WATCHERS OF THE SKY

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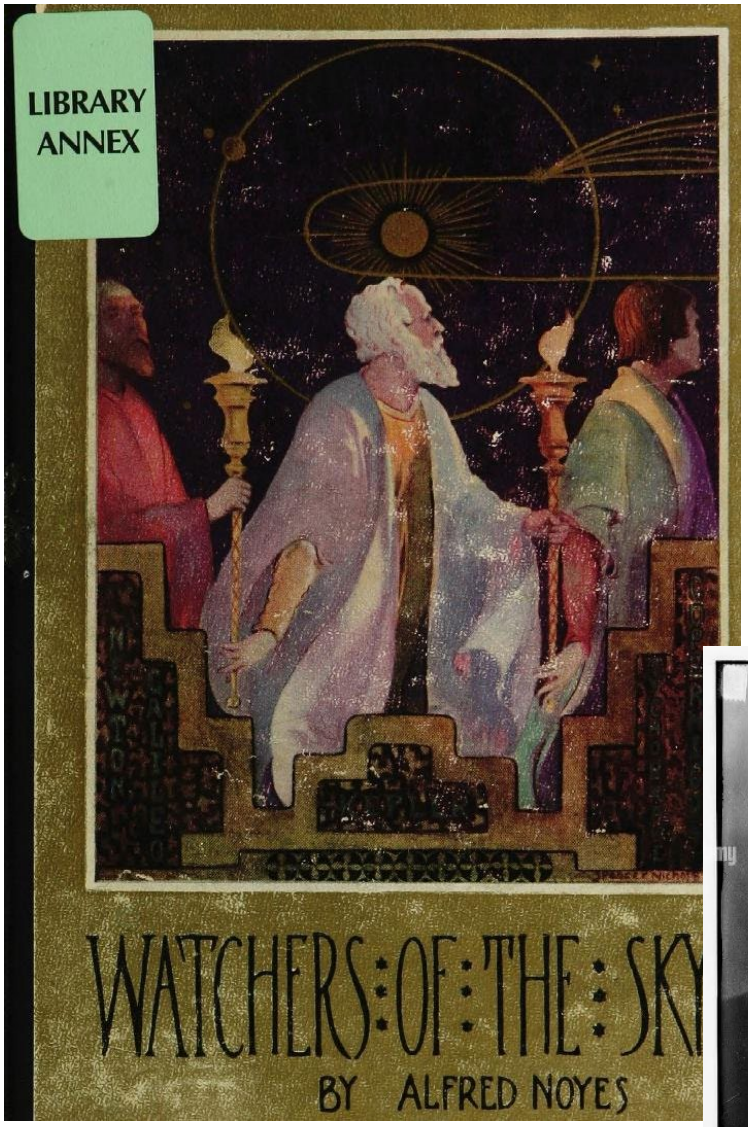
phughes@umich.edu

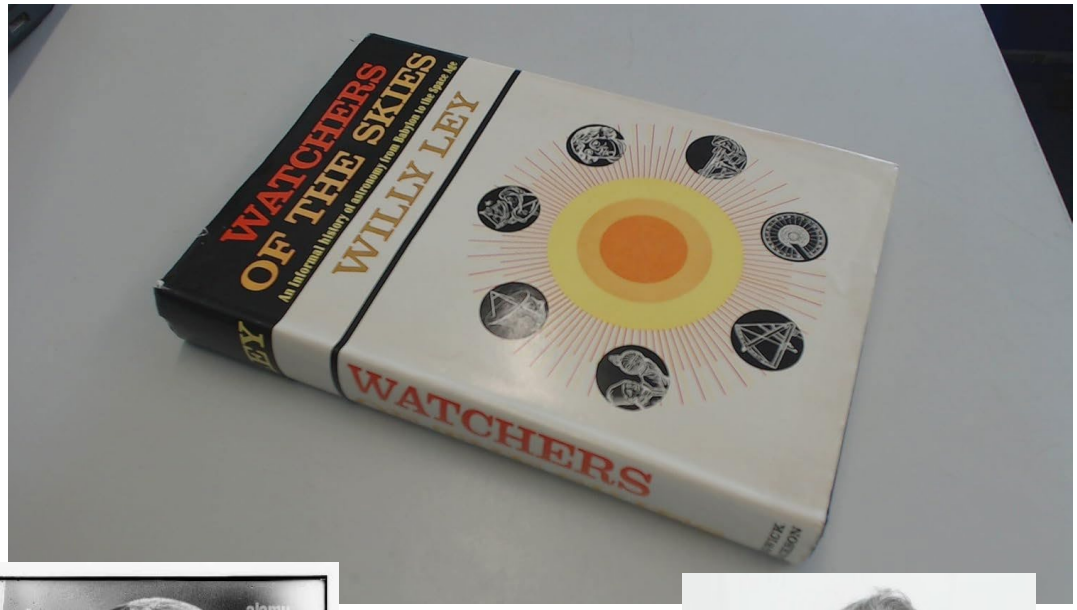
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Overview

- Background
  - Astronomy
  - Physics
  - Technology
- Facts & Figures
  - What makes this unique?
  - Gee whiz factors
- Science Goals

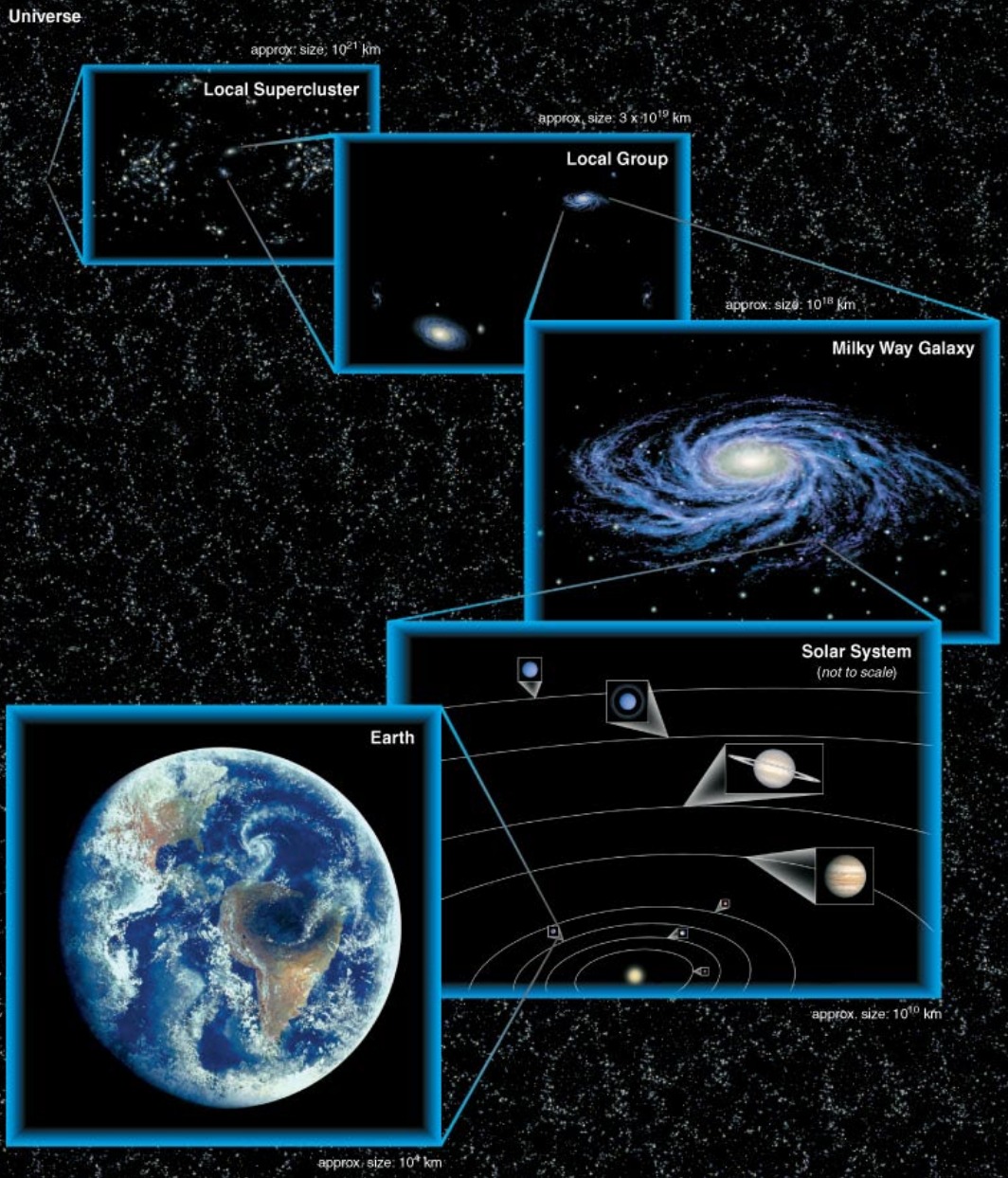
What's In A Name?





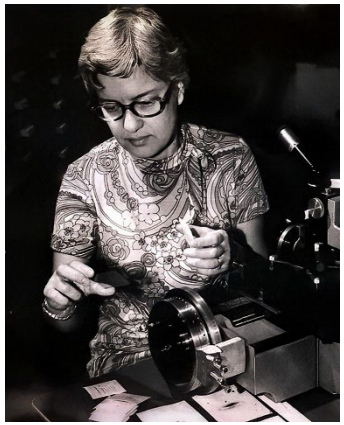





Universe
approx. size: 10^{21} km
Local Supercluster
approx. size: 3×10^{19} km
Local Group
approx. size: 10^{18} km
Milky Way Galaxy
Solar System
(not to scale)
approx. size: 10^{10} km
Earth
approx. size: 10^{4} km

Vera C. Rubin Observatory

- Named for Vera Rubin, who is best known for her work on galactic rotation, revealing the existence of dark matter



- The telescope is named the Simonyi Survey Telescope following a major donation from the Charles & Lisa Simonyi Fund



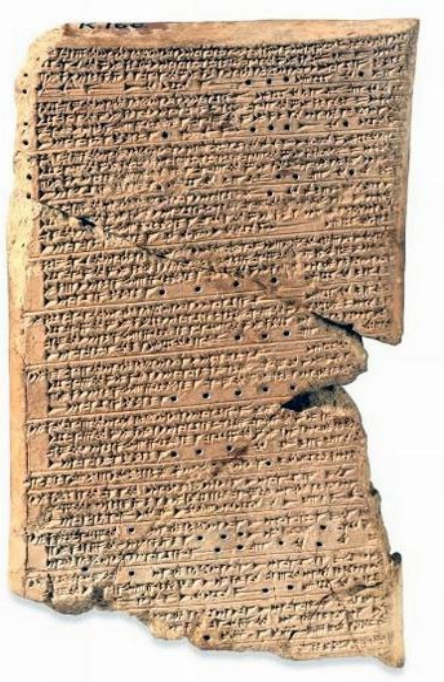
- Originally the Large Synoptic Survey Telescope, name cleverly repurposed as Legacy Survey in Space and Time

What Matters?

- **Time coverage**
- Field of view
- Depth
- Color coverage

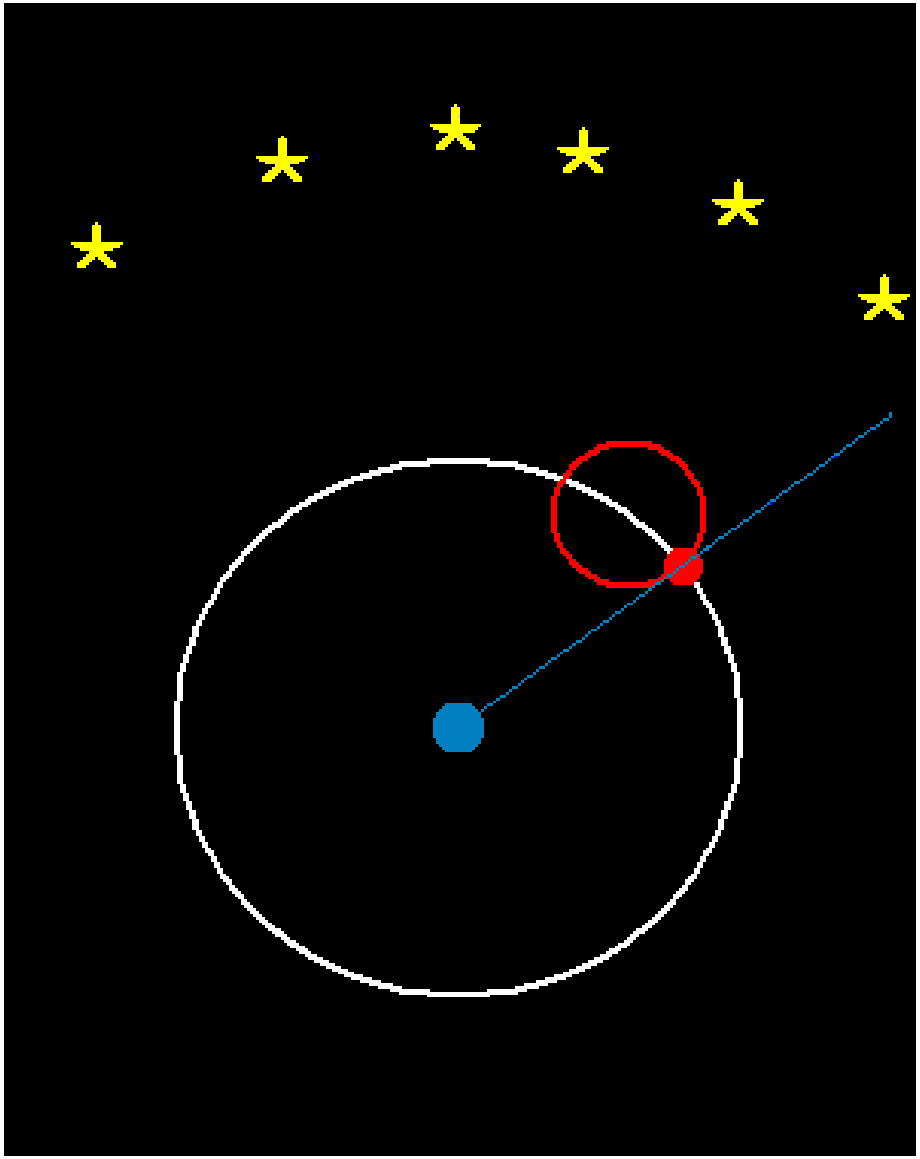
Babylonian Astronomy

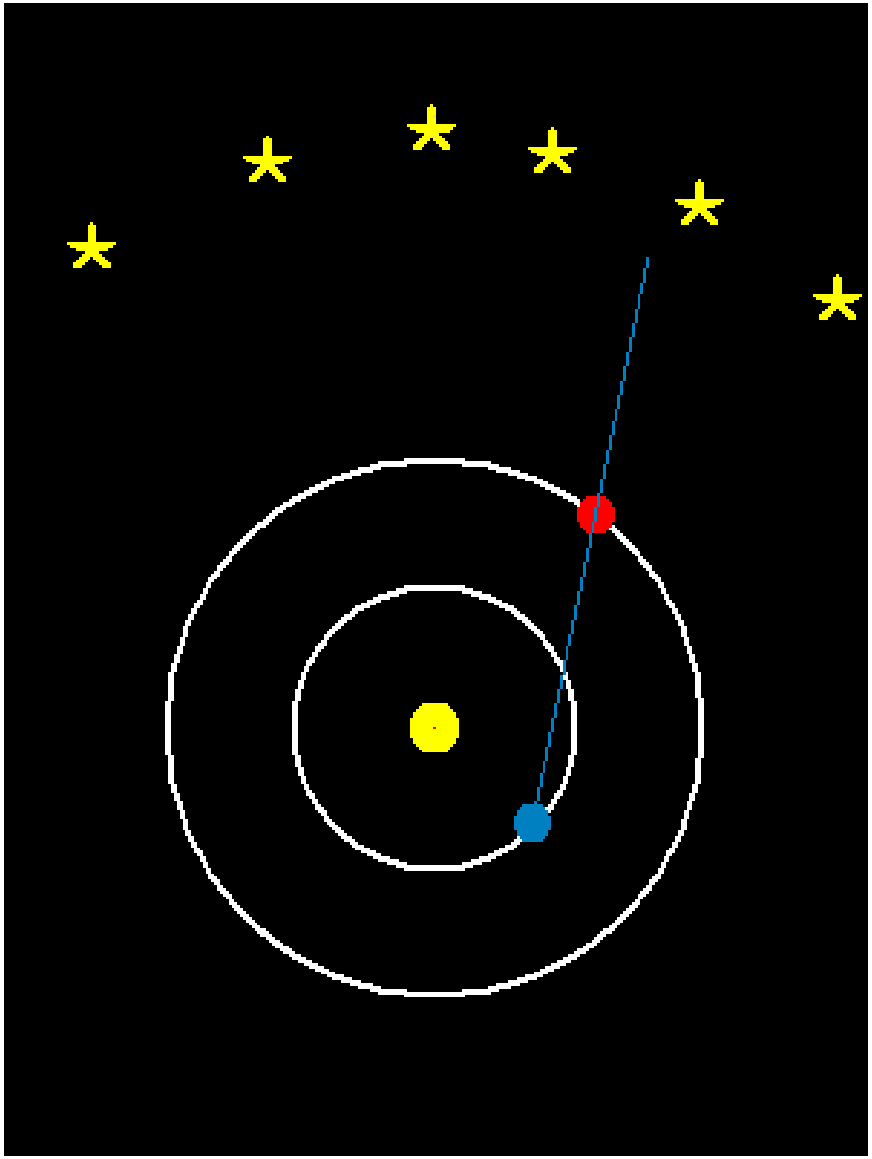
- Catalogs of stars and constellations
- Recognized periodic phenomena:
  - variation in length of day over year
  - earliest risings of Venus etc., over decades
- Identified the planets **and their motions**
- Identified cycles of lunar/solar eclipses
- Babylonian data are the `launching pad' of Greek cosmology



Venus tablet of Ammisaduqa

Ptolemy v. Copernicus



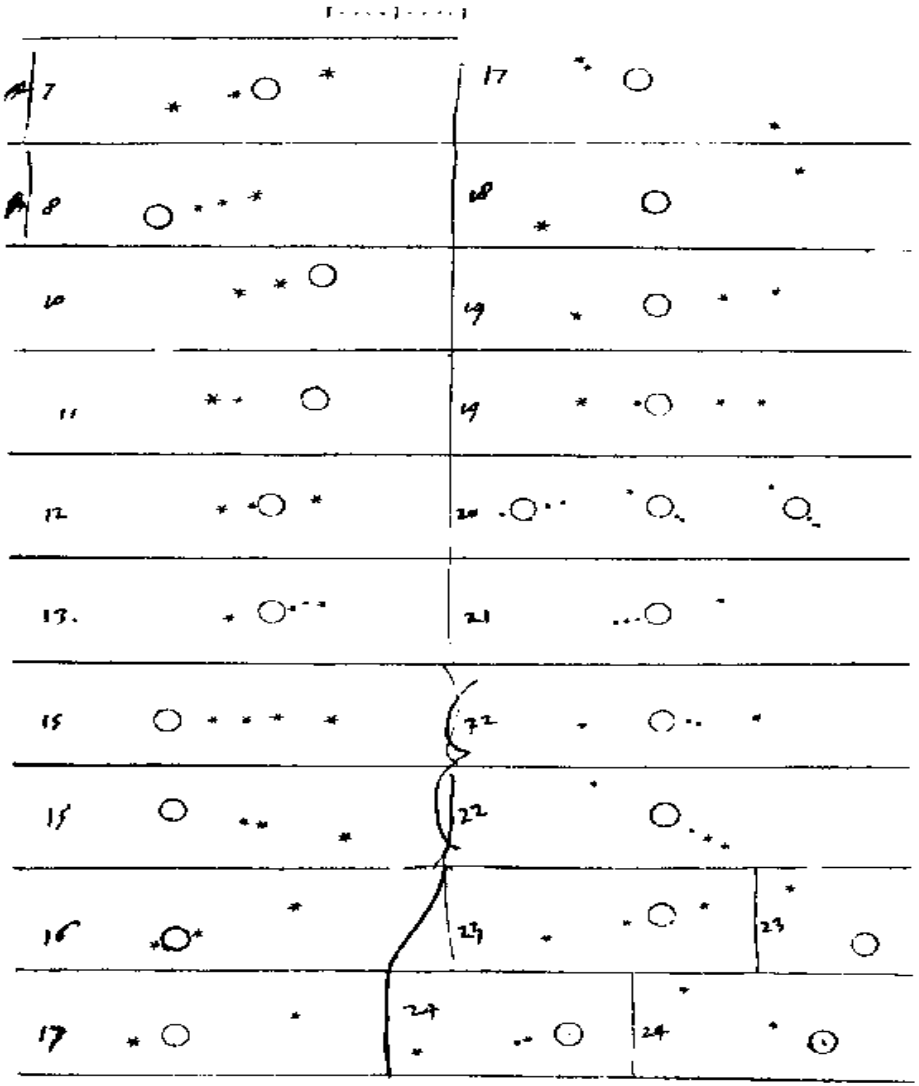


Brahe, Kepler & Newton

- Observations initiated by Brahe allowed Kepler to deduce the Laws Of Planetary Motion, which in turn motivated Newton's Law of Gravity – which underpins our measurement of mass throughout the Universe



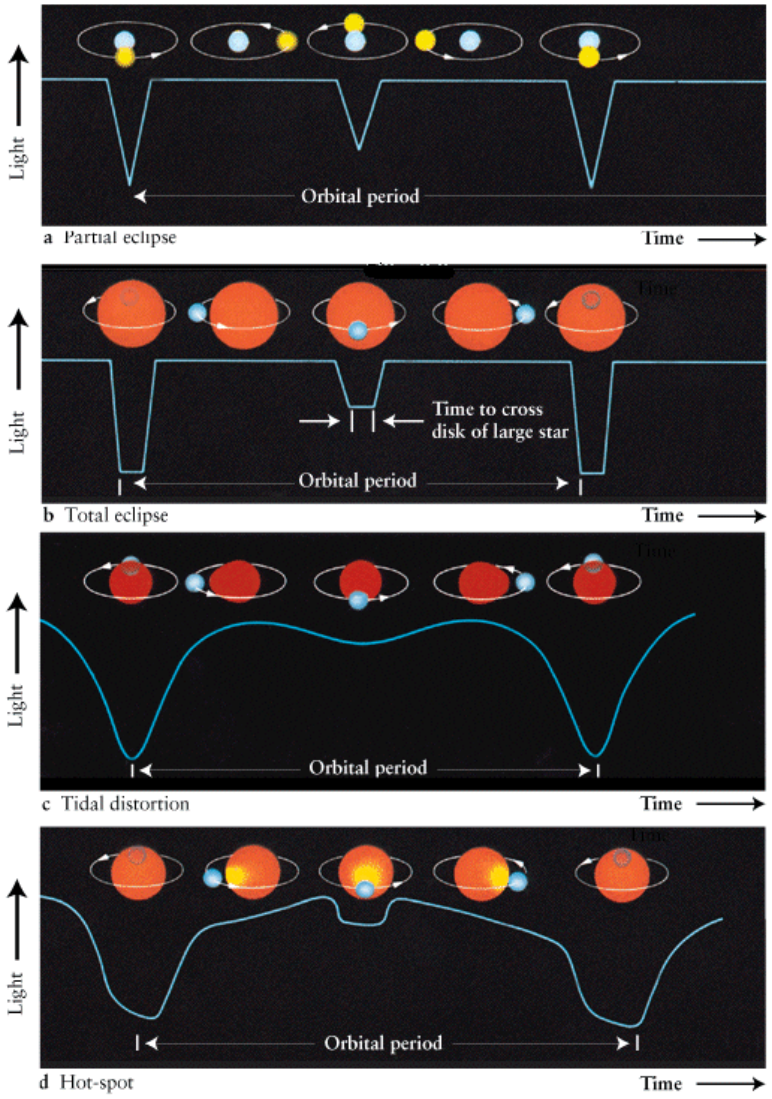
Galileo



- Observations of Jupiter's moons was a first step in the acceptance of "orbits"

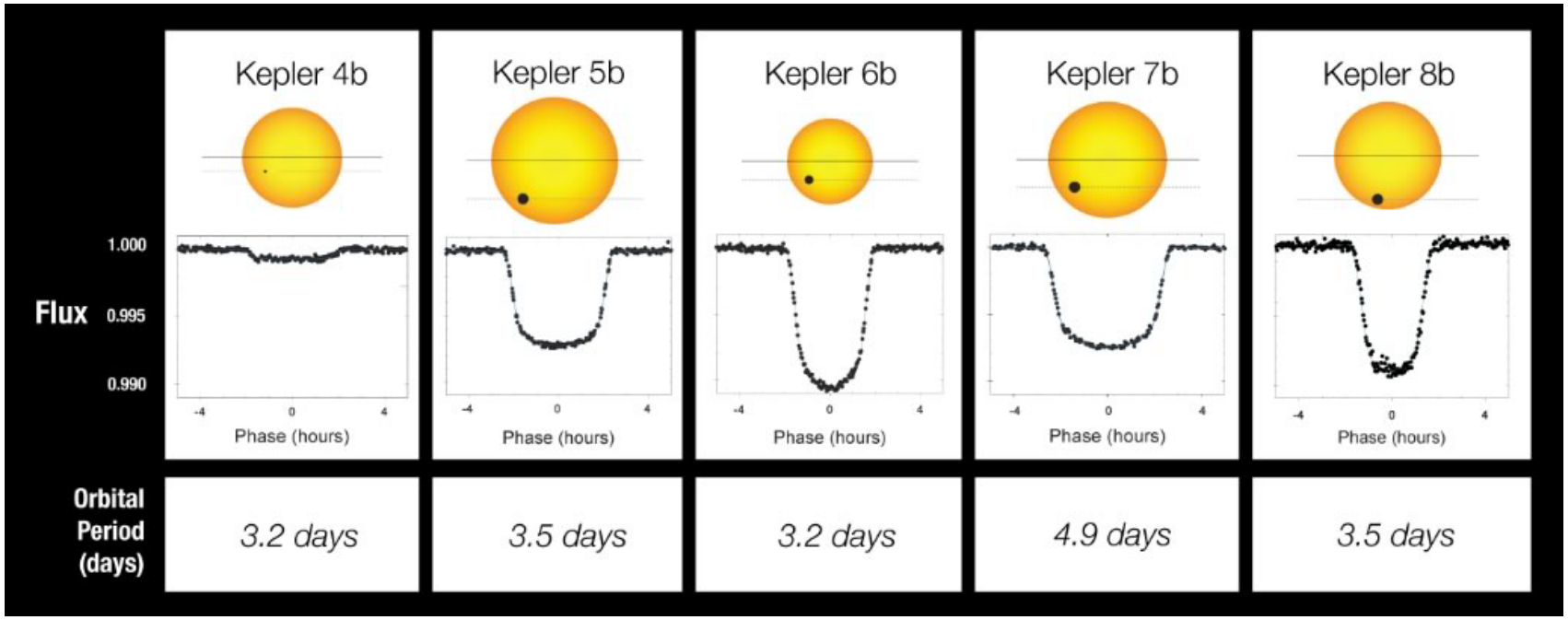
Stellar Variability

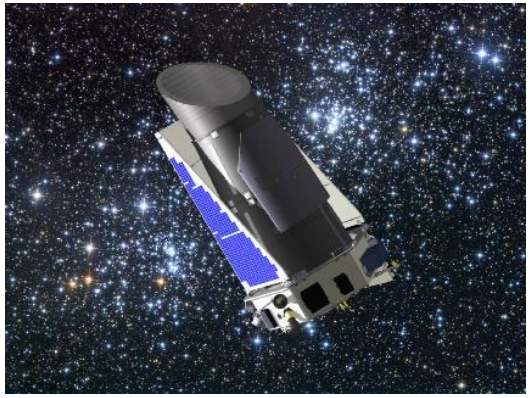
- Probes stellar properties and orbits

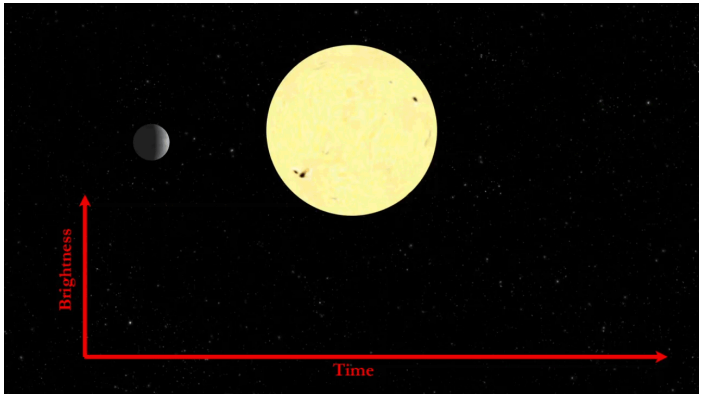


Stellar Variability

- Reveals exoplanets





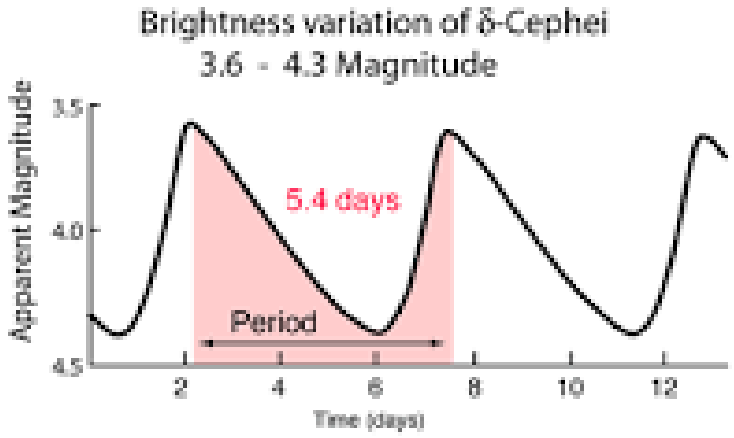


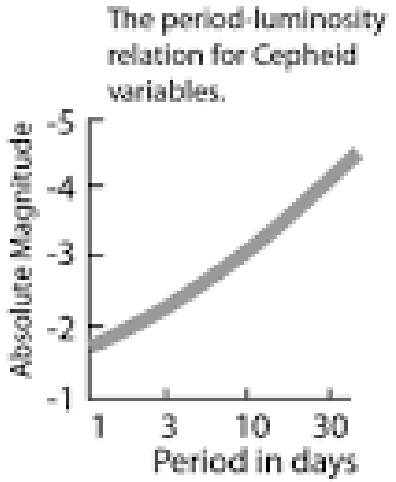
Stellar Variability

- Provides an extragalactic distance measuring tool



Henrietta Swan Leavitt (1868-1921)





Leavitt discovered the Cepheid period-luminosity relation by measuring the luminosities over time of 1200 Cepheids in the Small Magellanic Cloud.

- About 1920 Edwin Hubble measured the distance to the Andromeda Galaxy using Cepheid variable stars
- First person to show that “spiral nebulae” were separate galaxies.

A Movie Of The Sky

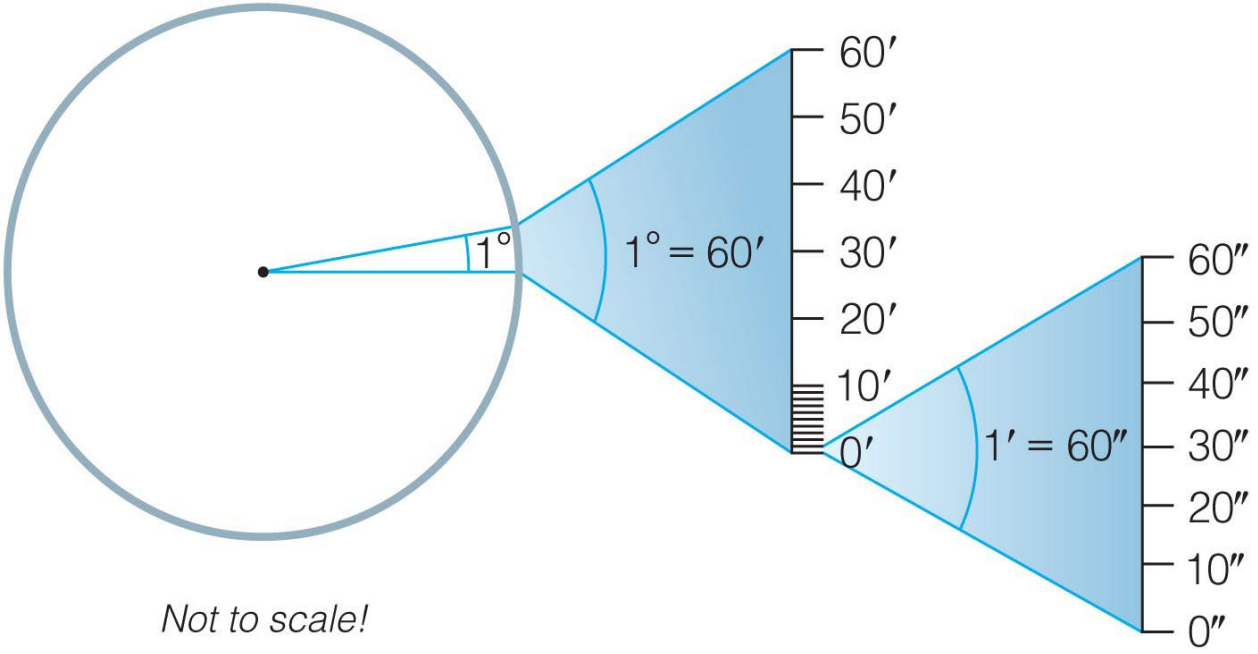
- Rubin will image the sky about 1000 times per night, covering the entire visible sky once every 3-4 nights
- The project has a 10 year life
- Thus each location will be imaged about 800 times – producing an unprecedented **movie** of extraordinary area and depth

What Matters?

- Time coverage
- **Field of view**
- Depth
- Color coverage

Angular Measure

- Full circle = 360^o
- 1^o = 60’ (arcminutes)
- 1’ = 60” (arcseconds)



1 arcsecond = 1” = (1/3600) degree
(a dime at 2.5 miles)

Field Of View

- The field of view of modern, large telescopes is **very small** – this is a liability for surveys, as many *pointings* will be required

- <u>Example: HST</u>
- *Advanced Camera for Surveys* (ACS) is 202” x 202”
- *Wide Field Camera 3* (WFC3) is 160” x 160”

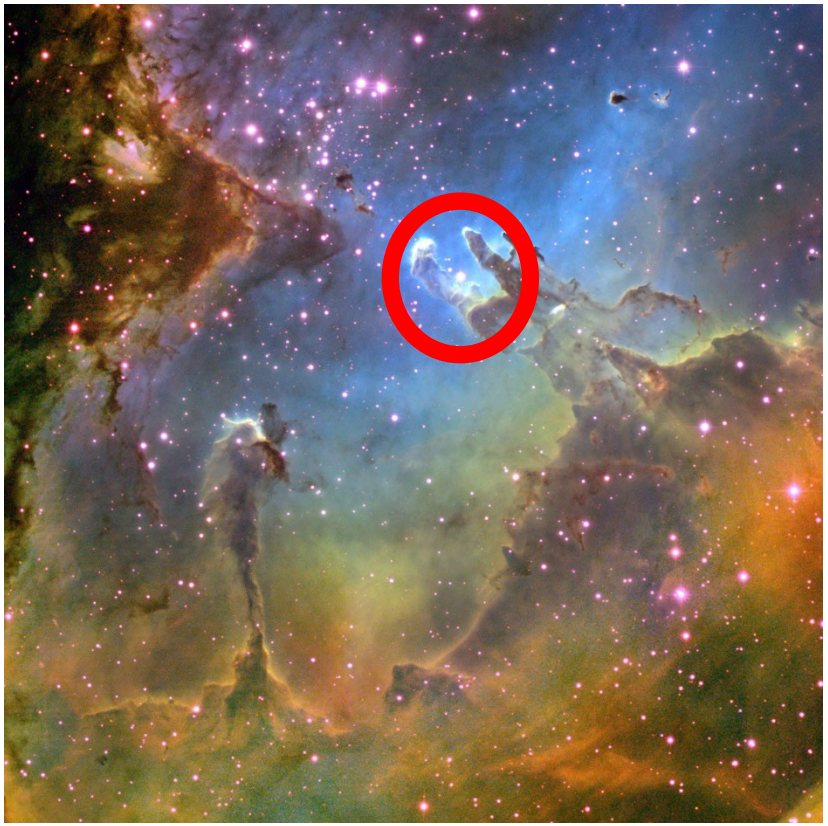
- 200” is about 10% the diameter of the full Moon

M16 / Eagle Nebula

- 2014 “Pillars Of Creation” image is essentially the WFC 3 ‘footprint’; larger fields require ‘mosaicking’ or specialist instrumentation

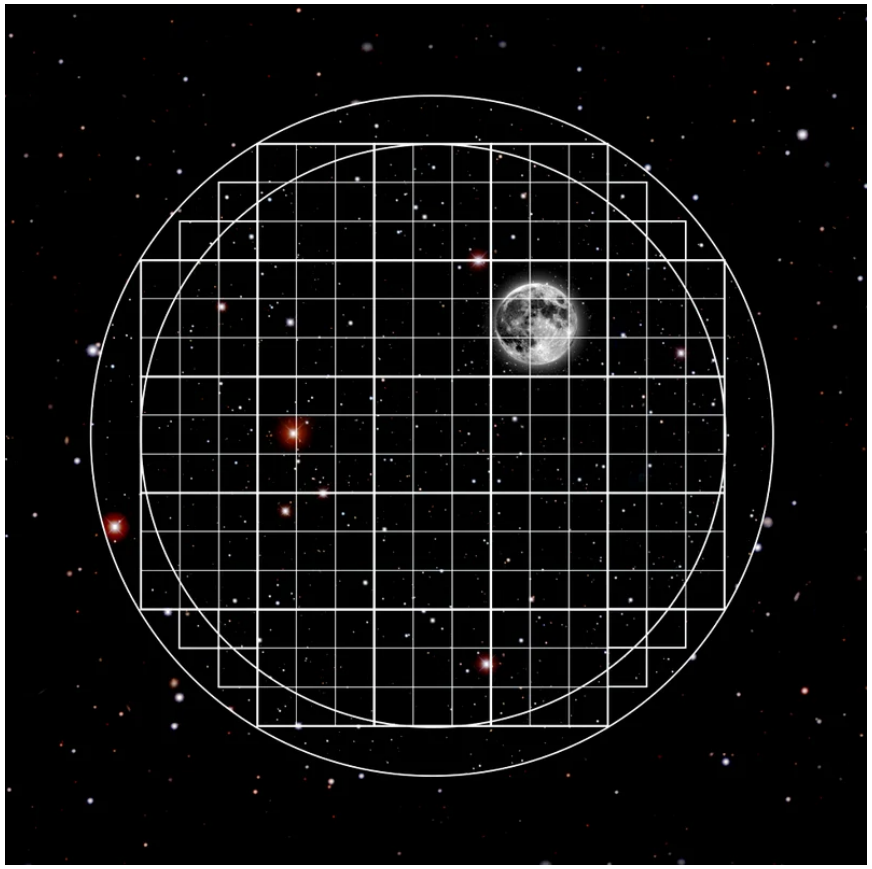


- The entire nebula photographed with the NOAO Mosaic CCD camera: 8 CCDs tiled together, used with a wide field imager



Field Of View

- With a novel optical design and gigantic camera, Rubin will have a field of view with diameter 3.5 degrees (9.6 square degrees – about 45 full Moons)

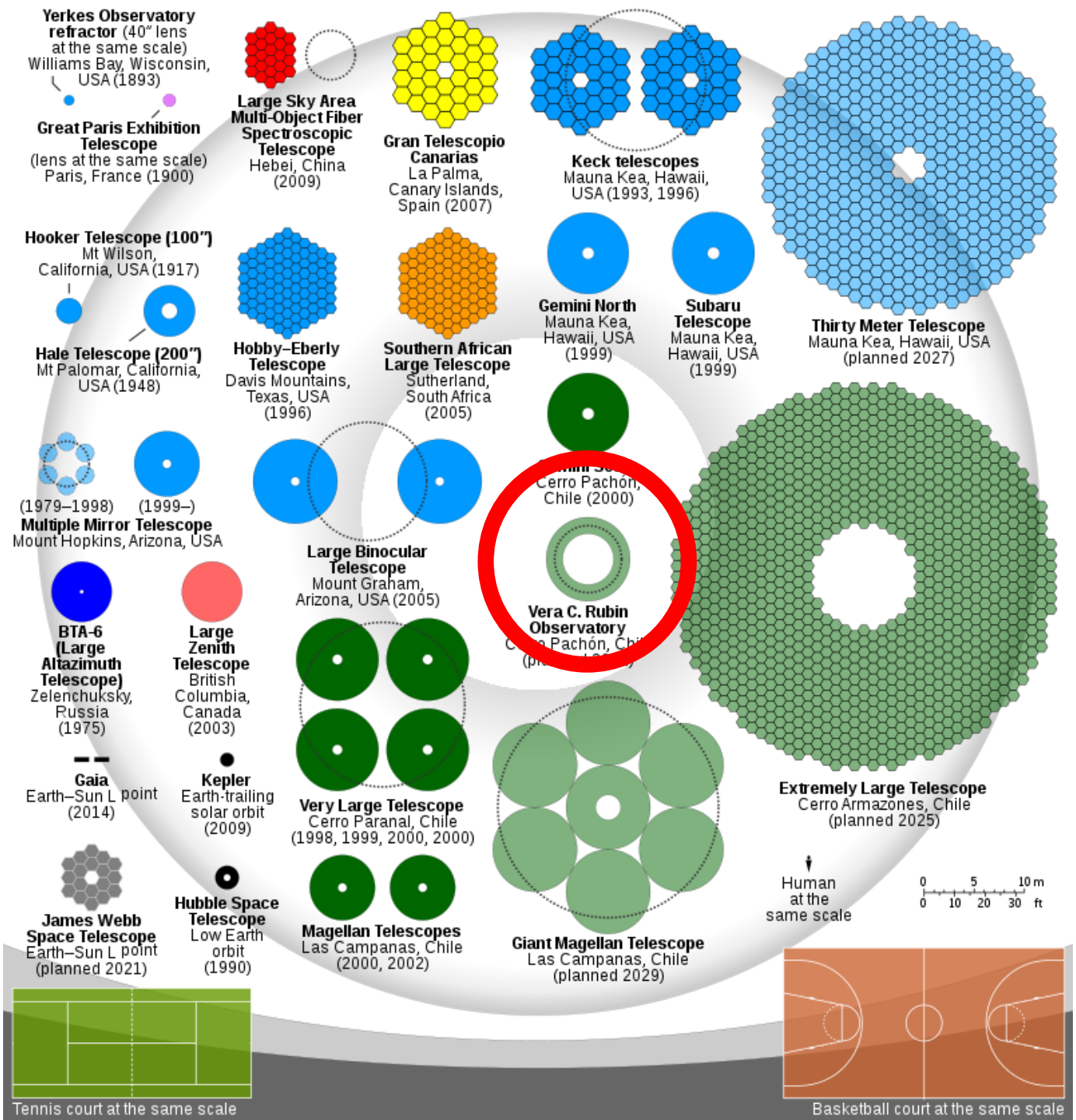


What Matters?

- Time coverage
- Field of view
- **Depth**
- Color coverage

How Far/Faint?

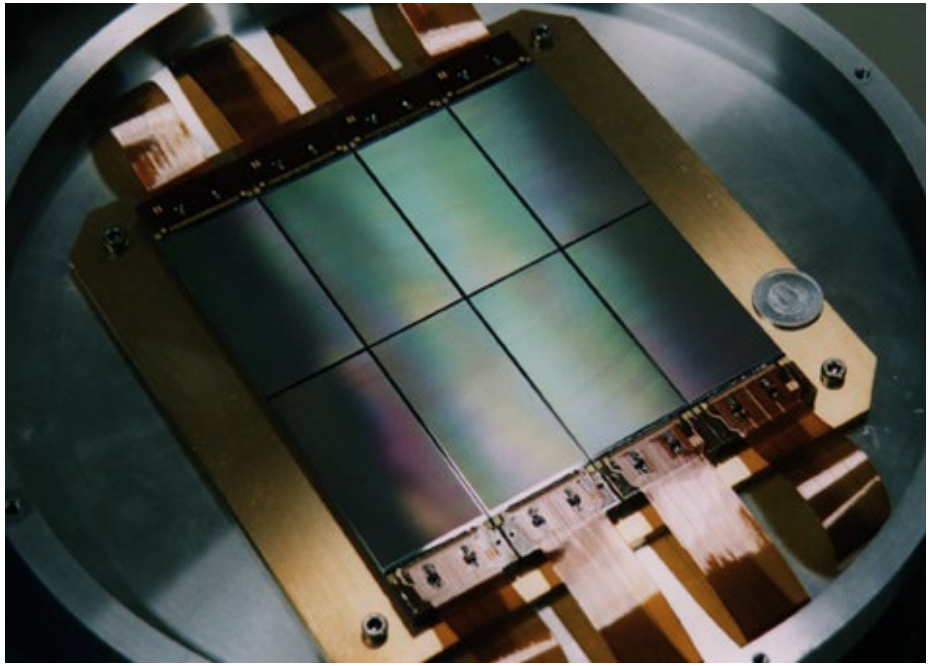
- Observations (particularly surveys) are shallow or deep
- How far/faint you can see are not the same: intrinsically low luminosity objects will be faint even when quite close; luminous objects (eg, SN Ia) are visible to great distances
- The ability to see faint objects is a function of telescope, camera and exposure time


Yerkes Observatory refractor (40″ lens at the same scale)
Williams Bay, Wisconsin, USA (1893)
Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck telescopes
Mauna Kea, Hawaii, USA (1993, 1996)
Thirty Meter Telescope
Mauna Kea, Hawaii, USA (planned 2027)
Hooker Telescope (100″)
Mt Wilson, California, USA (1917)
Hale Telescope (200″)
Mt Palomar, California, USA (1948)
Hobby–Eberly Telescope
Davis Mountains, Texas, USA (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii, USA (1999)
Subaru Telescope
Mauna Kea, Hawaii, USA (1999)
(1979–1998)
(1999–)
Multiple Mirror Telescope
Mount Hopkins, Arizona, USA
Large Binocular Telescope
Mount Graham, Arizona, USA (2005)
Cerro Pachón, Chile (2000)
Vera C. Rubin Observatory
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth–Sun L point (2014)
Kepler
Earth-trailing solar orbit (2009)
Very Large Telescope
Cerro Paranal, Chile (1998, 1999, 2000, 2000)
Extremely Large Telescope
Cerro Armazones, Chile (planned 2025)
James Webb Space Telescope
Earth–Sun L point (planned 2021)
Hubble Space Telescope
Low Earth orbit (1990)
Magellan Telescopes
Las Campanas, Chile (2000, 2002)
Giant Magellan Telescope
Las Campanas, Chile (planned 2029)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Tennis court at the same scale
Basketball court at the same scale

Centuries Of Progress







A Comparison

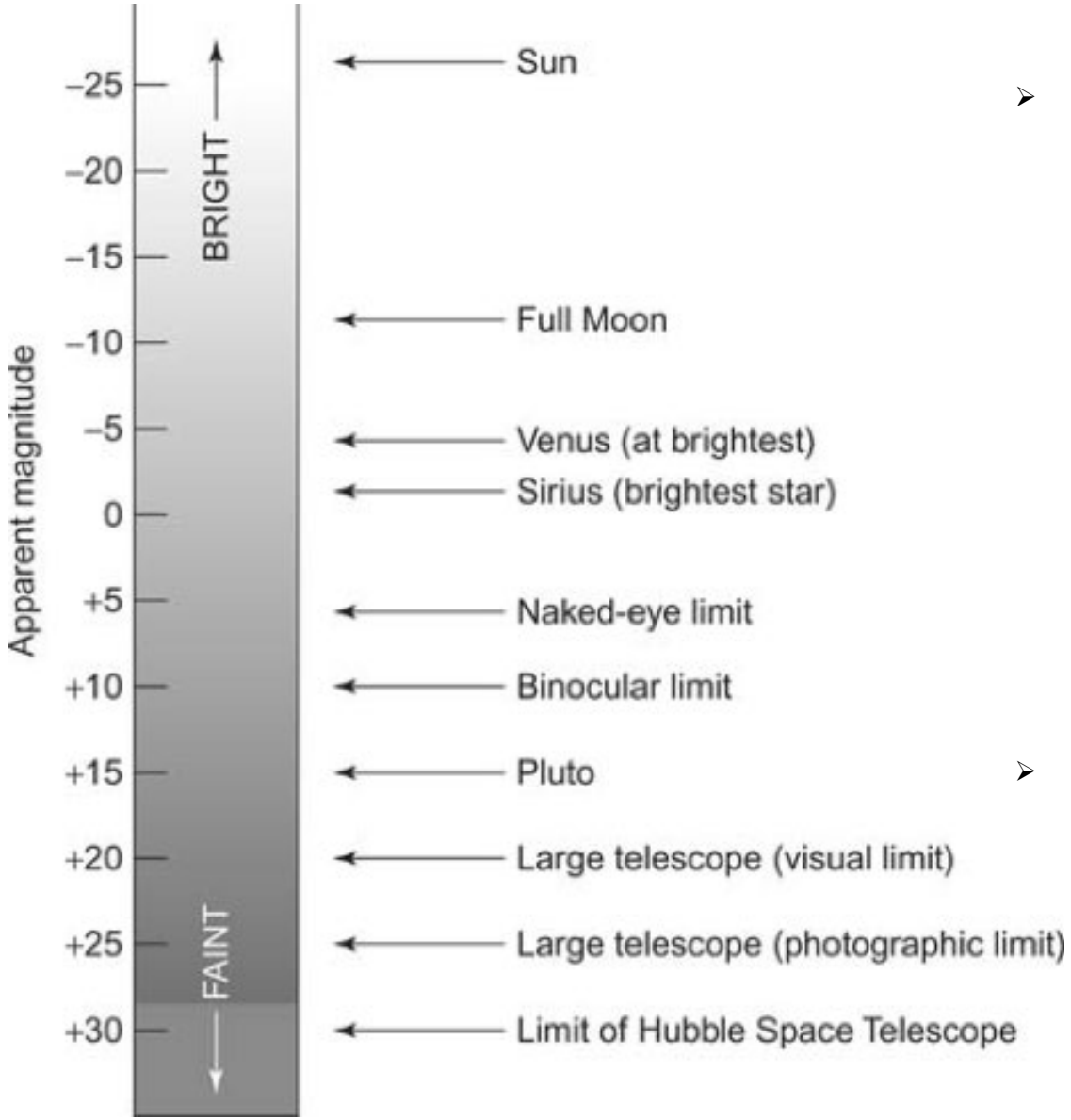
- Emulsion
  - Quantum Efficiency 1-2%
  - Spectral Range “optical”
  - Dynamic Range 100
  - Non-linear
  - Analog
- CCD
  - Quantum Efficiency 70-90%
  - Spectral Range X-rays to 1000 nm
  - Dynamic Range 10,000
  - Linear
  - Digital readout

The Competition

- Atmosphere – airglow (natural luminescence in upper atmosphere), scattered sunlight and light pollution (often the biggest problem for Earth-based telescopes)
- Zodiacal Light – sunlight scattered by interplanetary dust
- Diffuse Galactic Light – the diffuse light from stars and dust in the Milky Way
- Extragalactic Background Light – from all galaxies/groups/clusters in the Universe (usually only important in eg, deep Hubble images)

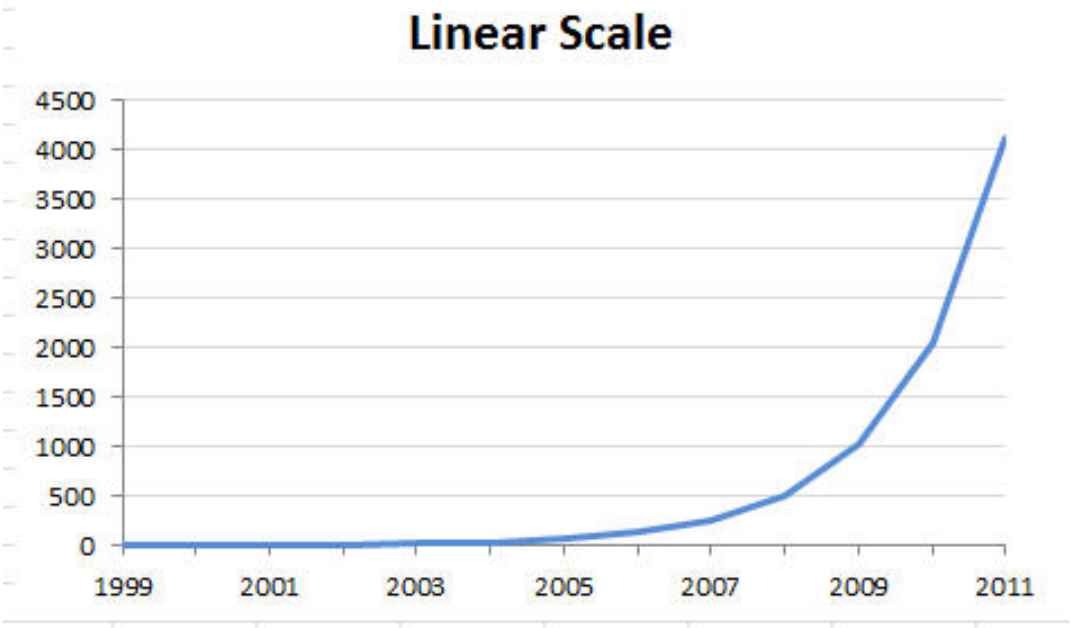


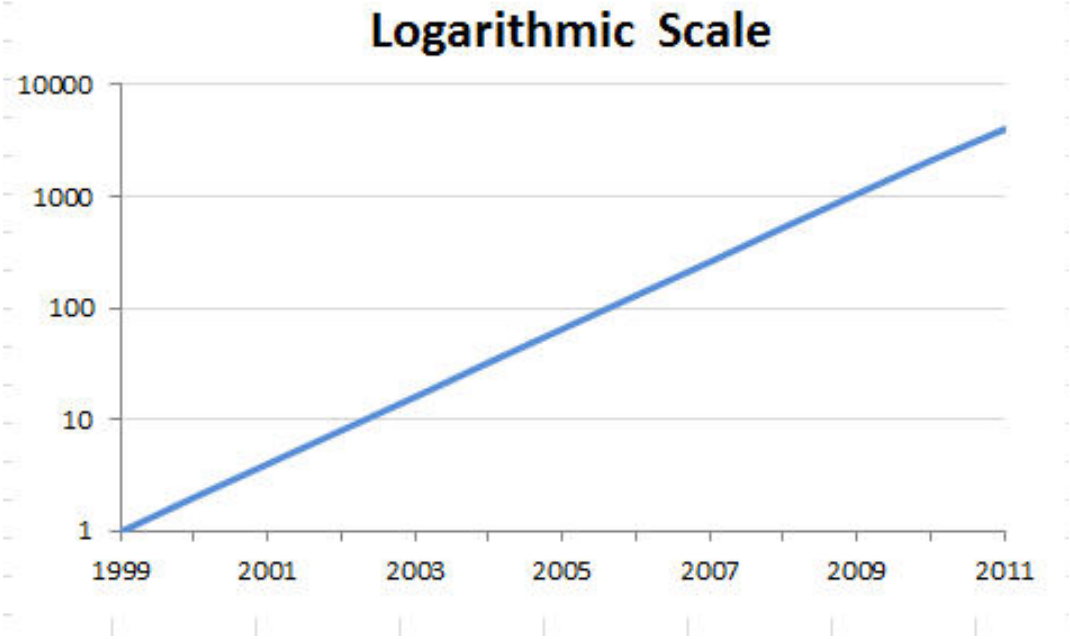
The Bottom Line



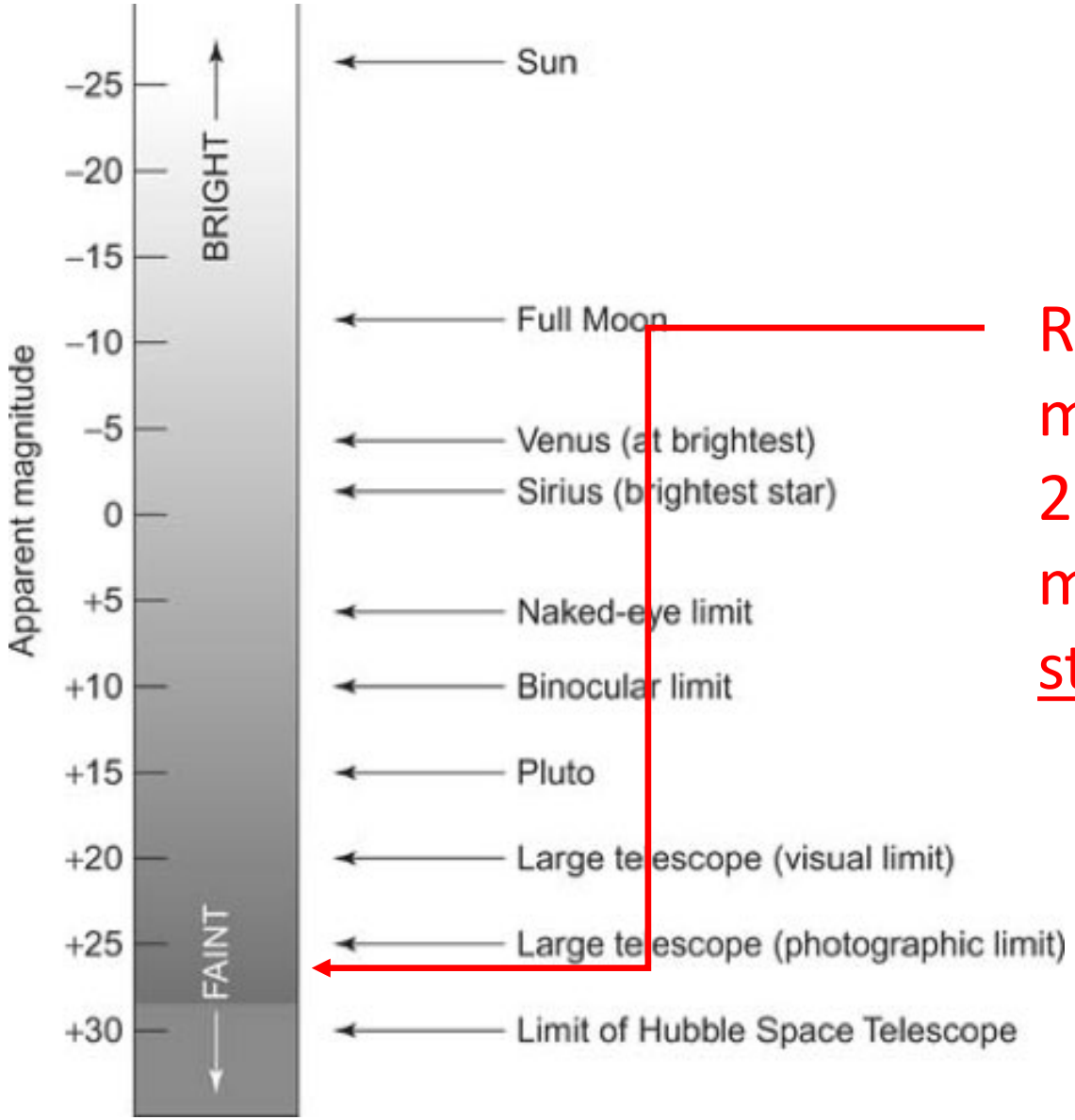
- Apparent magnitudes; a logarithmic scale in which a mag. -25 object is 10^{20} times brighter than a mag. +25 object

- Hubble reached mag. 31 with 800 x 20 min = 113 days for the Ultra Deep Field


Linear Scale
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1999
2001
2003
2005
2007
2009
2011


Logarithmic Scale
10000
1000
100
10
1
1999
2001
2003
2005
2007
2009
2011

The Bottom Line



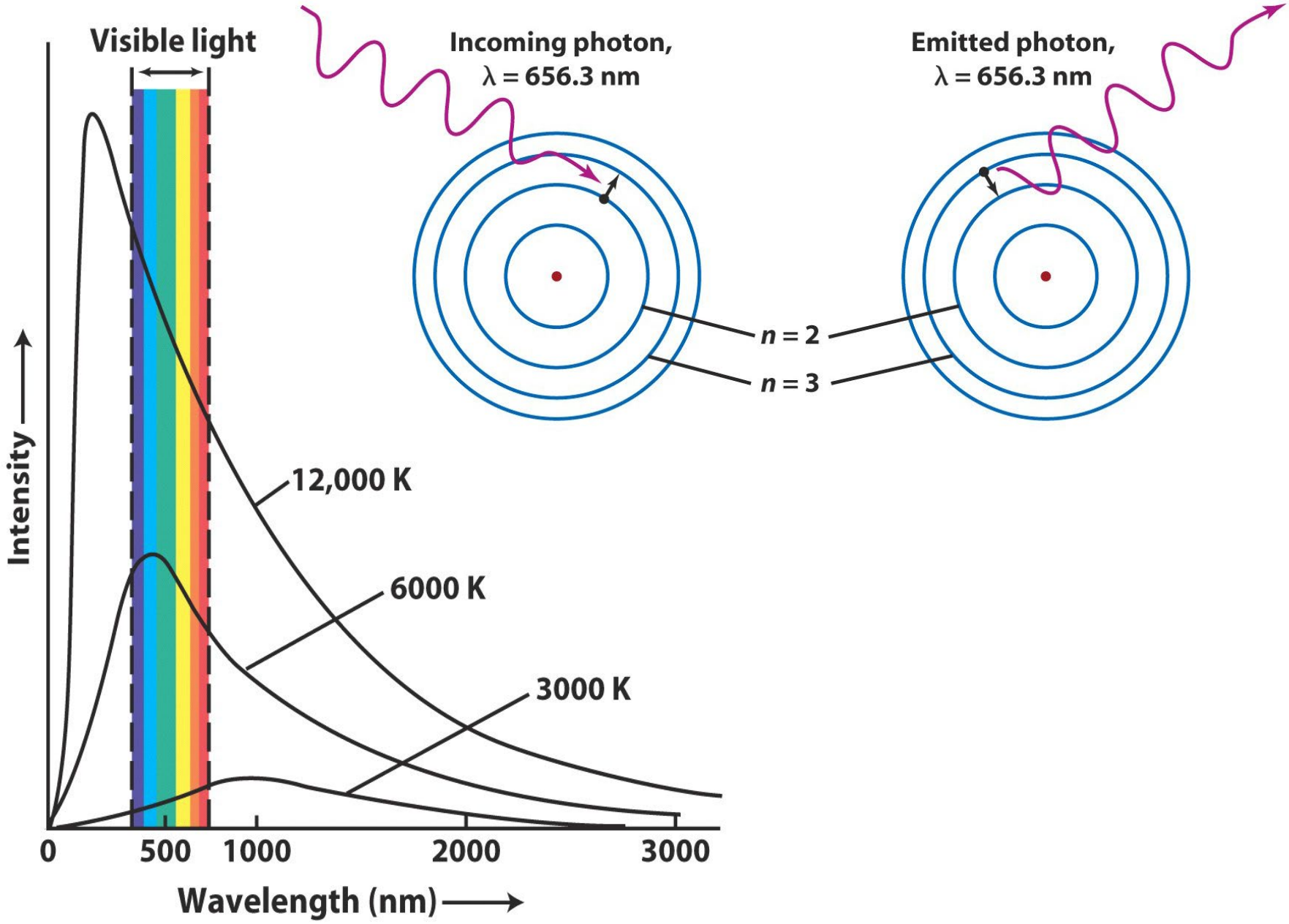
Rubin: 24th r-band magnitude;
27.8th r-band magnitude after stacking

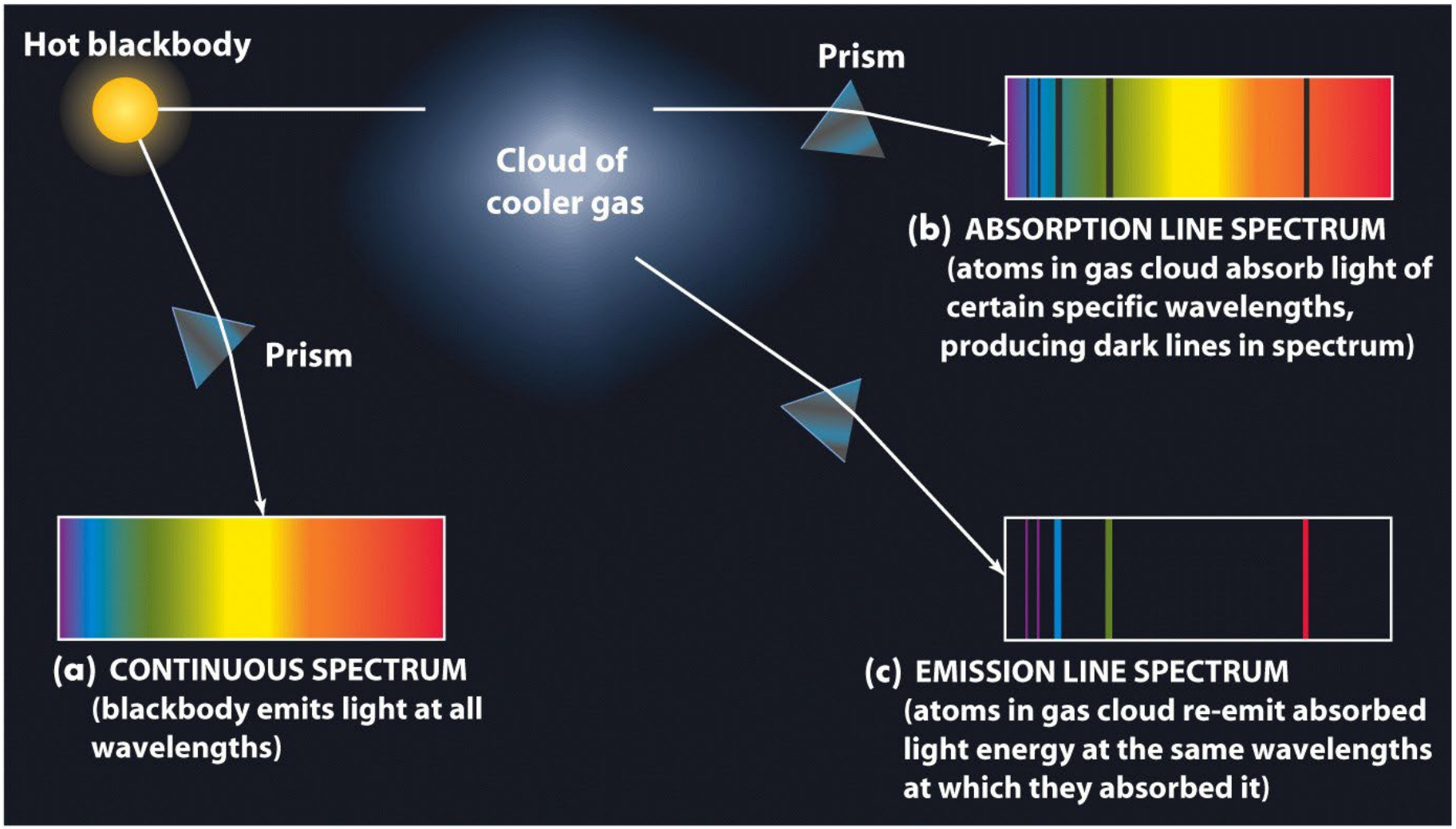
What Matters?

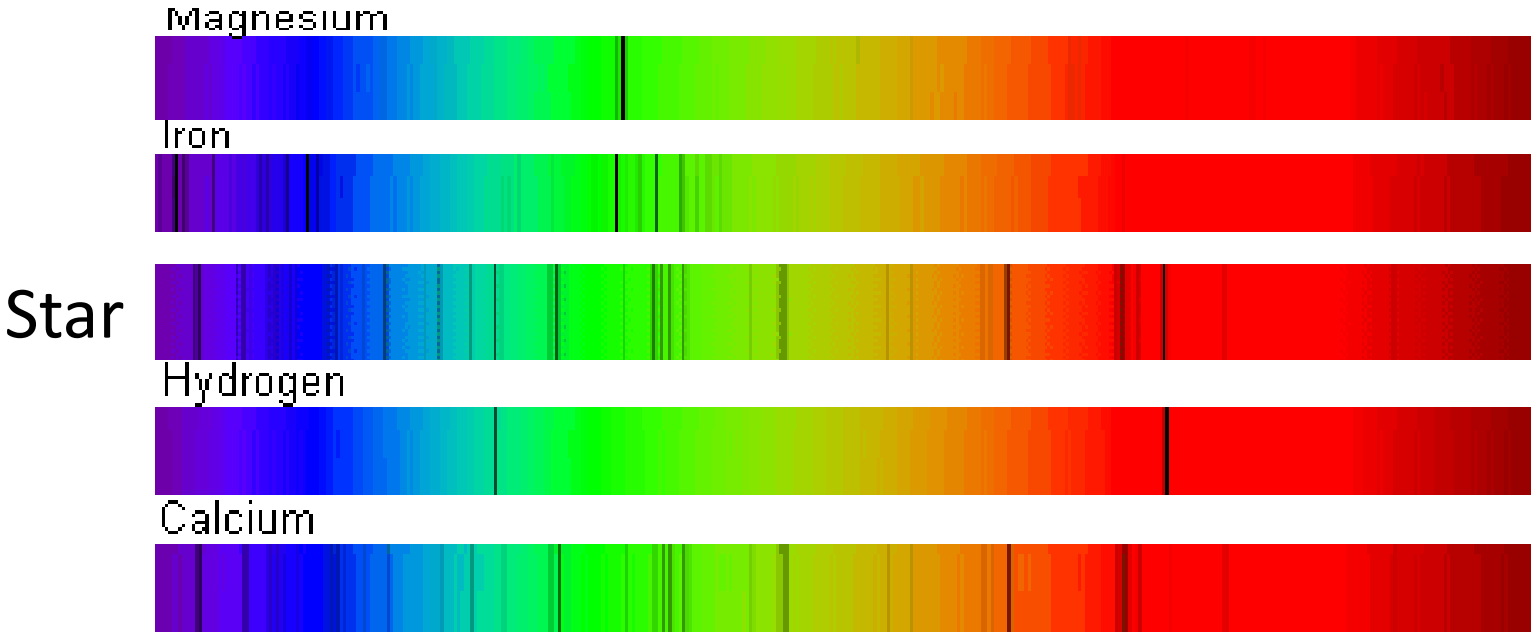
- Time coverage
- Field of view
- Depth
- **Color coverage**

The Spectrum

- Astronomy is far more than pretty pictures
- Filters isolate particular parts of the whole spectrum
- Spectroscopy reveals spectral lines


Visible light
Incoming photon,
λ = 656.3 nm
Emitted photon,
λ = 656.3 nm
n = 2
n = 3
Intensity
12,000 K
6000 K
3000 K
0
500
1000
2000
3000
Wavelength (nm)


Hot blackbody
Prism
Cloud of cooler gas
(b) ABSORPTION LINE SPECTRUM
(atoms in gas cloud absorb light of certain specific wavelengths, producing dark lines in spectrum)
Prism
(a) CONTINUOUS SPECTRUM
(blackbody emits light at all wavelengths)
(c) EMISSION LINE SPECTRUM
(atoms in gas cloud re-emit absorbed light energy at the same wavelengths at which they absorbed it)



Which elements are seen in the spectrum of this star?

a) All 4 b) Fe + H c) H + Ca d) Fe, H & Ca

Hydrogen and Calcium are strong

The Spectrum

- Astronomy is far more than pretty pictures
- Filters isolate particular parts of the whole spectrum and thus probe **temperature**
- Spectroscopy reveals spectral lines and thus probe **composition**
- ….and **density, pressure, velocity**, etc.

Caution!

- Astronomical images are composites from various bands, and often highly processed

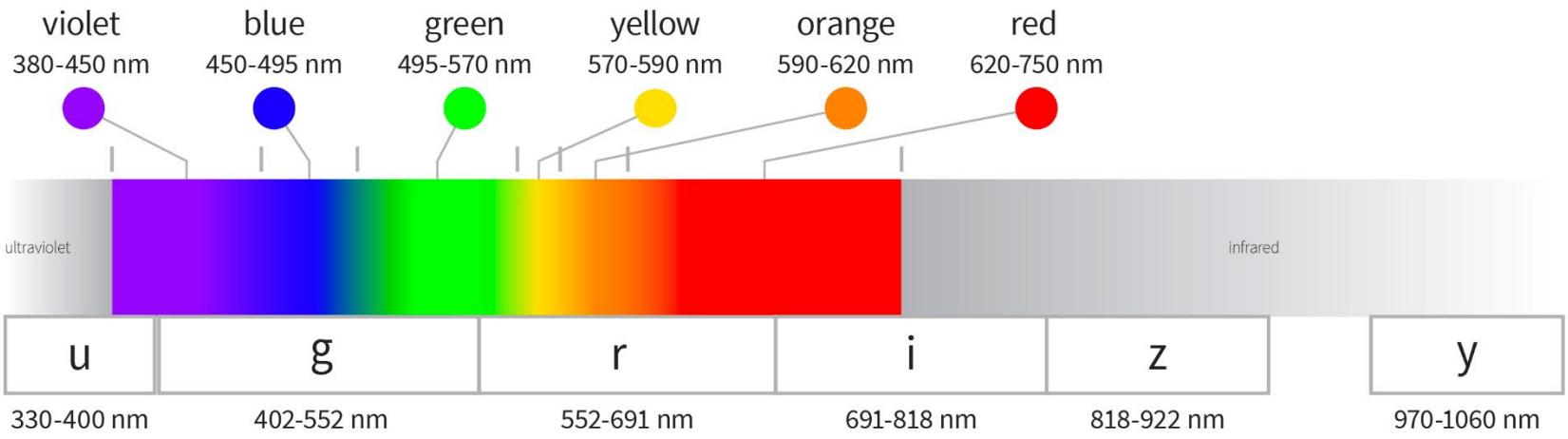


- Example:
- Blue – Oxygen
- Green – Hydrogen & Nitrogen
- Orange – Sulfur

Colors Galore

- Unlike a conventional telescope, Rubin does not have a spectrograph
  - But an auxiliary telescope (AuxTel) does: it facilitates correcting for atmospheric effects and in photometric calibration
- Rubin has a carousel of 6 filters with an extraordinary wavelength coverage:
- 330 nm (near UV)

  to
- 1060 nm (near IR)



Rubin Observatory LSST Camera filter ranges

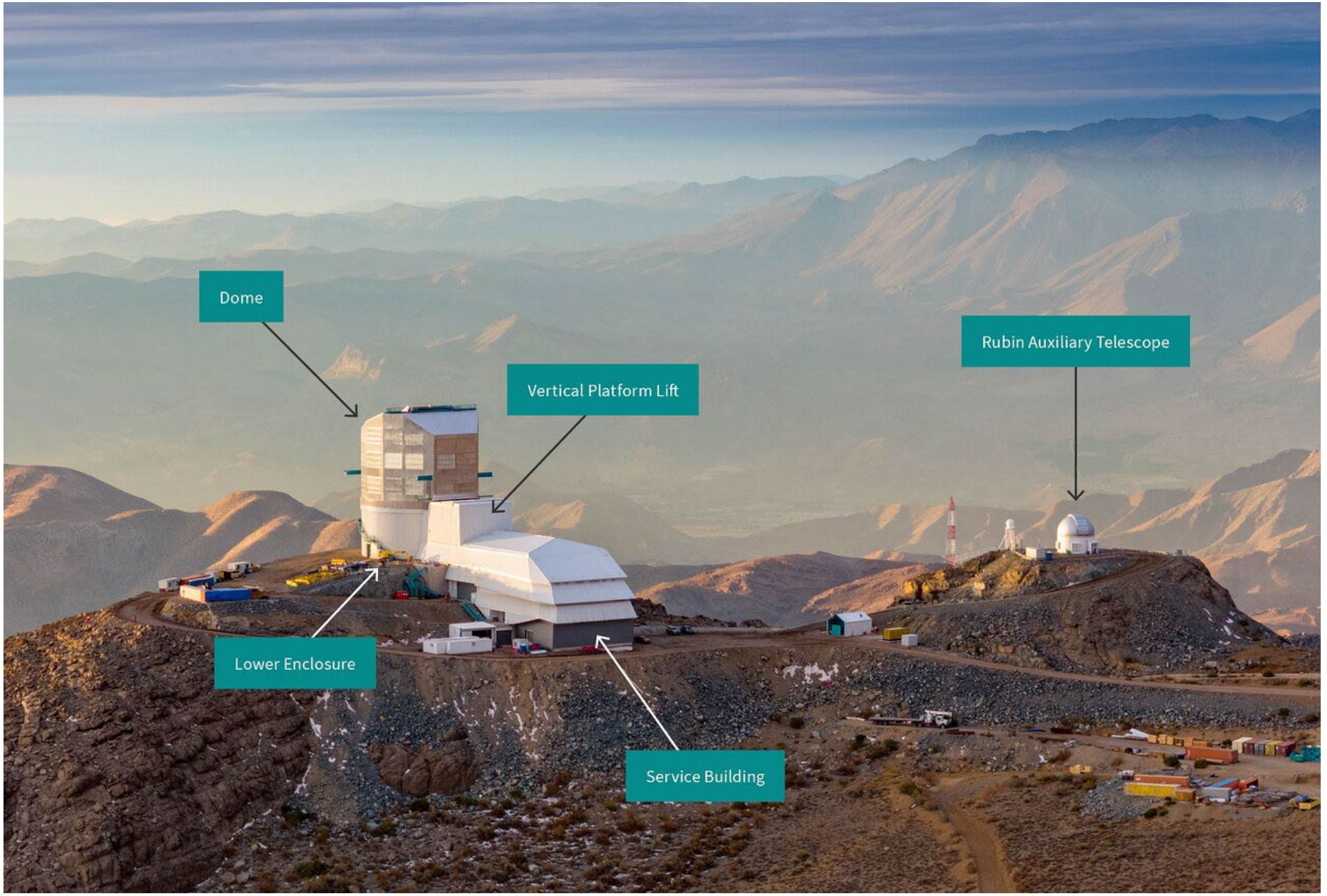
Colors Galore

- Unlike a conventional telescope, Rubin does not have a spectrograph
  - But an auxiliary telescope (AuxTel) does: it facilitates correcting for atmospheric effects and in photometric calibration
- Rubin has a carousel of 6 filters with an extraordinary wavelength coverage:
- Filters can change up to 4 times per night
- There is a complex observing strategy, with the Wide-Fast-Deep Survey covering the sky in all six filters over 10 years

Location

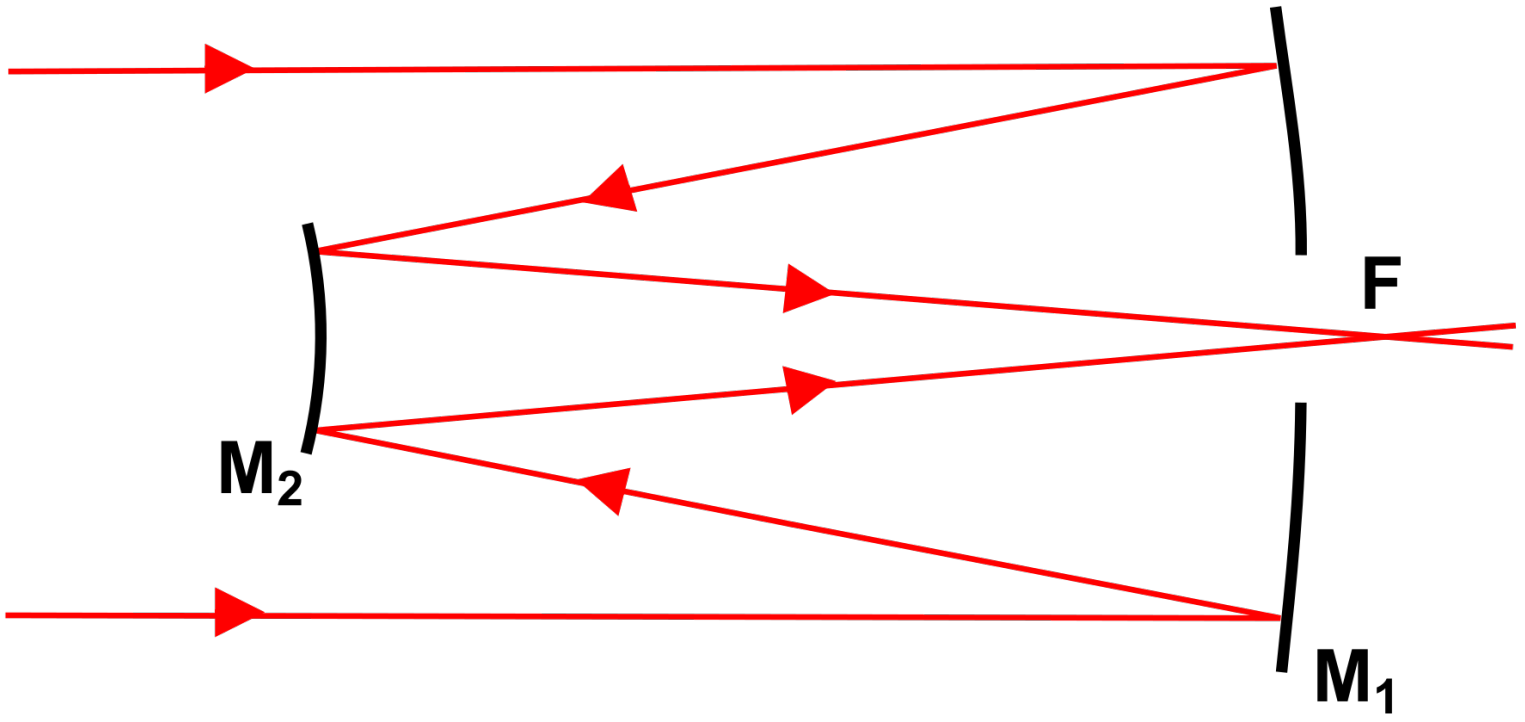
- Management: Association of Universities for Research in Astronomy (AURA) – Tucson, AZ
- Base Facility: La Serena, Chile
- Rubin Observatory: Cerro Pachon, Chile
- Data Handling: SLAC National Accelerator Lab. – Menlo Park, CA



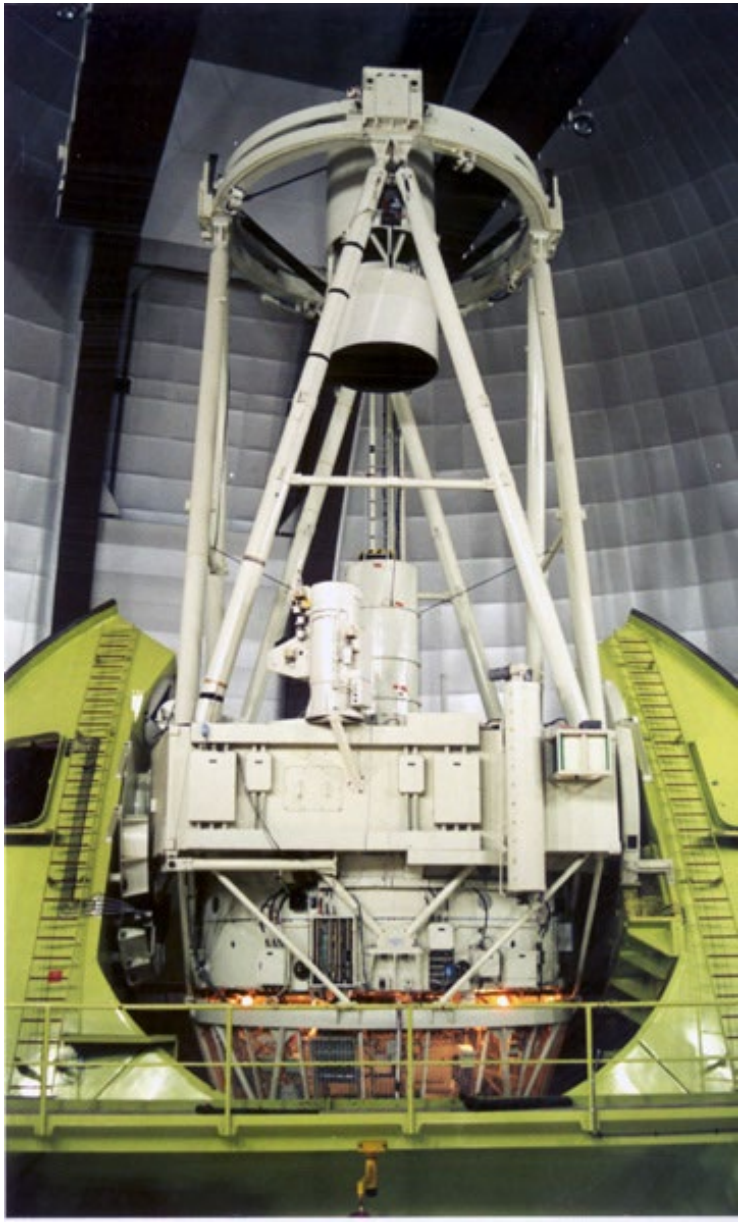

Dome
Vertical Platform Lift
Rubin Auxiliary Telescope
Lower Enclosure
Service Building

Recap: Reflecting Telescopes

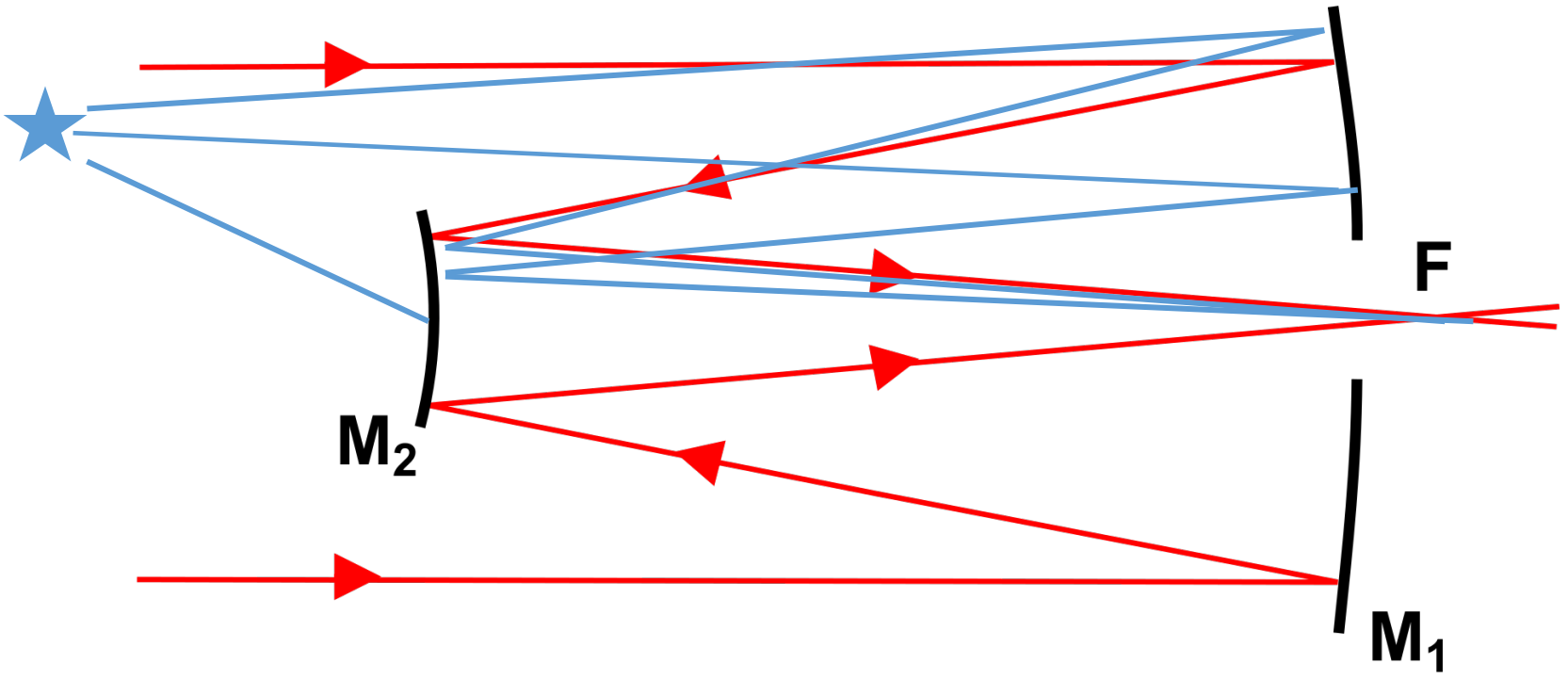
- Two mirror design: Cassegrain focus



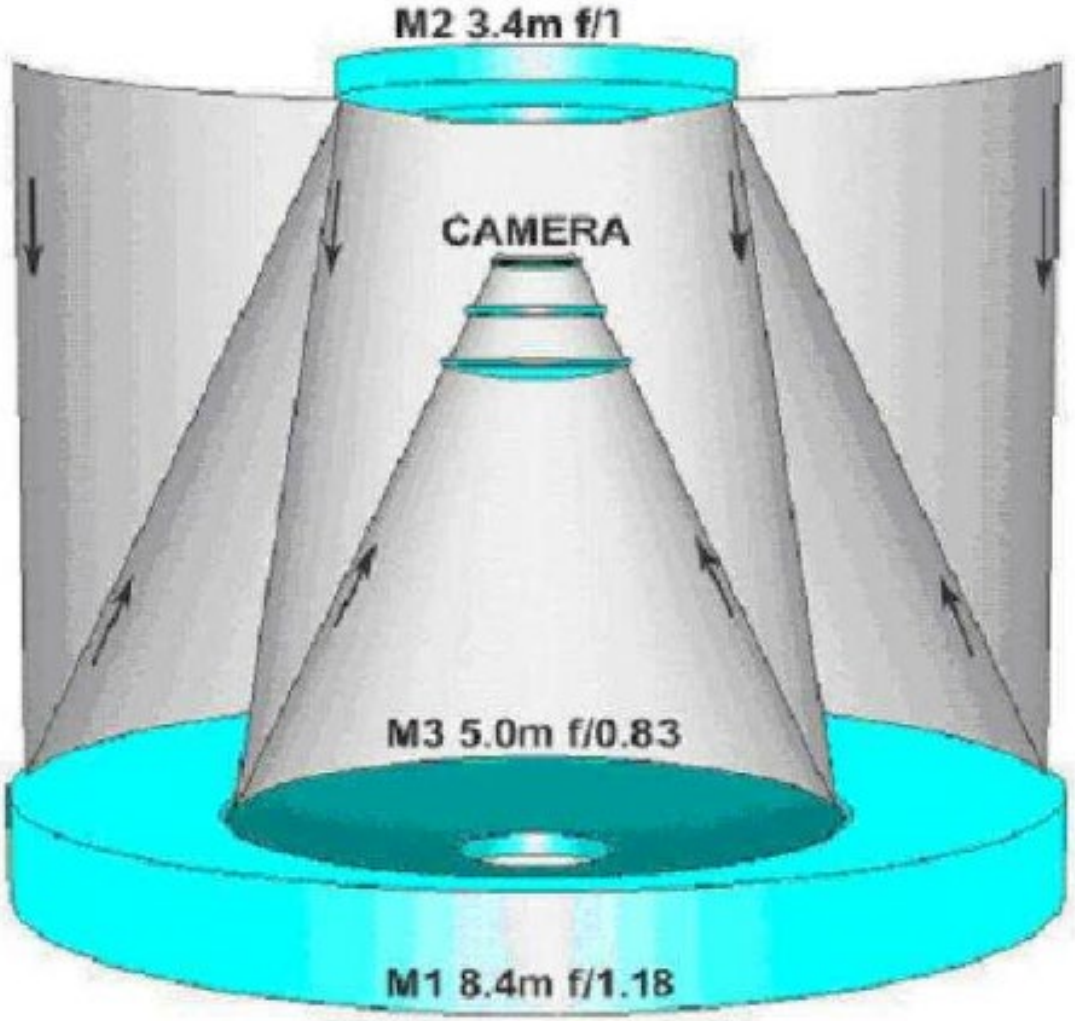
Recap: Reflecting Telescopes

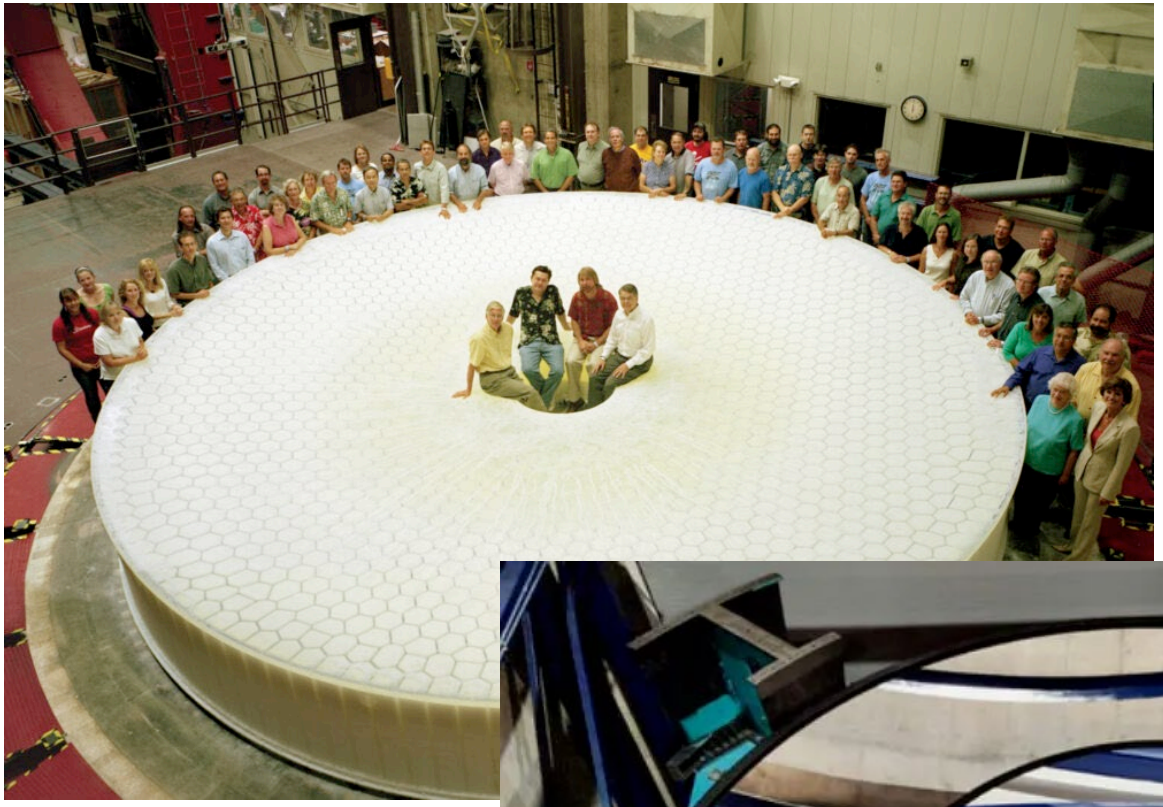


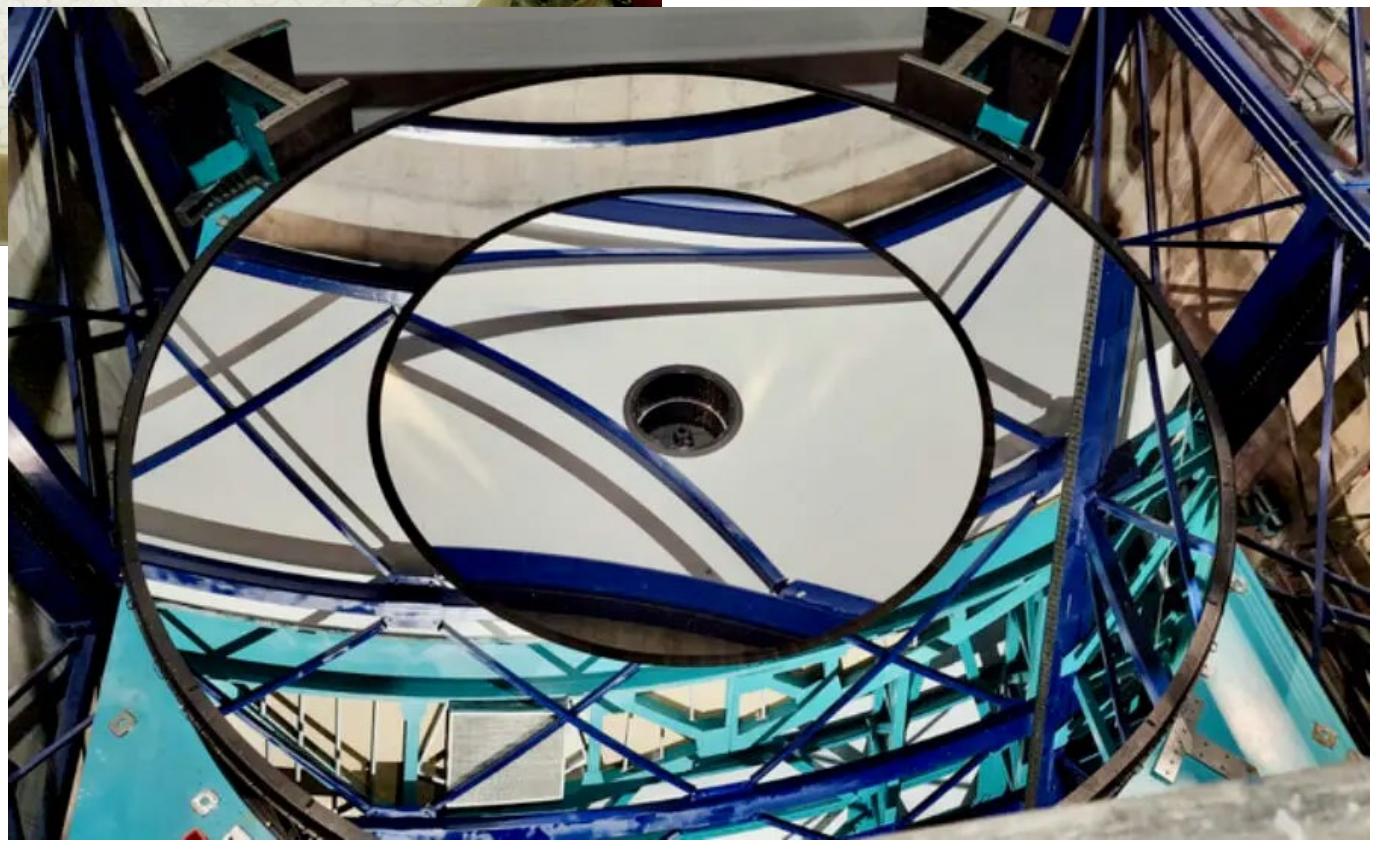
Recap: Reflecting Telescopes



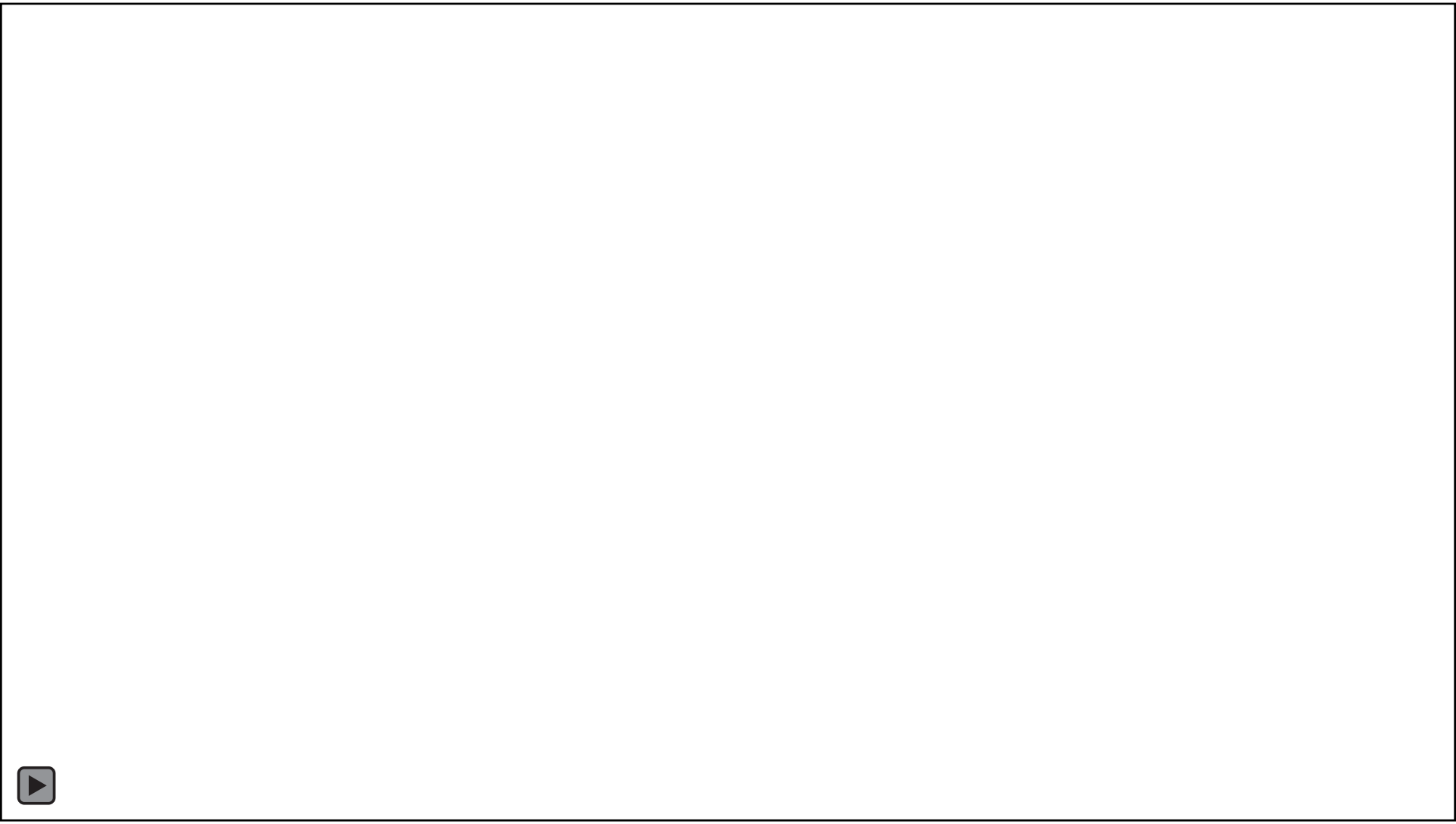
Rubin/Simonyi: Unique 3-Mirror Design



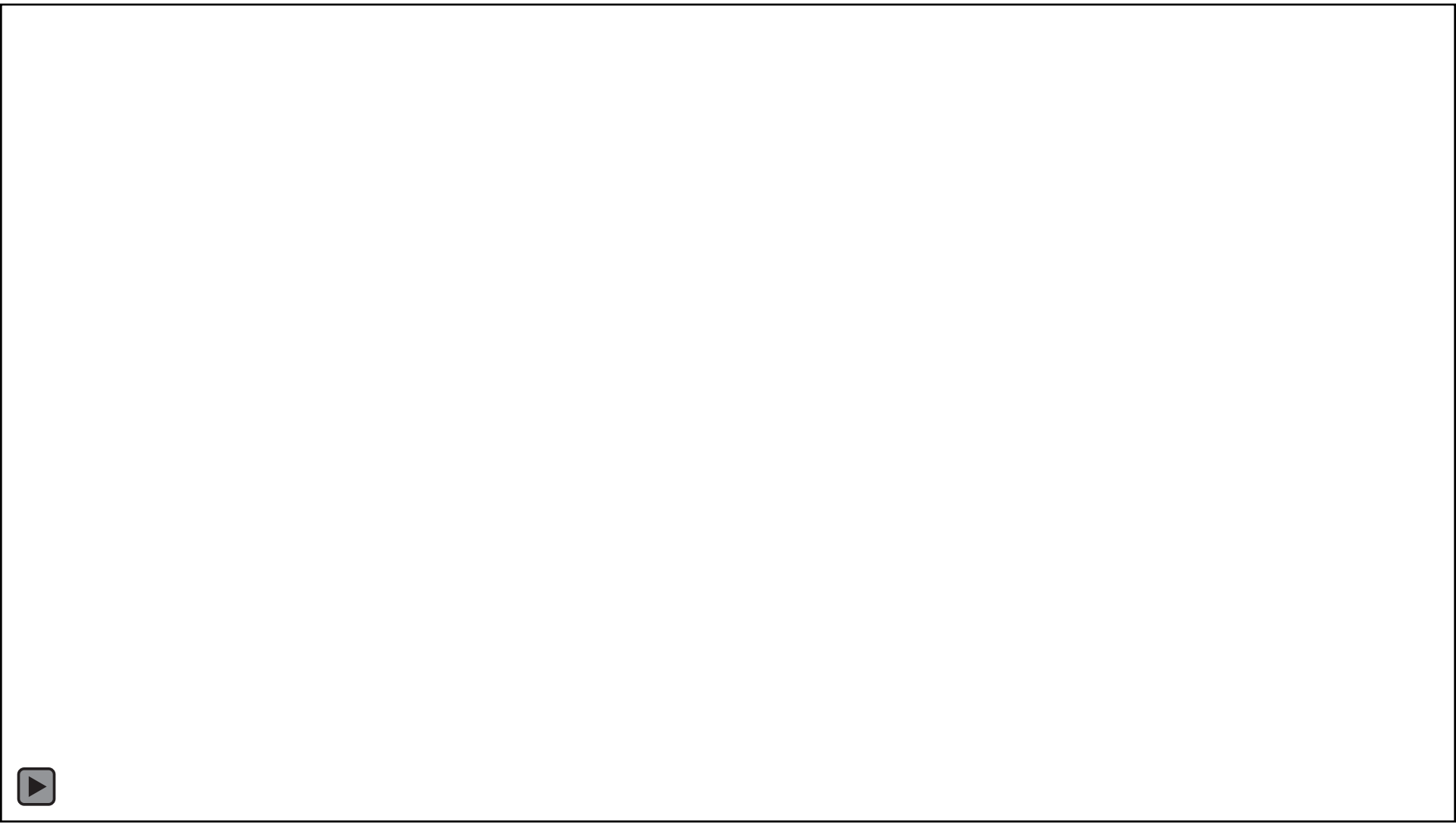




Recap: Equatorial Mount



Recap: Alt-Az Mount



Rubin/Simonyi Mount

- Alt-Az mount needs an image rotator in the camera assembly, but yields:

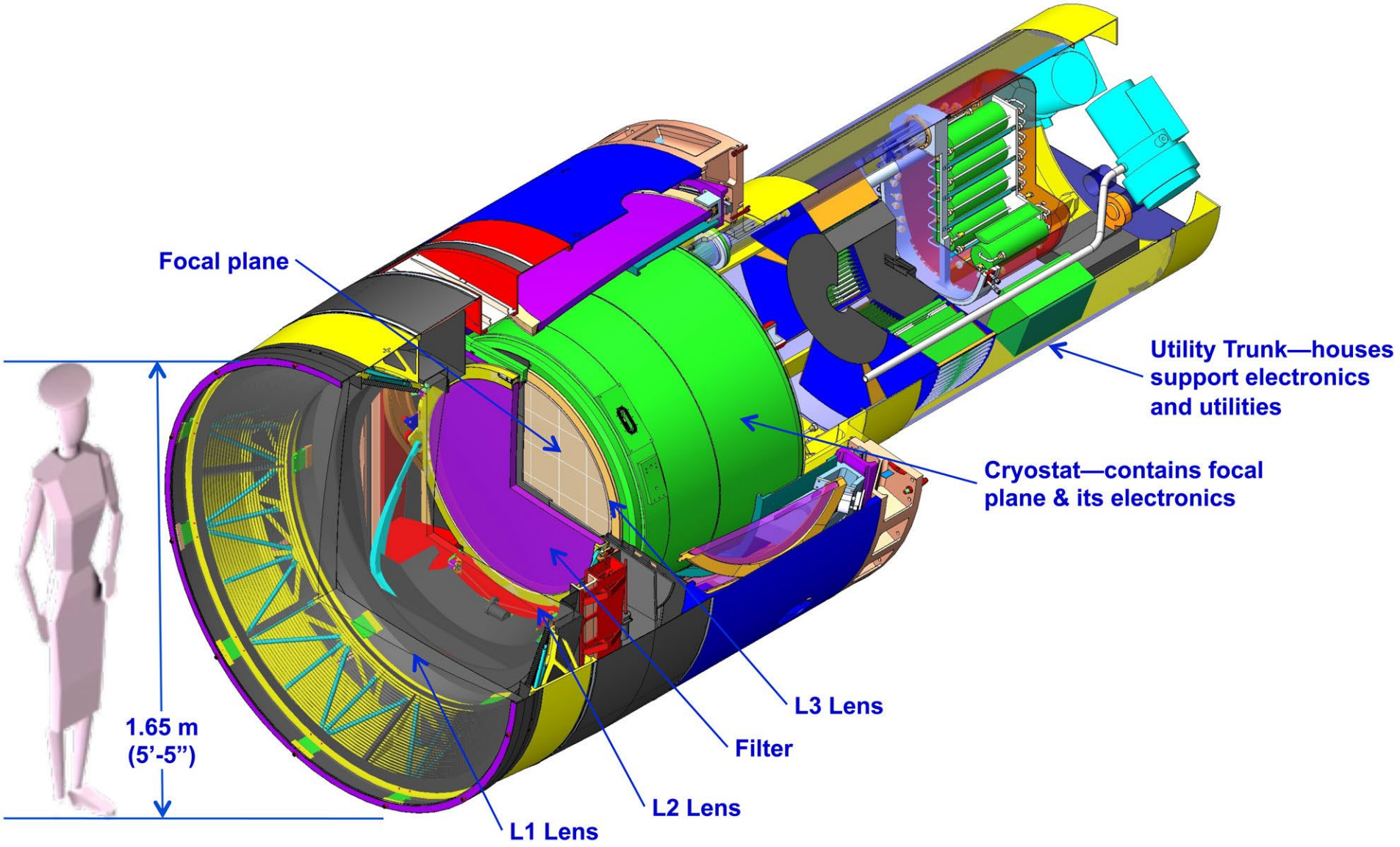
- Structural stability & simplicity, with cost reduction
- Compact observatory dome, with cost reduction
- Extraordinarily rapid slewing (about 10 degrees per second; *3.5 degree slew and settle in 4 seconds*) for fast repositioning
  - Impressive acceleration
  - Minimal recovery time from vibration
- Total weight of the M1M3 assembly, M2 assembly, and camera is about 24 US tons

Mirror Support/Alignment

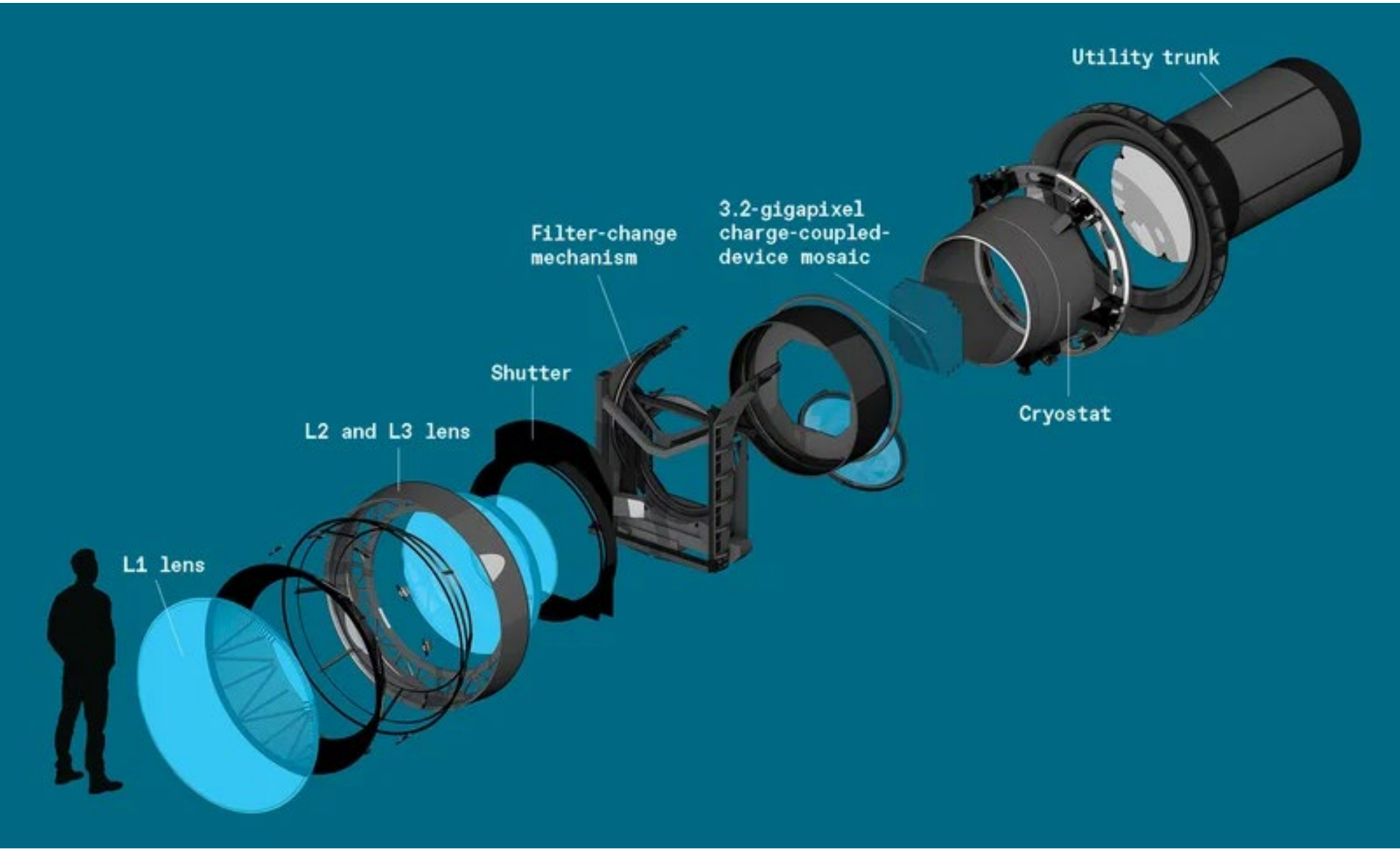
- M1M3 is in a mirror cell with active support structure
- Force actuators – small motors – preserve precise optical alignment regardless of orientation
- An Active Optics System (AOS): laser trackers, and sensors at edge of focal plane, enable the correction of component positions
- Curvature Wavefront Sensors (CWFS) enable Adaptive Optics – <u>see next week on the ELT</u>

Gigapixel Camera

- **Resolution**: 3.2 Gigapixels (3200 Megapixels)
- **Sensors**: 189 individual CCDs in an array
- **Weight**: 3 tons
- **Cooling**: cooled to minimize thermal noise



Camera ¾ Section


Utility trunk
3.2-gigapixel charge-coupled-device mosaic
Filter-change mechanism
Shutter
L2 and L3 lens
L1 lens
Cryostat

Cooling

- Two stage cooling
- **Cryo-system**: cools the CCDs to -100 ^{o}C (-148 ^{o}F) – a special blend of refrigerants is circulated in multiple circuits to ensure uniform cooling
- **Cold-system**: cools the readout electronics to as little as -10 ^{o}C (-14 ^{o}F)

Data

- For reference: a modern smartphone has typically 128 GB of storage
- For reference: a modern laptop has typically 256GB to 1 TB of storage

- **Rubin**
- Nightly: 20 TB of raw data (3 years of Netflix)
- Total Survey: 60 PB (60,000 TB)
- Processed data: 500 PB (500,000 TB)

Data

- Time to transfer one image from Cerro Pachon (by dedicated fiberoptic cable to La Serena) and on to Menlo Park, compare with archive, and generate alerts based on changes: **60 seconds**

- Likely alerts per night: **10 million**

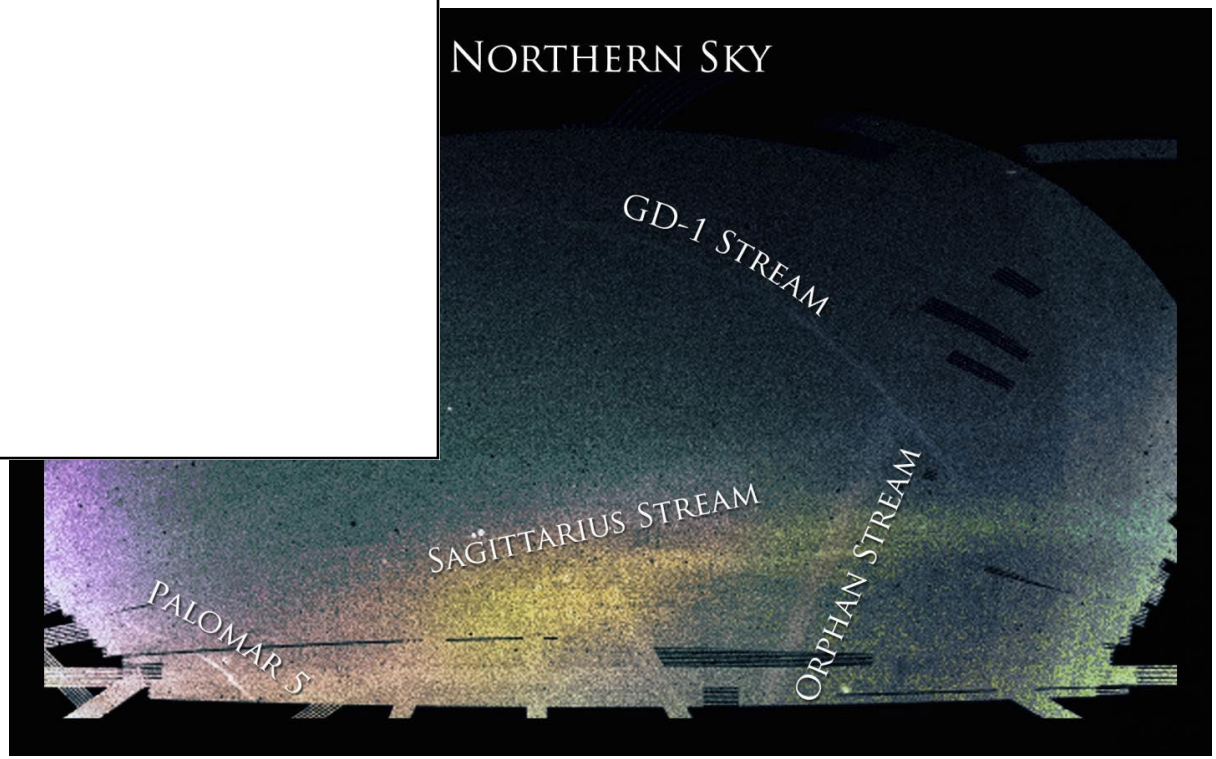
- Storage/access: cloud-based storage around the world, with access through the **Rubin Science Platform**

LSST Science Goals 1

- **Exploring the Transient Optical Sky**
- Early supernova light curves & supernovae (Ia & II)
- Kilonovae (merging neutron stars)
- Microlensing events from stars & planets
- Tidal disruption events by supermassive black holes
- Stellar flares & pulsations
- Active Galactic Nuclei
- *New classes of events!!*

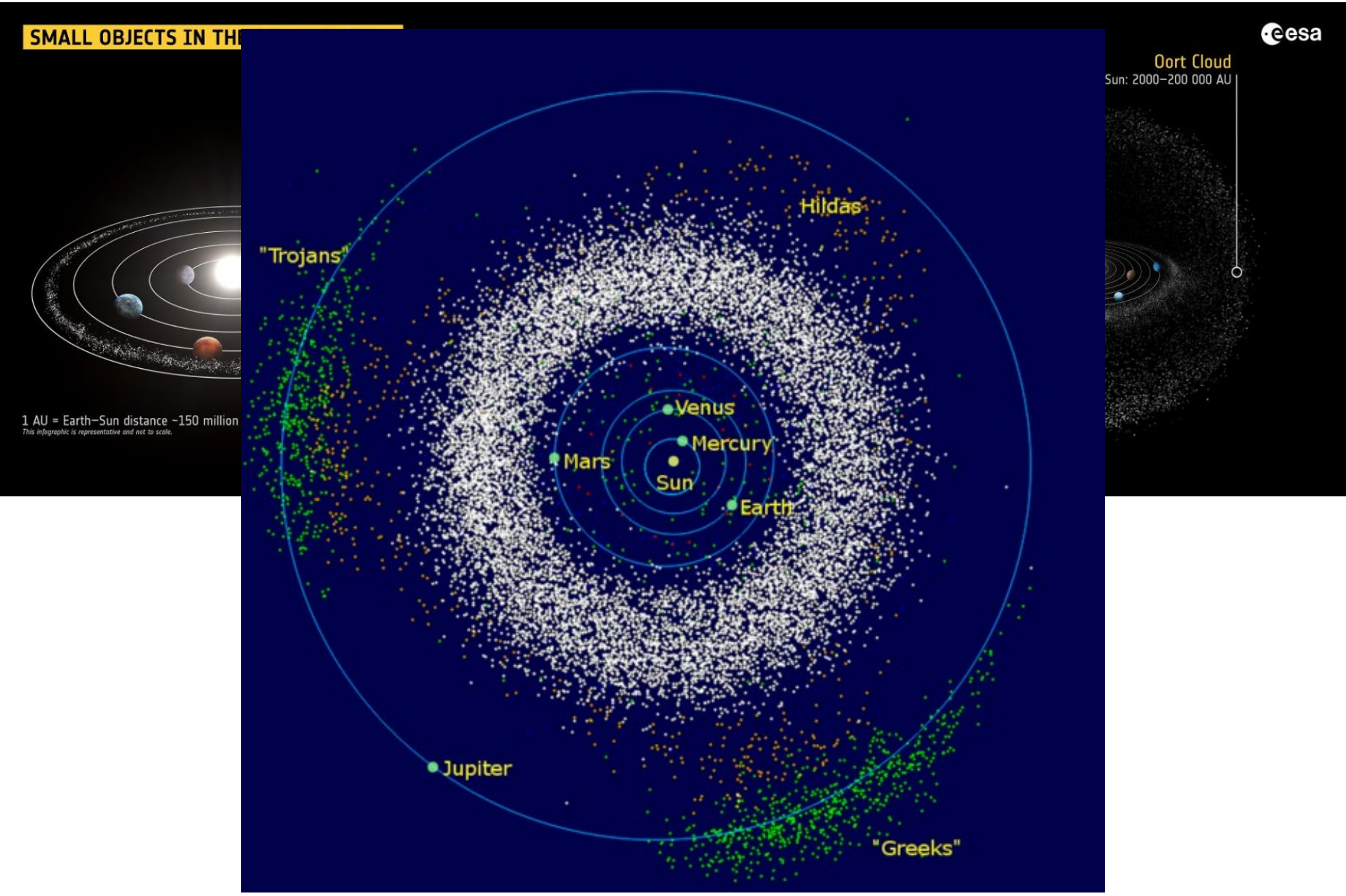
LSST Science Goals 2

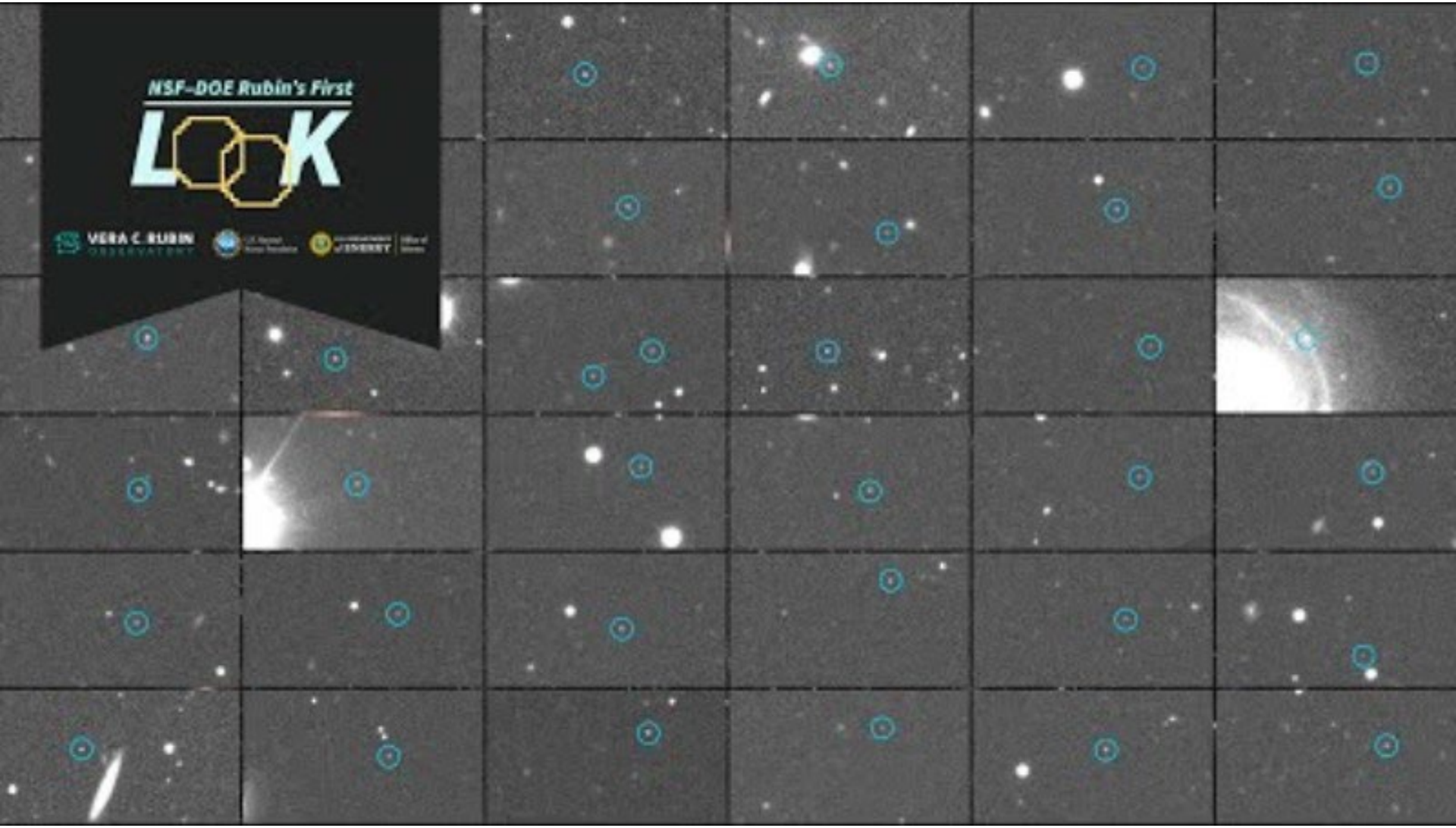
- **Mapping the Milky Way**
- Stars, star clusters & satellite galaxies – position, motion & chemical composition
- Will provide a unique 3D map including faint stars and stellar streams
- Will identify stellar populations
- Thus probe “construction” history and star formation history of Galaxy
- Probe the dark matter structure


Northern Sky
GD-1 Stream
Sagittarius Stream
Orphan Stream
Palomar 5

LSST Science Goals 3

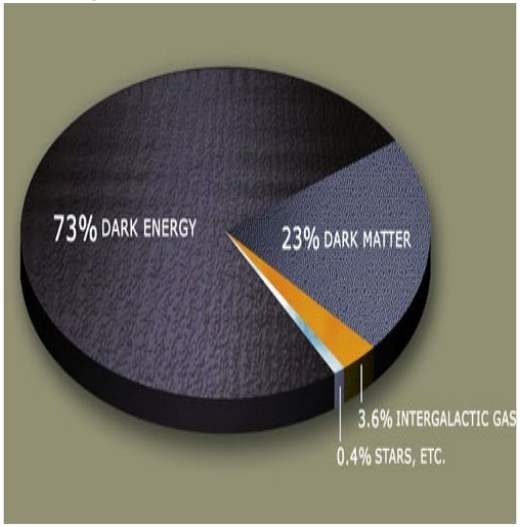
- **Inventory of the Solar System**
- A vastly expanded catalog of Solar System objects will improve our understanding of the formation and history of the Solar System
  - Number of known small bodies will increase by x10-100
  - More (faint) Kuiper Belt objects
  - Info on composition, shape & rotation yields a better probe of diverse asteroid populations (main belt, Trojans, Centaurs, etc.)
- Definitively test the Planet 9 hypothesis
- *Reveal potentially hazardous near-Earth asteroids*


SMALL OBJECTS IN TH
esa
Oort Cloud
Sun: 2000–200 000 AU
1 AU = Earth–Sun distance ~150 million
This infographic is representative and not to scale.
Hildas
"Trojans"
Venus
Mercury
Mars
Sun
Earth
Jupiter
"Greeks"


NSF–DOE Rubin's First
LOOK
VERA C. RUBIN
OBSERVATORY

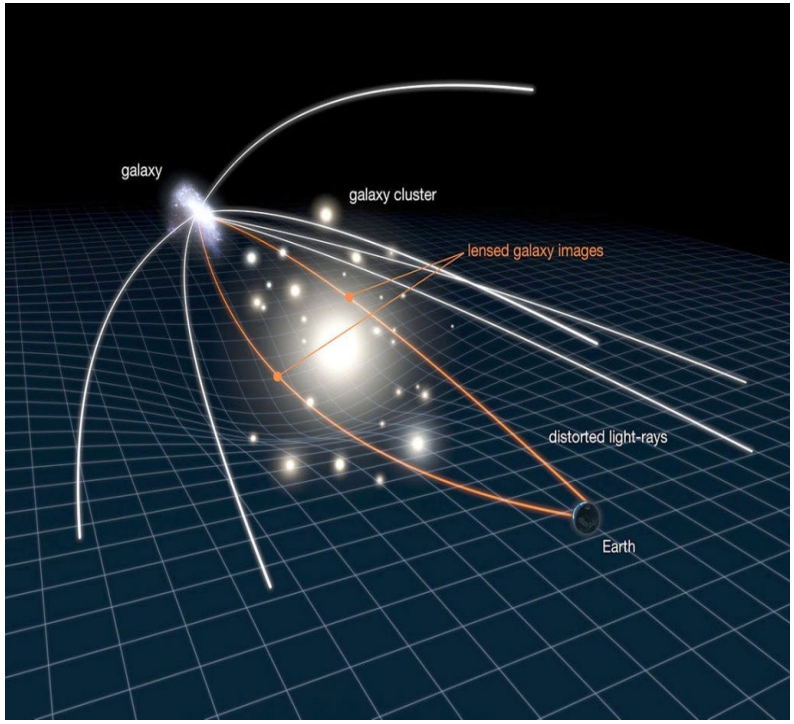
LSST Science Goals 4

- **Probing Dark Energy & Dark Matter**
- DE & DM account for more than 95% the mass of the Universe (less than 5% is in gas, dust, stars…)
- DE & DM control the evolution of the Universe and the formation of structures within it
- The presence of DE & DM is thus imprinted upon the structure and dynamics of the Universe



LSST Science Goals 4

- **Probing Dark Matter**
- Gravitational lensing will map dark matter in clusters, revealing the structure and evolution of dark matter over cosmic time

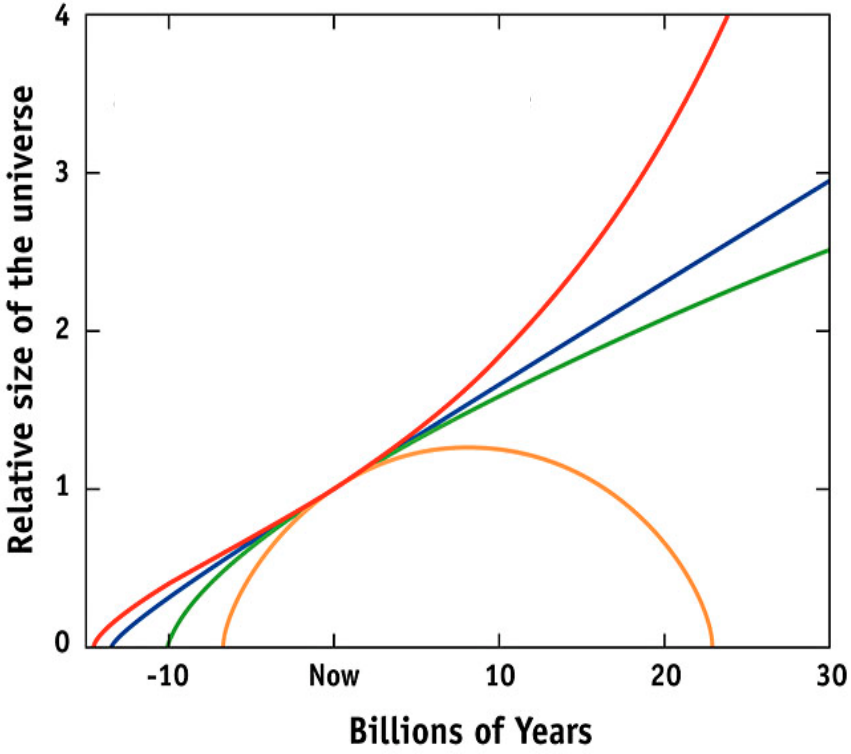


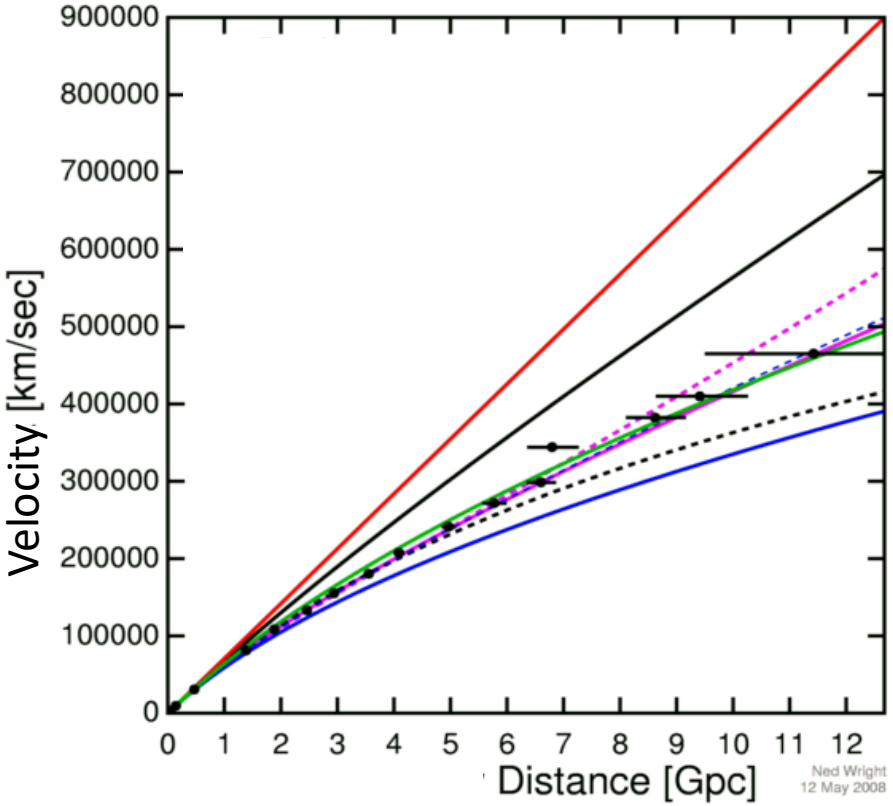


LSST Science Goals 4

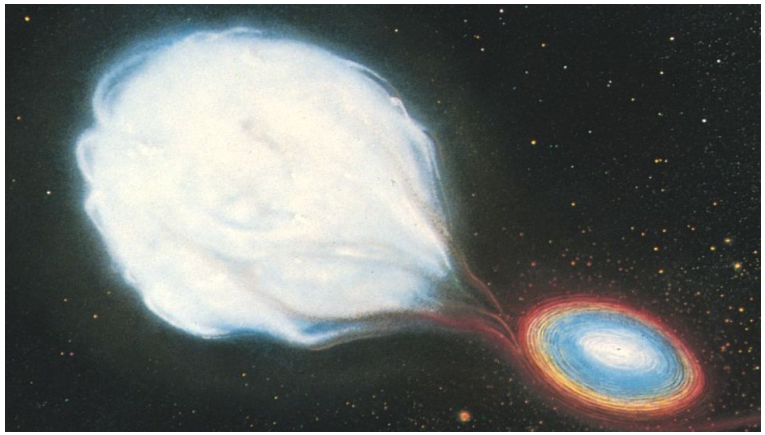
- **Probing Dark Energy**
- Gravitational lensing will map dark matter in clusters, and thus the density of clusters over cosmic time – *this is impacted by dark energy which plays a major role in its expansion history*
- Millions of SN 1a will be detected which will map the expansion history of the Universe

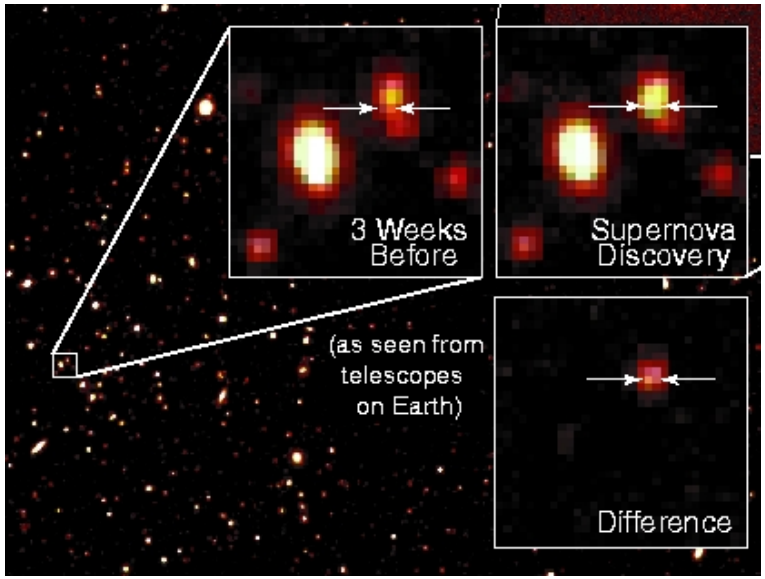
Expansion Of Universe

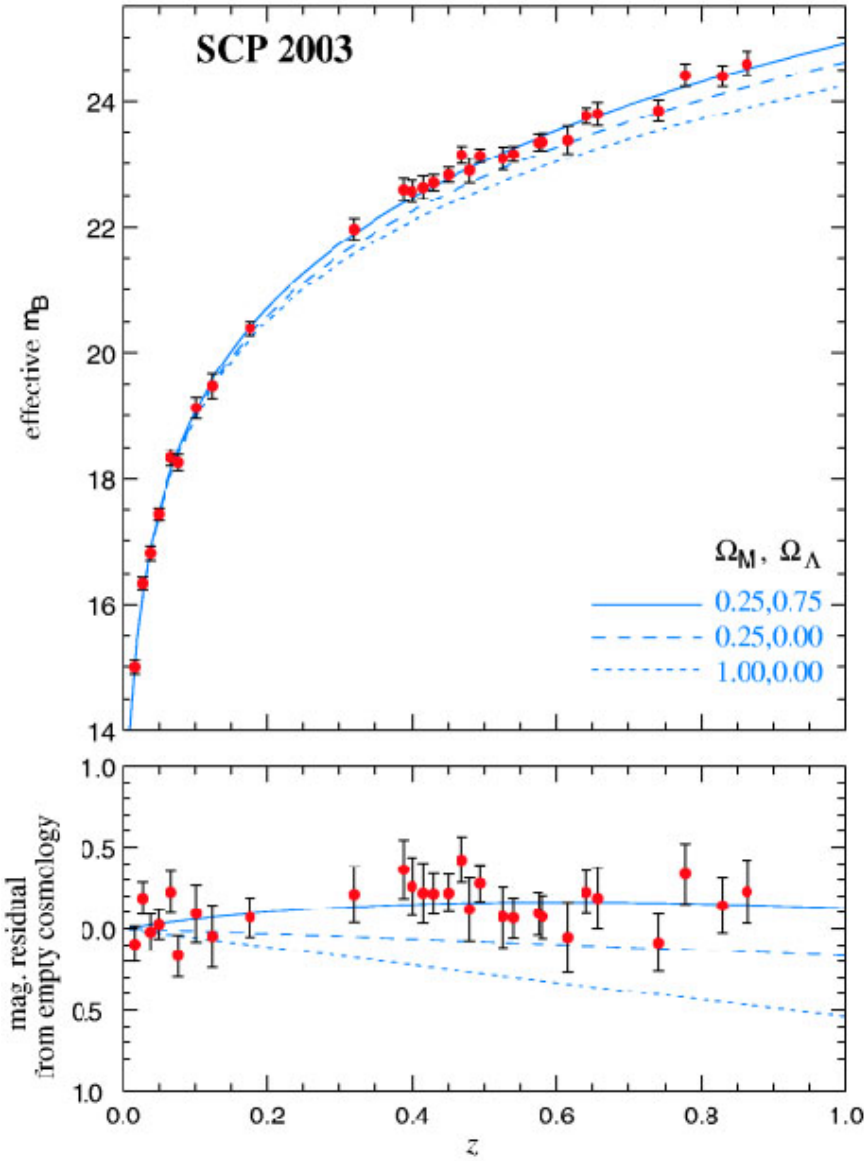




Type Ia Supernovae







The Mystery Of Dark Energy

- A property of space itself?
- A "field" *in* space?

- Do its properties evolve as the Universe evolves?

- Dark Energy Spectroscopic Instrument (DESI) 3D map of Universe plus latest SN 1a data *suggest* the role of DE is weakening
- Supported (at the 9σ level) by a recent study (Son et al. 11/6/25) allowing for evolution of SN 1a

Rubin to the rescue?

Is It Worth It?

- Construction cost: $810 million (mostly from NSF & DOE)
- Annual operations: $72 million
- Thoughts?