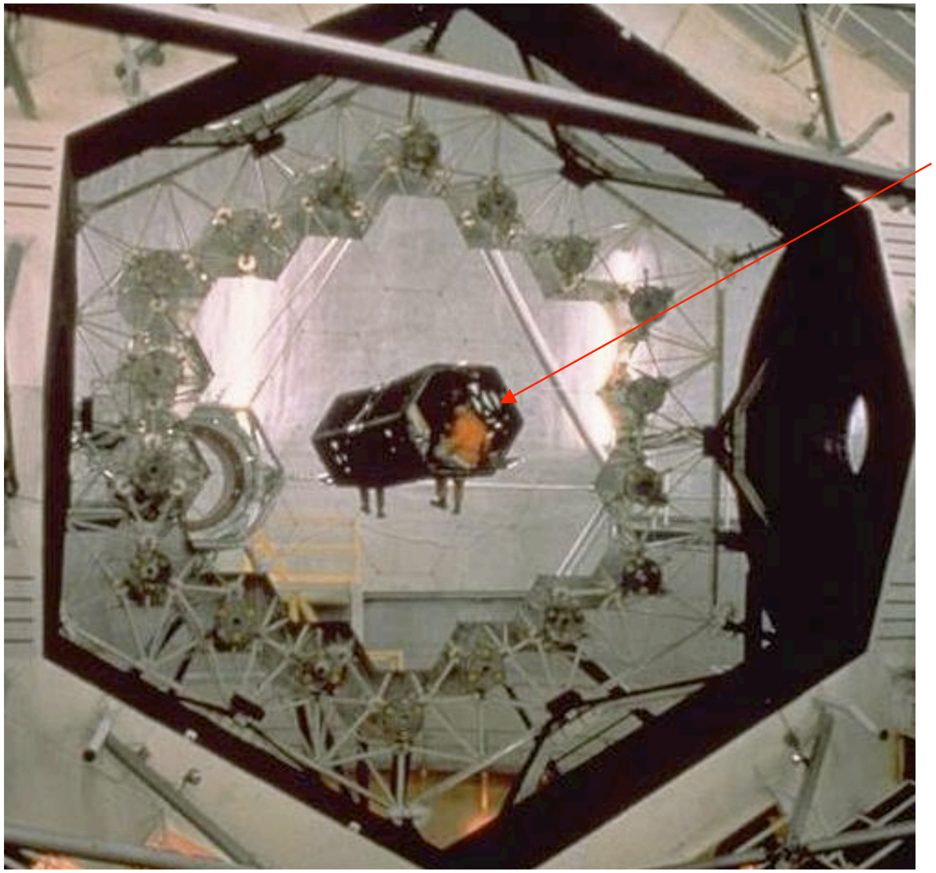
- The Blanco has a 4 meter mirror
- About 10% of the collecting area is blocked by the corrector



Professional telescope mirrors are huge

- The Keck I and Keck II are located on Mauna Kea, Hawaii
- Each has a 10 meter mirror

Large



10 meter Keck primary mirror

Larger

- Gran Telescopio Canarias (GTC) is a 10.4 meter reflecting telescope in Canary Islands.

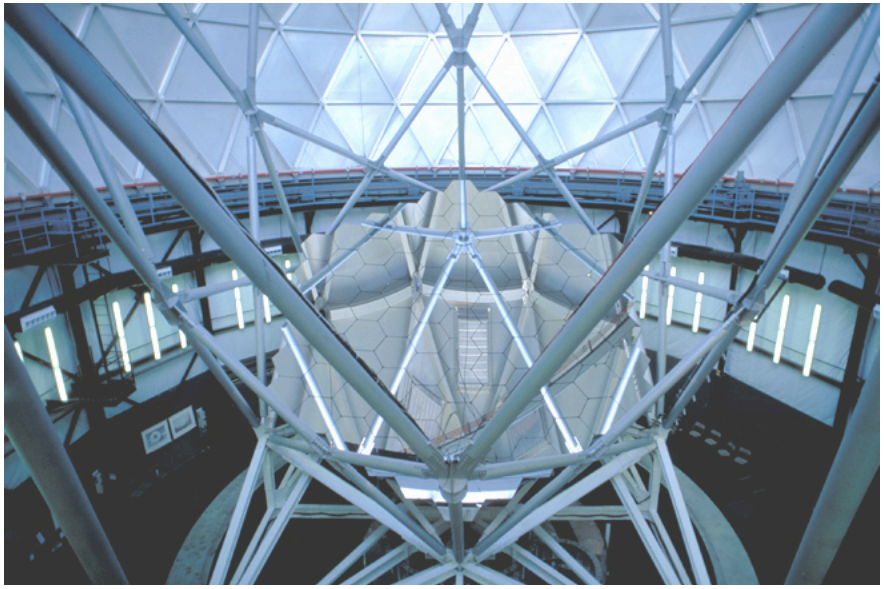
- The light gathering power of the GTC amounts to about 4 million human eyes!

$$\frac{LGP_{GTC}}{LGP_{eye}} = \frac{\pi(10{,}400mm/2)^2}{\pi(5mm/2)^2} \cong 4{,}326{,}400$$

10.4 meter GTC mirror

Largest!

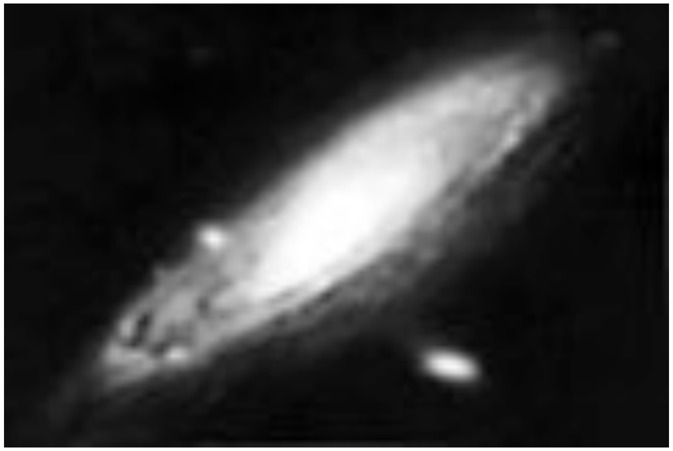
- The largest optical telescope is South Africa Large Telescope (SALT).
- 11 meters in diameter
- And today people are working on even larger telescopes!



SALT 11 meter SALT mirror

Resolution

- Larger telescopes have the nice 'side effect' of also providing higher resolution.
- Resolution is how fine a detail a telescope can see or how close together two objects (such as stars) can still be seen as two distinct objects.
- Resolution is proportional to $\frac{\text{wavelength of light observed}}{\text{diameter of telescope}}$



Low resolution

High resolution

What limits how much the naked eye can see?

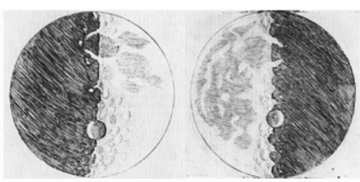
- Small aperture
- Short integration time
- Narrow bandwidth

How have astronomers overcome the limitations imposed by the human eye?

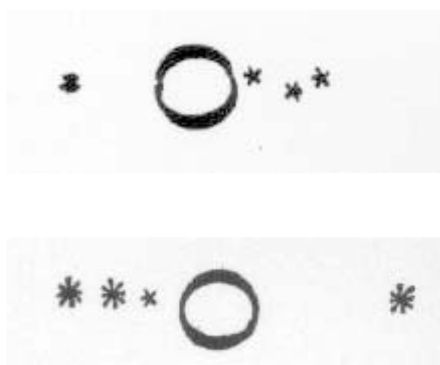
- Telescopes
- Cameras
- Telescopes and cameras that can detect colors beyond those the eye can see

Galileo

- Galileo was the first to use the telescope systematically to observe celestial objects and to record and publish his observations.
  - Observations were by eye
  - Observations were recorded manually
  - Galileo published his observations in a short treatise entitled *Sidereus Nuncius* (*Starry Messenger*)



Moon



Jupiter's moons

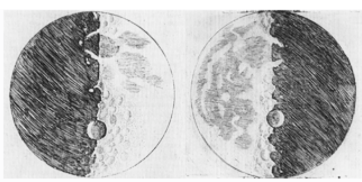
(referred to as Galilean moons)

The Pleiades

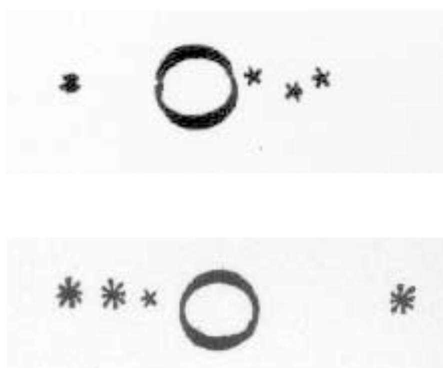
Showing more stars than are visible to the unaided eye.

Galileo

- Notice that the objects Galileo viewed were “nearby”.
- Even if he stared longer and longer into the telescope, he could not see fainter and fainter objects.
- This is because the eye “refreshes” every 50-100 ms.



Moon



Jupiter’s moons

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The Pleiades

Showing more stars than are visible to the unaided eye.

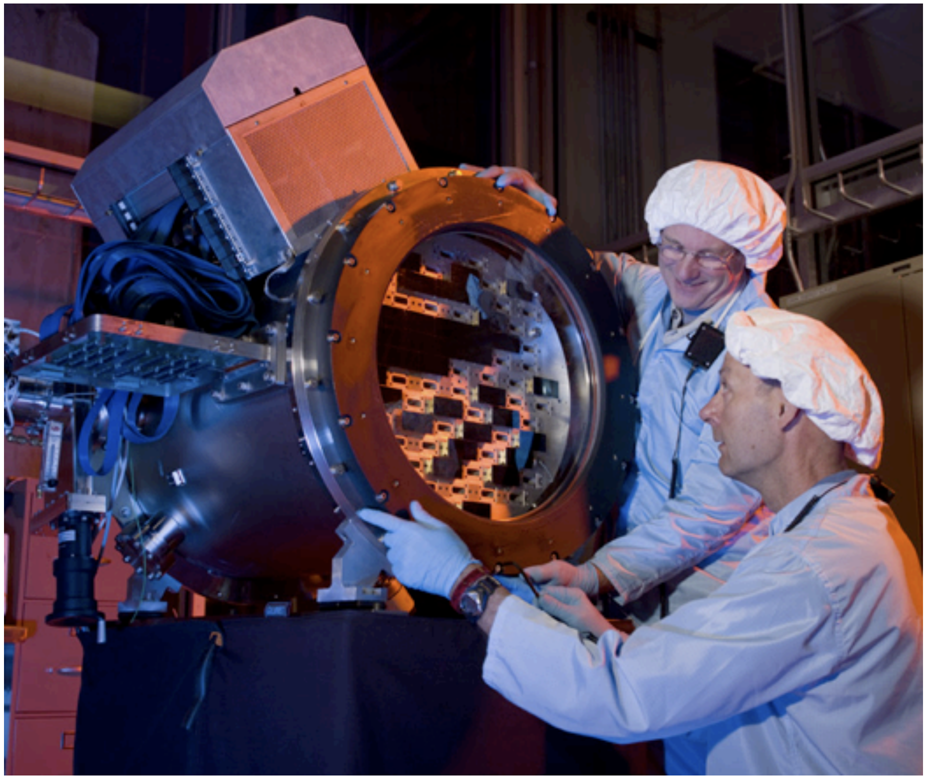
Film rate

- Through experience in the early days of film, it was determined that a frame rate of less than 16 frames per second caused the mind to see flashing images.
- This is because persistence of vision depends on chemical transmission of nerve responses, and this biochemical process takes about 50-100 milliseconds.

Photography and digital imaging

- However, photographic film and digital cameras CAN stare at the sky for a long time and store more and more light.

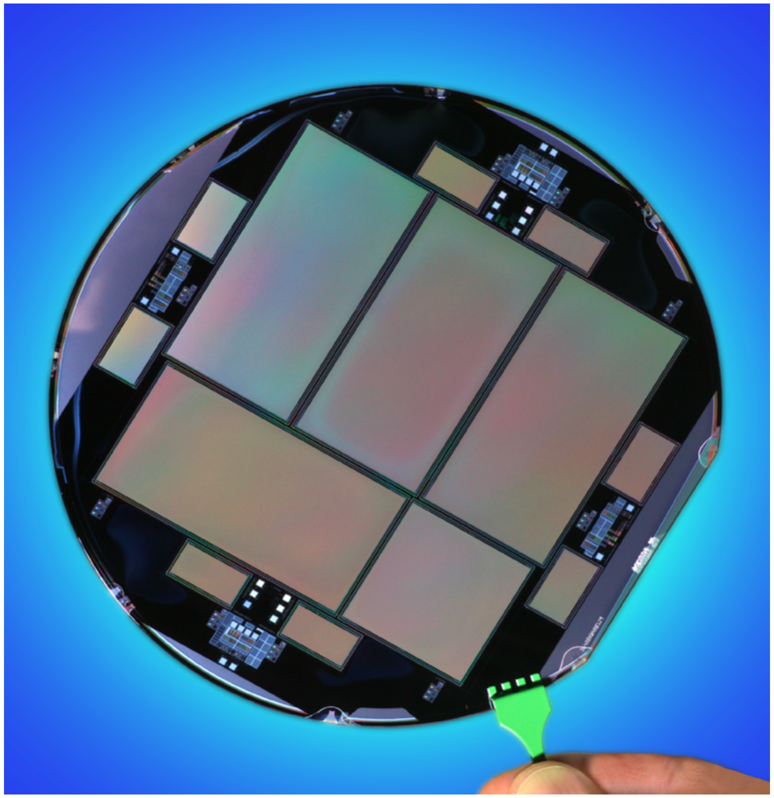
- Therefore, by replacing the human eye with cameras, we can detect fainter and more distant objects.



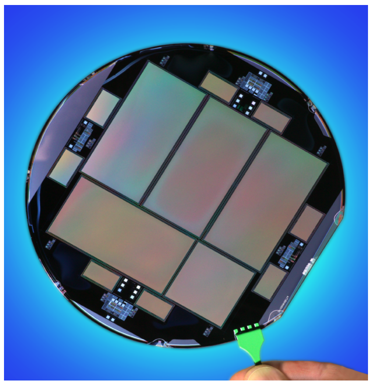
DECam focal plane and electronics

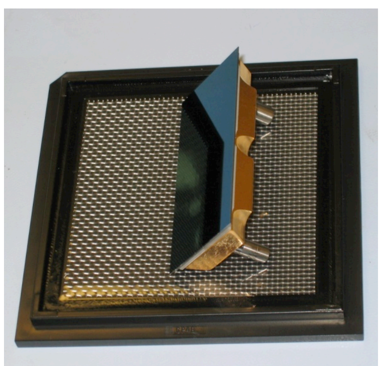
New red-sensitive CCDs

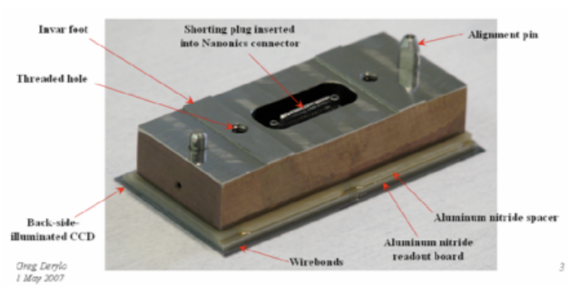
- DES CCDs are fabricated by Dalsa
- Further processing is done by Lawrence Berkeley National Laboratory (LBNL)
- Packaged and tested at Fermilab

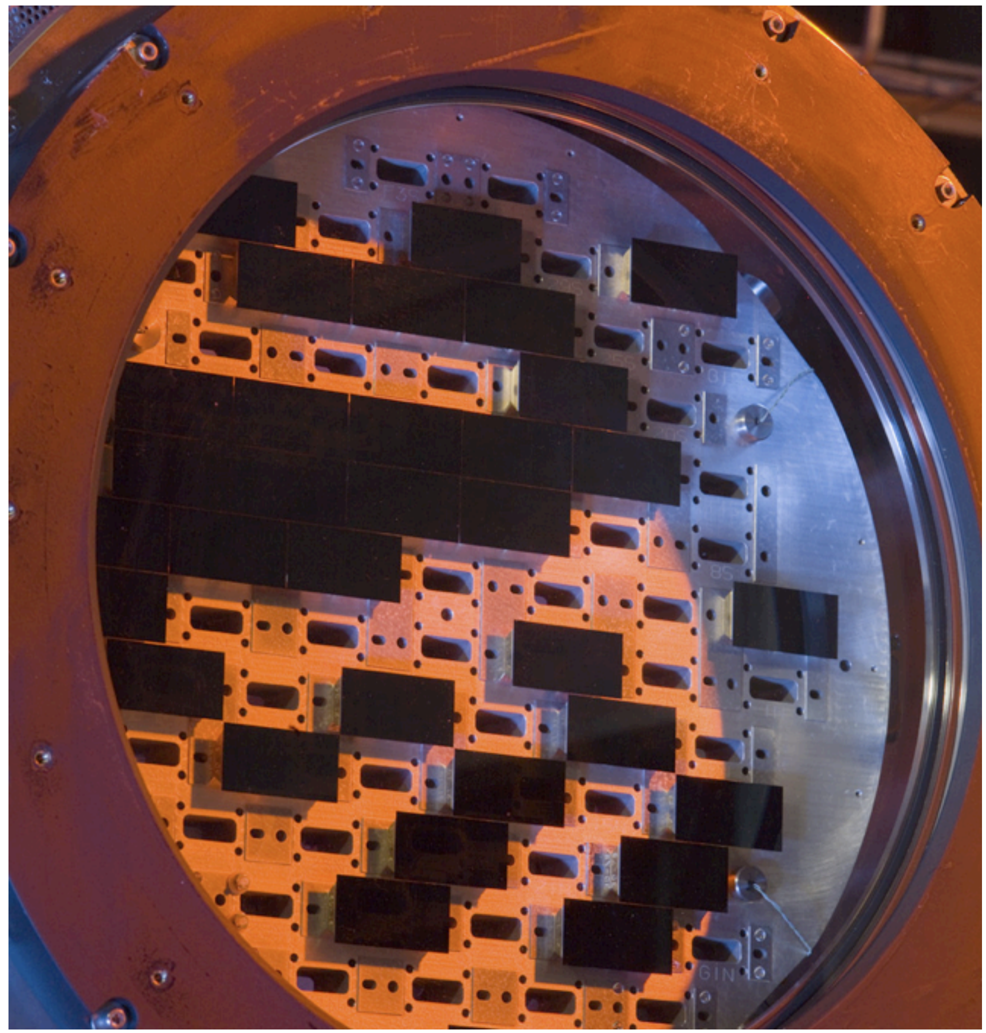


From wafer to focal plane

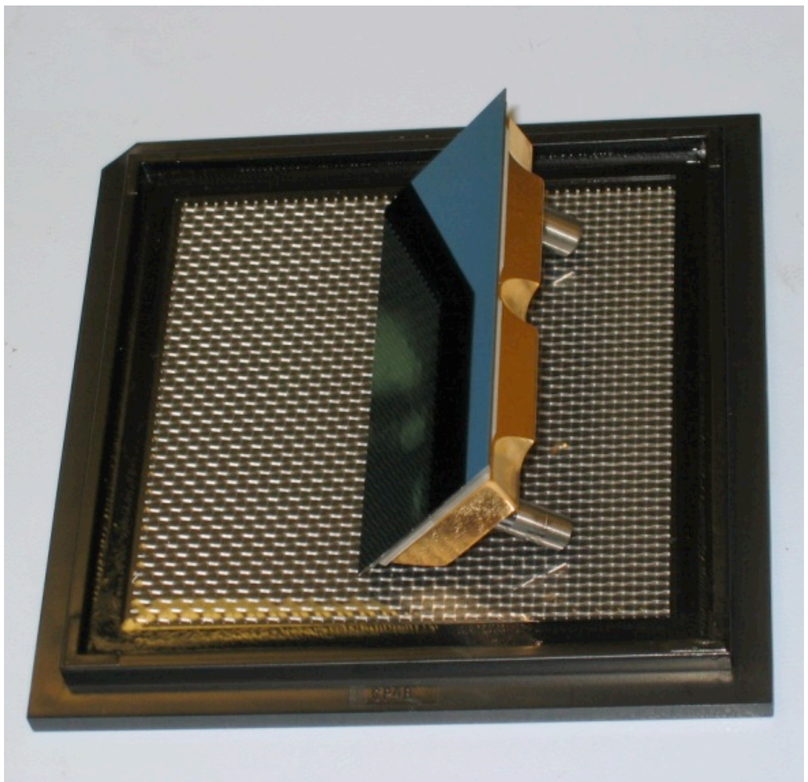
- 





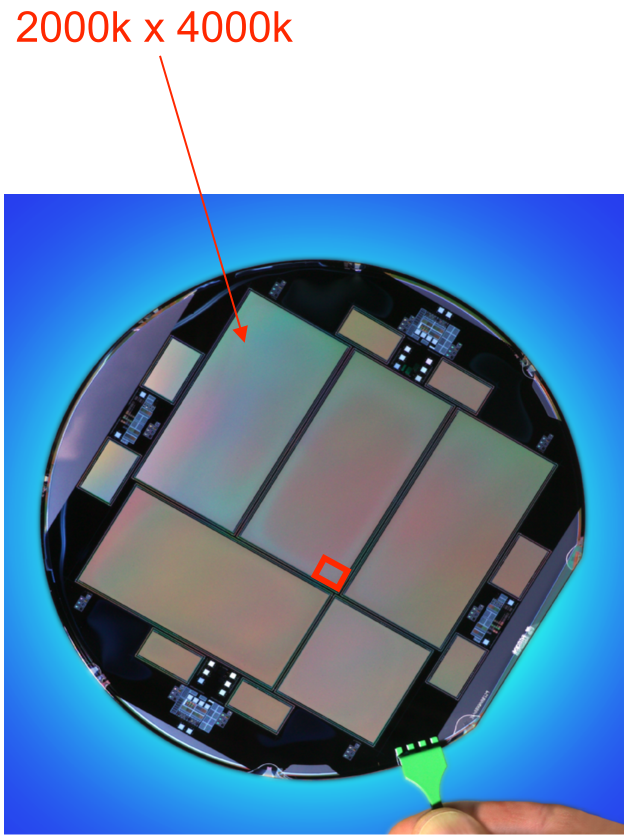


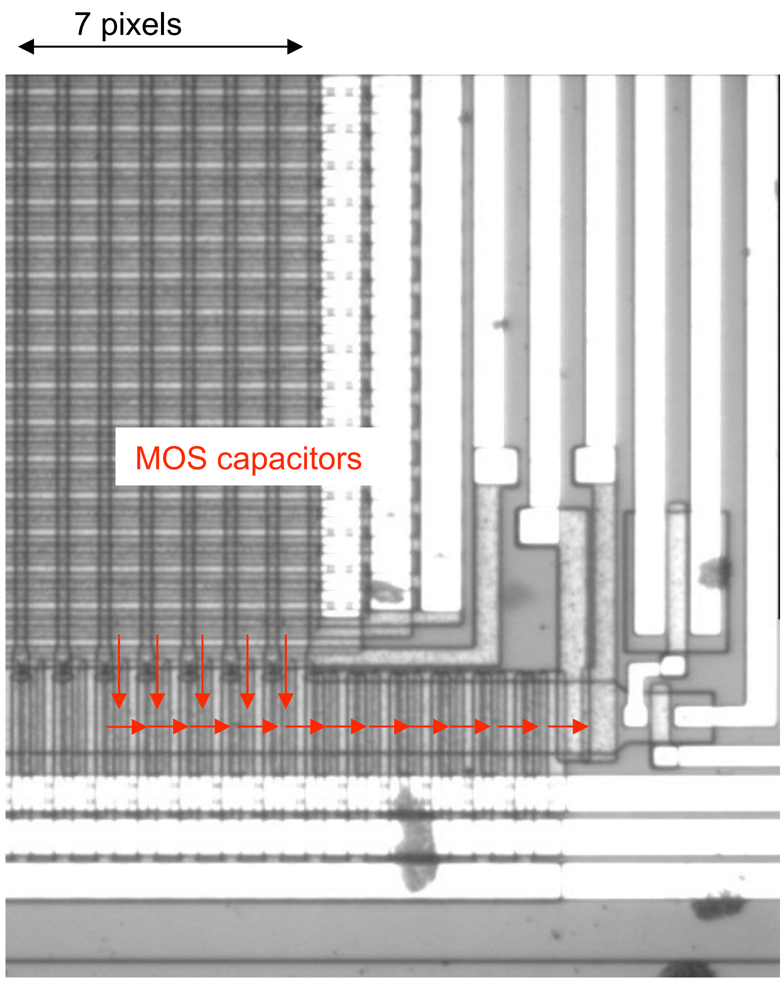
DECam CCDs



	DECam CCD Requirements
Pixel array	2048 · 4096 pixels
Pixel size	15 μm x 15 μm
# Outputs	2
QE(g,r,i,z)	60%, 75%, 60%, 65%
QE Instability	<0.3% in 12-18 hrs
QE Uniformity in focal plane	<5% in 12-18 hrs
Full well capacity	>130,000 e^-
Dark current	<~25 e^-/hr/pixel
Persistence	Erase mechanism
Read noise	< 15 e^- @ 250kpix/s
Charge Transfer Inefficiency	$<10^{-5}$
Charge diffusion	1D $\sigma < 7.5$ μm
Cosmetic Requirements	<# Bad pixels> <0.5%
Linearity	1%
Package Flatness	Effectively +-10 μm

CCD layout

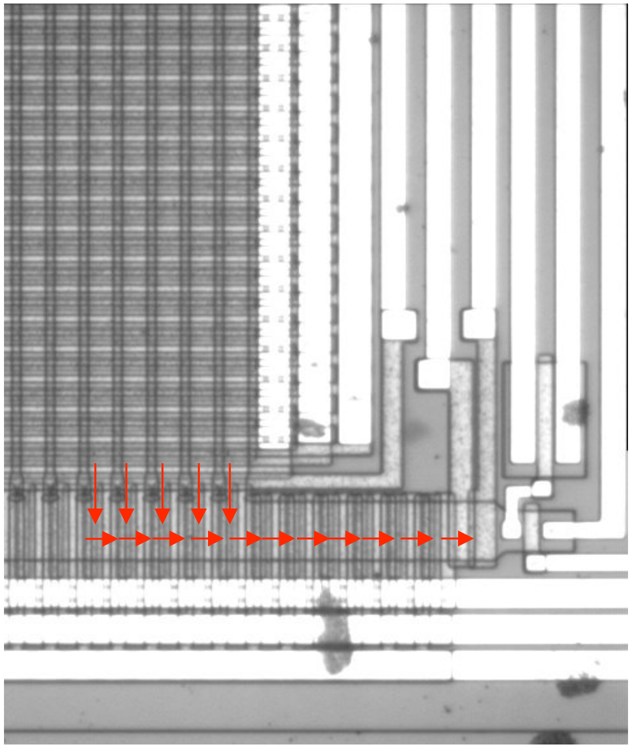


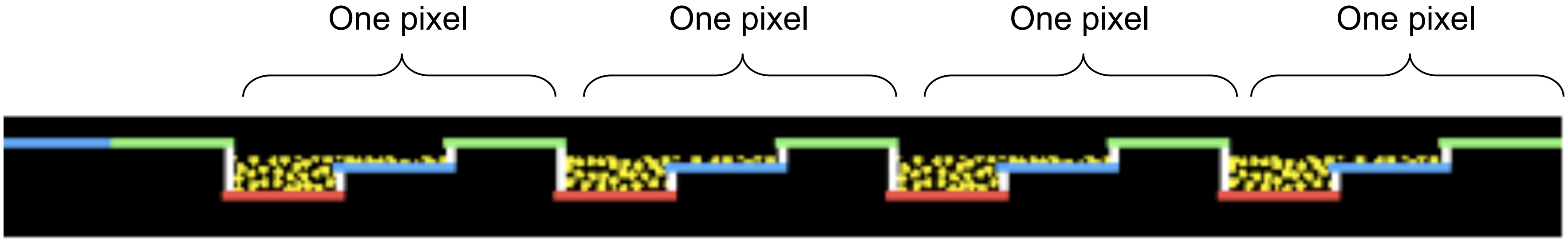


Dark Energy Survey CCD 700x

Charge collection

- Example shown is the most common, three phase transfer, which is used for the DES CCDs.
- Each pixel (MOS capacitor) has 3 gates (electrodes)
- During integration, one (or two) clocks are held low.
- This is where the photo-produced electrons will collect.





Charge transfer

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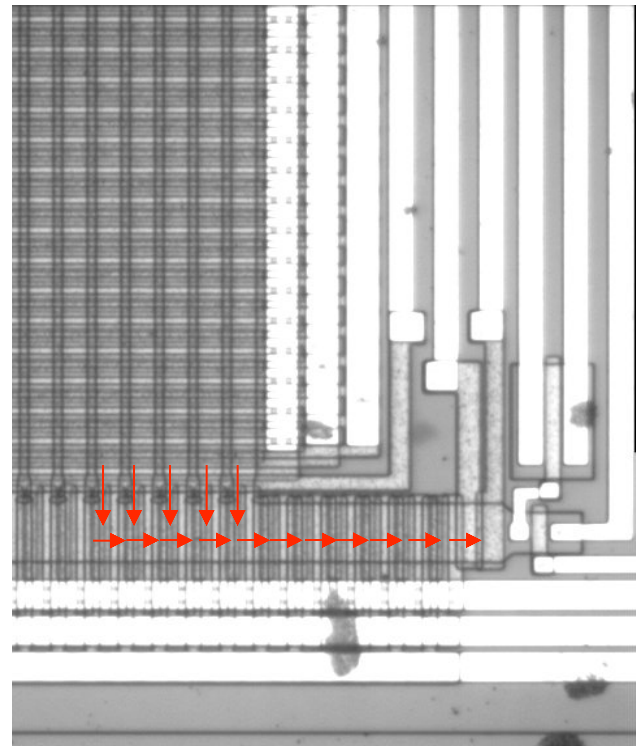
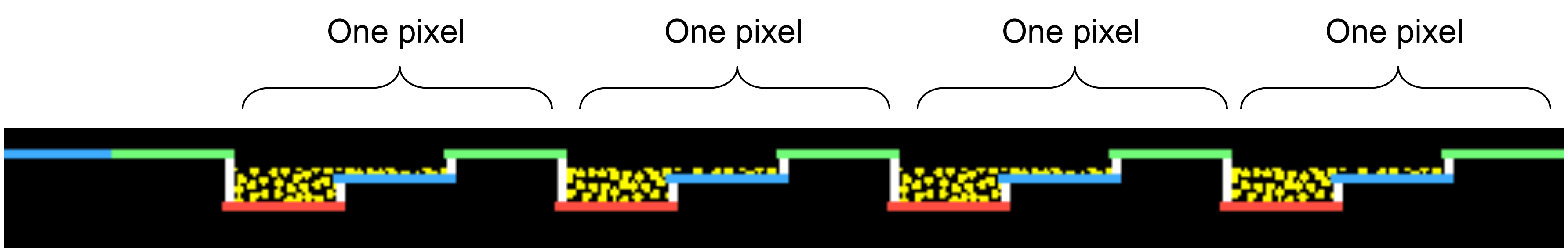
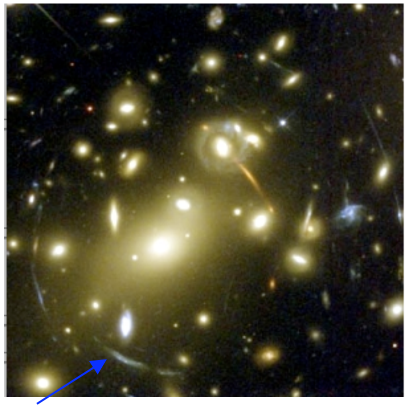




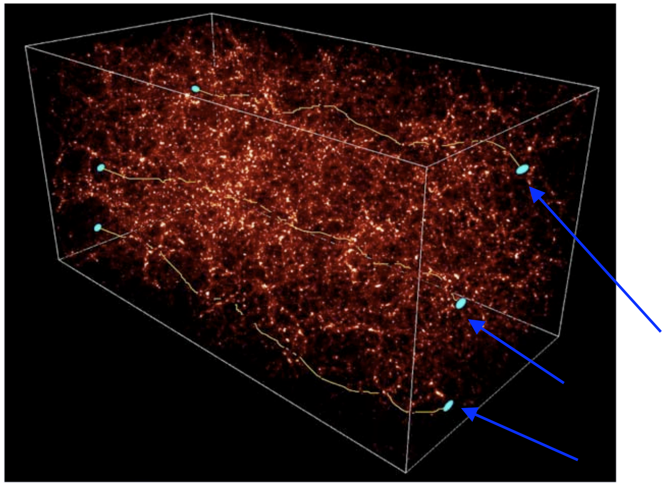
Will DECam use binning?

- The Dark Energy Survey will not use binning, because high resolution is desired, especially for weak lensing, where accurate measurements of galaxy shapes is difficult, yet critical.

- Binning may be provided as an option for community users.

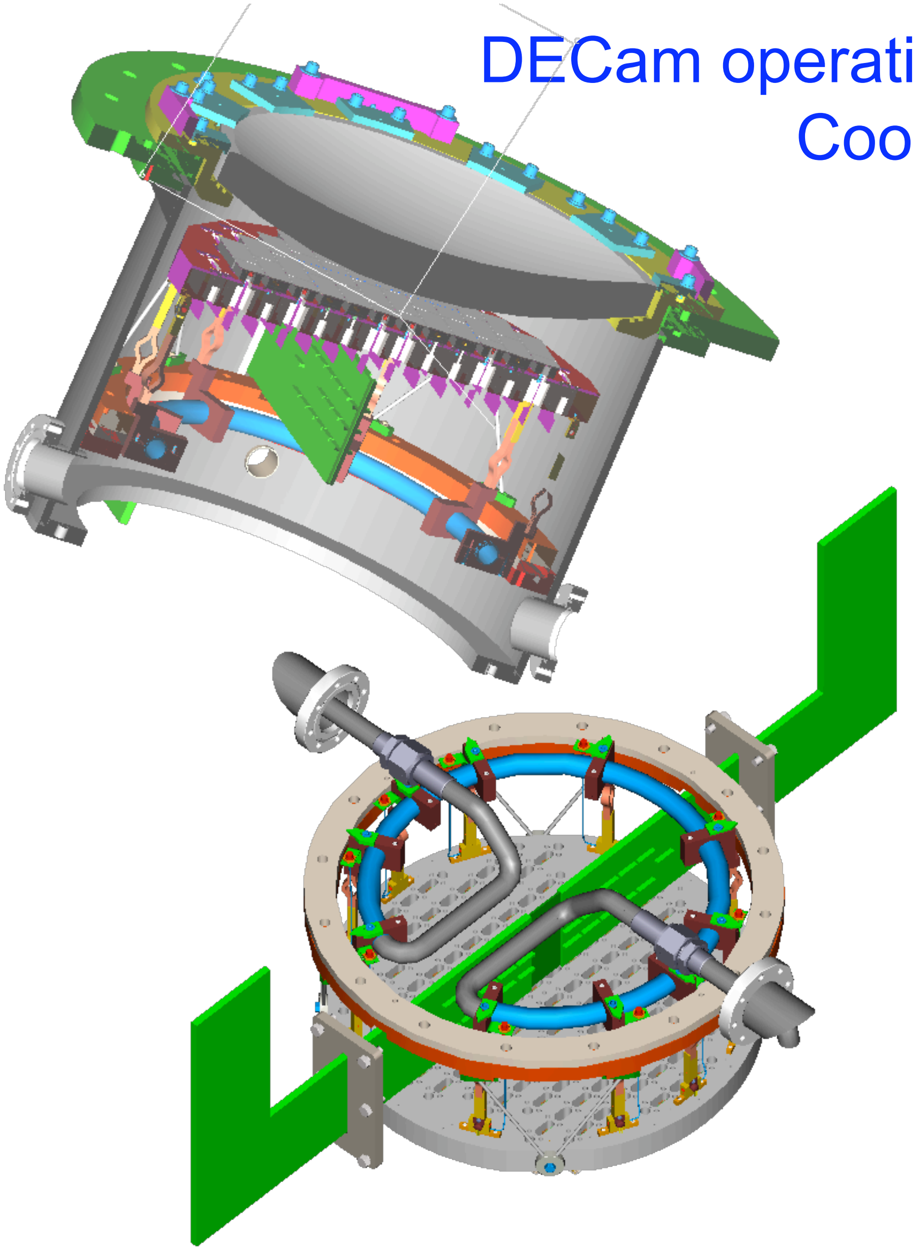


Arcs produced by strong lensing



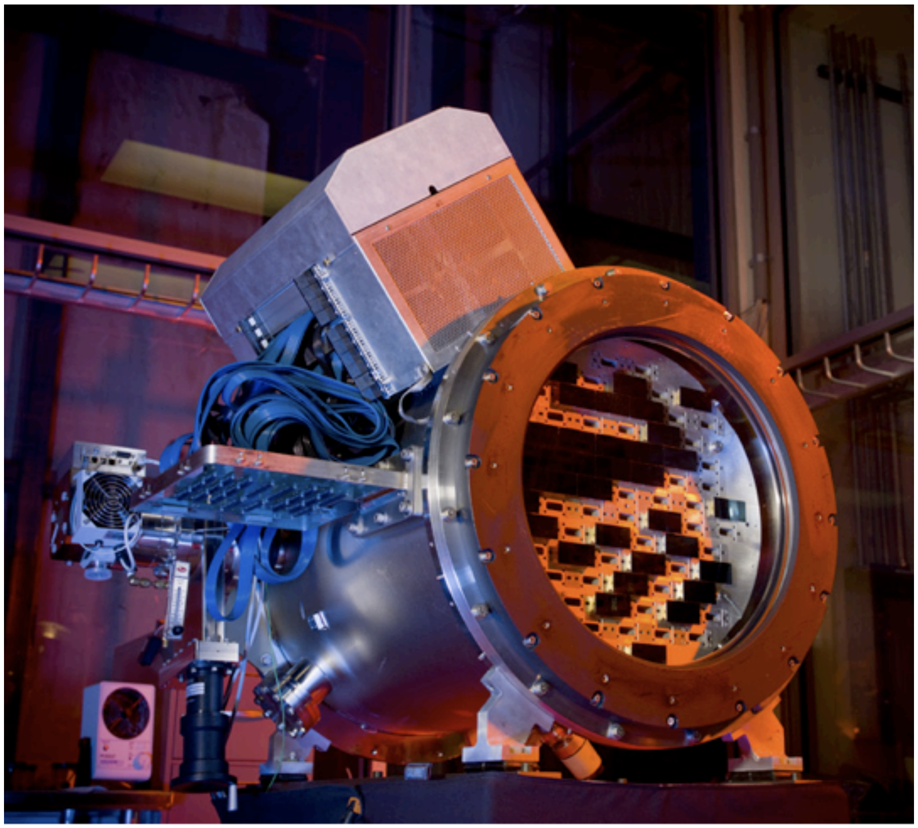
Weak lensing produces more subtle distortion of galaxy shapes

DECam operating parameters
Cooling



- DECam will operate at −100 degrees C
- ~1 W / CCD
  - ~1/3 W electrical (amplifiers)
  - ~1/6 W heat conduction from wiring
  - ~1/2 W radiation
- Cooled with liquid nitrogen

DECam operating parameters
Vacuum



- Operate at ~ 1E-6 Torr with ion pumping
  - Need to prevent condensation on surface of the CCDs.
  - The required pressure is a function of operating temperature, because the vapor pressure of water is a function of temperature.
  - When cold, the vacuum is even better due to cryo pumping.

What limits how much the naked eye can see?

- Small aperture
- Short integration time
- Narrow bandwidth

How have astronomers overcome the limitations imposed by the human eye?

– Telescopes

– Cameras

– Telescopes and cameras that can detect colors beyond those the eye can see

Optical

- Galileo observations only show us what things look like in the optical part of the spectrum: the light that the human eye can detect.

Hubble Ultra Deep Field

Rainbows

- But look at a rainbow…

- Each color transitions to the next, but when you get to either the red or the violet end, the rainbow seems to stop, or fade into nothing.

- Or does it just actually transition to colors that are invisible to our eyes?

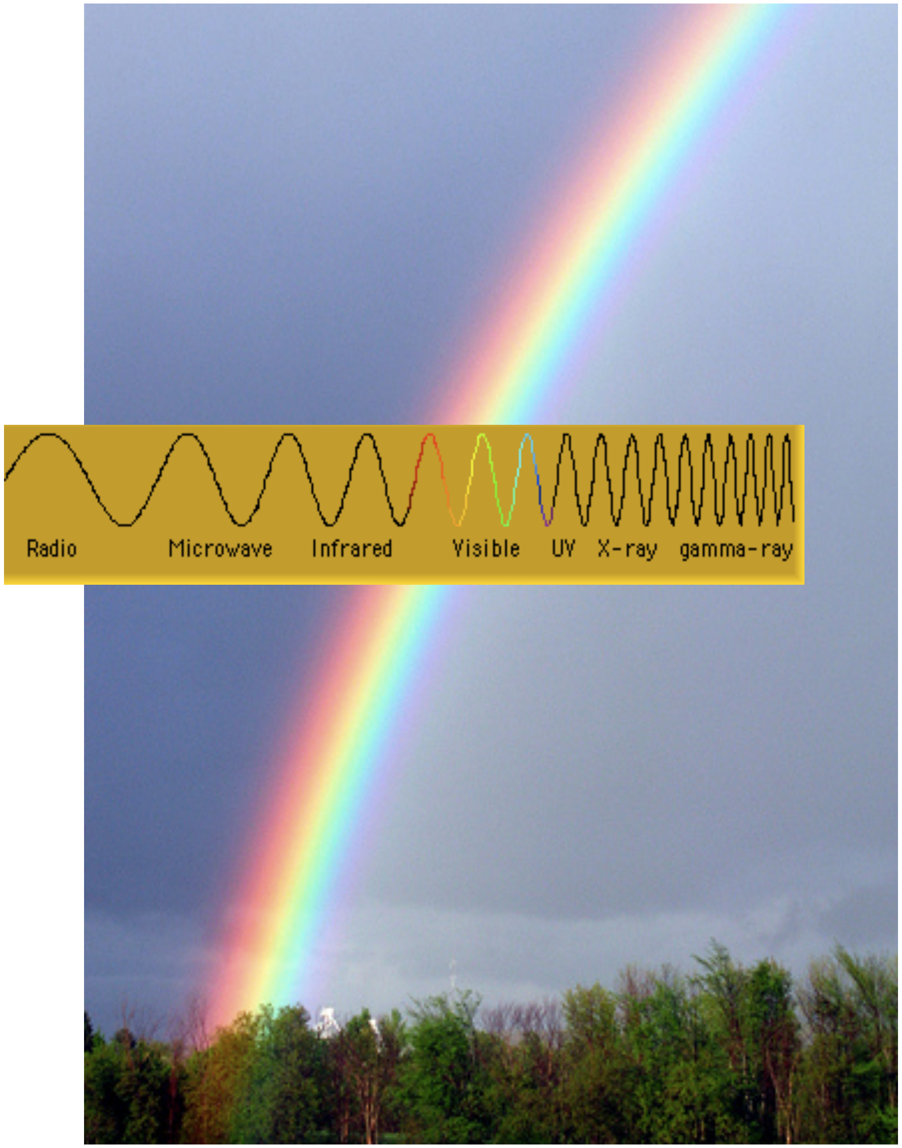
Rainbows

- If we put other detectors on either side of the rainbow, could we detect more ‘colors’?

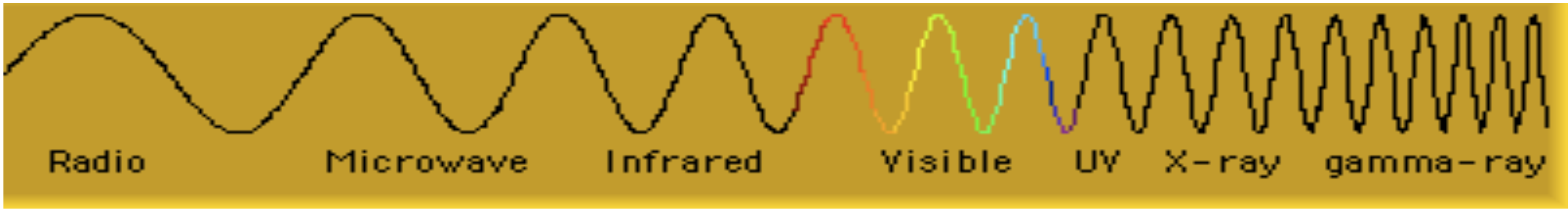
- Yes.

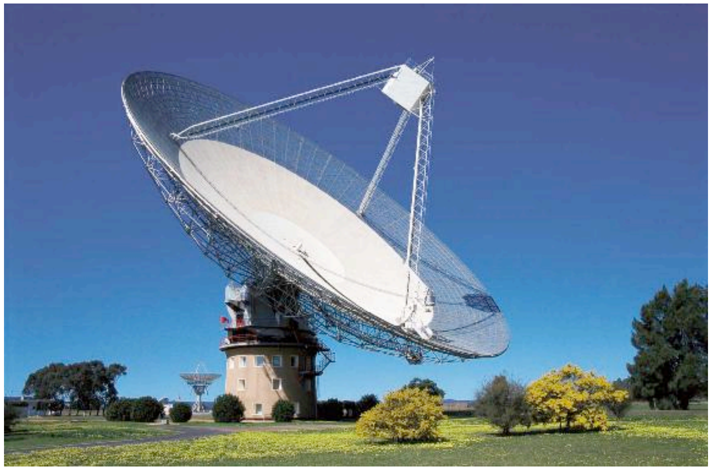
Wavelength

- The different ‘colors’ have different wavelengths.

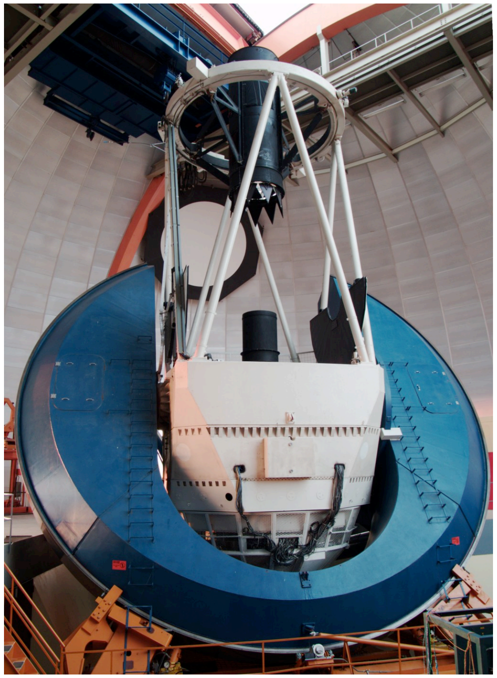


Different telescopes for different wavelengths





Radio



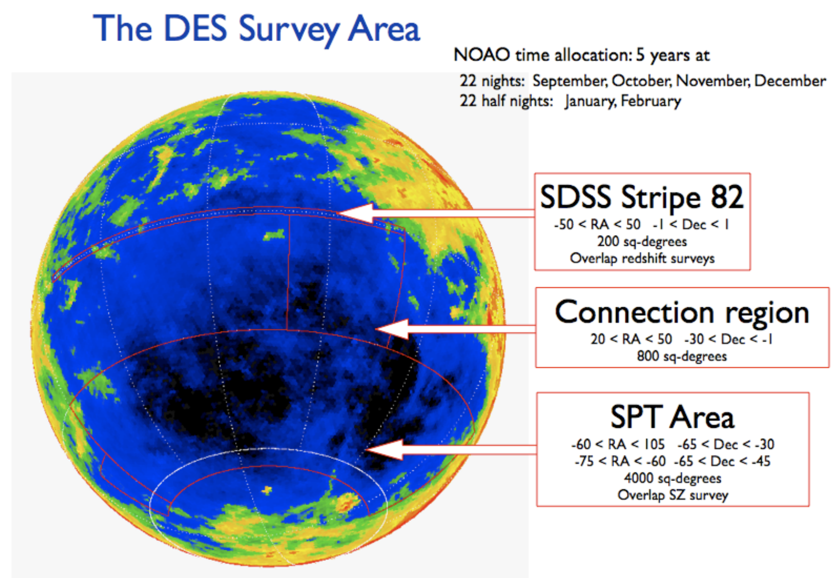
Optical

X-ray

Multiwavelength observations greatly increase our understanding of cosmology

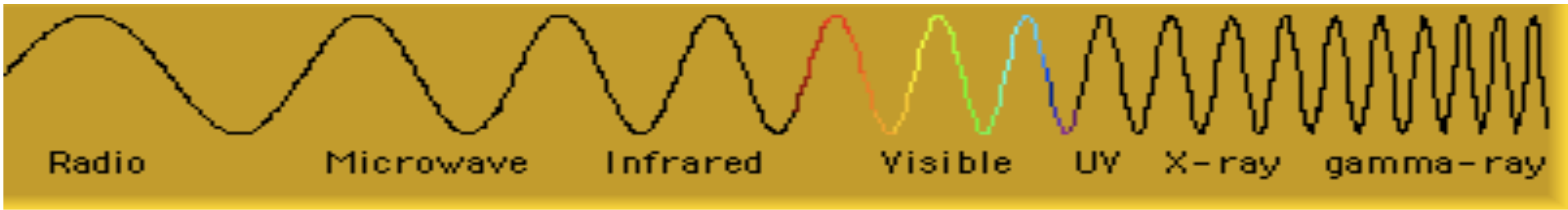
DES overlap with IR and millimeter wave telescopes

- Overlap with SPT
  - DES will provide SPT with redshifts
  - SPT will provide masses determined via Sunyaev Zeldovich effect (SZ effect)
- Overlap with SDSS Stripe 82
  - Provides calibration of DES photometric redshifts with SDSS spectroscopic redshifts
- Overlap with VISTA
  - DES will provide Y band to VISTA
  - VISTA will provide DES with near infrared data (improves DES photo-z)



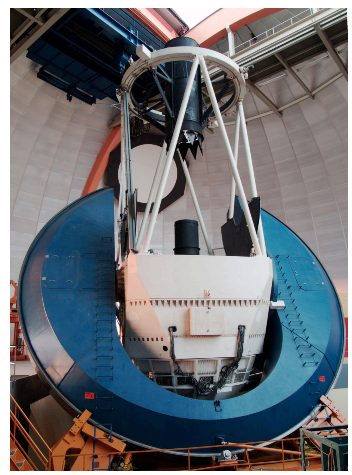
South Pole Teleccope

Different telescopes for different wavelengths



SPT
Millimeter wave

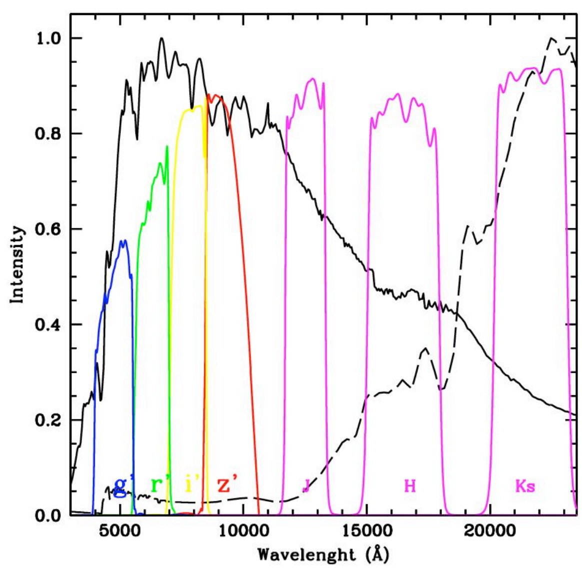
VISTA
Infrared



Blanco
Visible, near-IR

Visible and Infrared Survey Telescope for Astronomy (VISTA)

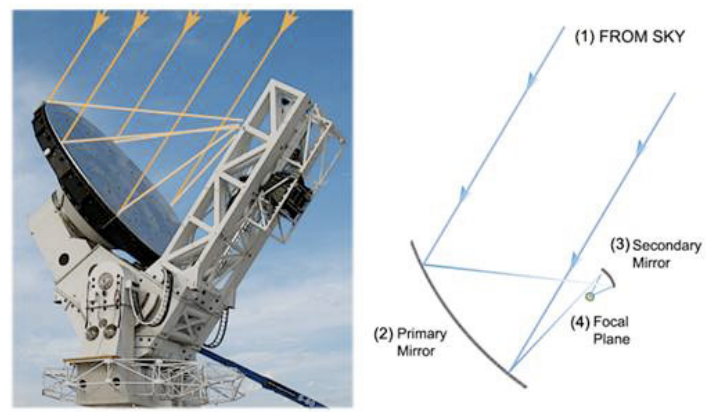
- VISTA is a 4-m class wide field survey telescope for the southern hemisphere, equipped with a near infrared camera (HgCdTe) and available broad band filters at Z,Y,J,H,K_s and a narrow band filter at 1.18 micron.



VISTA
Cerro Paranal Observatory

South Pole Telescope (SPT)

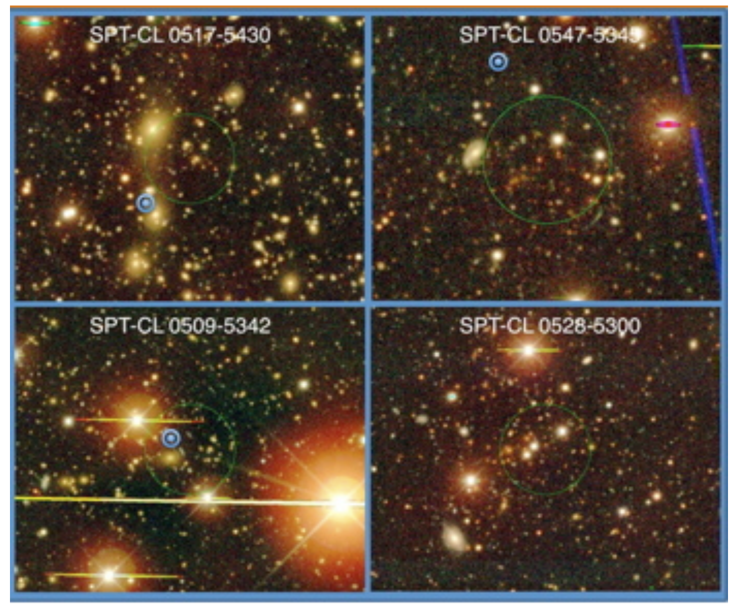
- The South Pole Telescope is designed to measure the properties of the Cosmic Microwave Background (CMB)
- Most of this light has traveled freely through empty space since its creation, and it arrives at the earth from all directions in the sky.
- Tiny features in these maps will indicate where clusters of galaxies have slightly altered the primordial CMB light, and through studying these clusters we can learn about the evolution of structures in the universe.



South Pole Telescope

South Pole Telescope (SPT)

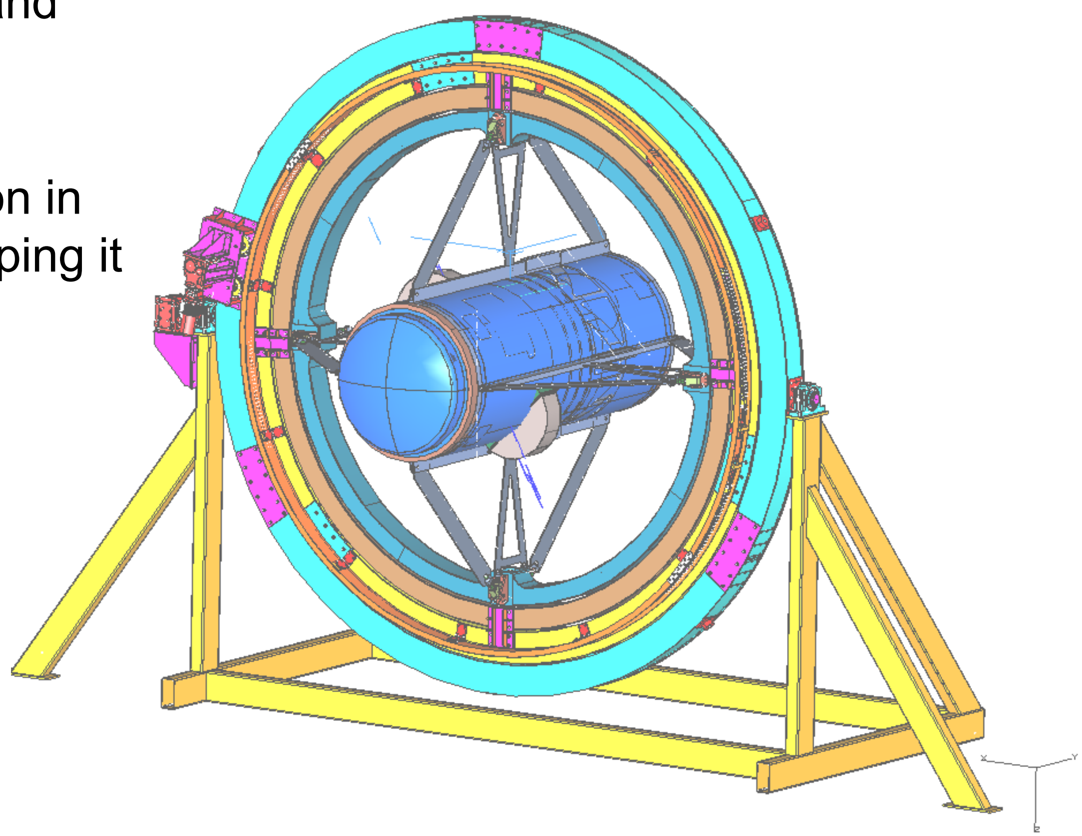
- The SPT can share information about the location and mass of cluster with the DES while DES can provide the SPT with redshift information about the clusters.
- This information is important, because the rate at which massive clusters form is sensitive to Dark Energy.



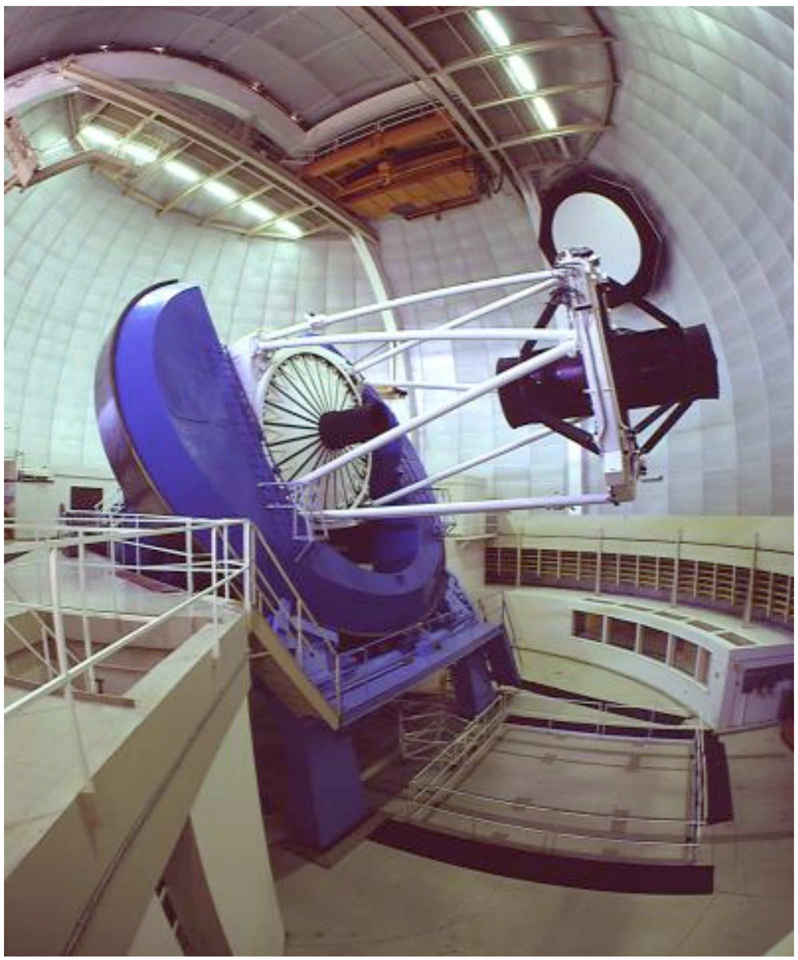
Clusters found using the SPT

Telescope simulator

- We will place the camera in a specially built stand to tilt and rotate it
- Allows us to verify operation in all orientations before shipping it to Chile



Goal: Fully commissioned by April 2011



The Future's So Bright, I Gotta Wear Shades

by Timbuk 3

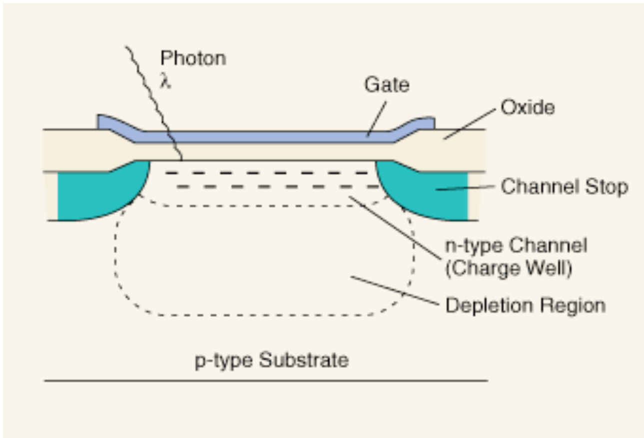
Girls Just Want to Have Fun!

How does a CCD work?

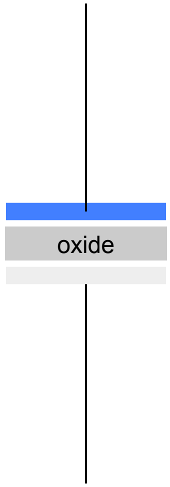
Charge-coupled devices
CCDs

- CCDs are Si-based “devices” used to convert light into an electrical signal

- The “devices” used to do this are Metal Oxide Semiconductor (MOS) capacitors

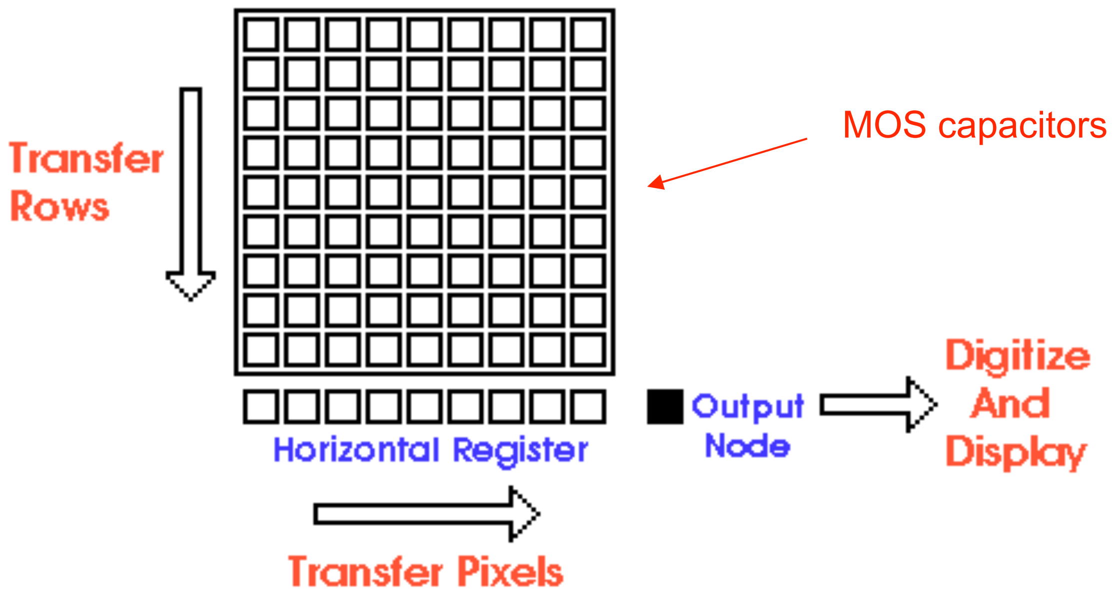


MOS capacitor



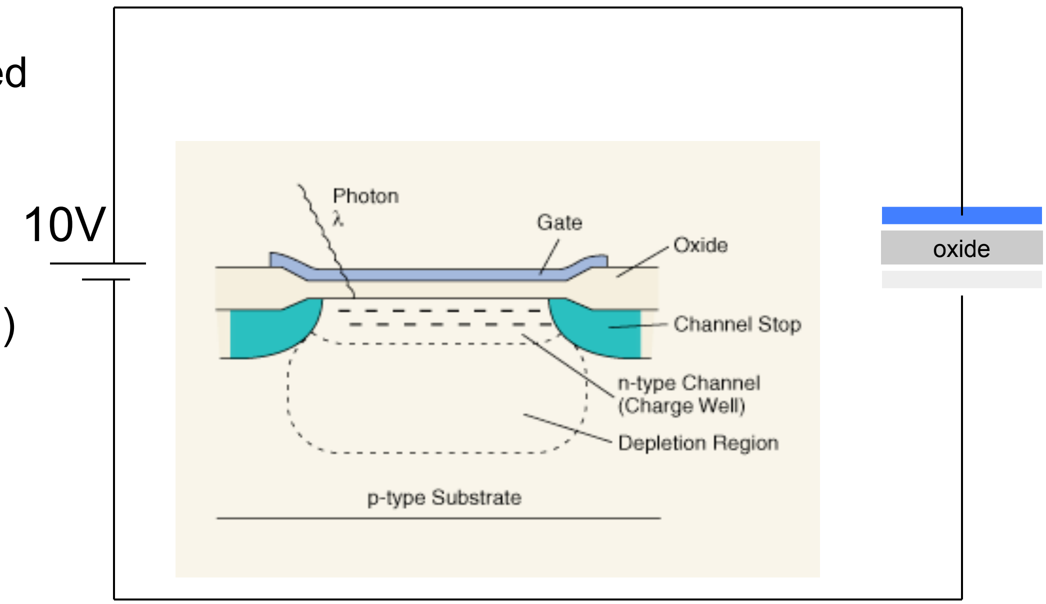
MOS devices

- A CCD is a huge array of several million MOS capacitors!



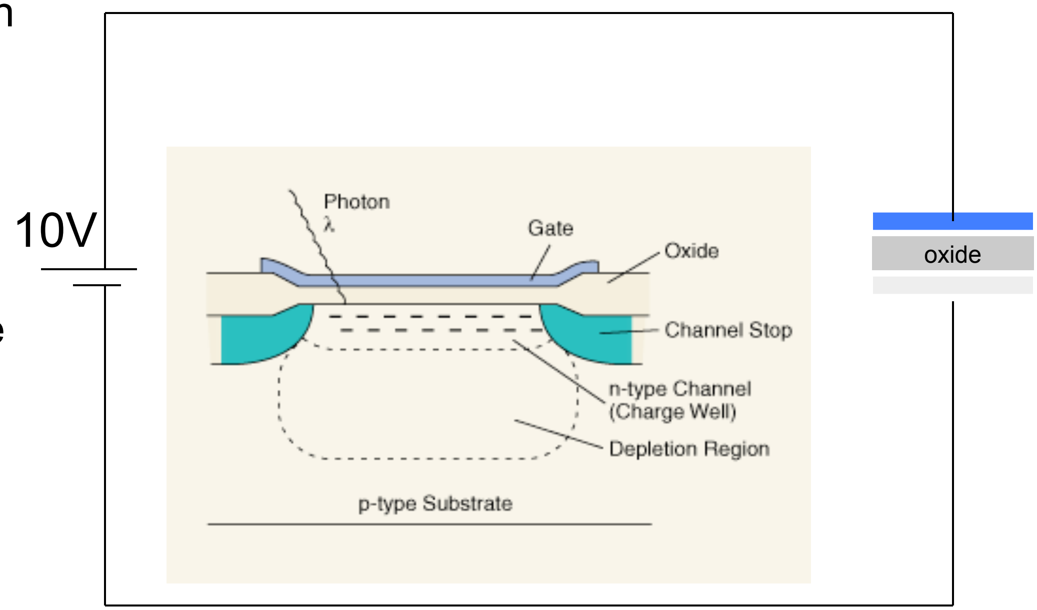
CCD operation

- Bias gate (typical 10 V)
- Majority carriers (holes) are pushed back into interior of substrate
- A zone almost free of majority carriers is then created at the SiO_2-Si interface (depletion region)



Charge injection

- Electron-hole pairs are created as photons pass through the depletion region
- These pairs are separated by the potential.
- The electrons accumulate near the SiO_2-Si interface forming an n-channel
- This is also called the inversion layer
- The inversion layer carries the information



Charge collection

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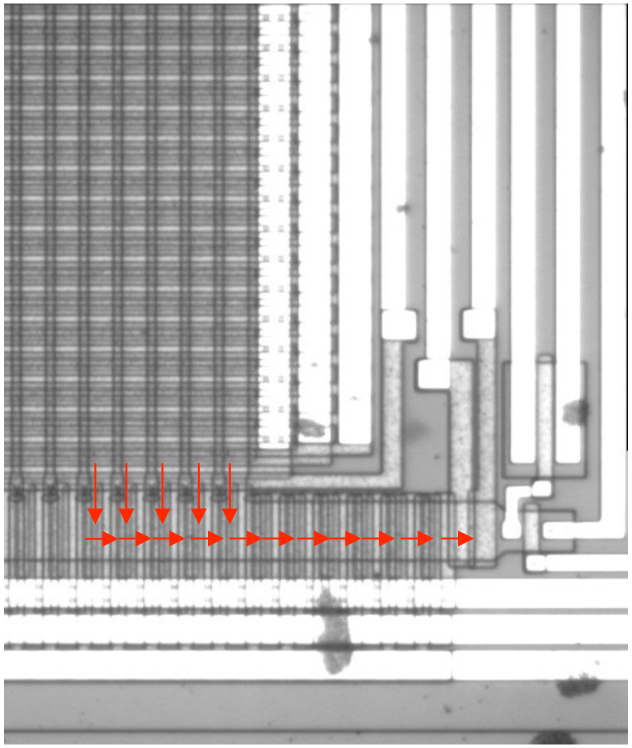

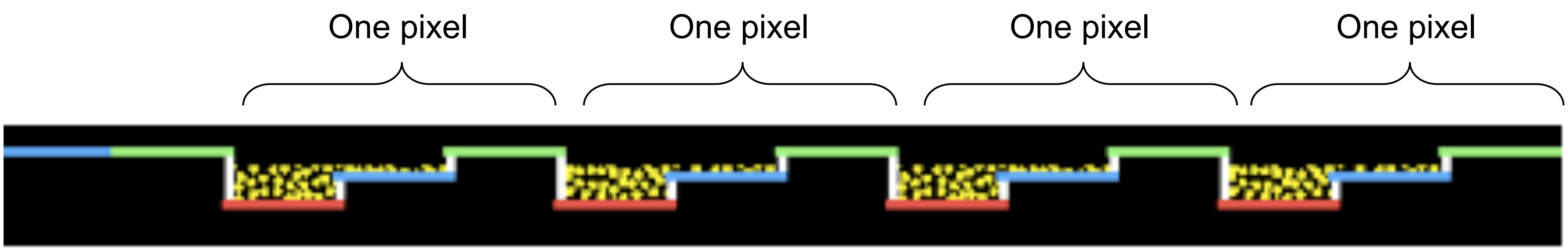

Charge transfer

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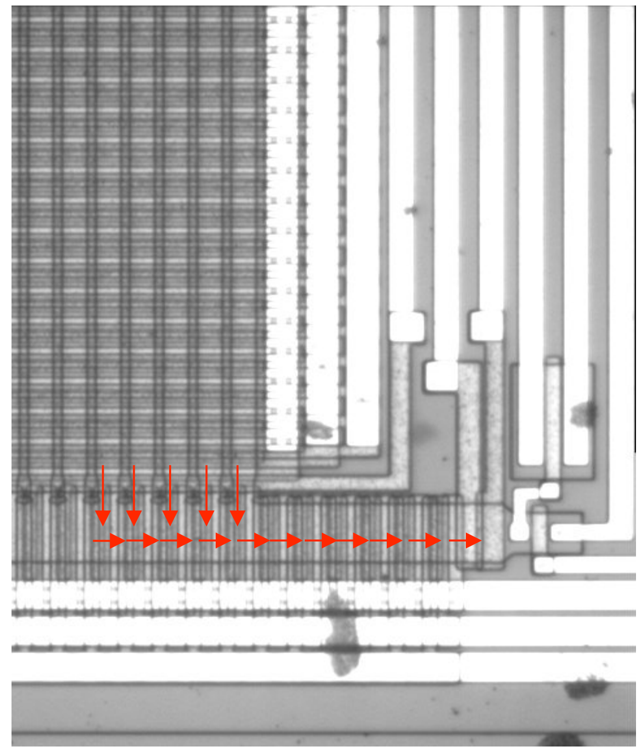
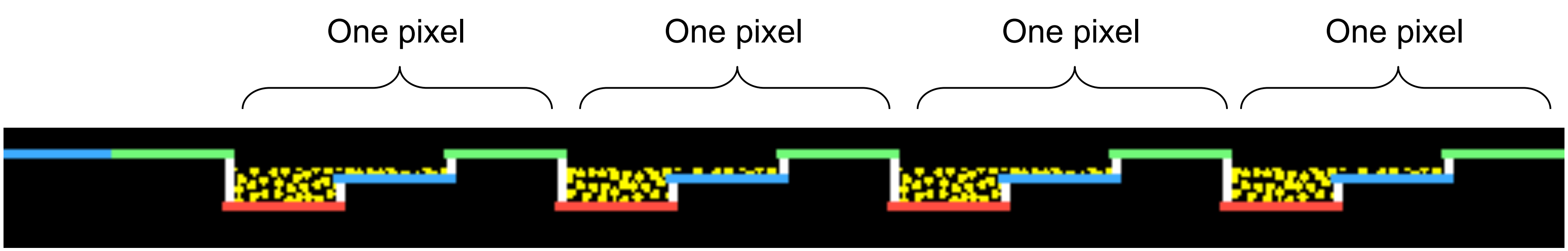
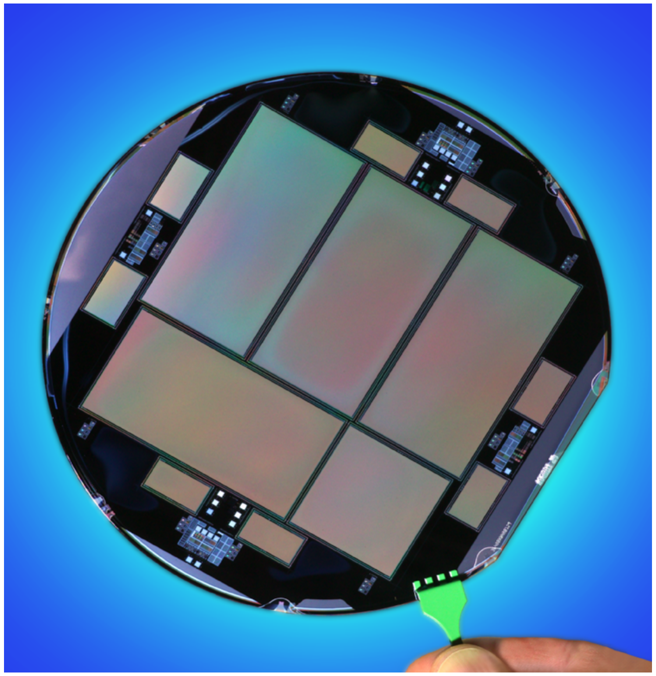




DECam’s souped-up CCDs

Astronomical imaging

- LBNL has developed red-extended CCDs for high redshift surveys (Supernovae Cosmology Project, SNAP, DES)
- Extended red response is extremely important due to the use of distant, high redshift supernovae for the determination of cosmological parameters and for deep surveys
- Detection and follow-up spectroscopy of high redshift objects would greatly benefit from CCDs with improved near-infrared response.



Astronomical imaging

- The large focal planes of astronomical telescopes require high-QE, large-format CCD detectors.
- In order to achieve high QE, the standard scientific CCD is thinned and back illuminated

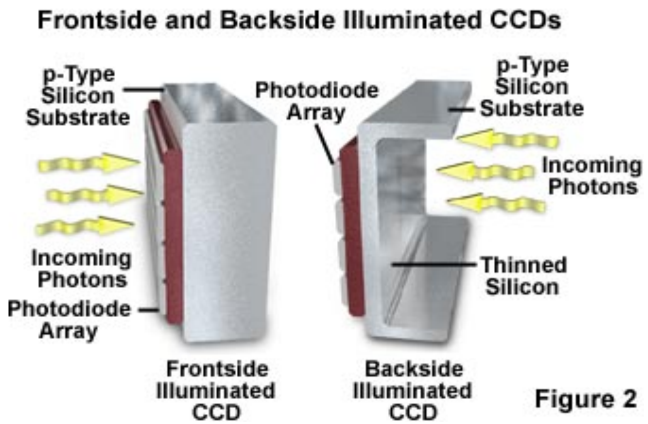


Figure 2

Frontside vs.backside

- Back-illuminated CCDs have exceptional quantum efficiency compared to front-illuminated CCDs
- To make a back illuminated CCD, take a front-illuminated CCD, thin it to ~20 μm, and mount it upside down on a rigid substrate
- The incoming light now has a clear shot at the pixel wells without the gate structures blocking the light

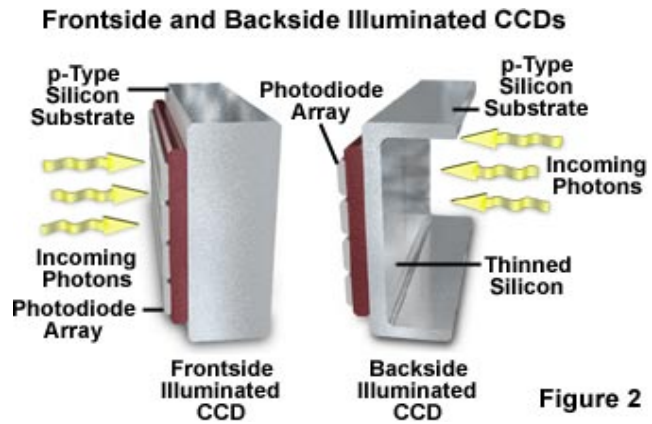
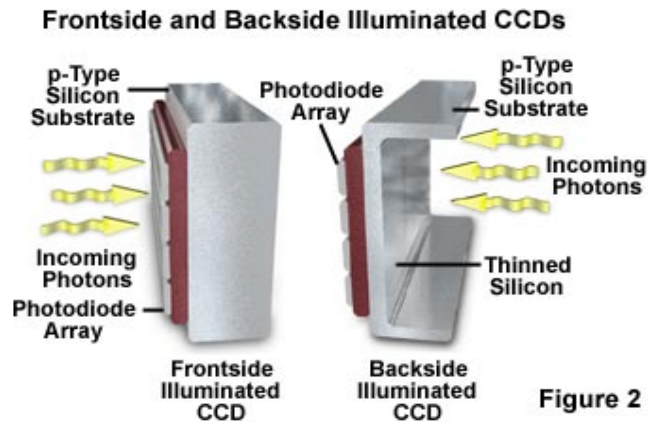


Figure 2

Thinning

- Thinning is required, because the relatively low-resistivity silicon used to fabricate scientific CCDs limits the depth of the depletion region.
- If left thick, the shorter- wavelength, short absorption-length photons will be absorbed before reaching the depletion region where the e-h pairs they create are more efficiently collected



Back-illumination

- However, this process degrades red and near-infrared responses due to the rapid increase in absorption length in silicon at long wavelengths.
- In addition, fringing patterns due to multiply-reflected light are observed in uniformly illuminated images taken at near-infrared wavelengths where the absorption length exceeds the CCD thickness.

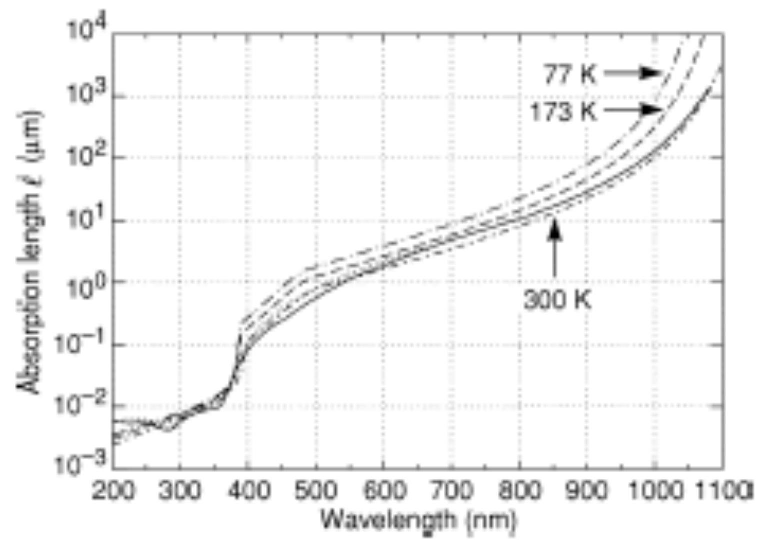


Fig. 2. Absorption length versus wavelength for silicon. Data and calculations (dashed lines) are taken from [18]. Additional room-temperature data (solid line) are taken from [1].

Absorption length

- Absorption length increases with wavelength.
- Absorption length increases as cooling is increased
- A “double whammy” for long wavelengths!

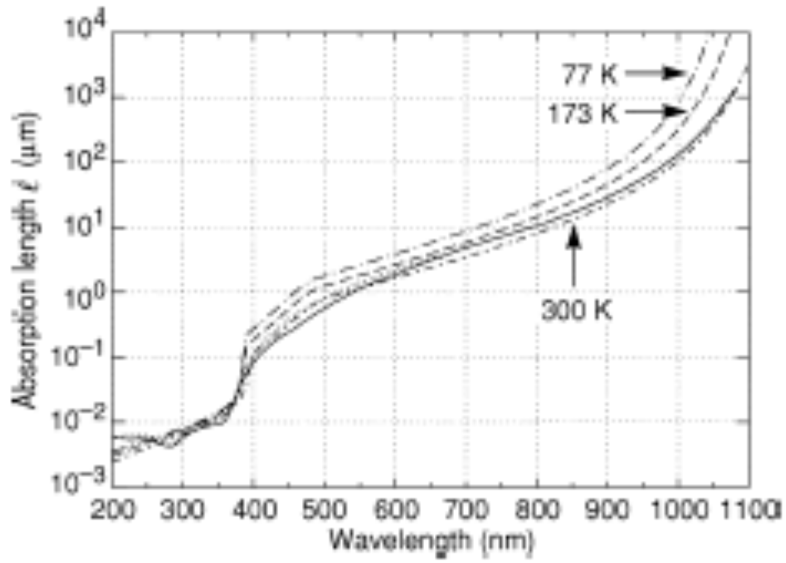


Fig. 2. Absorption length versus wavelength for silicon. Data and calculations (dashed lines) are taken from [18]. Additional room-temperature data (solid line) are taken from [1].

Astronomical imaging

- The CCD developed by LBNL achieves high QE in the red and near-infrared by using a thick depleted region made possible by the use of a <u>high-resistivity</u> silicon substrate.

- The high resistivity allows for fully-depleted operation (200-300um) at reasonable voltages.

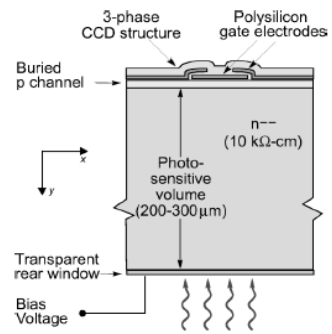
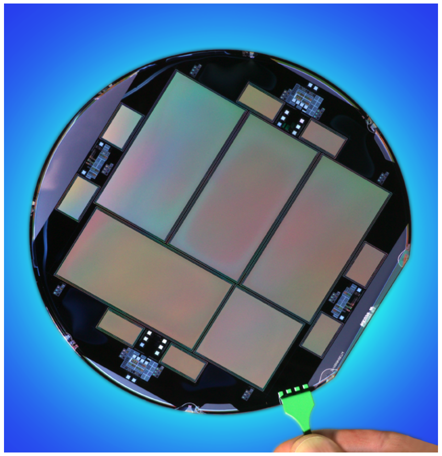
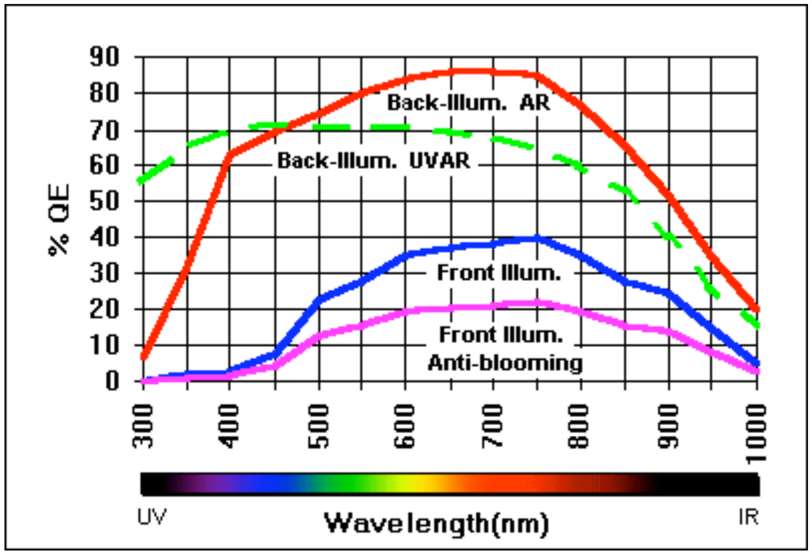


Fig. 1. Cross-sectional diagram of the CCD described in this work. The actual implementation of the substrate bias voltage connection is described in Section III.

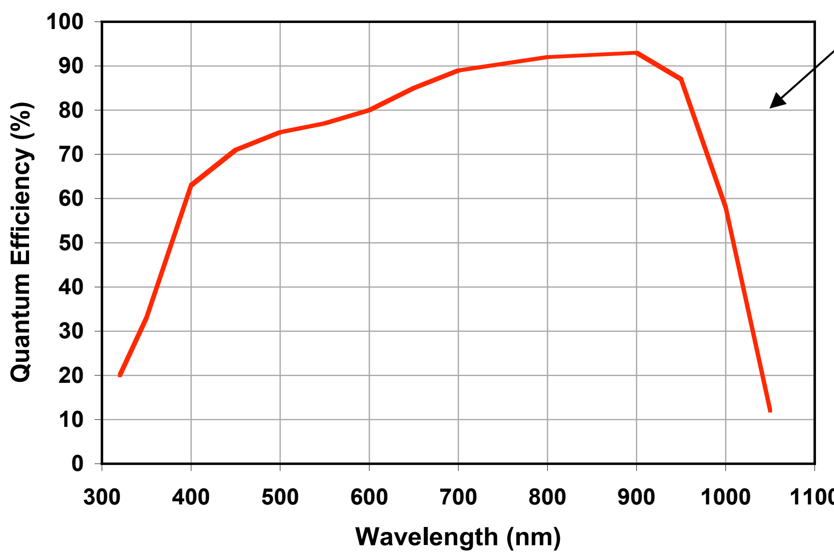


QE of LBNL CCDs



Typical Q.E. curves for front- and back-illuminated CCDs

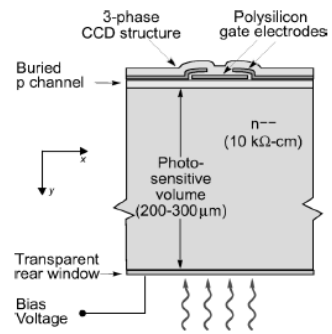
Much-improved IR sensitivity



LBNL CCD QE

Drawbacks of thick CCDs

- There are several drawbacks to a thick CCD
- Cosmic ray and terrestrial radiation sources will affect more pixels (more volume)
- More volume for dark current
- Depth of focus issues
- Light incident at large angles from the normal



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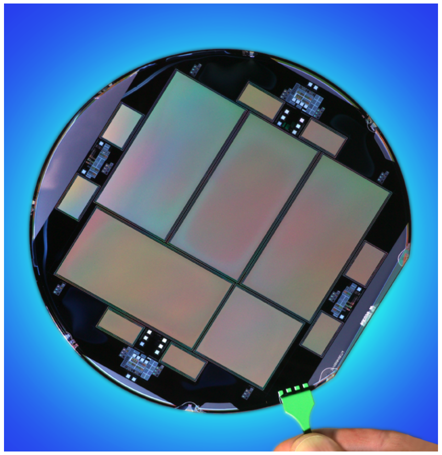
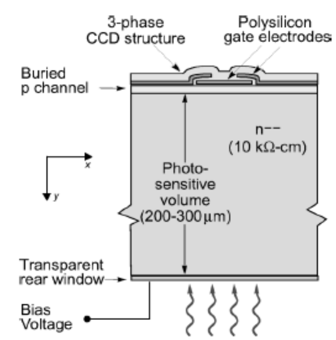


LBNL remedies to drawbacks

- LBNL CCD is p-channel (due to LBNL experience with fabrication low dark current p-i-n diodes)
  - Few e-/hour
- Degraded readout speed due to the lower mobility in p-channel is not of a concern for astronomy applications due to relatively low readout rates
- P-channel under study for space applications due to expected higher resistance to cosmic ray protons



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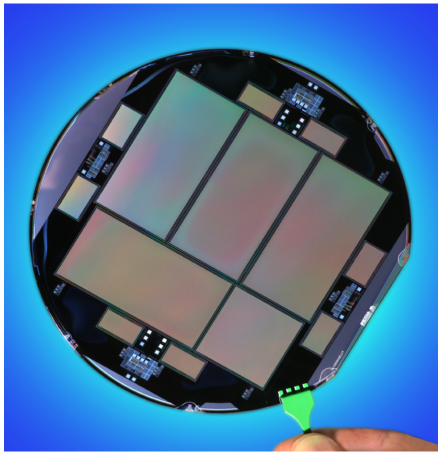
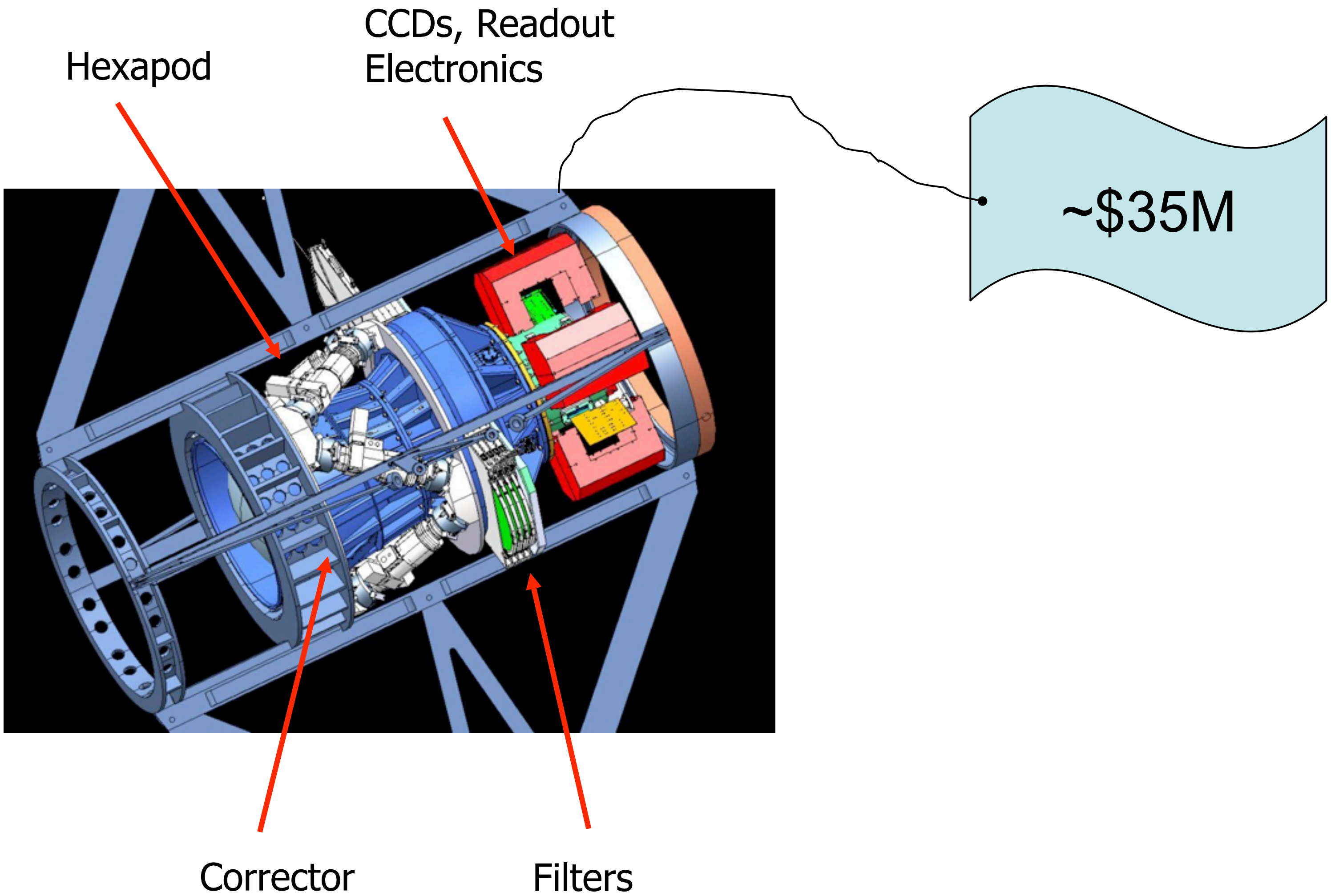
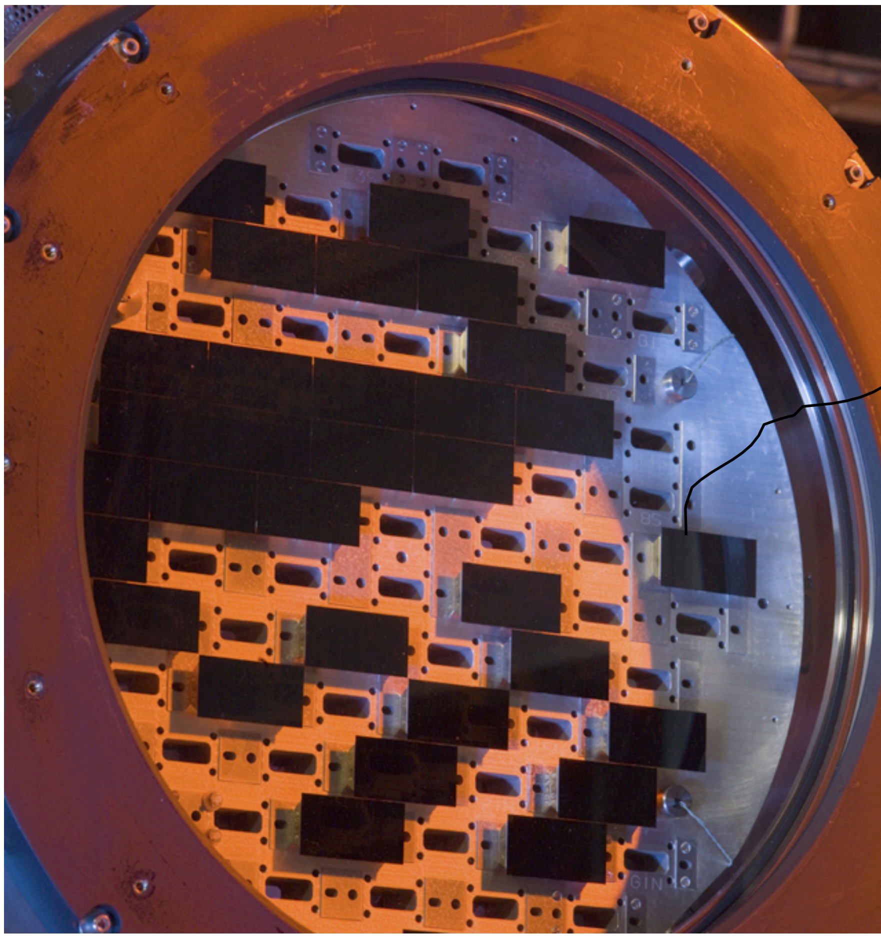


How much does DECam cost?



How much does a CCD cost?



~$50,000
ea.