Introduction to Observational Astronomy

UV — Optical — IR

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About Me

Faculty at Indian Institute of Astrophysics (IIA) since December 2017

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Research interest - UV, Optical & NIR Observational Astronomy

Imaging & IFU spectroscopy

Galaxy Formation and Evolution

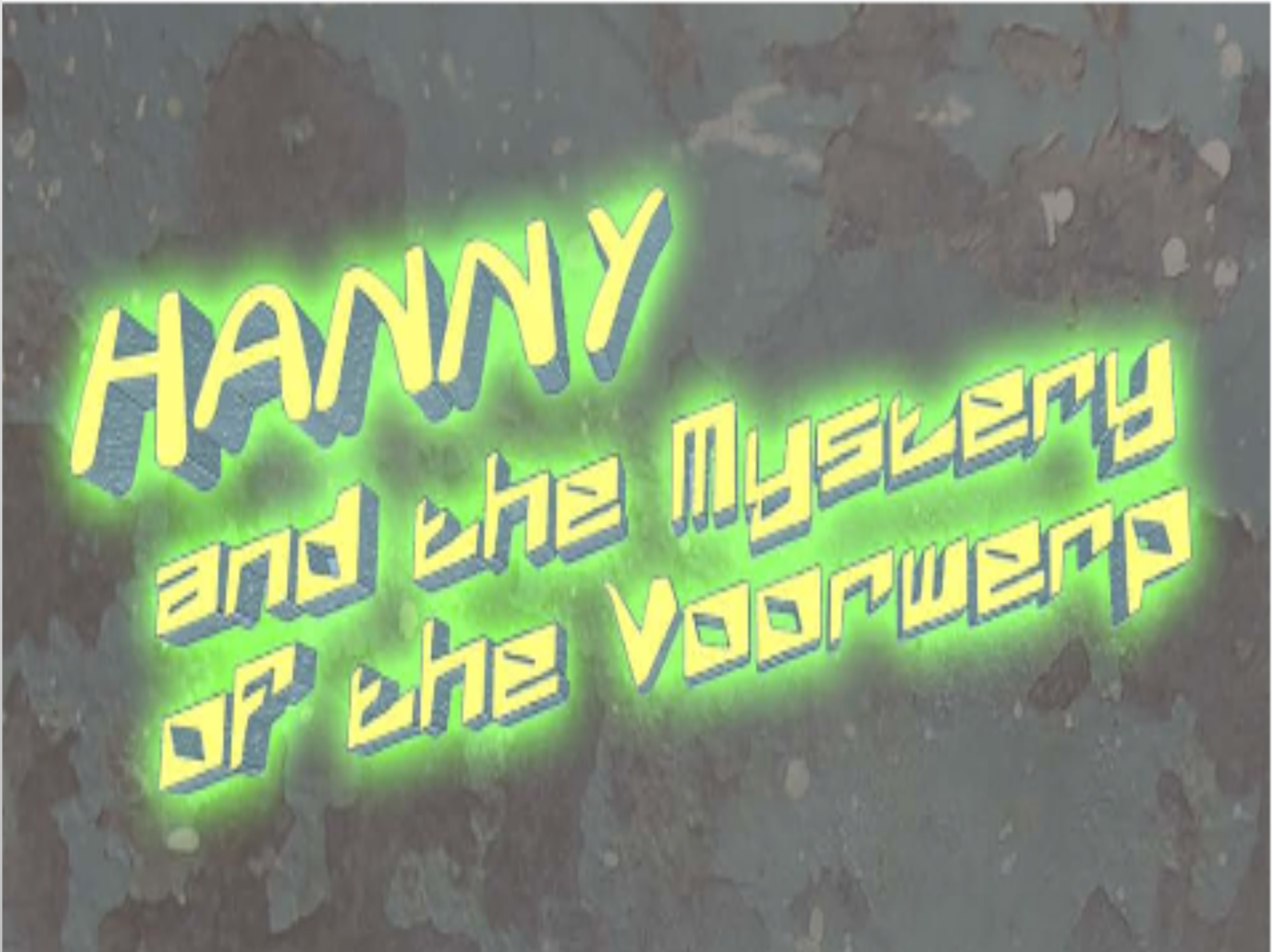
Early-type Galaxies (Ellipticals and Lenticulars)

Bulge-Bar Formation

Super Star Clusters in Galaxies

Transients, EMGW

Data Science, Astronomical Software R & D


HANNY
and the Mystery
of the Voorwerp

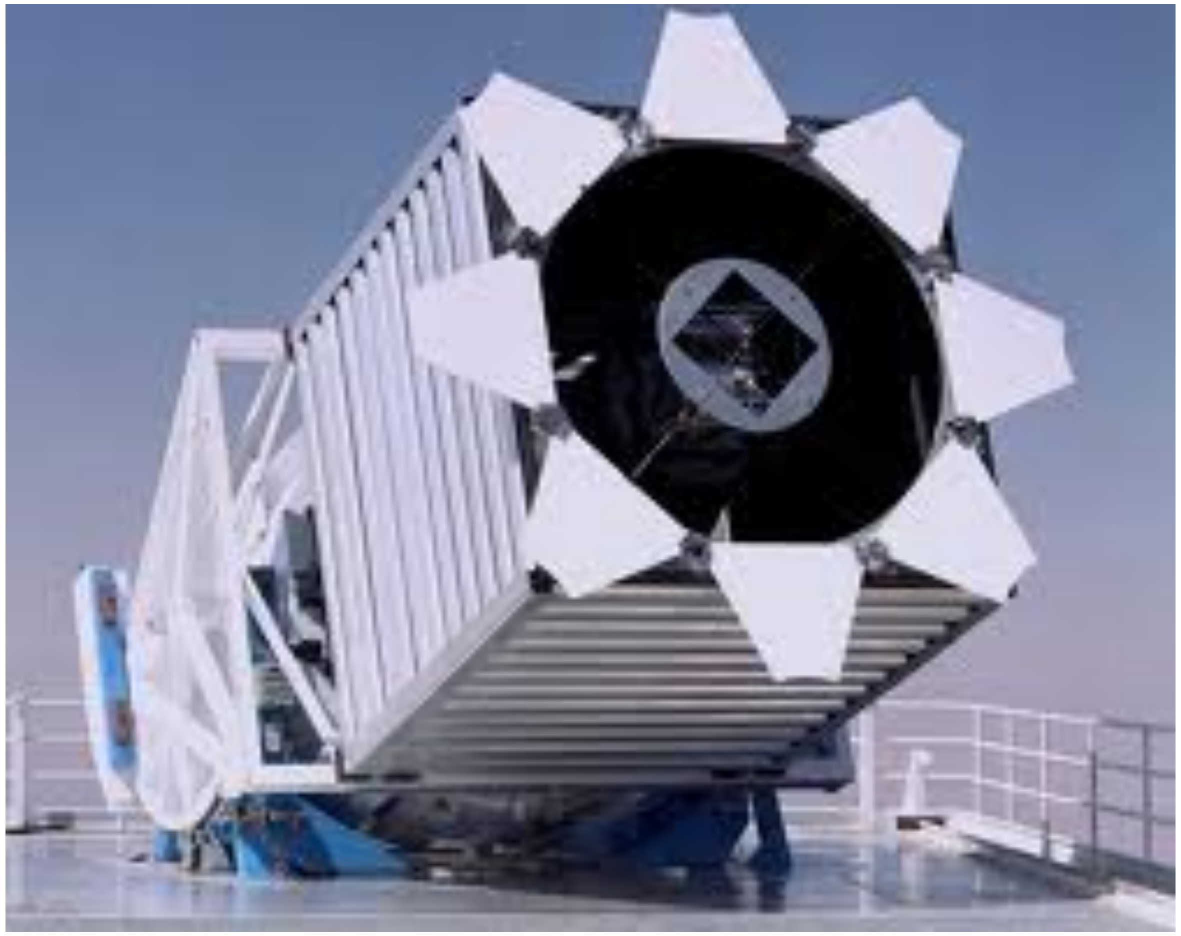
The story of Hanny and mystery of Voorwerp

Science is driven by that most basic of human impulses, curiosity

We want to know what is on the other side of next hill.... or hanging in the sky above us

The story of Hanny and the voorwerp speaks of that last curiosity - what is out there?

The story of Hanny and mystery of Voorwerp



The SDSS 2.5-meter telescope

The Sloan Digital Sky Survey (SDSS) robotically collects data on millions of objects - Stars, Nebulae, Galaxies

Lurking in SDSS images are treasures waiting to be discovered

The story of Hanny and mystery of Voorwerp

The Sloan Digital Sky Survey (SDSS) robotically collects data on millions of objects - Stars, Nebulae, Galaxies

SDSS DR17 data release –

DR17 Data Volume = 245 TB

Total Data Volume = 407 TB

The SDSS 2.5-meter telescope

The story of Hanny and mystery of Voorwerp

The Sloan Digital Sky Survey (SDSS) robotically collects data on millions of objects - Stars, Nebulae, Galaxies

are

The

SDSS DR17 database –

>1000 million objects

>245 TB

Over one million galaxies to morphologically classify

The story of Hanny and mystery of Voorwerp

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The

SDSS DR17 database –

>1000 million objects

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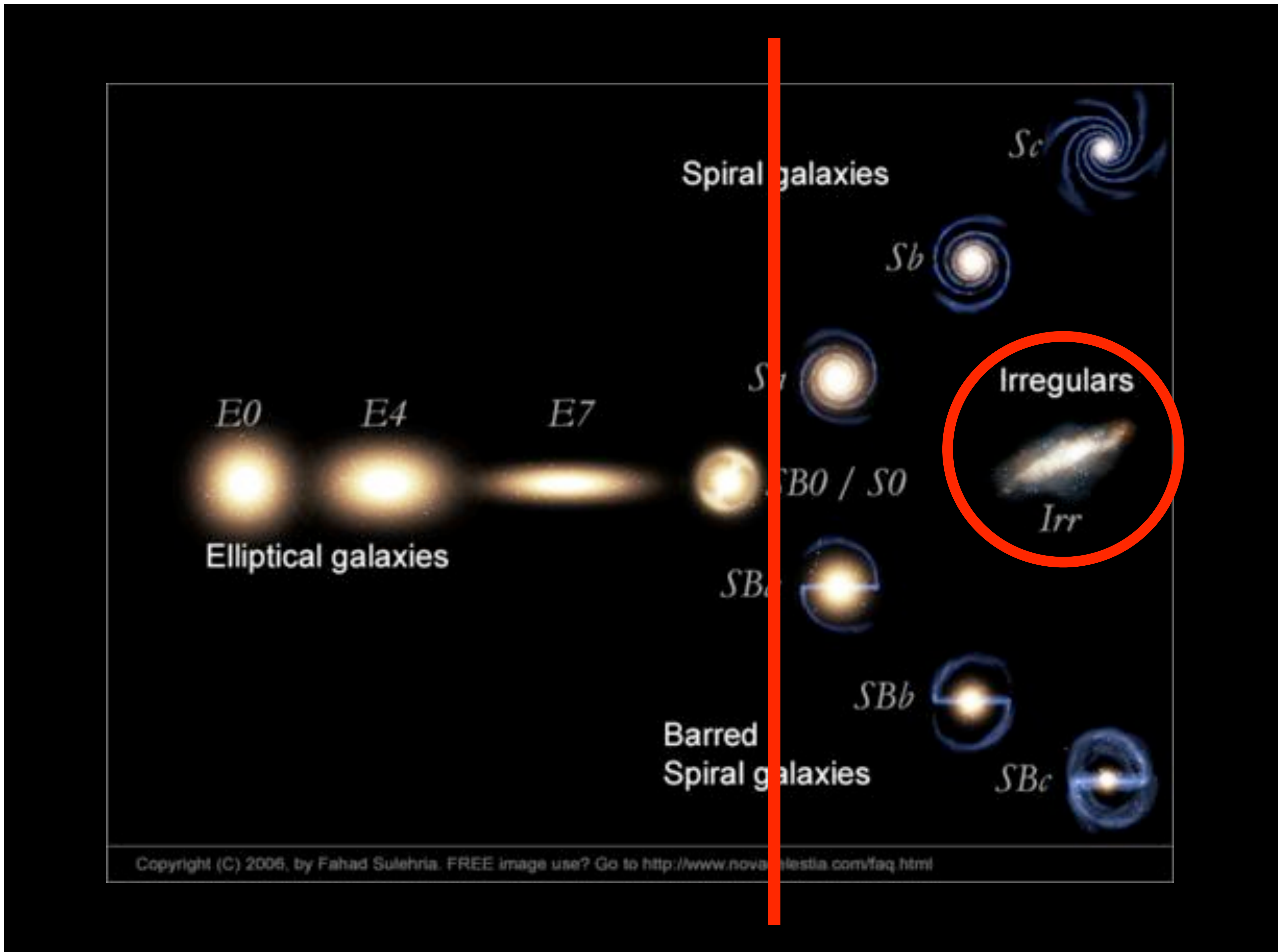
Over many million galaxies to morphologically classify

SDSS team - What if we asked the public to participate online?

The story of Hanny and mystery of Voorwerp


GALAXY ZOO


Spiral galaxies
Sc
Sb
S
Irregulars
E0
E4
E7
B0 / S0
Irr
Elliptical galaxies
SB
SBb
Barred
Spiral galaxies
SBc
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The story of Hanny and mystery of Voorwerp

While classifying galaxies online, on August 13, 2007, Dutch biology teacher Hanny van Arkel discovered a new object.

The story of Hanny and mystery of Voorwerp

While classifying galaxies online, Hanny van Arkel saw a strange green blob next to a spiral galaxy. “It looked like a dancing frog”, She says.

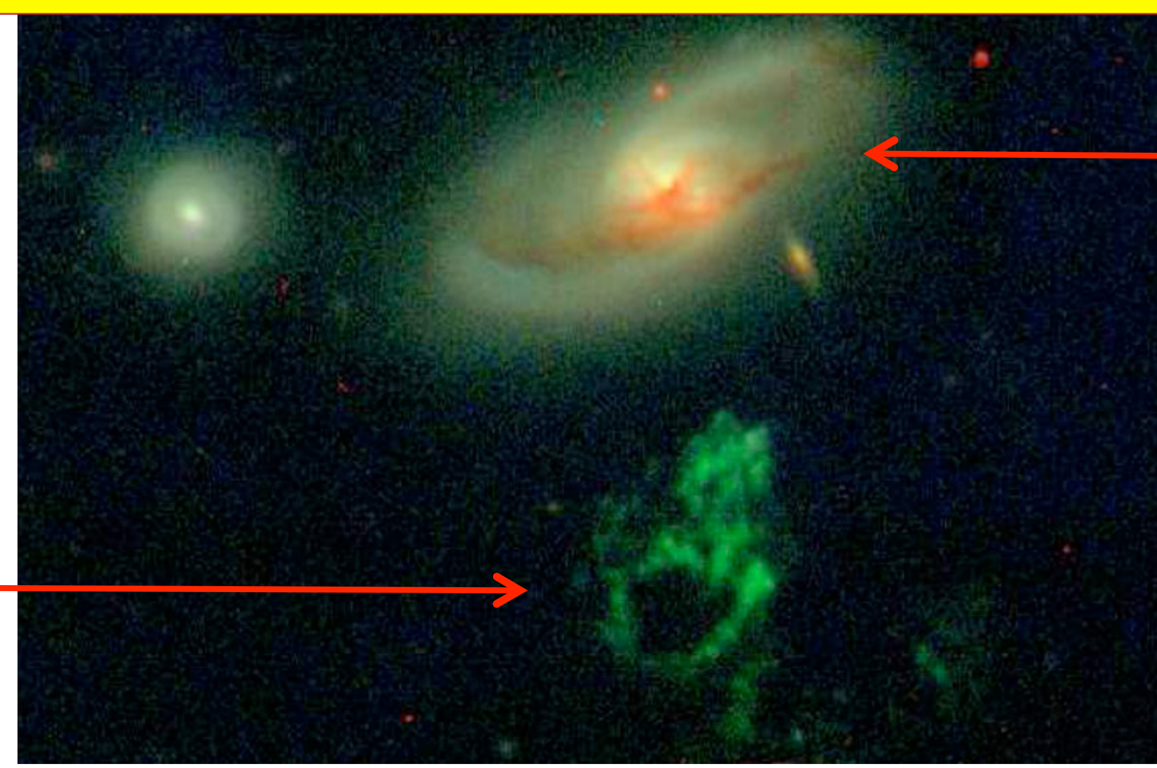
IC 2497

Vooerwerp

The story of Hanny and mystery of Voorwerp

While classifying galaxies online, Hanny van Arkel saw a strange green blob next to a spiral galaxy. "It looked like a dancing frog", She says.

To be continued.....



IC 2497

Vooerwerp

The story of Hanny and mystery of Voorwerp

This discovery was made because of the participation of public (including stduents) interested in astronomy/science.

- Sky
- Brief History of Astronomy
- Basic Measurements
- Telescope
- Detector
- Photometry - Magnitude system

Typical 15 hours of course

Daytime Sky

- East : direction of the rising Sun.
- Position of the rising Sun changes throughout the year. Northward (Tropic of Cancer) and southward (Tropic of Capricorn) movement. Path of the Sun = ecliptic.
- Length of the day also varies throughout the year. Equinox (21 Mar and 23 Sep) and solstices (21 June and 21 Dec).
- Sunrise, sunset, noon, twilight : wrt the Sun's position.
- Solar calendar. Tropical year (interval between two vernal equinoxes) = 365.242190 days.
- Julian calendar : year = 365.25 days. Leap year.
- Solar eclipse : corona and many other discoveries.

The Sky at Night

- On a cloudless, dark night one can see approximately 5000 stars.
- They twinkle, are of different brightnesses and colours.
- They are not uniformly distributed. In particular, the Milky Way can be seen.
- Patterns of stars (eg, the constellation of Big Dipper).
- Moon and its phases. Lunar calendar. Synodic month (interval between two new moons) = 29.536589 days. Sidereal month (wrt fixed stars) = 27.321662 days.
- Planets, meteors, and occasionally, comets. Rare appearance of ‘guest’ objects which is known as ‘Transients’
- Moon and planets also follow the ecliptic path. Zodiacal constellations.
- The brightness of planets (esp Venus and Mars) changes throughout the year.

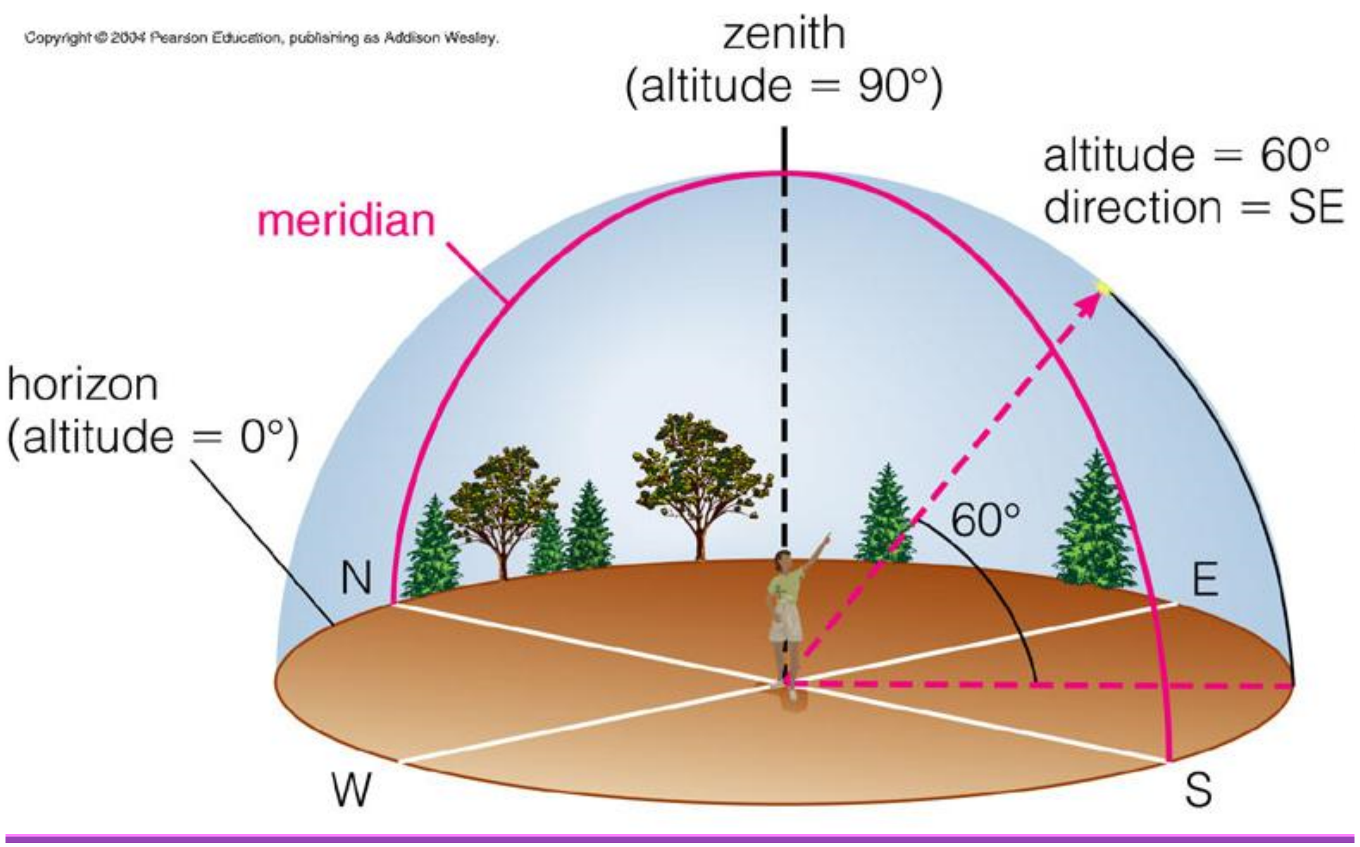
The Sky

Imagine the Earth is flat and the sky is a hemisphere centred on your position

The celestial poles and celestial equator are imaginary projections onto the sky of the Earth's polar axis and equator

Definitions

- **Cardinal points (4)**: intersections between meridian & horizon (N & S) and equator & horizon (E & W)
- **Zenith**: intersection of the normal to Earth's surface and celestial sphere ('straight up')
- **Nadir**: 'straight down'
- **Meridian**: the great circle which passes through the poles, zenith & nadir



At Earth's poles, the equivalent celestial pole is at the zenith and the equator runs around the horizon

A Brief History of Astronomy

- Naked eye astronomy since antiquity in almost all civilisations.
- Point sources (stars) and extended sources (Sun, Moon, planets, etc). Speculations regarding distances.
- Rising and setting of the Sun, Moon, Stars, Planets. Observations helped in human activities like navigation, calendars, seasons, farming, festivals.
- Eclipses and Conjunctions. Meteors and Comets.
- Position : Sundial, astrolabe, sextant, telescope.
- Time : Sundial, sand-clock, water-clock, chronometer.
- Till the 19th century, Astronomy was all about measuring positions and angular separations of stars, and making catalogues.
- Invention of the telescope led to observations of the surface of our Moon, moons of Jupiter, the rings of Saturn, etc.

History – cont'd

- In the 19th and 20th centuries, development of backend instruments led to a burst of activity in Physics in order to explain various observations and phenomena.
- Technological development after WW II led to the birth and development of astronomy at other wavelengths.
- Today, astronomy is done from the ground, air and space.

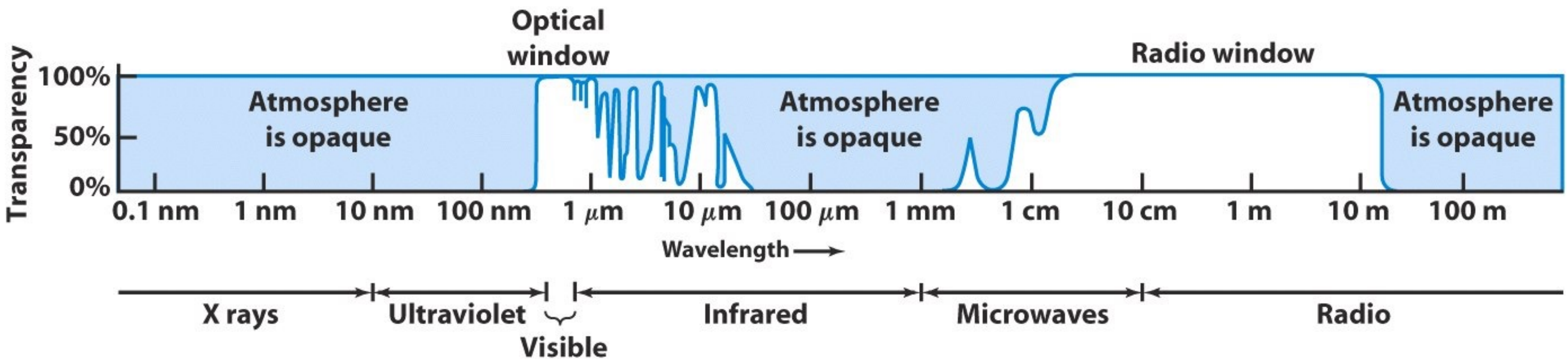
The Universe

- Solar System (Sun, planets, asteroids, comets)
- Single, binary and multiple stars
- Dust (circumstellar and interstellar), Interstellar Medium (ISM)
- Star clusters (open and globular)
- Milky Way (our Galaxy)
- Local group of galaxies (Milky Way, Large and Small Magellanic Clouds, M31 [Andromeda], M33 [Triangulum], etc)
- Intergalactic Medium (IGM)
- Clusters of galaxies (eg, Coma Cluster)
- Galaxy superclusters
- Transients

Measuring properties of celestial objects

- Astrometry – measure accurate positions and make predictions of positions.
- Photometry – measure fluxes, energy output.
- Imaging – study features in extended objects.
- Spectroscopy – calculate velocity, abundance, etc (emission and absorption lines).
- Polarimetry – calculate dust properties, magnetic field, asymmetry, etc (linear and circular polarization).
- Imaging Polarimtery – study features and polarization properties.
- Interferometry – measure with high spatial resolution.
- Changes are seen on various timescales in celestial objects depending on their type. So, measure time-variability of these properties.

Astronomy from Ground and Space



- The atmosphere is transparent in three wavelength regions, optical window, radio window, and some parts of near infrared.

- Dusts around stars and galaxies in infrared, hot stars and gas, the Sun's corona, and planets atmosphere in ultraviolet and X-rays, and some very energetic phenomena in γ-rays from the space.

Astronomer's Tools

- Telescopes – refractors and reflectors. Ground- and space-based. Balloons, Rockets and Aircraft.

- Mounts – different types. Sturdy base for a telescope.

- Detectors (some examples) :
  - UV – Scintillator, Multi-Channel Plate (MCP).
  - Optical – Photographic plates, Photomultiplier Tube (PMT), Charge-Coupled Device (CCD), CMOS.
  - Infrared – PbS, Si/ Ge, HgCdTe, PtSi, InSb.

- Instrument – photometer (imager), spectrograph, polarimeter.

- Computers for data acquisition and analysis.

- Catalogues and archives.

Modern Astronomy Trends

1. Observation from small/big telescopes
2. Combine your own observations with the data from multi−TB, billion−object surveys in the optical, IR, radio, X−ray, etc.
3. Combine the data from multi−TB, billion−object surveys in the optical, IR, radio, X−ray, etc.

Basic Measurements — Co-ordinate system

Basics of Positional Astronomy — Co-ordinate system

- How to describe the position of an object in the sky
- Different coordinate systems
- How to transform between coordinate systems
- What corrections have to be applied.

Basics of Positional Astronomy — Co-ordinate system

Coordinates

- Wide range of techniques used to study astronomical objects
- First must consider how describe position of objects
- Need to know where to point telescope at given time

Basics of Positional Astronomy — Co-ordinate system

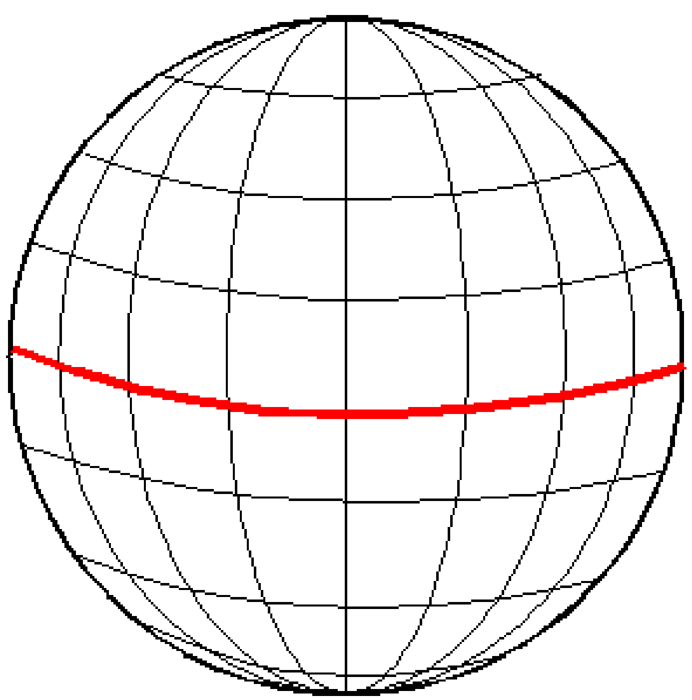
The Celestial Sphere

- From our point of view, astronomical objects (stars, galaxies etc) appear to lie on spherical surface
- Distances not important for describing position
- Define coordinate grid on this sphere using circles
  - Given by intersections of planes with spherical surface

Basics of Positional Astronomy — Co-ordinate system

Spherical Coordinates

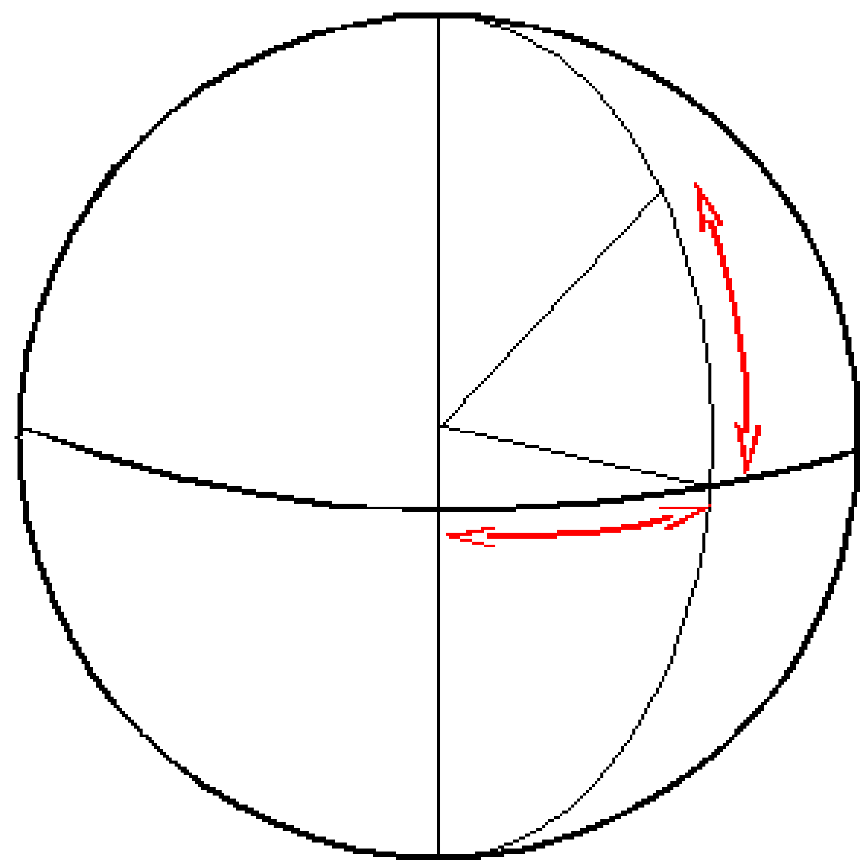
- Choose a great circle as the equator of sphere
  - define grid of small circles parallel to equator and great circles perpendicular to equator
  - poles are points 90° from all points on equator



Basics of Positional Astronomy — Co-ordinate system

Spherical Coordinates

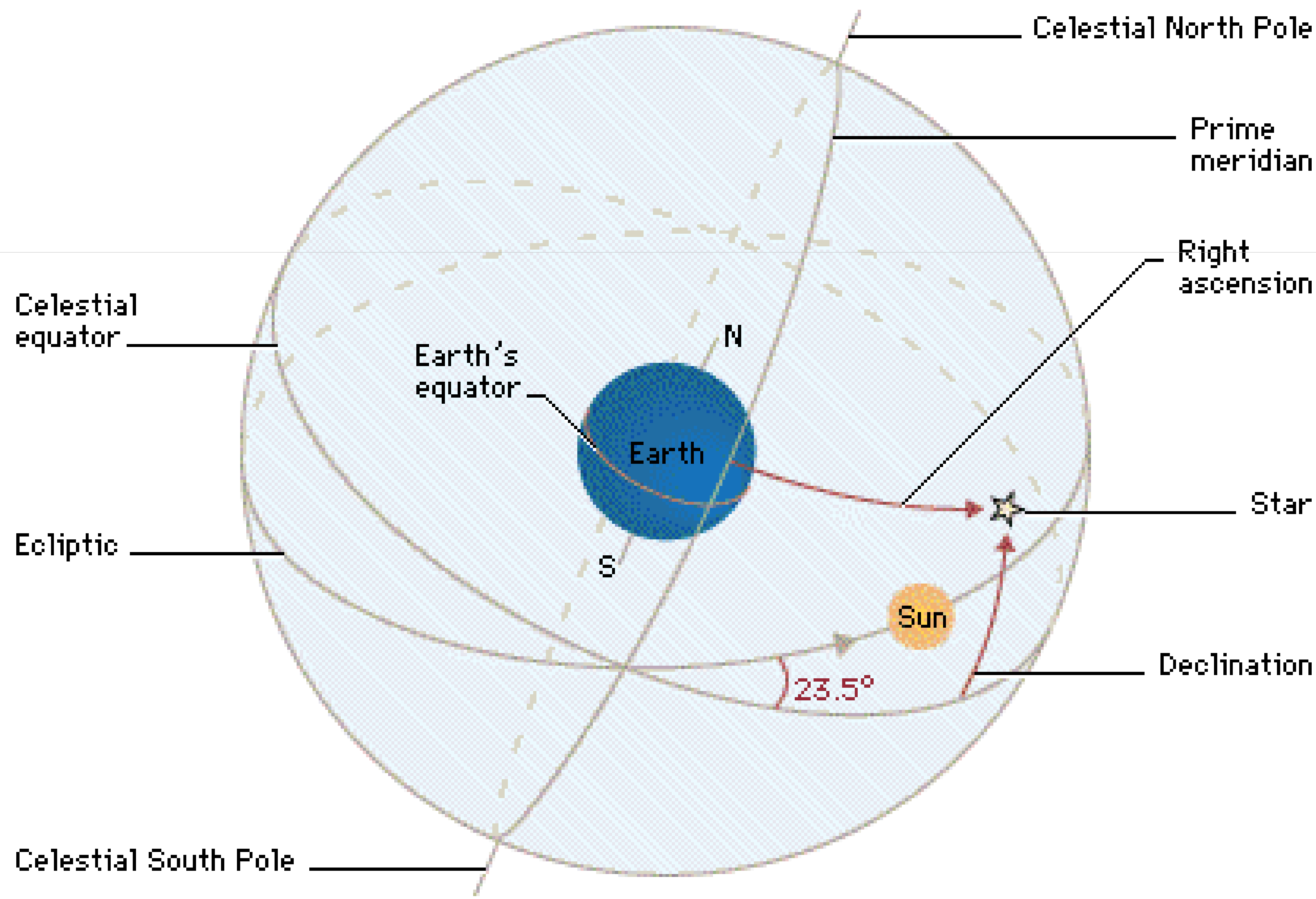
- The position of any two point on sphere then described by 2 angles
  - angle around equator and angle up/down from equator



- Need origin on equator to measure angle from
- Coordinate system defined by equator and origin

Basics of Positional Astronomy — Co-ordinate system

The Celestial Sphere



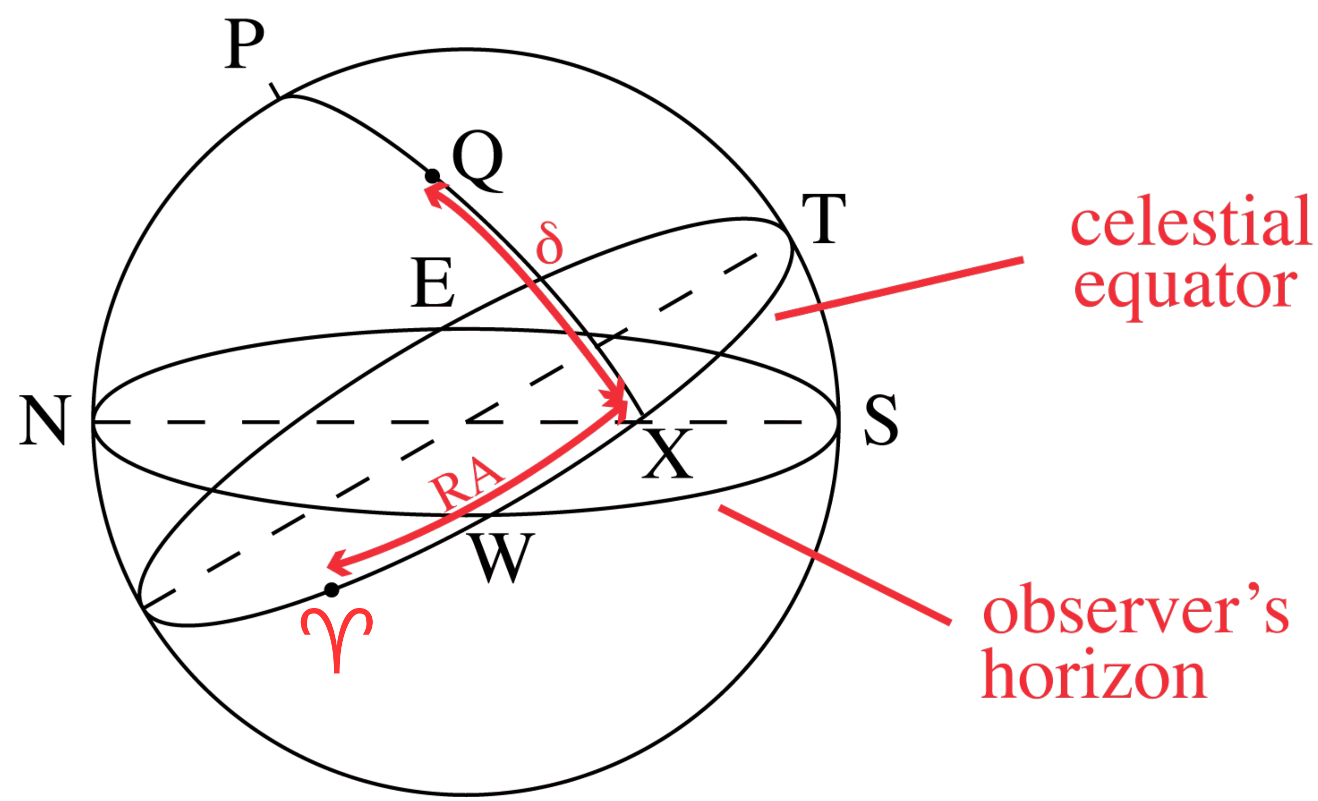
This form a basis for Equatorial System

Basics of Positional Astronomy — Co-ordinate system

Equatorial System

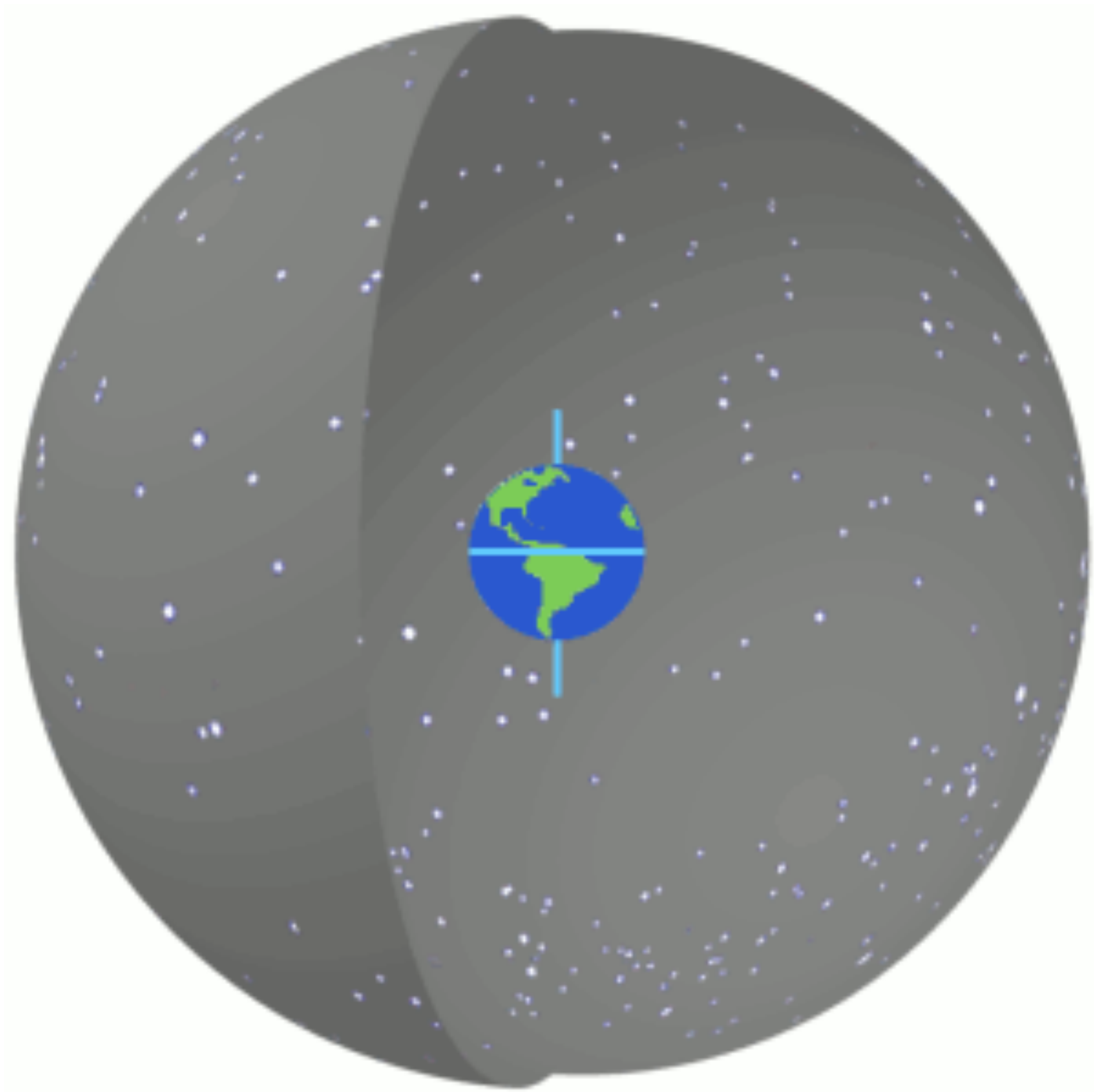
- Coordinates of star Q defined by great circle through P and Q cutting celestial equator at X
- **Declination δ** is arc QX, range +90°N to -90°S
- **Right Ascension, RA** arc ♈ X measured east from **First Point of Aries**, ♈ in hours, mins, secs with 360° = 24 hours

For direction east, imagine you are travelling on outside of sphere



Basics of Positional Astronomy — Co-ordinate system

Equatorial System



Source — Wikipedia

Basics of Positional Astronomy — Co-ordinate system

Equatorial System

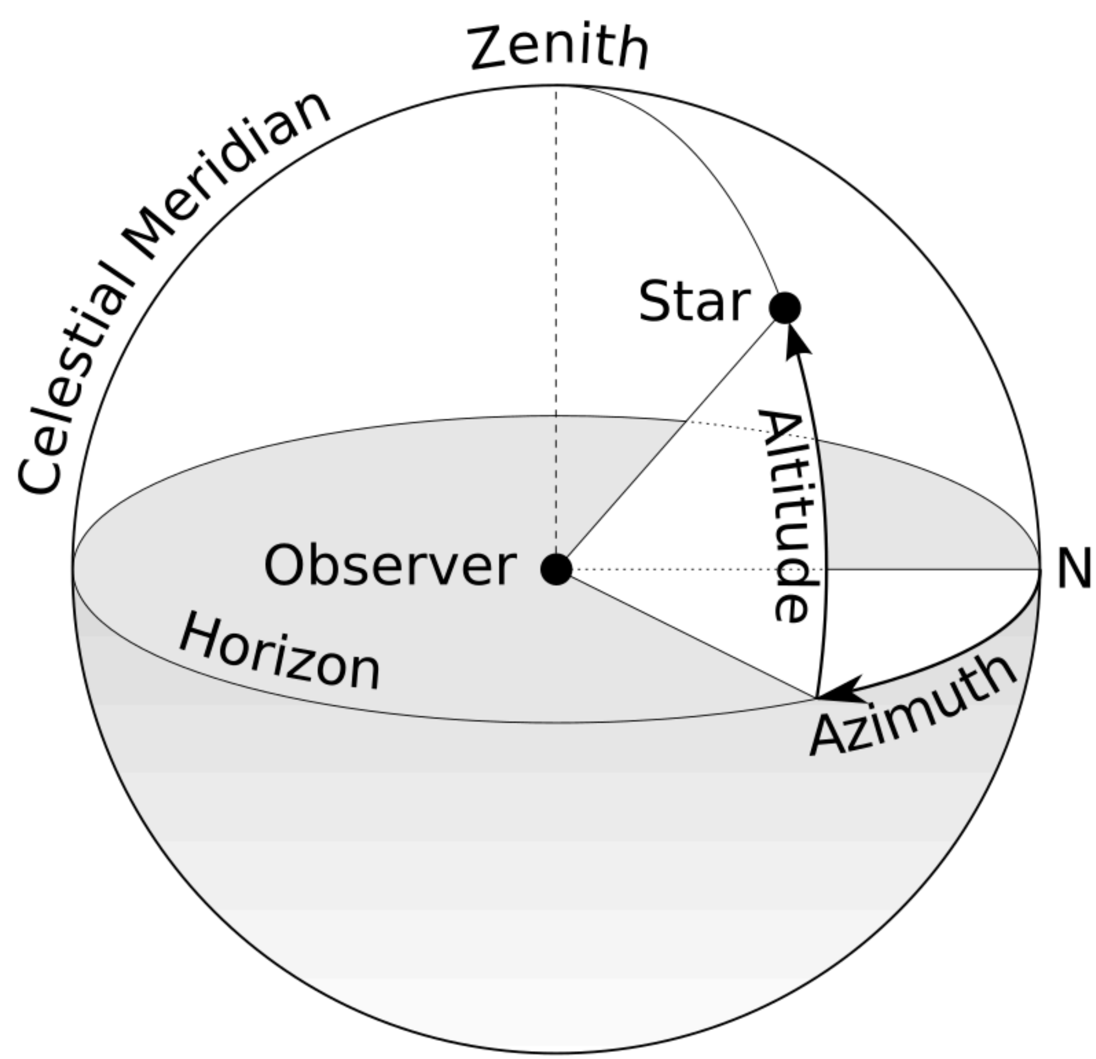
- The origin at the centre of Earth means the coordinates are **Geocentric**
- A primary direction towards the **Vernal Equinox** hence a **right-handed** convention
- A right-handed convention means that coordinates increase northward from and eastward around the plane.
- A slow motion of Earth's axis, **Precession**, causes a slow, continuous turning of the coordinate system westward about the poles of the ecliptic, completing one circle in about 26,000 years. Superimposed on this is a smaller motion of the ecliptic, and a small oscillation of the Earth's axis, **Nutation (More about these effects discussed in later slides.)**
- In order to fix the exact primary direction, these motions necessitate the specification of the **Equinox or Epoch** of a particular date, when giving a position. The most commonly used is: Mean equinox of a standard epoch (usually **J2000.0**, but may include **B1950.0**, **B1900.0**, etc.)

Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System

- This coordinate system that uses the observer's local **horizon** as the fundamental **plane**.

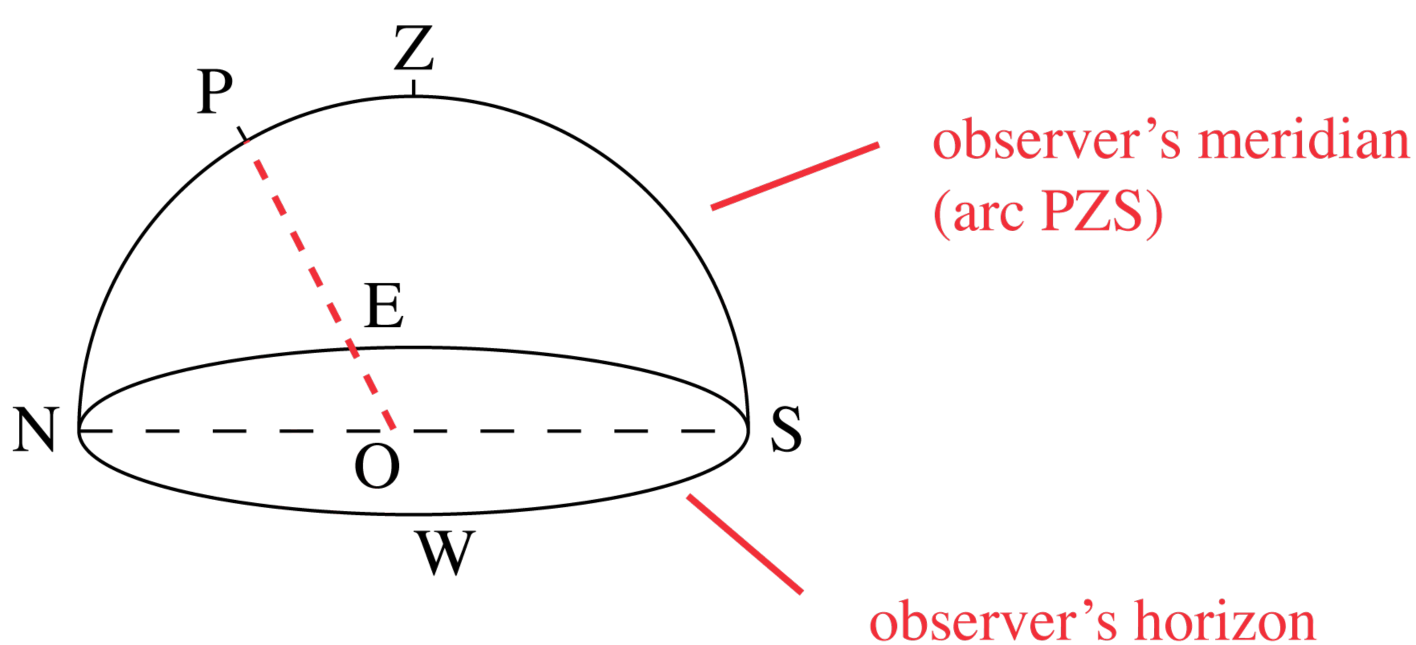
- Coordinates of an object in the sky are expressed in terms of **altitude** (or elevation) angle and **azimuth**.



Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System

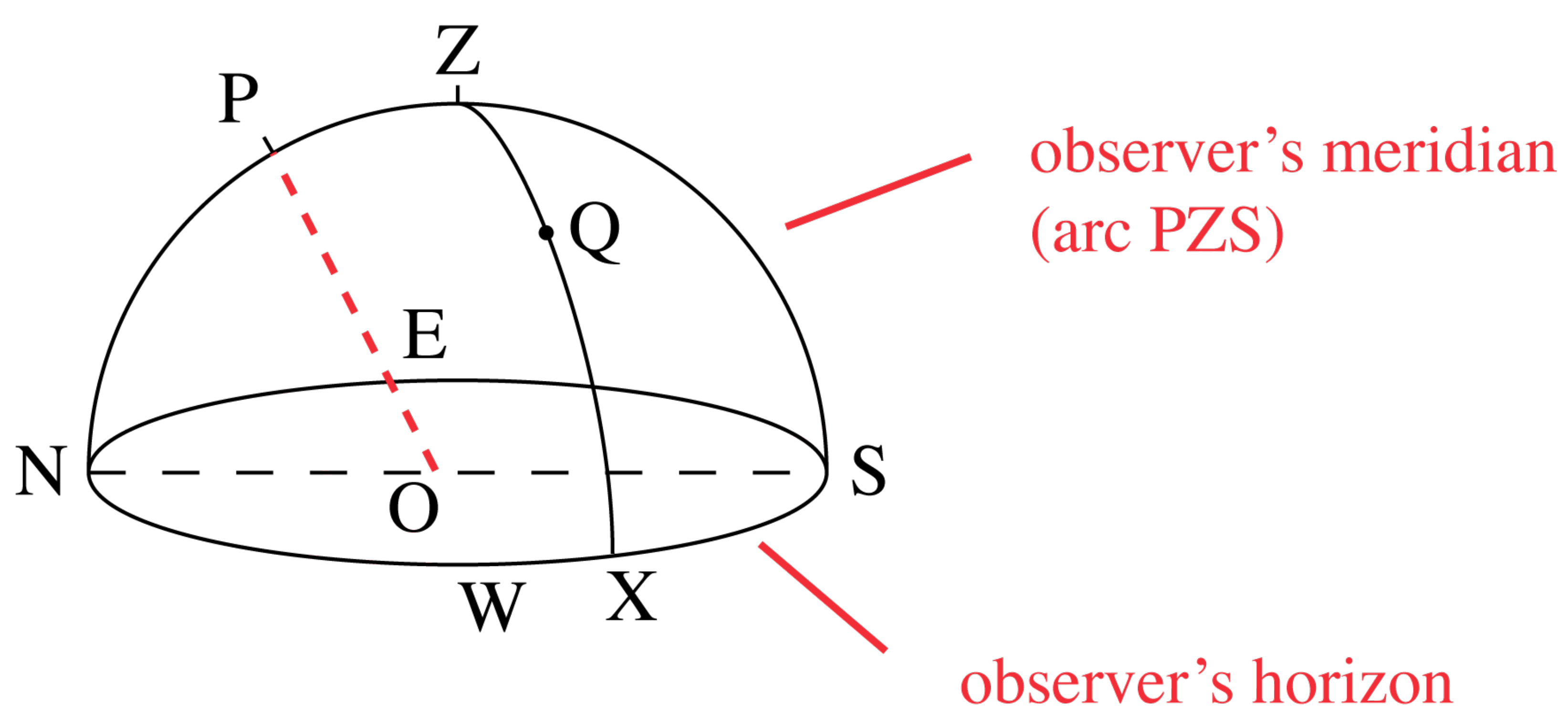
- Consider observer's view of the sky
  - half of celestial sphere on plane of observer's horizon
  - mark on cardinal points N, E, S, W and Zenith Z and North Celestial Pole P
- Arc PZS is called the observer's meridian – Part of the great circle through P and Z



Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System

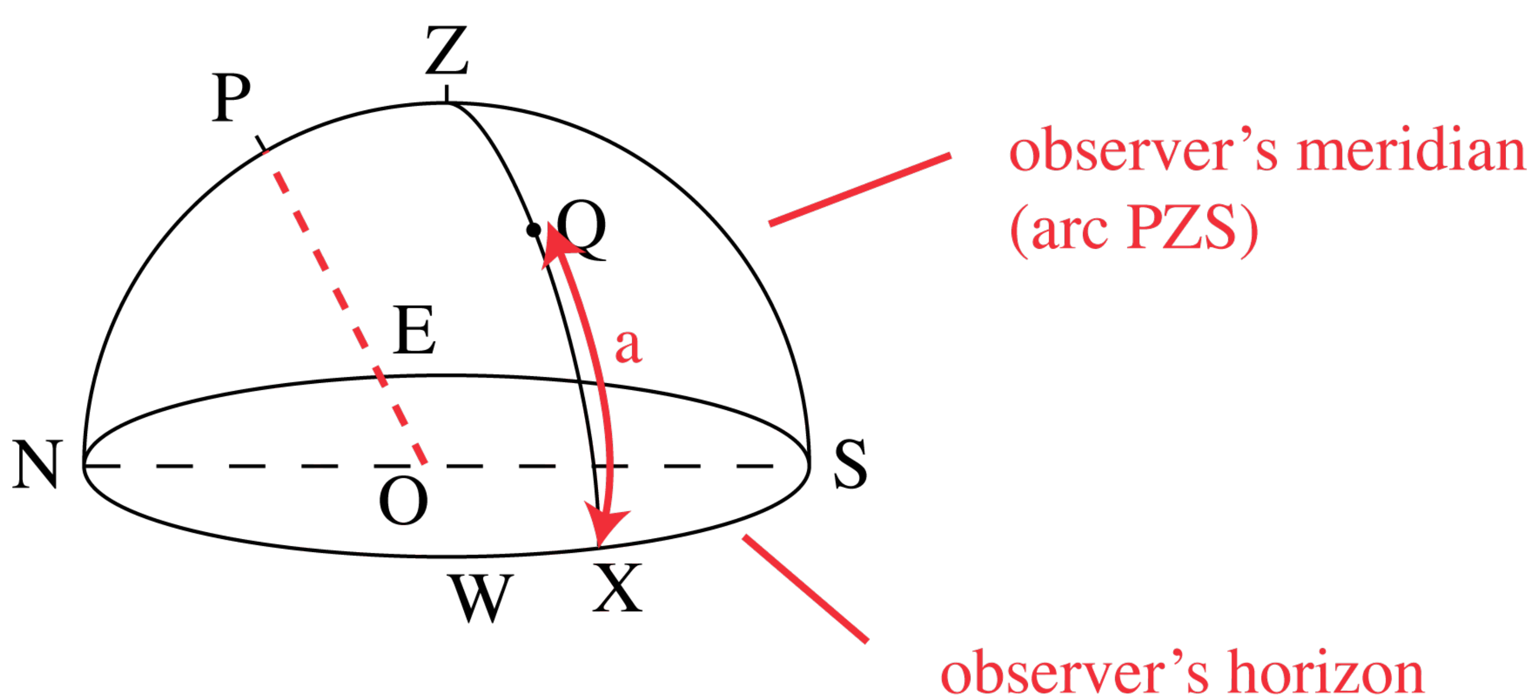
- Coordinates of a star Q defined by drawing great circle through Z and Q – cuts horizon at X
- Position of Q then given by:



Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System

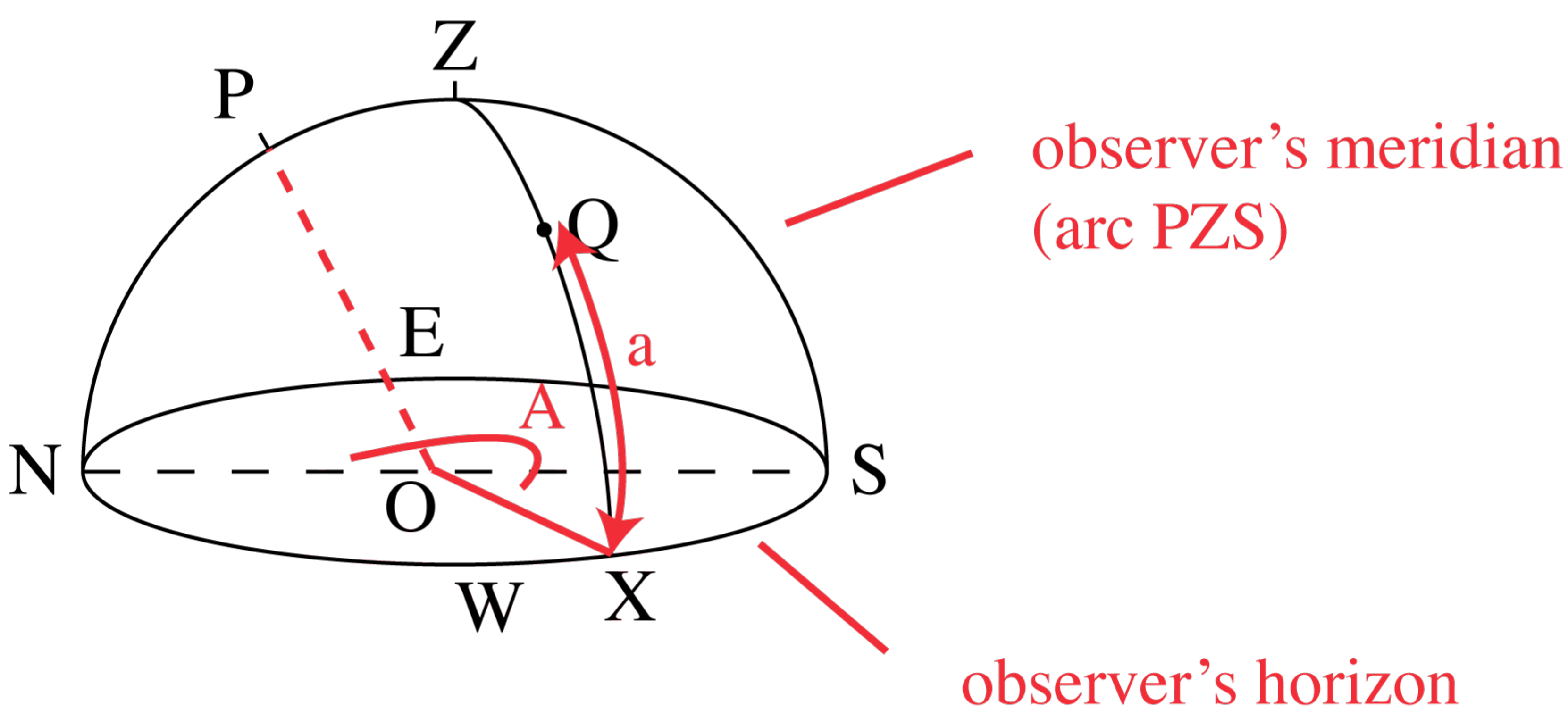
- Coordinates of a star Q defined by drawing great circle through Z and Q – cuts horizon at X
- Position of Q then given by:
- **altitude (or elevation) a** – the arc QX or
- **altitude (or elevation) —** is the angle between the object and the observer's local horizon.
- For visible objects, it is an angle between 0° and 90°.



Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System

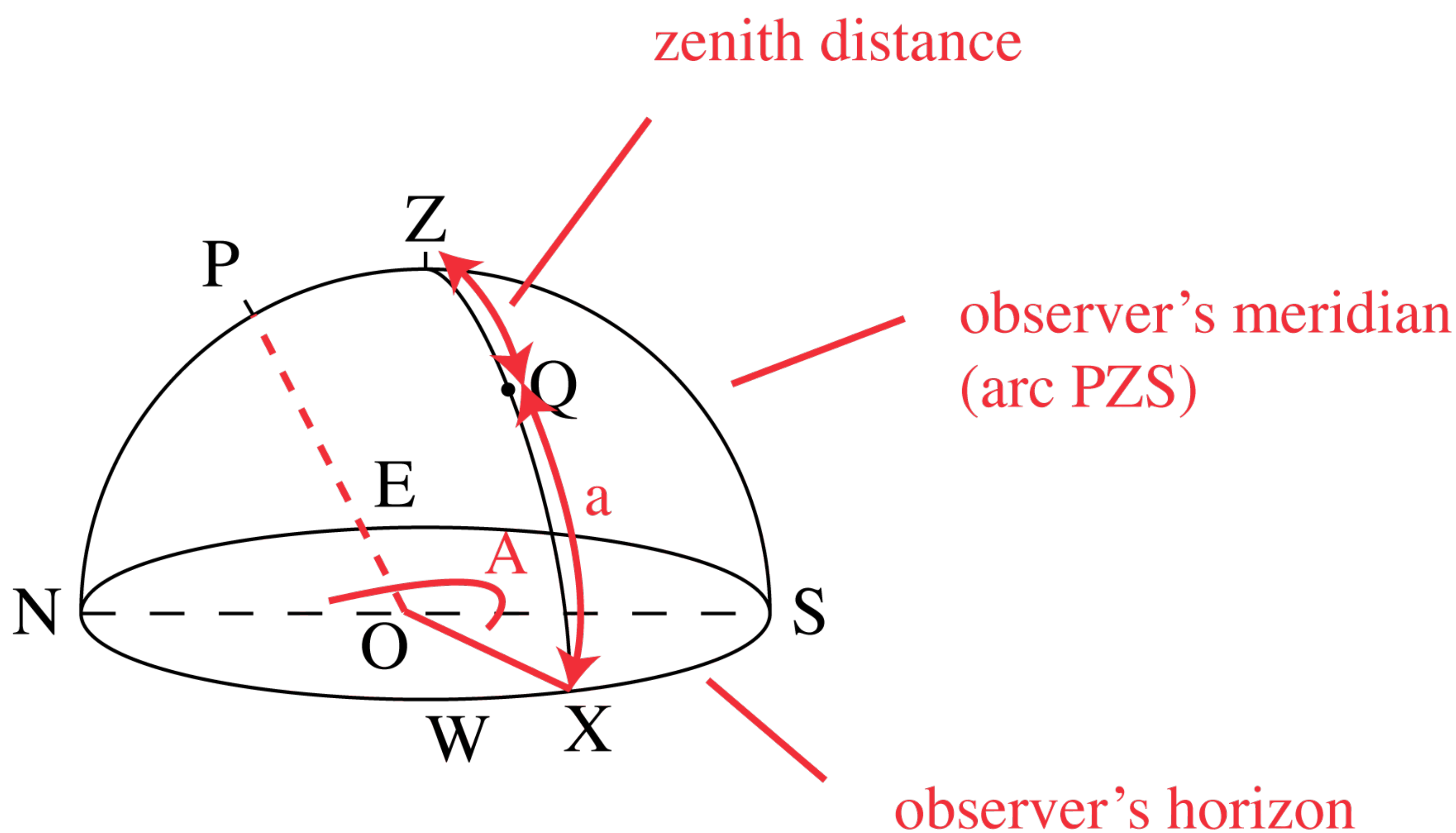
- Coordinates of a star Q defined by drawing great circle through Z and Q – cuts horizon at X
- Position of Q then given by:
- **altitude (or elevation) a** – the arc QX
- **azimuth, A** – the arc NX eastward from N
- **azimuth, A** – is the angle of the object around the horizon, usually measured from true north and increasing eastward.



Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System

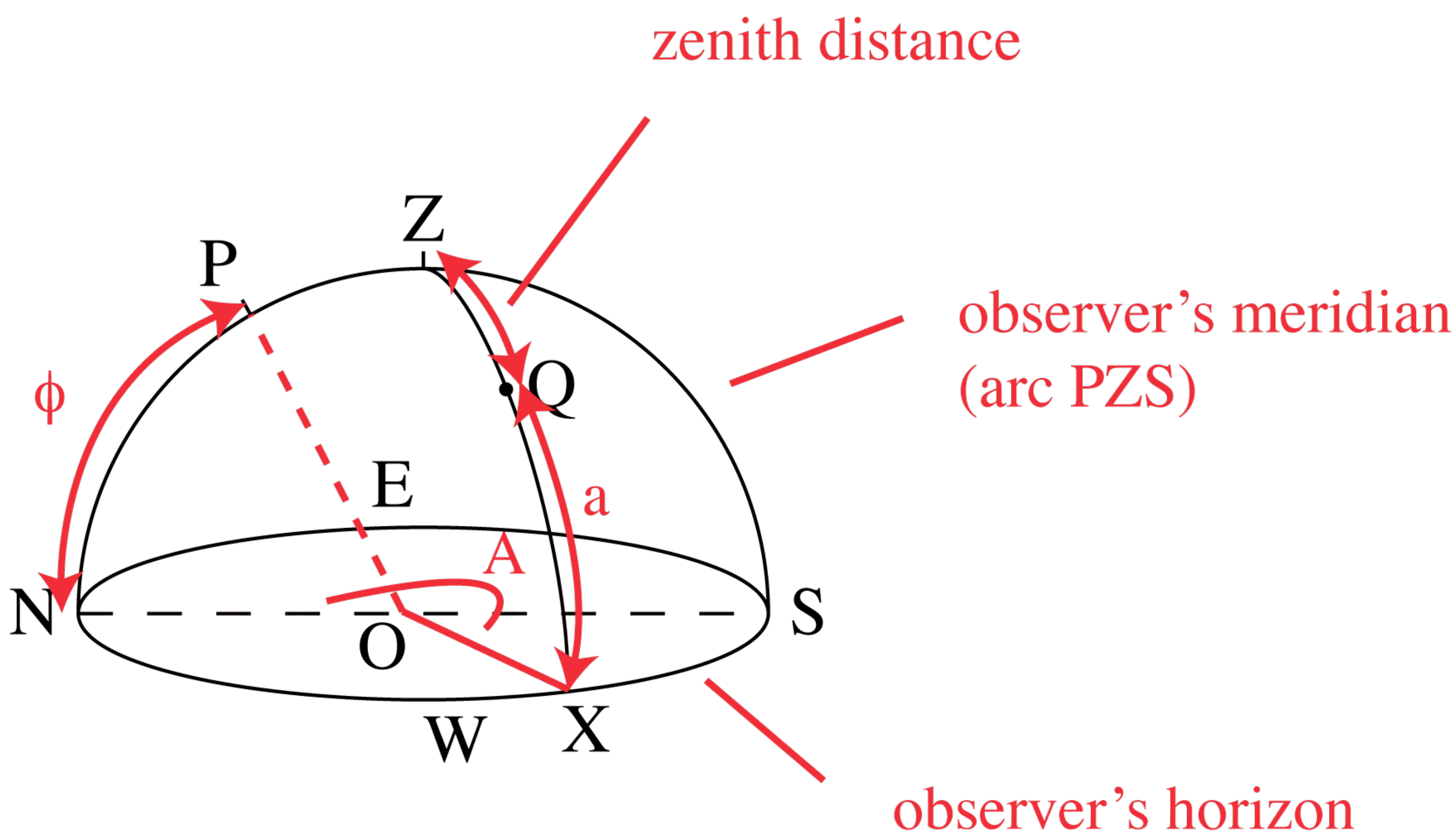
- The arc QZ is called the **zenith distance** of point Q.
- The zenith distance is the complement of altitude, so that the sum of the altitude and the zenith distance is 90°.
- What is the altitude of P (North Celestial Pole)?



Basics of Positional Astronomy — Co-ordinate system

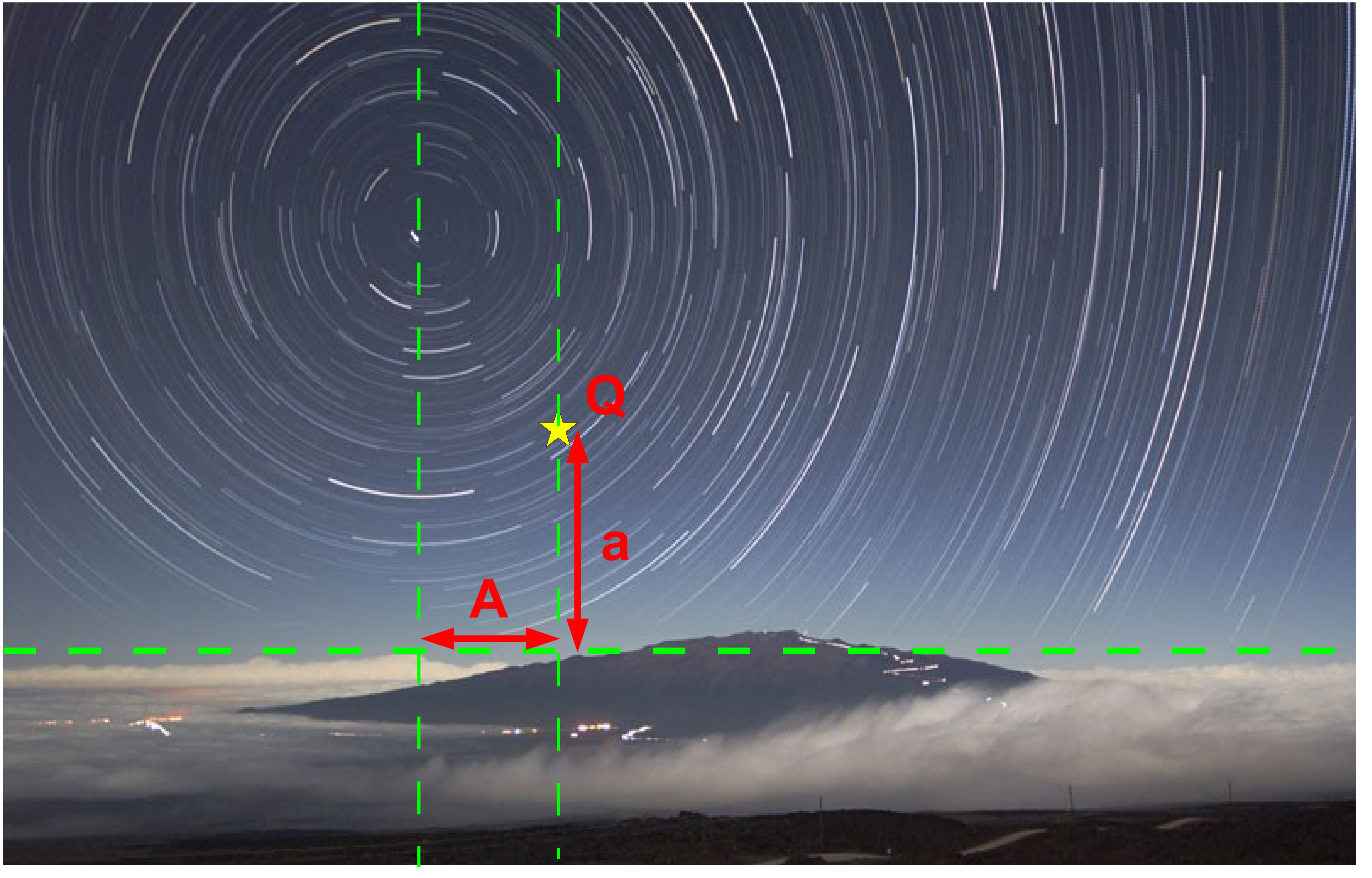
Alt-Azimuth System

- The arc QZ is called the **zenith distance** of point Q
- What is the altitude of P (North Celestial Pole)?
- equal to latitude of the observer



Basics of Positional Astronomy — Co-ordinate system

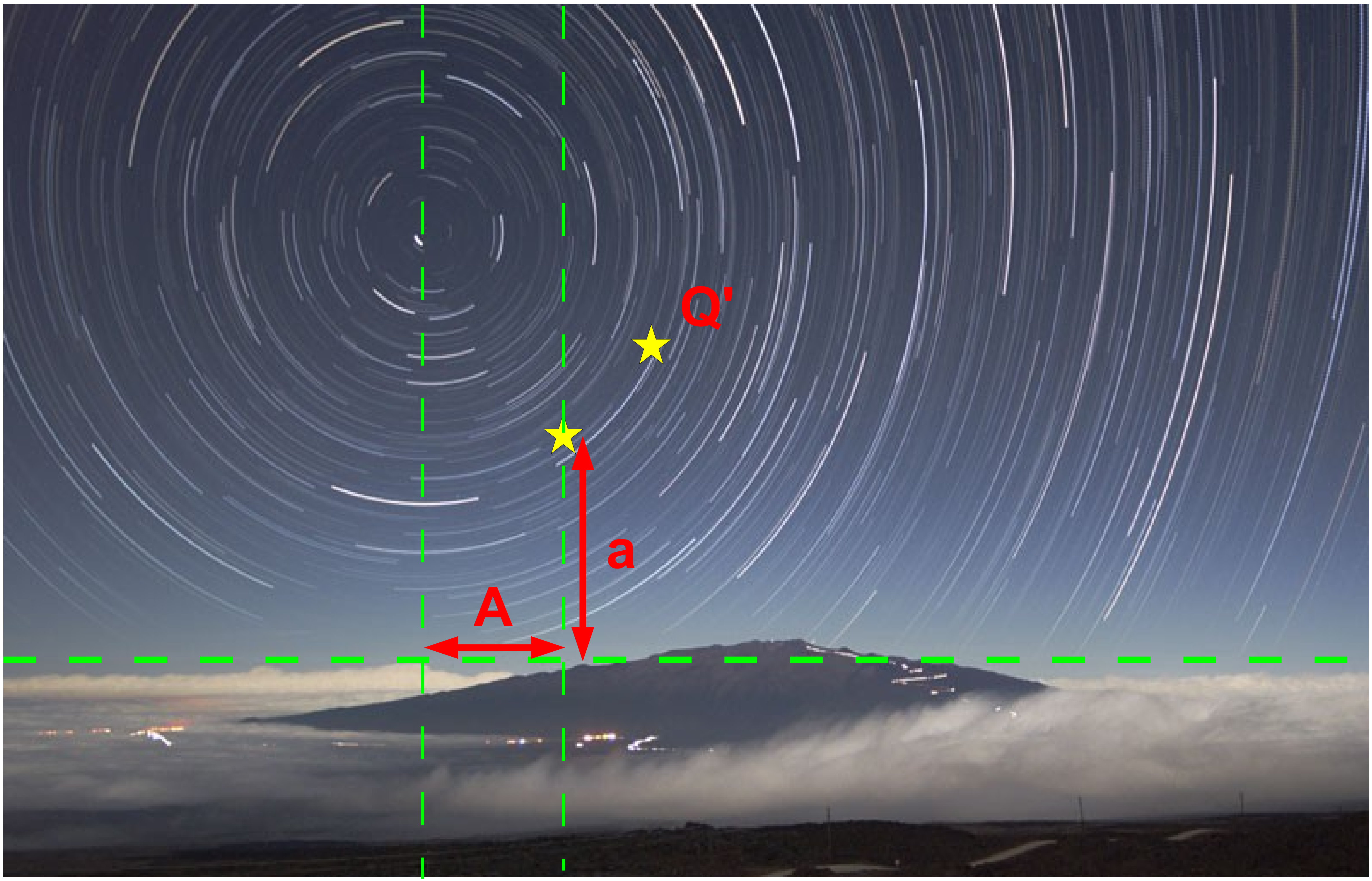
Alt-Azimuth System



Note- These lines are not really parallel – meet at zenith

Basics of Positional Astronomy — Co-ordinate system

Alt-Azimuth System



Basics of Positional Astronomy — Co-ordinate system

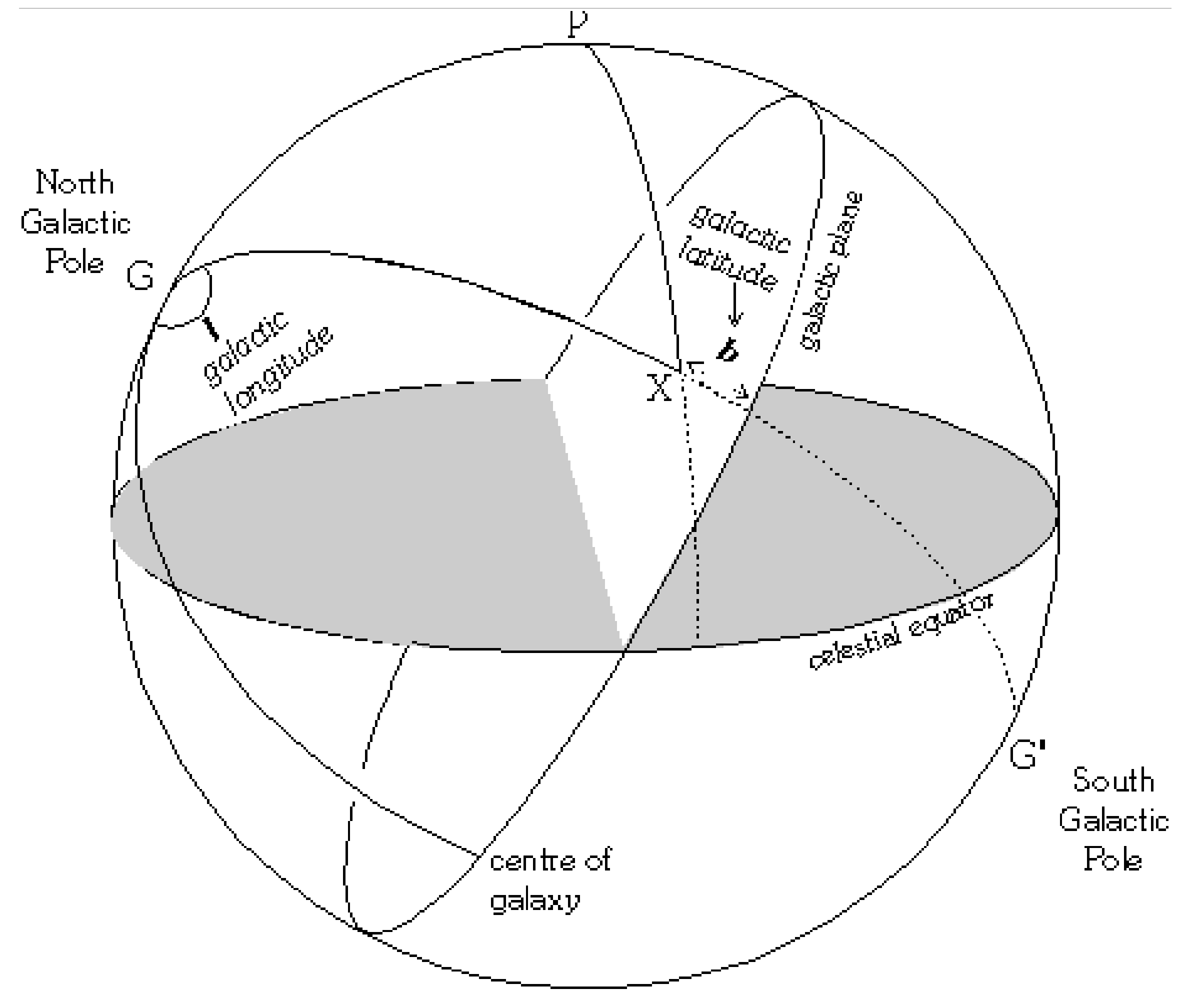
Alt-Azimuth System

- The Alt-Azimuth coordinate system is fixed to a location on Earth, not the stars.
- Therefore, the **altitude** and **azimuth** of an object in the sky changes with time, as the object appears to drift across the sky with Earth's rotation.
- In addition, since the horizontal system is defined by the observer's local horizon, the same object viewed from different locations on Earth at the same time will have different values of altitude and azimuth.
- Alt-Azimuth coordinates system are very useful for determining the rise and set times of an object in the sky.
- When an object's altitude is 0°, it is on the horizon. If at that moment its altitude is increasing, it is rising, but if its altitude is decreasing, it is setting.
- If the azimuth is between 0° and 180° (north–east–south), the object is rising.
- If the azimuth is between 180° and 360° (south–west–north), the object is setting.

Basics of Positional Astronomy — Co-ordinate system

Galatic Co-ordinates

- Based on the plane of the Milky Way ("galactic plane")
- Coordinates are galactic longitude (l) & latitude (b)
- Similar to all the equatorial systems
- Galactic centre is at l=b=0º (RA = 17h 46m Dec = -28º 46')



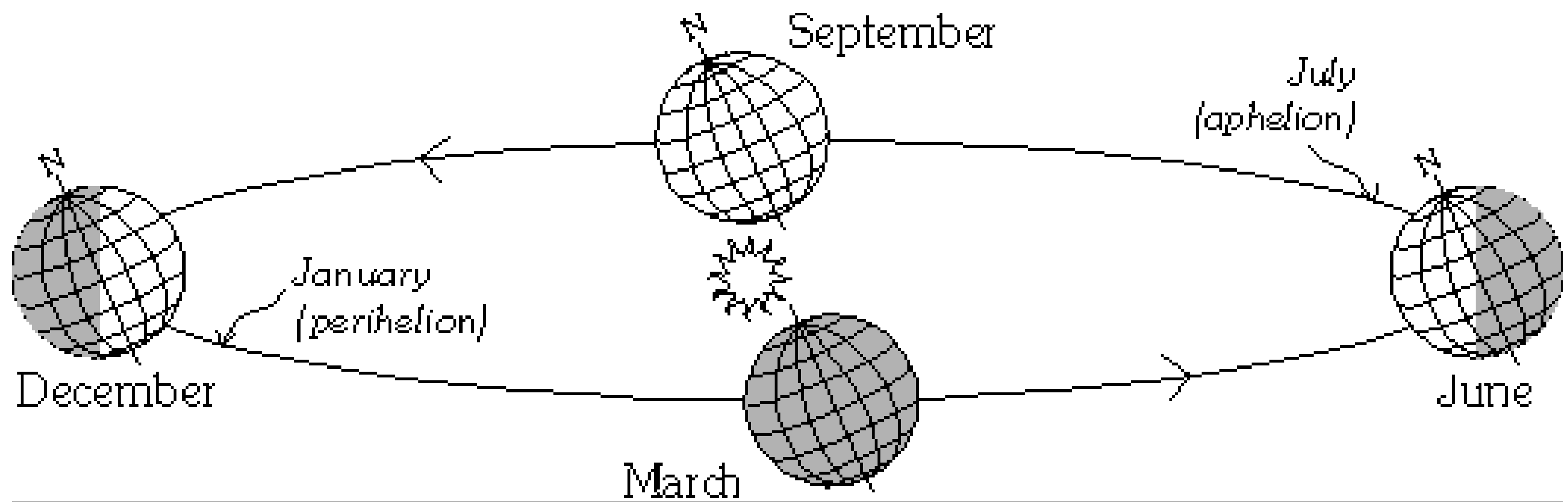
Galatic Co-ordinates

	Right ascension	Declination	Constellation
North Pole +90° latitude	$12^h 51.4^m$	+27.13°	Coma Berenices (near 31 Com)
South Pole –90° latitude	$0^h 51.4^m$	–27.13°	Sculptor (near NGC 288)
Center 0° longitude	$17^h 45.6^m$	–28.94°	Sagittarius (in Sagittarius A)
Anticenter 180° longitude	$5^h 45.6^m$	+28.94°	Auriga (near HIP 27088)

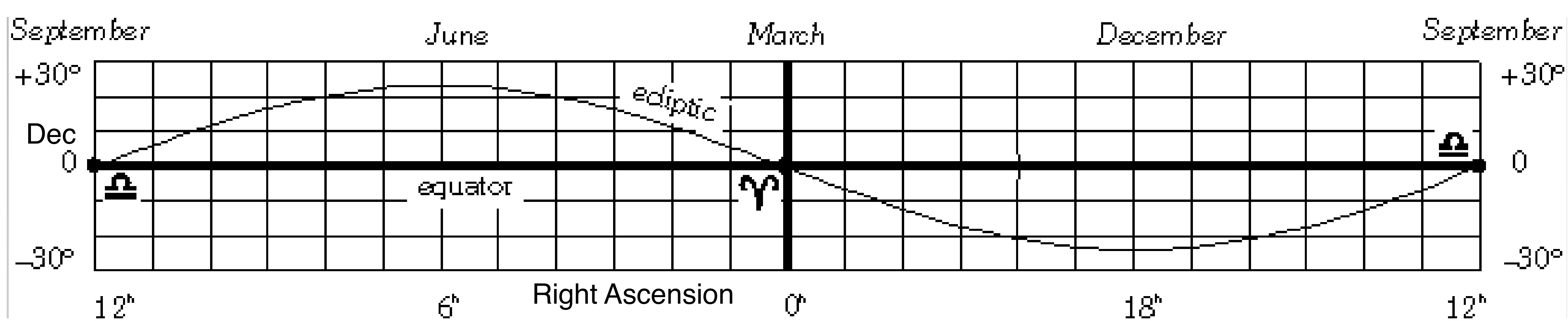
Basics of Positional Astronomy — Co-ordinate system

Ecliptic Co-ordinates

Because of the tilt of Earth's axis by 23º 26', the Sun's path across the sky during the course of a year does not follow the equator



Instead it follows a **great circle** called the **ecliptic**



Basics of Positional Astronomy — Co-ordinate system

Ecliptic Co-ordinates

- The ecliptic is therefore the intersection of the Earth's orbital plane with the celestial sphere

- Since the Earth and the planets are confined to orbit in the same plane, then all the other planets also follow the ecliptic

- Ecliptic coordinate system has
  — Fundamental circle = ecliptic
  — Poles are the north and south ecliptic poles
  — Origin of the coordinate system is **♈** (First Point of Aries, or Vernal Equinox)

Coordinate are measured in terms of:

ecliptic longitude (λ): measured east from **♈**

ecliptic latitude (β): measured from ecliptic to poles (-90° to +90°)

— The ecliptic and equator intersect at the equinox **nodes**

"ascending node": when Sun moves from S to N at ♈ (λ = 0°, RA = 0 h)
also known as **Vernal** or **Spring Equinox**
"descending node": when Sun moves from N to S at ♎ (λ = 180°, RA = 12 h)

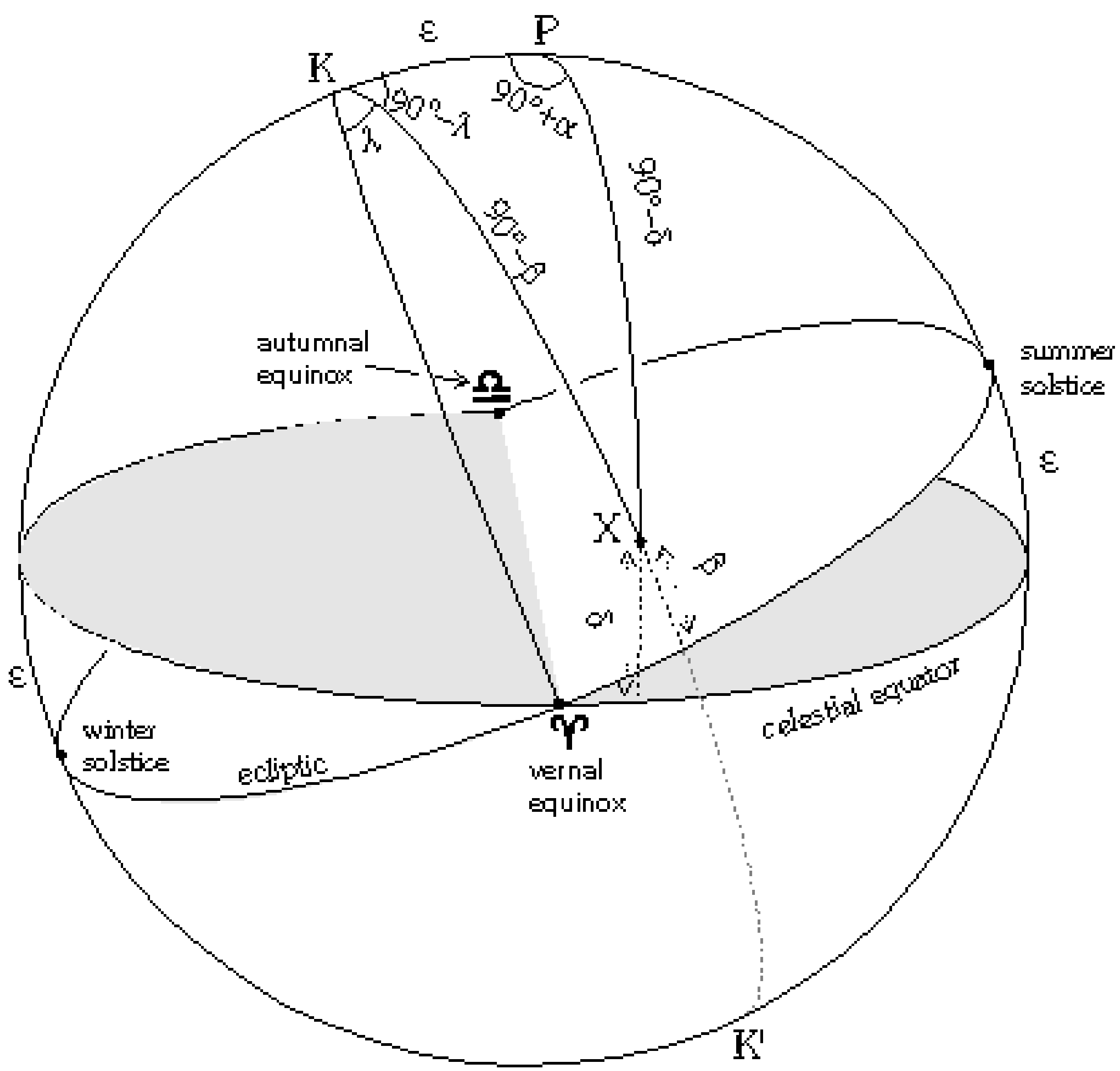
also know as **Autumnal Equinox**

At the equinoxes: length of day & night are equal

Basics of Positional Astronomy — Co-ordinate system

Ecliptic Co-ordinates

Spherical trigonometry (cosine & sine rules) can be used to convert from equatorial to ecliptic coordinates & vice versa



Basics of Positional Astronomy — Co-ordinate system

General Observations

- Due to Earth's rotation, objects appear to rise in the east and set in the west, excepting for those that are '**circumpolar**' and never set.
- Objects appear to travel across the sky along small circles of constant declination
- When an object passes its highest point in the sky, this occurs when it crosses the meridian and is called **culmination**
- Declination and Right Ascension are essentially fixed for most objects, like latitude and longitude are fixed for geographical positions on Earth
- Exceptions to the above are for:
  - Precession and nutation (wobbling of Earth's spin axis)
  - Motion of nearby objects, e.g. solar system objects, or even nearby stars
- Hour Angle is dependent on observers location, since it refers to the local meridian

Basics of Positional Astronomy — Co-ordinate system

General Observations

A **circumpolar star** is a star that, as viewed from a given latitude on Earth, never sets (that is, never disappears below the horizon), due to its proximity to one of the celestial poles.

Summary

- Observer, horizon, zenith, nadir, meridian.
- Different co-ordinate systems depending on the reference plane
- Horizon co-ordinates : altitude and azimuth.
- Equatorial co-ordinates : Right Ascension(RA or α) and Declination(δ)
- Ecliptic co-ordinates : λ and β
- Galactic co-ordinates : l and b

Basic Measurements — Time system

Recap

- Observer, horizon, zenith, nadir, meridian.
- Different co-ordinate systems depending on the reference plane
- Horizon co-ordinates : altitude and azimuth.
- Equatorial co-ordinates : Right Ascension(RA or α) and Declination(δ)
- Ecliptic co-ordinates : λ and β
- Galactic co-ordinates : l and b

Basics of Positional Astronomy — Time system

Sunrise Sunset

The times at which the apparent upper limb of the Sun is on the astronomical horizon. In The Astronomical Almanac they are computed as the times when the true zenith distance, referred to the centre of the Earth, of the central point of the disk is 90 deg 50 min, based on adopted values of 34 arcmin for horizontal refraction and 16 arcmin for the Sun semidiameter.

Twilight

The interval of time preceding sunrise and following sunset during which the sky is partially illuminated. Civil twilight comprises the interval when the zenith distance, referred to the centre of the Earth, of the central point of the solar disk is between 90 deg 50 min and 96 deg, nautical twilight comprises the interval from 96 to 102 deg, astronomical twilight comprises the interval from 102 to 108 deg

Basics of Positional Astronomy — Time system

Time is complicated!

- The Astronomical Almanac (used to be the standard observer's handbook before computers. Some 'old hands' still use it and its full of interesting stuff!) lists no less than a dozen different time systems!
- For astronomical measurements its crucial to know what time system is being used (particularly for time varying or time critical phenomena, like eclipses, periodic variations in stars or coordinating observations from different observatory on ground and in space). Partial Lunar eclipse on 8 August 2017 OR Total Solar eclipse on 21 August 2017

Two major way of measuring time:

- With respect to the rotation of the Earth
  1. But rotation rate is not uniform and results in secular (long-term) changes of the order of ~ 1 sec per year.
  2. Up until atomic clocks, Ephemeris Time (used until 1984) was the standard, which used the best theory of Earth's rotation.
- Using the frequency of atomic oscillation
  1. Since the 1950's, atomic time, which is accurate to microseconds (10^{-6}) per year, has taken over

Basics of Positional Astronomy — Time system

Earth Rotation Time

Local Apparent Time

- Based on when the Sun crosses the meridian each day
- So as to start a new day at midnight rather midday, this is defined as:
    1. Solar Hour Angle + 12 hours
- This implies that local Noon is when the Sun is at its highest in the sky and that different longitudes would have different time
    1. Very confusing for people travelling in longitude
- But even local Apparent Time is **not** strictly constant due to:
    1. Eccentricity of the Earth's orbit, which means the Sun's distance changes over a year and therefore its apparent angular motion on the sky changes
    2. The Earth (and therefore the Sun's projection on the celestial sphere) moves faster at perihelion (closest approach) in July and slowest at aphelion (furthest separation) in January.
    3. Obliquity of the ecliptic: the Sun's varying velocity in ecliptic longitude

Earth Rotation Time

The Equation of Time

- Because of the Earth's orbital eccentricity and its axis tilt (obliquity), time measured by the Sun's position varies throughout the year
- Correct for this using the equation of time
- This applies a correction to the time derived from the Sun's position (e.g. from a Sun dial) to account for these affects.
- The corrected time is referred to as the Mean Time which is defined by a fictitious Sun (the mean Sun) having a constant velocity around the celestial equator.

Basics of Positional Astronomy — Time system

Greenwich Mean Time (GMT)

- Defined by the location (Hour Angle) of the mean Sun at Greenwich
- So 12:00:00 GMT is when the mean Sun crosses the meridian at Greenwich
- In order to avoid the complexity of every place on Earth operating on their Local Mean Time, a system of time zones was set up 100 years ago

Universal Time (UT or UT1)

- Different versions of "universal times", but most are defunct now or not widely used anymore (e.g. UT0, UT2, UTS)
- The one in wide usage is UT1, or simply called UT

    1. A measure of the true rotation period of the Earth with respect to a fixed frame of reference. As this not uniform, UT1 has an uncertainty of ± 3 milliseconds per day, implying drifts of ~1 sec per year with respect to atomic clock time (TAI).
    2. Essentially the same as GMT.
    3. It is the same everywhere on Earth.

Why UT is important in observational astronomy?

Basics of Positional Astronomy — Time system

Greenwich Mean Sidereal Time (GMST)

- Measures the Hour Angle of the mean Vernal Equinox (**Y**) at Greenwich
- Accounts for precession but not short-term nutation (the correction for nutation is defined as Greenwich Apparent Sidereal Time or GAST)
- IAU convention links GMST and UT1 through a formulae based on Julian Date (to be defined later)

Local Mean Sidereal Time (LMST)

- LMST = GMST + observers east longitude (in time)
- Usually the same as just LST (= Hour Angle – RA)

Basics of Positional Astronomy — Time system

Atomic Times

- Based on atomic transitions and reaching accuracies of 10^{-15} to 10^{-17} sec
- Keeping time to 1 sec in 3 billion years! Need to take account of General Relativity effects (gravitational redshift) by Correcting for their mean altitude above sea level

Ephemeris Time (ET) & Terrestrial Dynamic Time (TT)

- ET used before widespread use of atomic clocks and was the closest to a uniform time
- ET replaced in 1984 by TT, which is based on TAI

Barycentric Dynamic Time (BDT)

- Similar to TT, but corrections are made to move the origin from Earth's gravitational field to the barycentre of the Solar System (within the Sun)
- The difference only amounts to 1.6 milliseconds an is only relevant for the timing extremely fast phenomena (e.g. millisecond pulsars)

Years

Tropical Year

- The time between two successive passages of the mean Sun through the Vernal Equinox = 365.2421988 days (UTC) and is decreasing by 0.53 sec per century
- "Natural" yearly timescale since it defines the seasons

Sidereal Year

- The time between two successive passages of the mean Sun with respect to the distant stars = 365.256366 days (UTC)
- Longer than a Tropical Year due to the retrograde motion of the Vernal Equinox (Y) due to precession

Anomalistic Year

- Interval between two successive passages of the Earth through perihelion = 365.259636 days. Longer than Sidereal Year due to precession of the line of apsides (semi-major axis of Earth's orbit).

Years

Civil Year

- For "civil" purpose, a year should:
    1. Contain integer numbers of days
    2. Stay in phase with the seasons
- Achieved by having repeat cycles of
    1. 3 years of 365 days
    2. 1 year of 366 days (?? What is it called??)
    3. Average length of year over this 4 year cycle is 365.25 days
    4. Very close to the length of a Tropical Year (365.2422 days)
- This was the basis of the **Julian** calendar
- Difference amounts to ~8 days over 1,000 years
    1. Calendar reformed in 1582 by Pope Gregory XIII (Gregorian calendar)
    2. Modification of Julian calendar (3 days every 400 years are omitted)
    3. Now the error is reduced to ~1 day every 4,000 years
    4. The revised rule for a leap year in the **Gregorian** calendar is

       Year divisible by 4; except years which are multiples of 100; unless they are divisible by 400

       2004,2008,2012…are leap year;1700,1800,1900 are not; 1600,2000,2400 are

Julian Dates

Julian Day Number, or Julian Date, was adopted to avoid complications calculating elapsed time with calendars

- Devised by Josephus Scaliger (1540 – 1609) and named, not for Julius Caesar (as Julian Calendar was), but probably his father!
- Day 0 in Julian Date is 1 January 4713 BC at 12:00:00 GMT (**what a day!**)

1. **Why? What's so significant about this date, some 6,720 years ago?**

Julian Dates

Julian Day Number, or Julian Date, was adopted to avoid complications calculating elapsed time with calendars

- Devised by Josephus Scaliger (1540 – 1609) and named, not for Julius Caesar (as Julian Calendar was), but probably his father!
- Day 0 in Julian Date is 1 January 4713 BC at 12:00:00 GMT (what a day!)
    1. Why? What's so significant about this date, some 6,720 years ago?
    2. **Chosen because 3 important (back then!) cycles, extrapolated back in time, were all in phase and beginning together on that date:**
        - **The 19 year Lunar Metonic cycle**
        - **The 15 year Indiction Cycle (a Roman taxation cycle! Tell SARS)**
        - **The 28 year Solar Cycle of the Julian calendar (nothing to do with Sunspots!)**
    3. **Julian Date for 24 August 2020 at 11:20 IST (5:50 UTC) is 2459085.74306**
- Since JD starts at Noon, this means over a given night in Europe/Africa that the JD has the same integer value
- Because JD is a long number (7 digits before the decimal!), sometimes the abbreviated Modified Julian Date (MJD) is used

  MJD = JD - 2450000.5000

  So MJD changes day at midnight UTC instead of 12:00 UTC

Basics of Positional Astronomy — Time system

Heliocentric Julian Date

This is a further modification to Julian Date to take account of the following:

- As the Earth moves around its orbit, it changes its distance with respect to objects being observed
- Due to the finite speed of light, the distance changes can lead to timing changes
  1. When observing time varying phenomena (e.g. eclipses) we have to account for the different light travel times
  2. Correction varies systematically over the orbit
  3. Can amount to a ~17 minutes delay comparing timing from one side of the orbit (when closest to the object) to the other side (when furthest away)
- The times are therefore corrected to a time as if the observation was taking place at the centre of the Sun, hence heliocentric
- The correction is:

$$HJD = JD + K\,R\,(\cos L \cos\alpha \cos\delta + \sin L\,(\sin\varepsilon \sin\delta + \cos\varepsilon \cos\delta \sin\alpha))$$

Where:

K = Mean Sun-Earth travel time (0.000578 days),
R = Ratio of true Earth-Sun distance to mean Earth-Sun distance
L = longitude of Sun, ε = obliquity of the equator (23º 26’ 21.448” for 2000.00)

α, δ = Right Ascension & Declination coordinates of the object

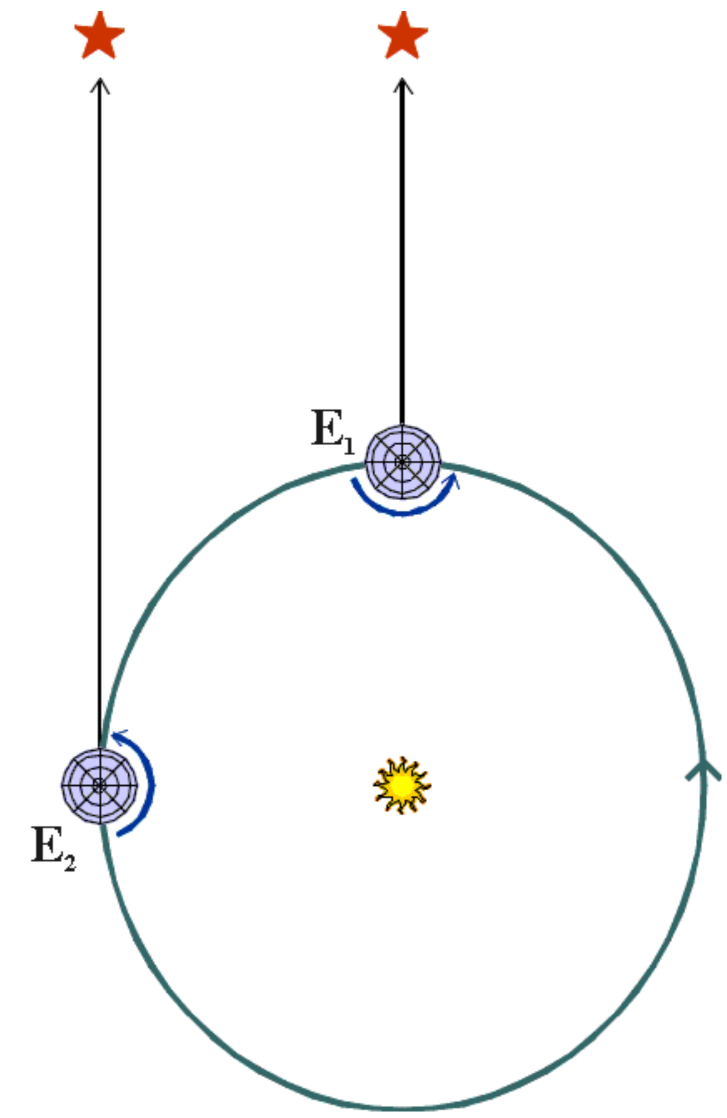
Barycentric Julian Date (BJD)

- For the most accurate timing (e.g. milliseconds or microseconds) of phenomena
- Corrects for time from the perspective of the barycentre (centre of gravity) of the entire Solar System.
- Takes out the slight wobble of the Sun produced by the gravitational forces of the planets
- Dominated by the effect of Jupiter
- Amplitude of the difference between HJD (Sun-centred) and BJD (Solar System Centred) is ~4 sec over the 11 year orbital period of Jupiter

Time - Recap

- Astronomers use Universal Time (UT) to measure time. UT ≈ GMT.
- Julian Date (JD) is the number of days elapsed since noon at Greenwich on 1 Jan 4713 BC.
- 16 May 2017 : JD (for 0^h UT) is 2457889.5
- Modified JD (MJD) is counted since 17 Nov 1858 (i.e., JD = 2400000.5). So, MJD for 16 May 2017 at 0^h UT is 57889.
- The Local Sidereal Time (LST) is the Right Ascension (α) of the observer's meridian.
- On 16 May 2017, at 0^h UT, the LST at Greenwich is $15^h\ 35^m\ 36.081^s$
- A star ('Starius') of this RA is on the observer's meridian at this point.
- The Hour Angle (HA) is LST - RA. At this point, the HA of Starius is 0^h. After an hour, the LST becomes $16^h\ 35^m\ 36.081^s$. Starius has moved westward, its HA is now 1^h.

Sidereal Time



Which stars are on your local meridian?

- It depends on the time at which you observe.
  In fact, it depends on both the *date* and the (clock) time, because the Earth is in orbit around the Sun.
- Consider the Earth at position E_1 on the diagram.
  The star shown is on the meridian at midnight by the clock. But three months later, when the Earth reaches position E_2 , the same star is on the meridian at 6 pm. by the clock.
- Our clocks are set to run (approximately) on **solar time** (sun time).
  But for astronomical observations, we need to use **sidereal time** (star time).

Consider the rotation of the Earth relative to the stars.

We define one rotation of Earth as one sidereal day, measured as the time between two successive meridian passages of the same star.
Because of the Earth's orbital motion, this is a little shorter than a solar day.
(In one year, the Earth rotates 365 times relative to the Sun, but 366 times relative to the stars. So the sidereal day is about 4 minutes shorter than the solar day.)

Basics of Positional Astronomy — Time system

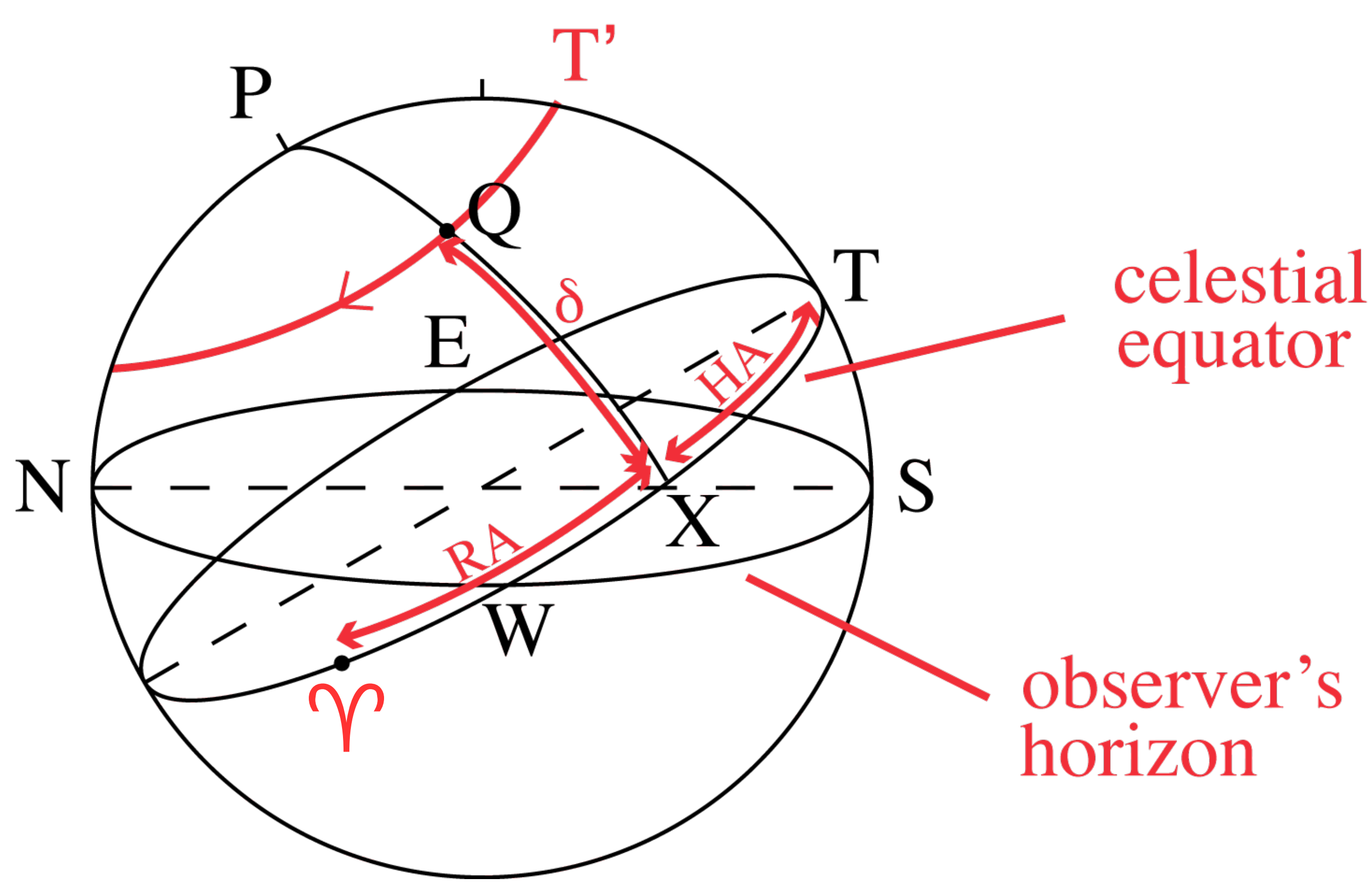
Sidereal Time

- The length of a sidereal day is 23 hour 56 minutes 4.1 seconds
- This is very close, but not exactly, equal to the rotation period of the Earth as measured with respect to the stars
    1. Due to the precession of the Earth's axis, the position of the Vernal Equinox (where the Sun crosses the equator) drifts ~50 arcsec per year
    2. A sidereal day is therefore 0.009 seconds shorter than the true rotation period of the Earth around the Sun, an extra Sidereal Day is produced each year.
- Another way of looking at this is that because of the motion of the Earth
- A normal year (from Earth's rotation) consists of ~365.25 Solar days and 366.25 Sidereal Days

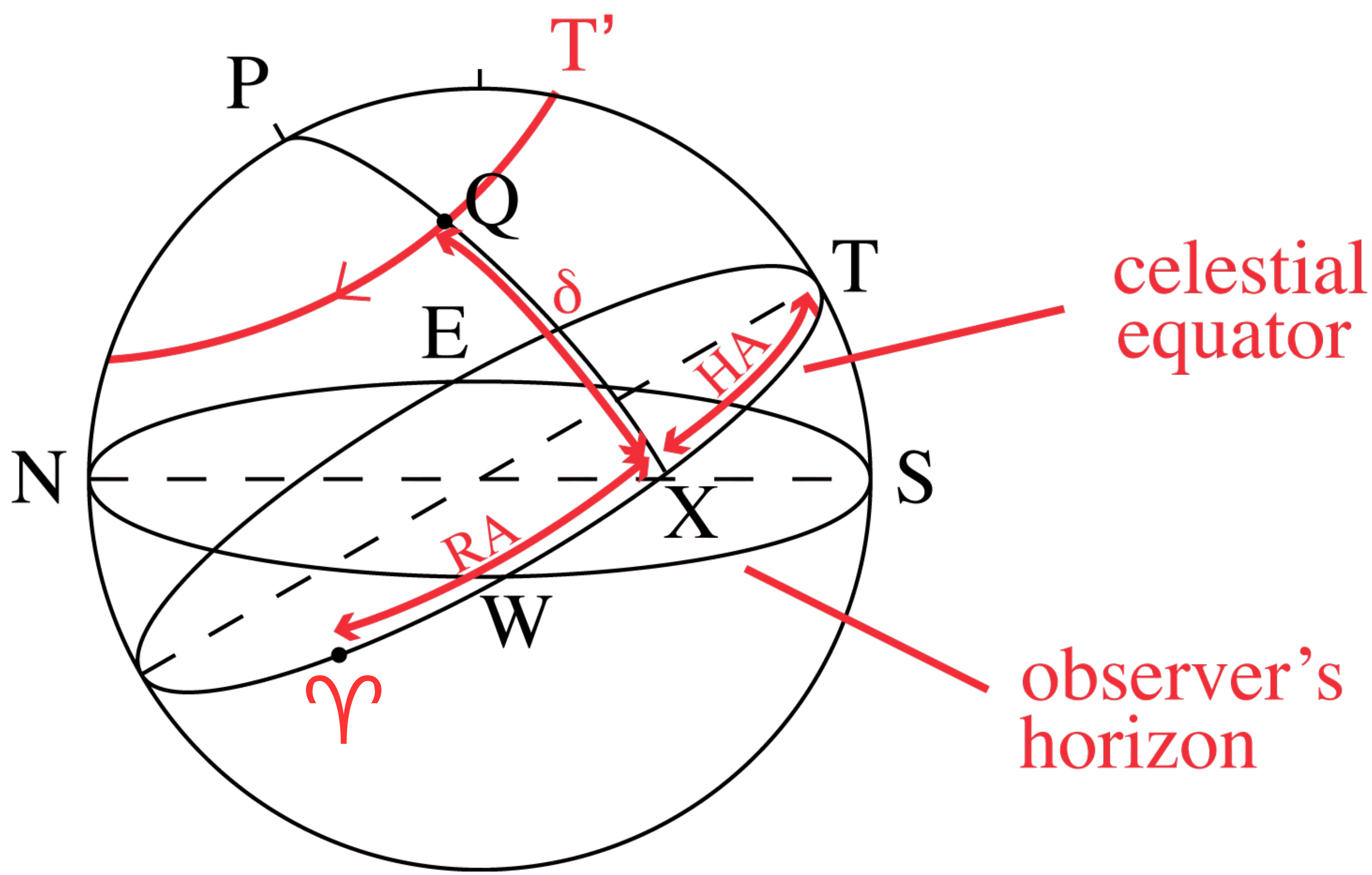
  – 1 Sidereal Day = 365.5/366.25 Solar Days = 0.9973 Solar Day = 0.9973 x 24 hours = 23 hours 56 mins 04 sec
- Relative to the stars, the Sun moves 360^{o} in 365.25 days, or a bit less that a degree/day. In RA, this is ~4 minutes a day (average).

Basics of Positional Astronomy — Time system

- As Earth rotates, star Q moves along small circle
  - RA and δ of Q remain constant
- Star crosses observer's meridian at T'
  - Star's transit
  - Time between transits is 1 **sidereal** day (sidereal = with respect to the stars)

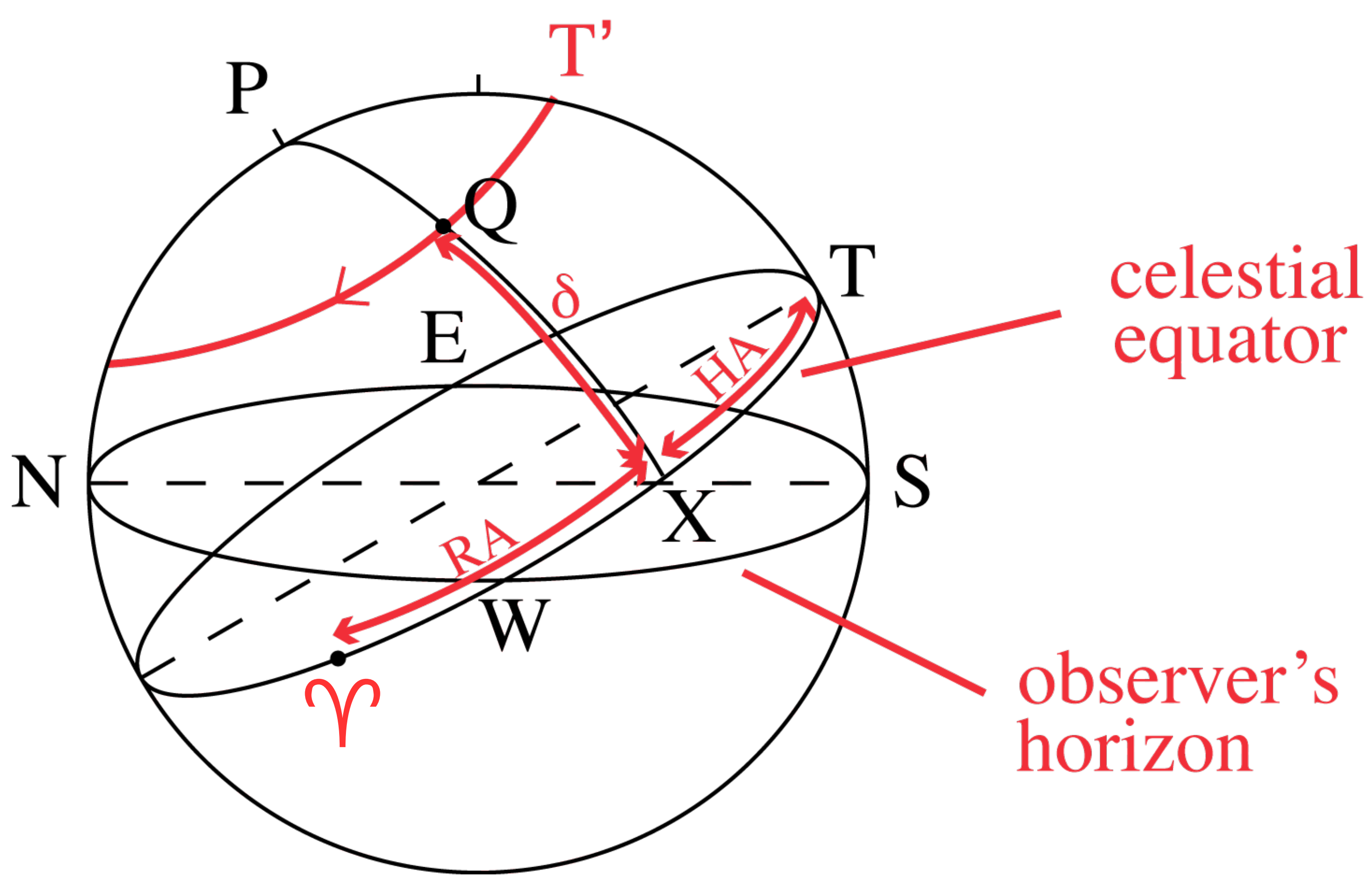


- **Hour Angle, HA:** arc TX, measured west from observer's meridian in hours, mins, secs



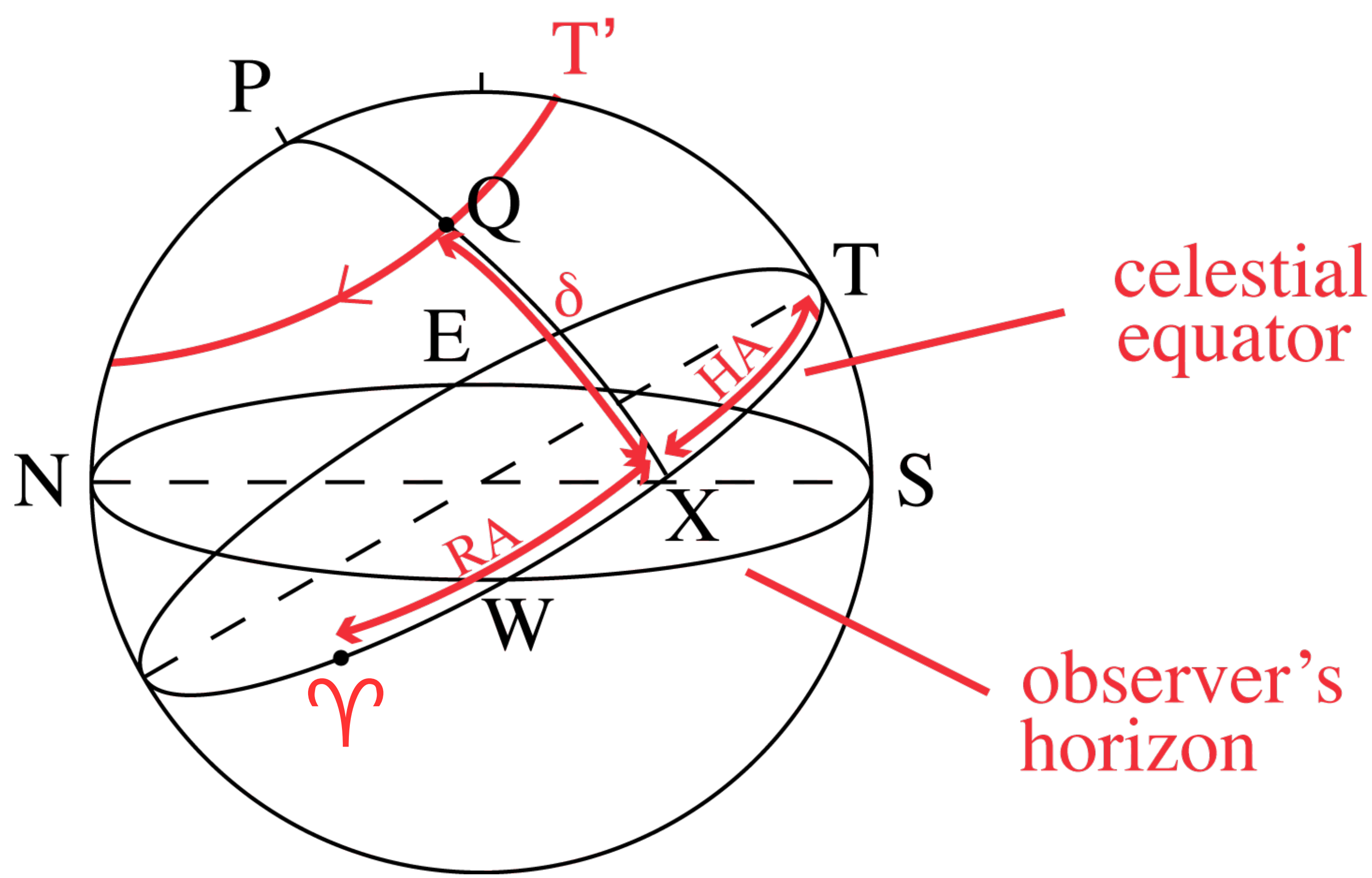
Basics of Positional Astronomy — Time system

- While RA & δ are constant, HA changes continuously
- HA of ♈ acts as clock, specific to particular observer
  - Observer's **Local Sidereal Time, LST**
- For any object Q, LST=RA(Q)+HA(Q)



Basics of Positional Astronomy — Time system

- For any object Q, LST=RA(Q)+HA(Q)
- So, given RA and δ of object, and LST of our observatory from sidereal clock
  - Determine HA and find object on sky



Recap

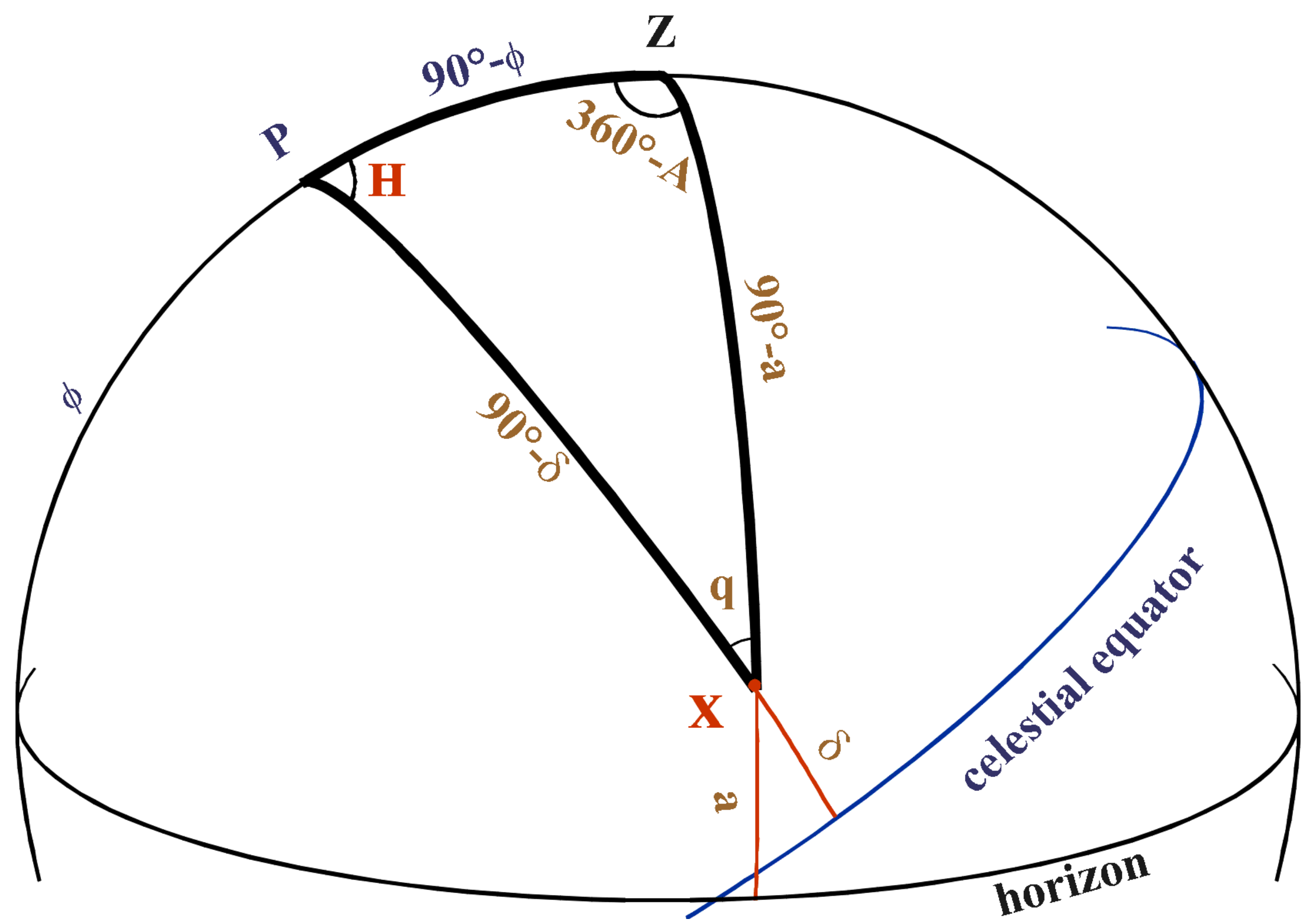
Sidereal Time, Right Ascension and Hour Angle

- Local Sidereal Time (LST): The instantaneous Hour Angle (HA) of the First Point of Aries (♈, whose RA = 0)
- LST depends on the longitude of the location, hence ‘local’
- The start of a new sidereal day (0 hours 0 min 0 sec) is when ♈ crosses the meridian.
- ♈ is the ‘zero point’ of RA coordinate
- For a star on the meridian: LST = RA of star
- Once you have LST (e.g. from a clock or time tables) and RA (from a catalogue), you can locate an object in the sky from its HA

Basics of Positional Astronomy — Recap

Co-ordinate Conversion

Lets consider Horizontal (or Alt-Az) and Equatorial systems.



φ = latitude; A = azimuth; a = altitude; H = Hour Angle; δ = Declination;
q = parallactic angle

Basics of Positional Astronomy — Recap

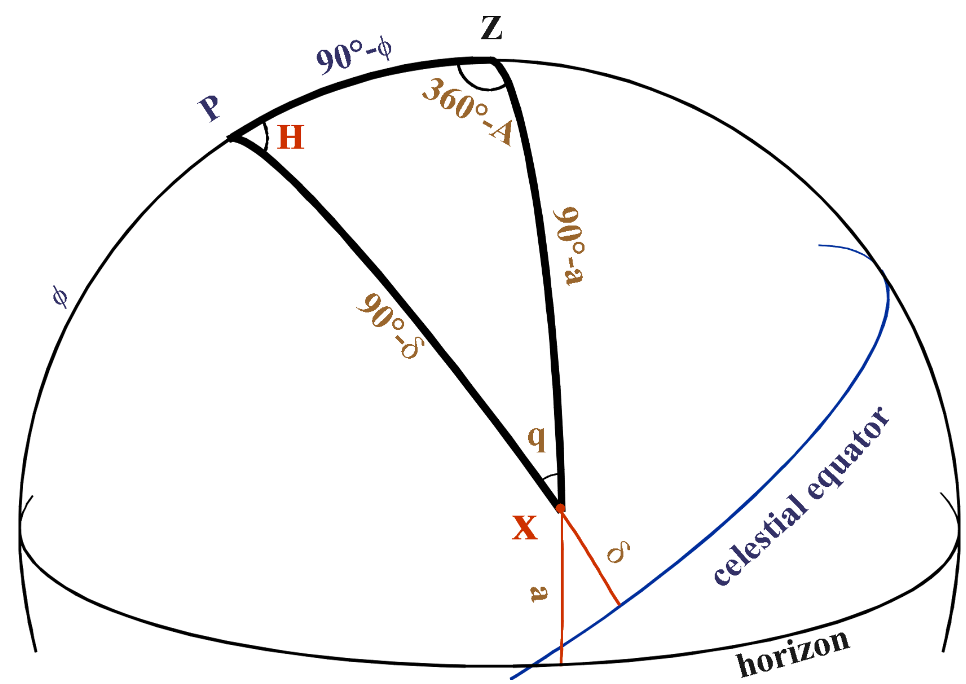
Co-ordinate Conversion

Lets consider the spherical triangle formed between arbitrary object (X), the pole (P) and the zenith (Z):

Using the cosine rule

$$\cos(90 - a) = \cos(90 - \delta)\cos(90 - \phi) + \sin(90 - \delta)\sin(90 - \phi)\cos H \Rightarrow$$

$$\sin a = \sin\delta\sin\phi + \cos\delta\cos\phi\cos H$$



Using the sine rule

$$\frac{\sin(360 - a)}{\sin((90 - \delta)} = \frac{\sin H}{\sin(90 - a)}$$

$$\Rightarrow$$

$$\sin A = -\frac{\sin H \cos\delta}{\cos a}$$

Similar expressions can be derived for the inverse transformations (H & δ from a & A or α & δ from LST, a & A)

Basics of Positional Astronomy — Time system

Recap

- Local Sidereal Time
  LST = 6.6460556+2400.0512617(JD-2415020)/36525
  +1.0027379(UT)-Longitude(hour)-24(Year-1900)
  where JD = Julian date

- JD = 2415020+365(Year-1900)-0.5+(UT/24)
  +(days starts from year)+(no. of leap year since 1900)

Effect of (Earth's) motion

The measured position of a star is different from its true position due to :

- Aberration
- Parallax – due to Earth's orbital motion.
- Precession – due to the slow motion of the Earth's rotation axis.
- Nutation – Earth-Moon interaction.
- Proper motion – due to the actual motion of the star wrt Earth.

Effect of (Earth's) motion

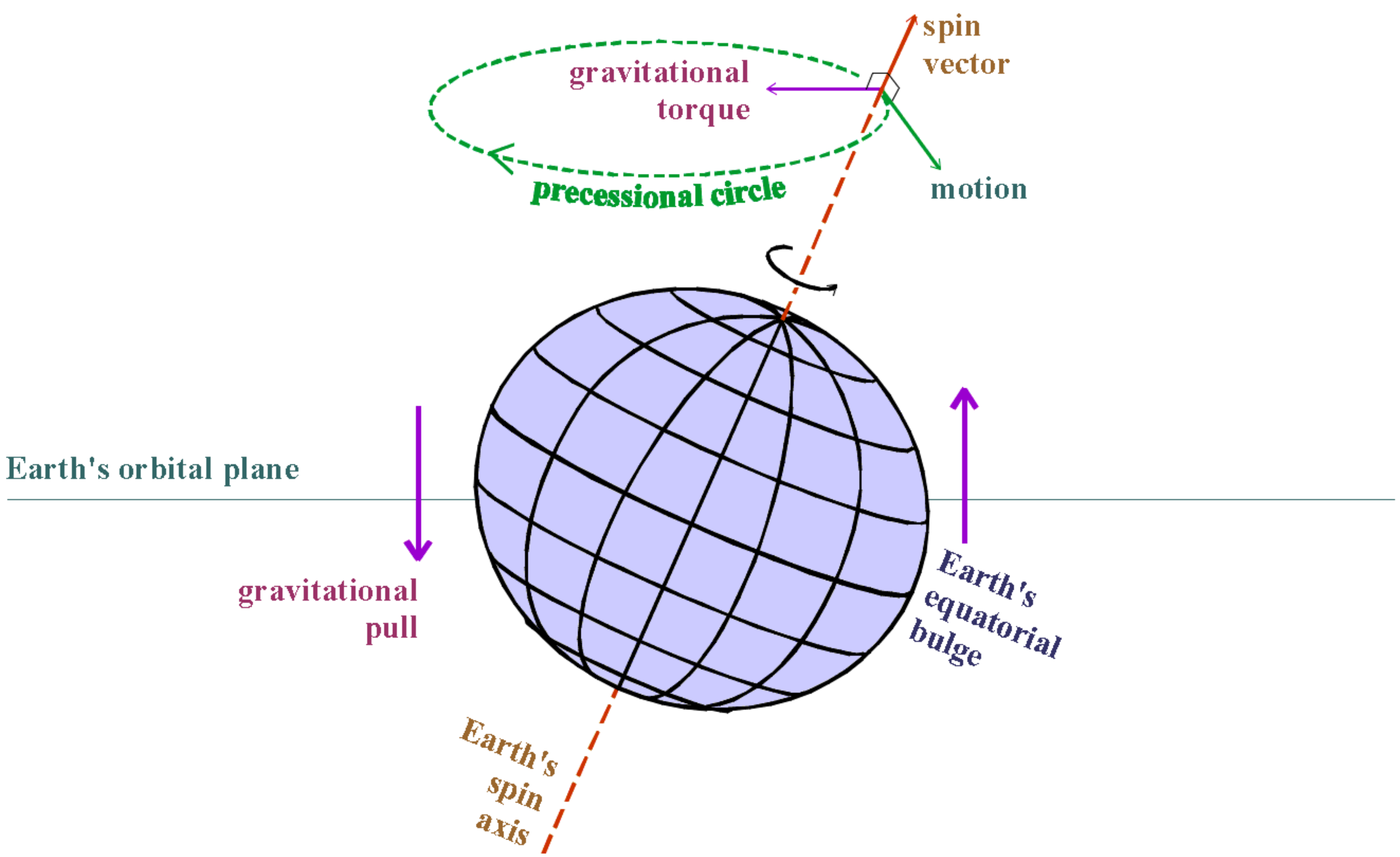
- Long time-scale variation due to 'wobbling' of the Earth's rotation axis: precession & nutation
- Gradual changes in the coordinate system over time (repeating every ~26,000 years)
- Due to gravitational effects of mostly Moon & Sun (also planets) on the non-spherical Earth
- Periodic variations: aberration and parallax
- Changes apparent position cyclically
- Daily ("diurnal"); yearly ("annual")
- Earth's atmosphere: refraction effects
- Changes apparent position as a function of Zenith Distance
- Secular variations: due to the real space motion of objects (particularly Solar System object and nearby stars)

Effect of (Earth's) motion

Precession

The Earth's axis is tilted to its orbital plane. The gravitational pull of the Sun and the Moon on the Earth's equatorial bulge tend to pull it back towards the plane of the ecliptic. Since the Earth is spinning, its axis precesses. The North Celestial Pole traces out a precessional circle around the pole of the ecliptic, and this means that the equinoxes precess backwards around the ecliptic, at the rate of 50.35 arc-seconds per year (around 26,000 years for a complete cycle).

Because of precession, our framework of Right Ascension and declination is constantly changing. Consequently, it is necessary to state the equator and equinox of the coordinate system to which any position is referred. Certain dates (e.g. 1950.0, 2000.0) are taken as standard epochs, and used for star catalogues etc.



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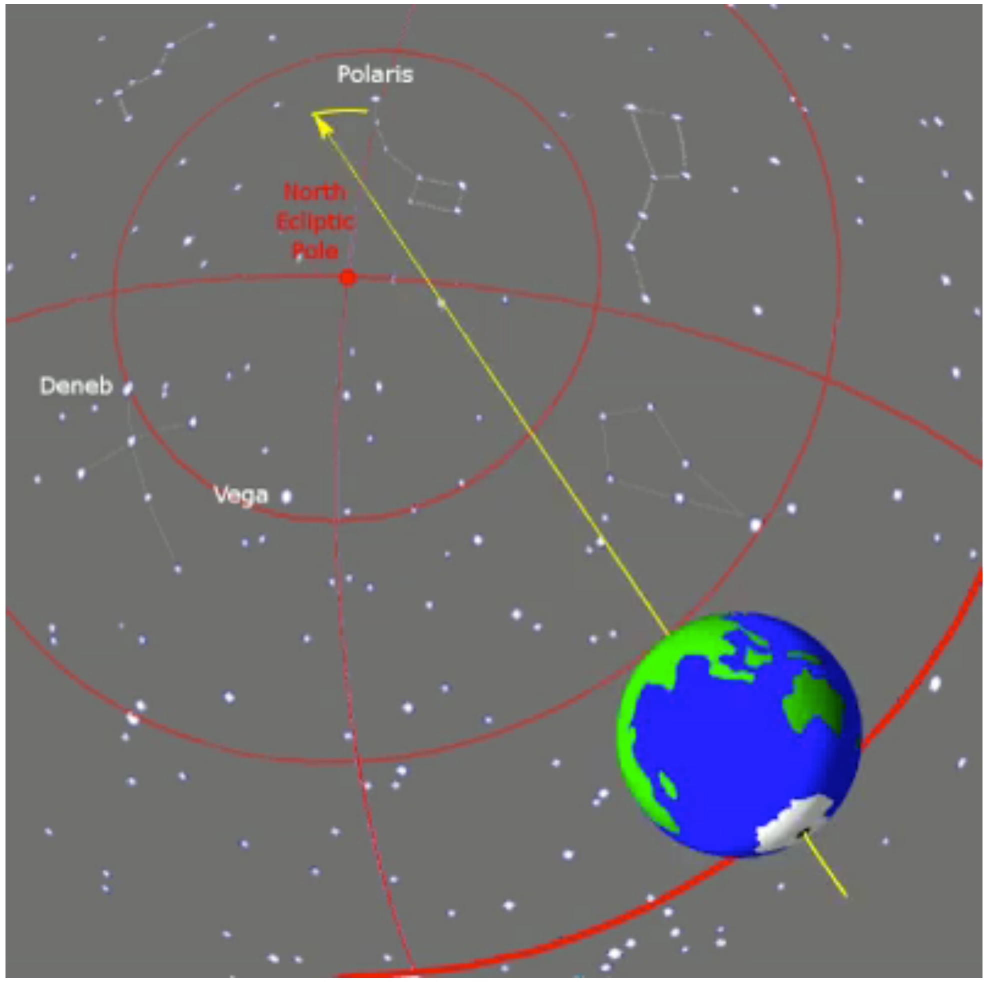
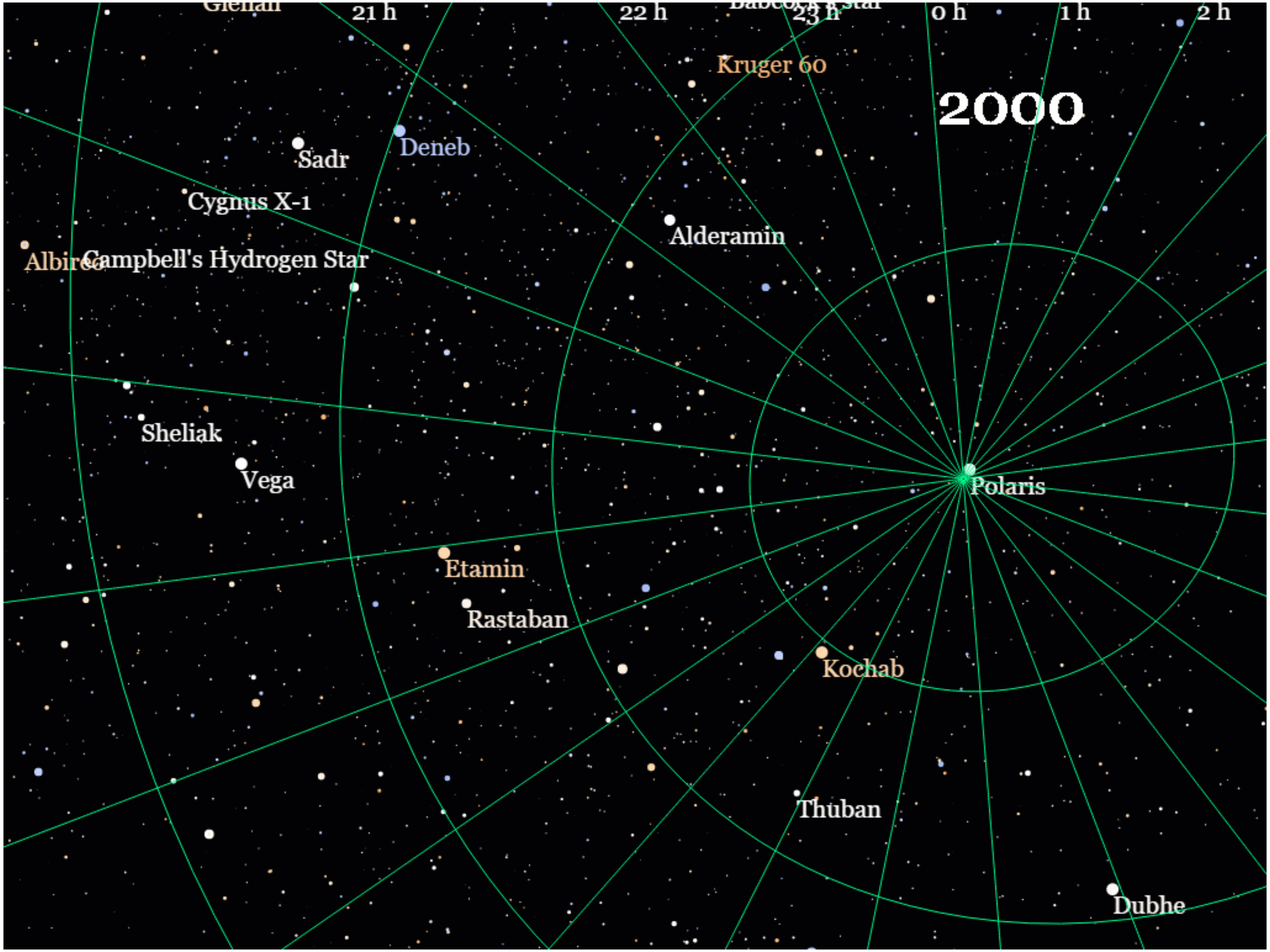


Effect of (Earth's) motion

Precession



Effect of (Earth's) motion

Precession — Changing Pole (Northern) Stars

Present Pole star Polaris is extremely well suited to mark the position of the north celestial pole, as Polaris is a moderately bright star with a visual magnitude of 2.1 (variable), and it is located about one degree from the pole.

The previous pole star was Kochab (Beta Ursae Minoris, β UMi, β Ursae Minoris), located 16 degrees from Polaris. It held that role from 1500 BC to AD 500. It was not quite as accurate in its day as Polaris is today.

Thuban in the constellation Draco, which was the pole star in 3000 BC, is much less conspicuous at magnitude 3.67 (one-fifth as bright as Polaris).

Vega in the constellation Lyra was the pole star around 12,000 BC and will do so again around the year 14,000, however, it never comes closer than 5° to the pole.

Effect of (Earth's) motion

Precession — Changing Pole (Southern) Stars

The Southern Cross constellation functions as an approximate southern pole constellation.

Around 200 BC, the star Beta Hydri was the nearest bright star to the Celestial south pole. Around 2800 BC, Achernar was only 8 degrees from the south pole.

In the next 7500 years, the south Celestial pole will pass close to the stars Gamma Chamaeleontis (4200 CE), I Carinae, Omega Carinae(5800 CE), Upsilon Carinae, Iota Carinae (Aspidiske, 8100 CE) and Delta Velorum (9200 CE)

From the eightieth to the ninetieth centuries, the south Celestial pole will travel through the False Cross.

Around 14,000 CE, when Vega is only 4° from the North Pole, Canopus will be only 8° from the South Pole and thus circumpolar on the latitude of Bali (8°S).

What do you know about BC, BCE and AD?

Effect of (Earth's) motion

Nutation

Precession is caused by the Sun and the Moon. However, the Moon does not orbit exactly in the ecliptic plane, but at an inclination of about 5° to it. The Moon's orbit precesses rapidly, with the nodes taking 18.6 years to complete one circuit. The lunar contribution to luni-solar precession adds a short-period, small-amplitude wobble to the precessional movement of the North Celestial Pole; this wobble is called **Nutation.**

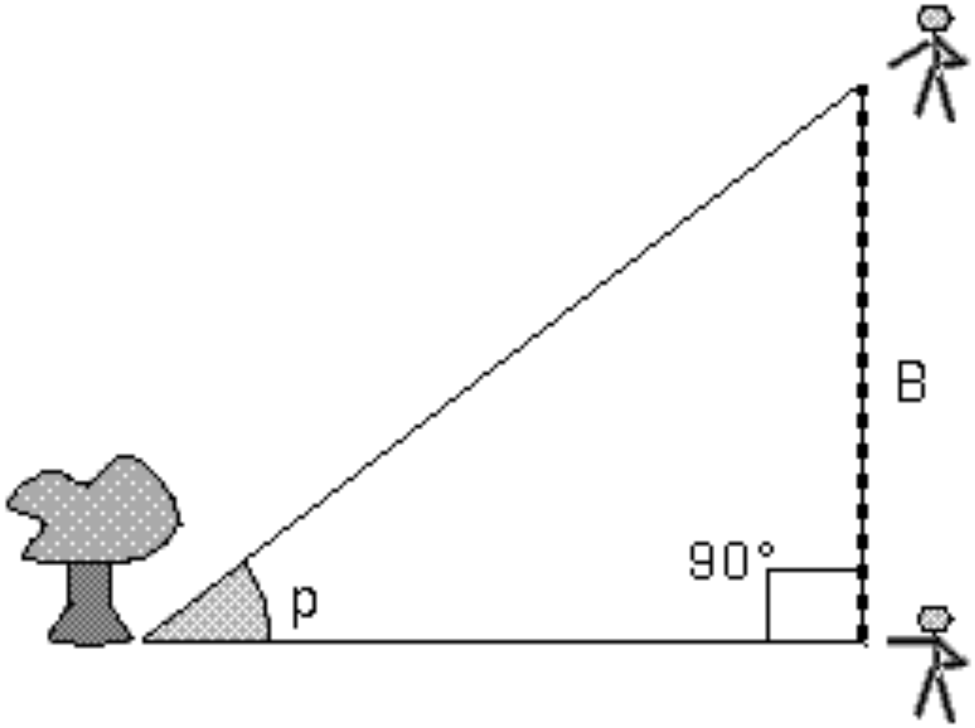
Nutation

- Due to Moon's non-circular orbit and precession of nodes of its orbit with a period of 18.6 years
- Produces an additional "nodding" motion on the Earth's axis
- Quite complex, with many non-harmonic components (106!) for Moon/Sun/planet interactions

Effect of (Earth's) motion

Trigonometric Parallax

- A favourite way to measure great distances is a technique used for thousands of years
- Look at something from two different vantage points and determine its distance using trigonometry.
- The object appears to shift positions compared to the far off background when you look at it from two different vantage points.
- The angular shift, called the *parallax*, is one angle of a triangle and the distance between the two vantage points is one side of the triangle.
- Basic trigonometric relations between the lengths of the sides of a triangle and its angles are used to calculate the lengths of all of the sides of the triangle.
- This method is called **trigonometric parallax**.

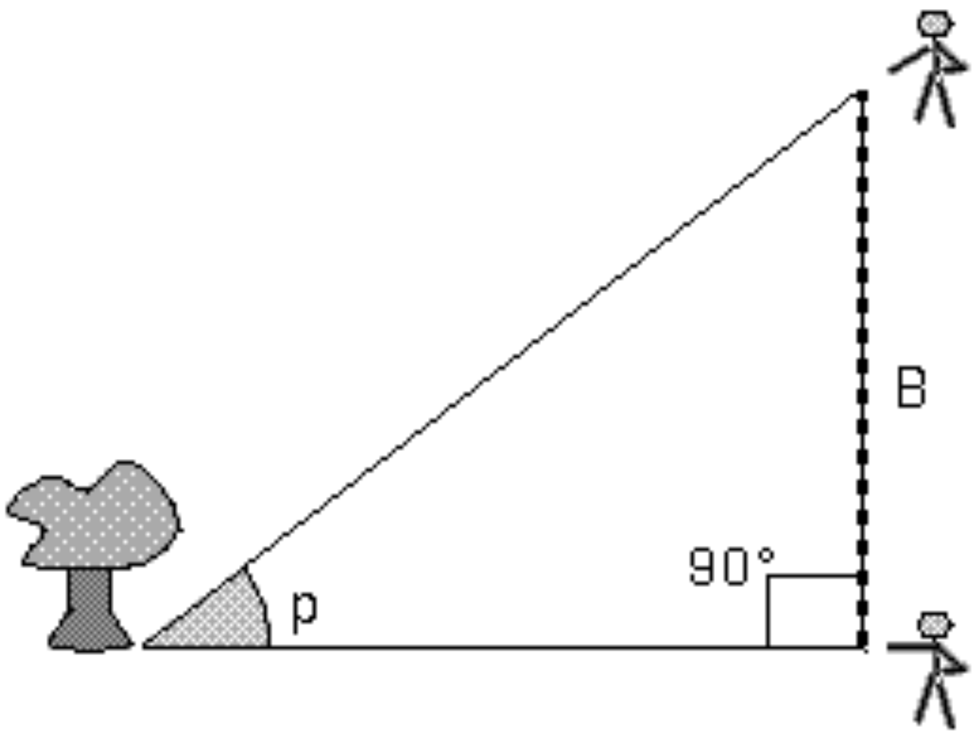


If we know one side (B) and one angle (p) of a right triangle, we can derive the length of the other two sides.

Effect of (Earth's) motion

Trigonometric Parallax

- The side of the triangle between the observers, labelled "B" in the figure, is called the *baseline*.
- The size of the parallax angle p is proportional to the size of the baseline. If the parallax angle is too small to measure because the object is so far away, then the person in the figure have to increase their distance from each other.
- Ordinarily, you would have to use trigonometric functions like a *tangent* or a *sine*, but if the angle is small enough, you find a very simple relation between the parallax angle p, baseline B, and the distance d:
- $p = (206{,}265 \times B)/d$ (small angle formula!)
- where the angle p is measured in the tiny angle unit called an *arc second*.
- The farther away the object is, the less it appears to shift. Since the shifts of the stars are so small, arc seconds are used as the unit of the parallax angle.
- There are 3,600 arc seconds in just one degree. The ball in the tip of a ballpoint pen viewed from across the length of a football field is about 1 arc second.



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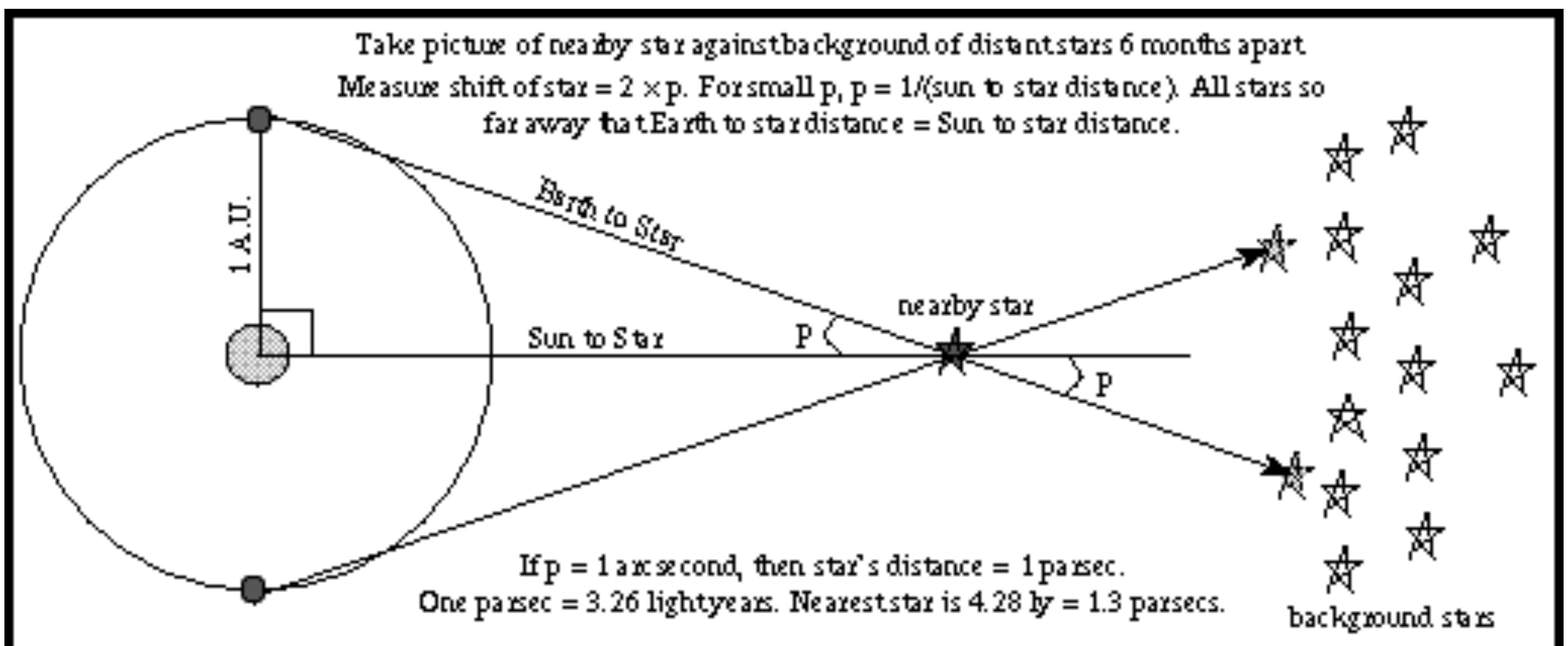
Effect of (Earth's) motion

Trigonometric Parallax

- **Trigonometric parallax** is used to measure the distances of the nearby stars.
- The stars are so far away that observing a star from opposite sides of the Earth would produce a parallax angle much, much too small to detect.
- As large a baseline as possible must be used.
- The largest one that can be easily used is the orbit of the Earth. In this case the baseline is the distance between the Earth and the Sun---an **astronomical unit** (AU) or 149.6 million kilometers!
- The image below of a nearby star is taken against the background of stars from opposite sides of the Earth's orbit (six months apart). The parallax angle *p* is one-half of the total angular shift.



Effect of (Earth's) motion

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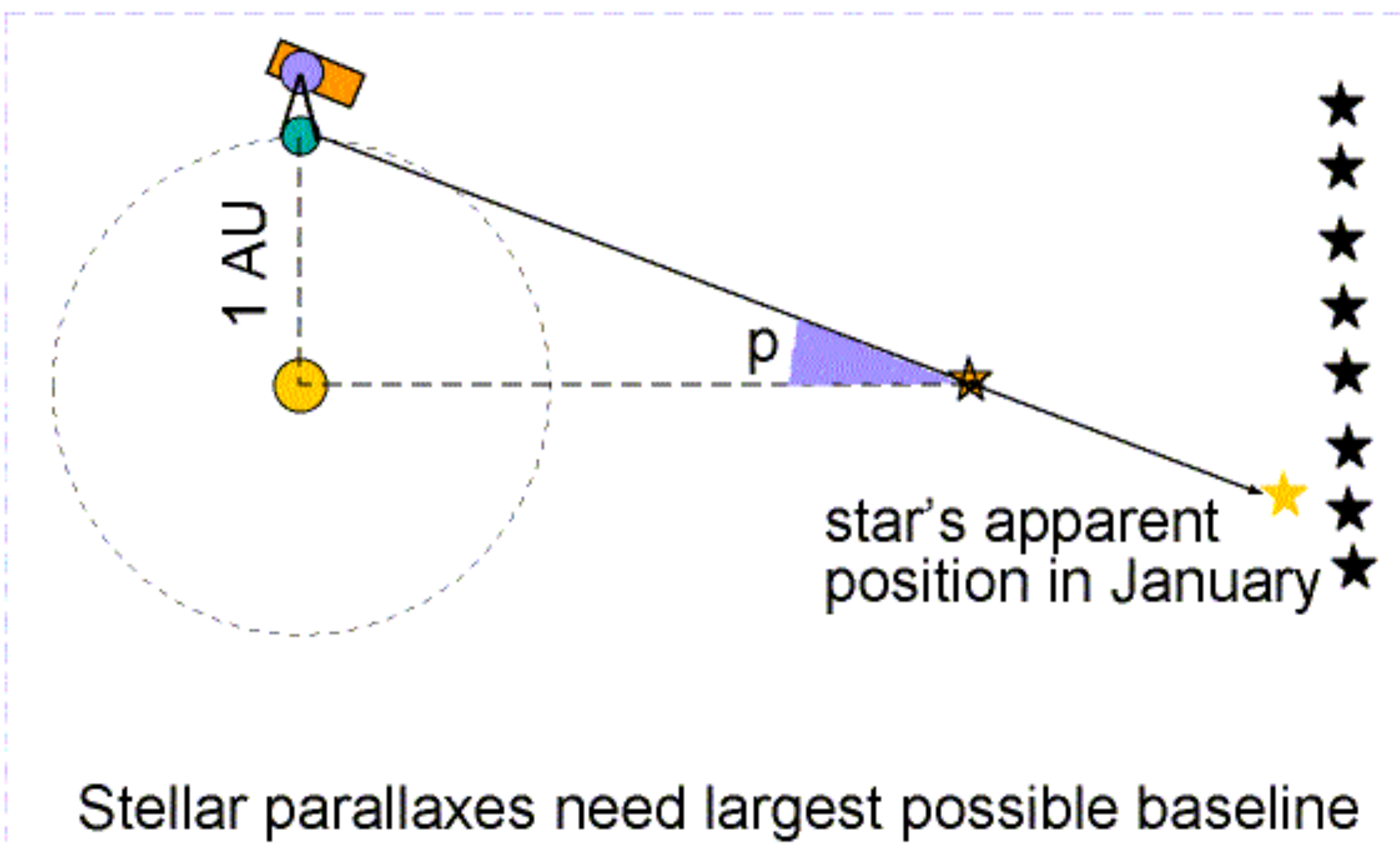


Effect of (Earth's) motion

Trigonometric Parallax

- The image (on previous slide) of a nearby star is taken against the background of stars from opposite sides of the Earth's orbit (six months apart). The parallax angle p is one-half of the total angular shift.
- However, even with this large baseline, the distances to the stars in units of astronomical units are huge, so a more convenient unit of distance called a **parsec** is used (abbreviated with ``pc'').
- A parsec is the distance of a star that has a <u>par</u>allax of one arc <u>sec</u>ond using a baseline of 1 astronomical unit. Therefore, one parsec = 206,265 astronomical units.
- The nearest star is about 1.3 parsecs from the solar system. In order to convert parsecs into standard units like kilometers or meters, you must know the numerical value for the astronomical unit---it sets the scale for the rest of the universe.
- In terms of light years, one parsec = 3.26 light years.
- Using a parsec for the distance unit and an arc second for the angle, our simple angle formula above becomes extremely simple for measurements from Earth:
- $p = 1/d$

Effect of (Earth's) motion

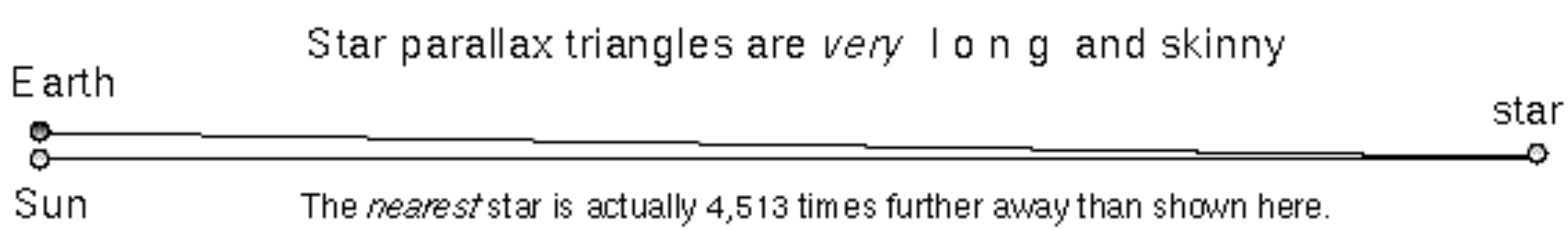
Trigonometric Parallax

- Parallax angles as small as 1/50 arc second can be measured from the *surface* of the Earth.
- This means distances *from the ground* can be determined for stars that are up to 50 parsecs away. If a star is further away than that, its parallax angle *p* is too small to measure and we have to use more indirect methods to determine its distance.
- Stars are about a parsec apart from each other on average, so the method of trigonometric parallax works for just a few thousand nearby stars.
- The Hipparcos mission greatly extended the database of trigonometric parallax distances by getting above the blurring effect of the atmosphere. It measured the parallaxes of 118,000 stars to an astonishing precision of 1/1000 arc second (about 20 times better than from the ground)! It measured the parallaxes of 1 million other stars to a precision of about 1/20 arc seconds.
- Twenty-three years after the Hipparcos mission ended, a much larger database of distances for over one billion stars was released from the Gaia mission. Gaia is able to measure parallaxes 200 times more accurately than Hipparcos, so it can measure parallaxes out to 30,000 light years. A second data release 1.5 years later included velocities for many of those stars, as well as, radii, luminosities, and temperatures.

Effect of (Earth's) motion

Trigonometric Parallax

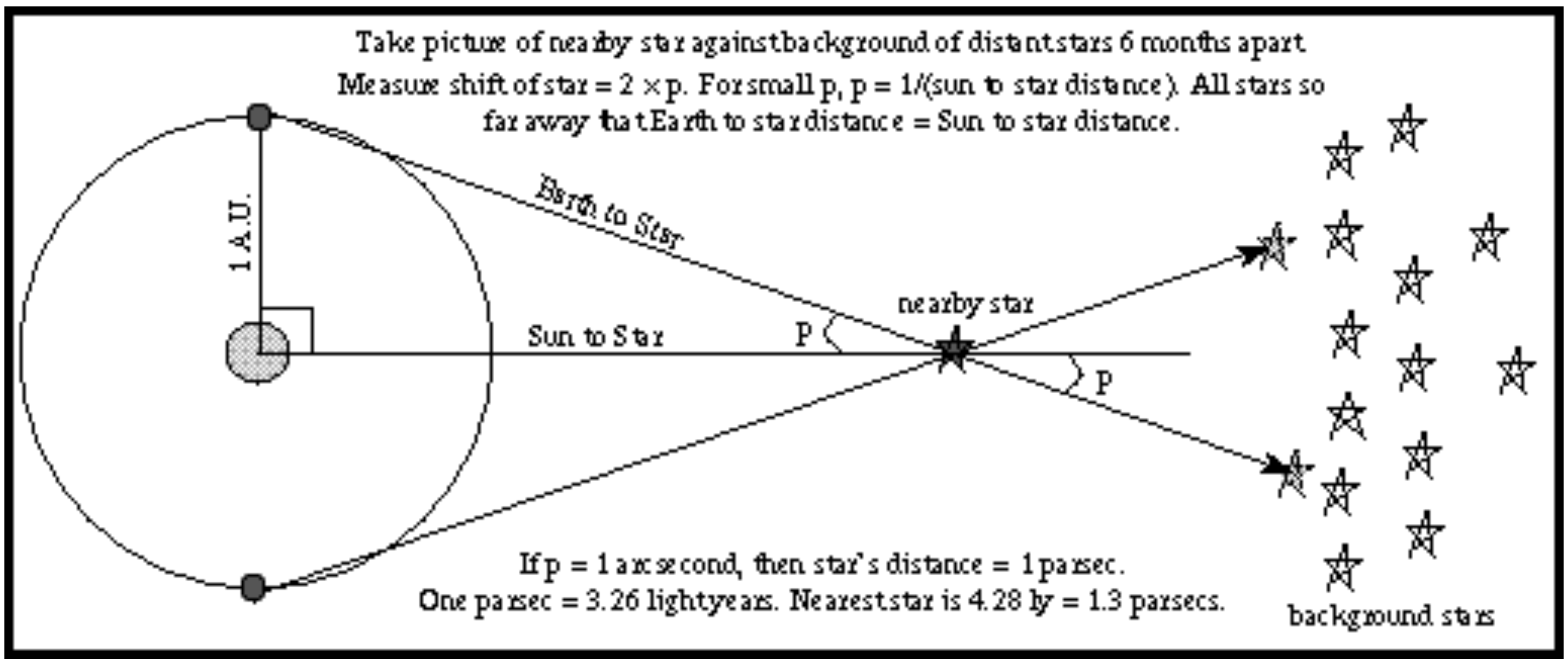
- Parallax angles as small as 1/50 arc second can be measured from the surface of the Earth.
- The actual stellar parallax triangles are much longer and skinnier than the ones typically shown in astronomy textbooks. They are so long and skinny that you do not need to worry about which distance you actually determine: the distance between the Sun and the star or the distance between the Earth and the star.
- Taking a look at the skinny star parallax triangle in the image below and realising that the triangle should be over 4,500 times longer (!), you can see that it does not make any significant difference which distance you want to talk about.
- If Pluto's entire orbit was fit within a quarter (2.4 centimeters across), the nearest star would be 80 meters away! But if you are stubborn, consider these figures for the planet-Sun-star star parallax triangle setup above (where the planet-star side is the hypotenuse of the triangle):
- the Sun--nearest star distance = 267,068.230220 AU = 1.2948 pc;
- the Earth--nearest star distance = 267,068.230222 AU = 1.2948 pc;
- Pluto--nearest star distance = 267,068.233146 AU = 1.2948 pc!



Effect of (Earth's) motion

Trigonometric Parallax

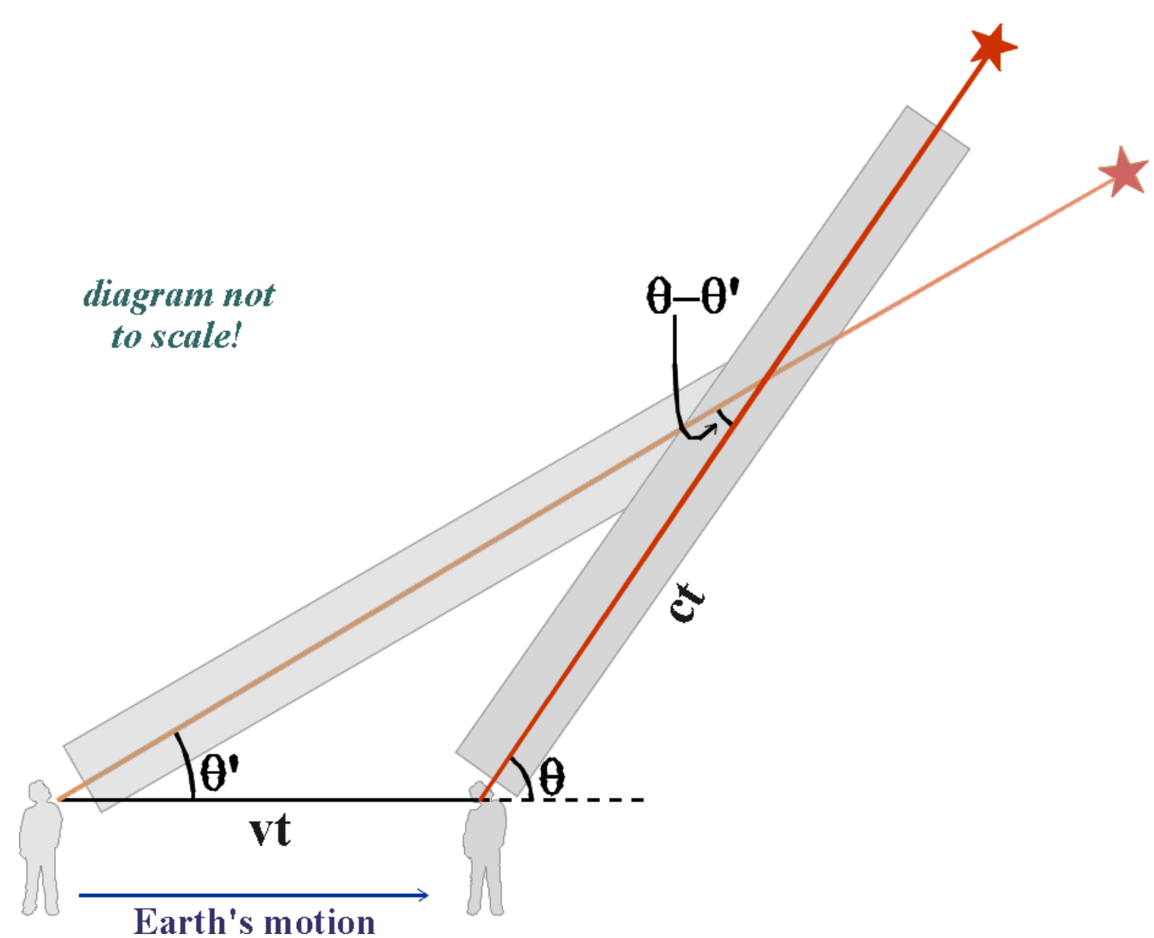
- Take picture of nearby star against background of distant stars 6 months apart.
- Measure shift of star = 2 x p.
- For small p, p = 1/ (sun to star distance)
- All stars so far away that Earth to star distance = Sun to star distance
- If p = 1 arc second, then star's distance = 1 parsec
- Nearest star (Alpha Centauri) is 4.28 light years = 1.3 parsecs
- Alpha Centauri is one of the brightest stars in the southern skies and is the nearest stellar system to our Solar System — only 4.3 light-years away. It is actually a triple star — a system consisting of two stars similar to the Sun orbiting close to each other, designated Alpha Centauri A and B, and a more distant and faint red component known as Proxima Centauri.



Effect of (Earth's) motion

Proper Motion

- Due to the real space motion of stars within the Galaxy
- Relative motion between star and the Sun (which is moving at ~200 km /s in its orbit around the Galaxy)
- Only really noticeable with ground based telescopes on the nearest or fastest moving stars (e.g. white dwarfs)
- Satellite observations have/will improve information on proper motions (e.g. Hipparcos & Gaia)



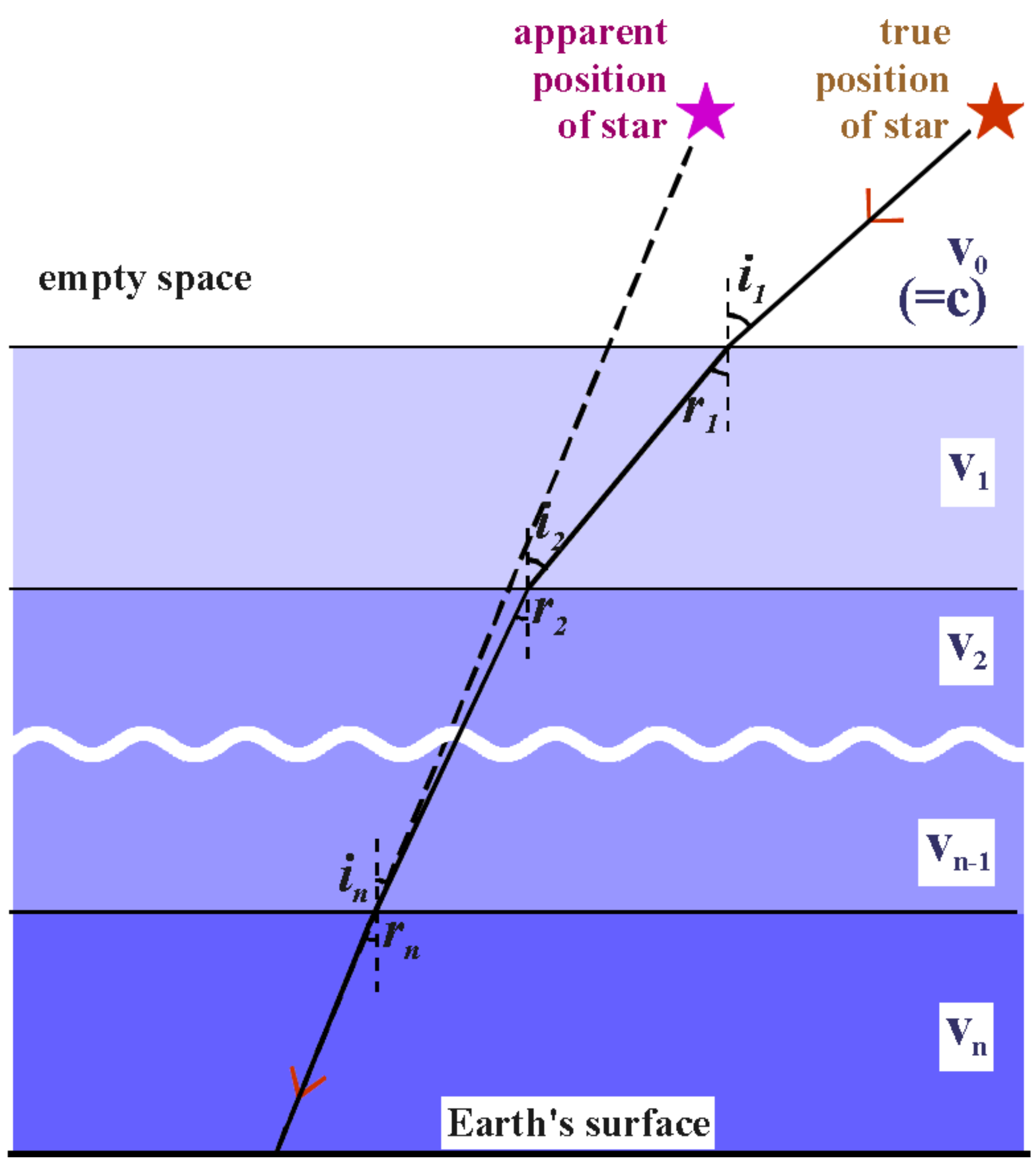
Effects of Earth's atmosphere on starlight

- Seeing – fuzzy appearance instead of being a diffraction pattern.
- Scintillation – rapid change in brightness (twinkling).
- Extinction – dimming.
- Refraction – bending of light esp for objects near the horizon.
- Dispersion – white light splits into constituent colours.

Atmospheric Refraction

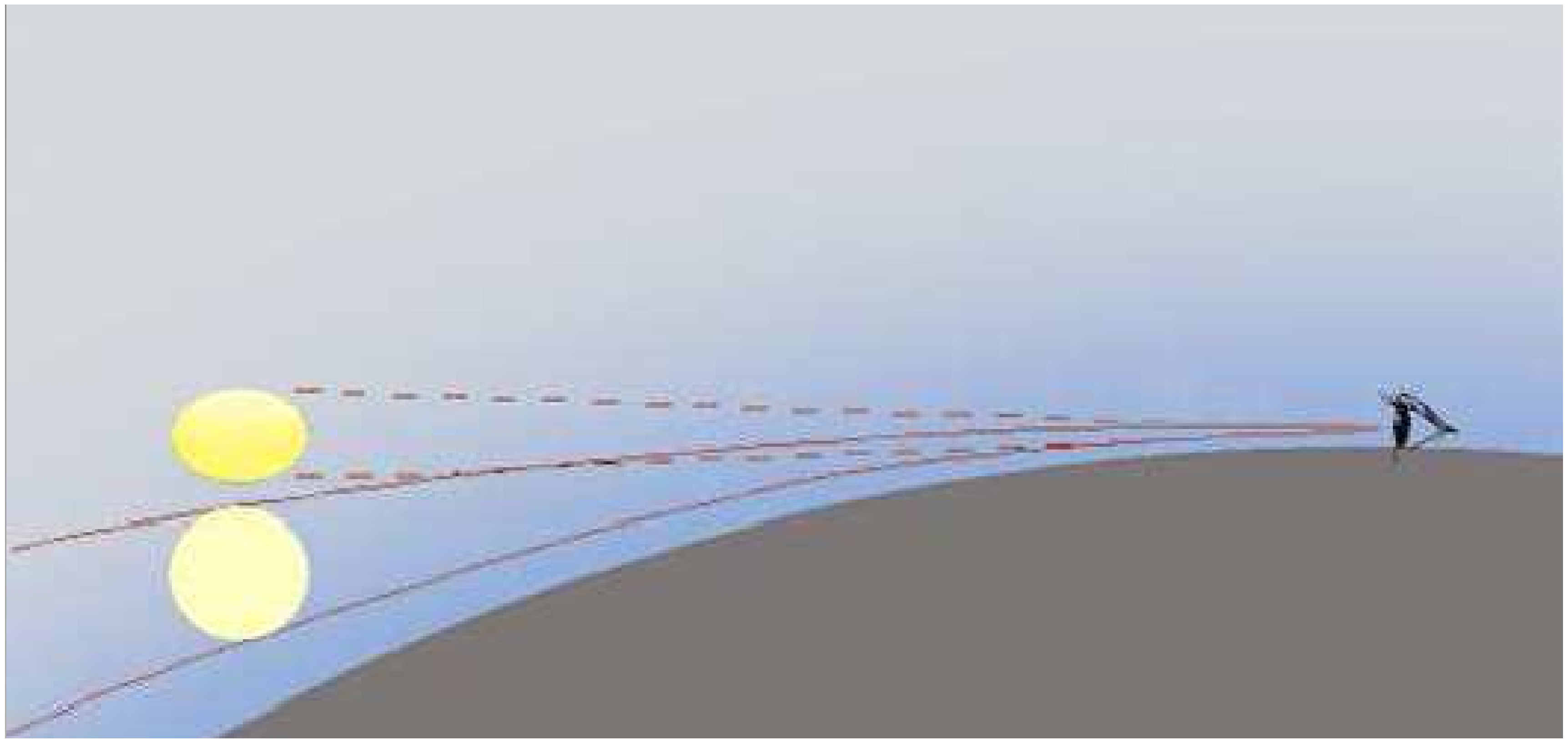
Atmospheric Refraction

- Earth's atmosphere acts like a lens due to the layered behaviour of the index of refraction of the atmosphere
- Refraction effects more apparent for higher angle of incidence ⇒ larger Zenith Distances of objects



Atmospheric Refraction

Atmospheric Refraction Effect on Setting/Rising Sun



Units used for astronomical measurements

- The **astronomical unit** (symbol: **au** or **AU**) — is a **unit of length**, roughly the distance from Earth to the Sun (**1 au = 1.495978707×10^{11} meters**)
- **light-year** (symbol: **ly**)— is the distance that light travels in vacuum in one Julian year (**1 ly = 9.4607×10^{15} meters**)
- The **parsec** (symbol: **pc**) is a unit of length used to measure the large distances to astronomical objects outside the Solar System.
- 1 pc — 3.0857×10^{16} meters; 2.06265×10^{5} au; 3.26156 ly

Telescope

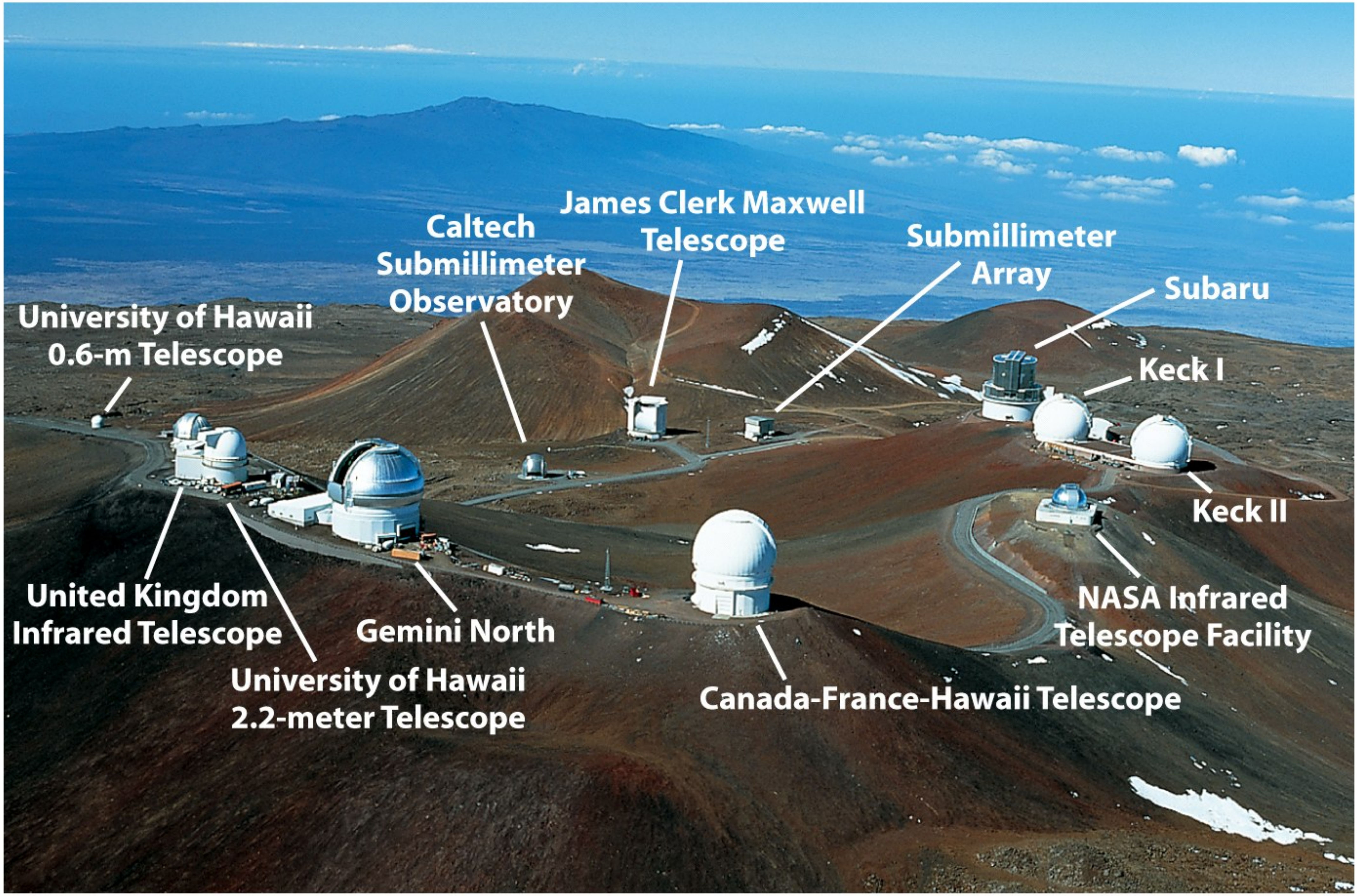
Telescopes

table 6-1 The World's Largest Optical Telescopes

Telescope	Location	Year of completion	Mirror diameter (m)
Gran Telescopio Canarias	La Palma, Canary Islands, Spain	2004	10.4
Keck II	Mauna Kea, Hawaii	1996	10.0
Keck I	Mauna Kea, Hawaii	1993	10.0
Hobby-Eberly Telescope	McDonald Observatory, Texas	1998	11.0*
South African Large Telescope	Sutherland, South Africa	2004	9.2
Large Binocular Telescope	Mount Graham, Arizona	2004–05	Two 8.4
Subaru	Mauna Kea, Hawaii	1999	8.3
VLT UT 1–Antu	Cerro Paranal, Chile	1998	8.2
VLT UT 2–Kueyen	Cerro Paranal, Chile	1999	8.2
VLT UT 3–Melipal	Cerro Paranal, Chile	2000	8.2
VLT UT 4–Yepun	Cerro Paranal, Chile	2000	8.2
Gemini North (Gillett)	Mauna Kea, Hawaii	1999	8.1
Gemini South	Cerro Pachón, Chile	2000	8.1

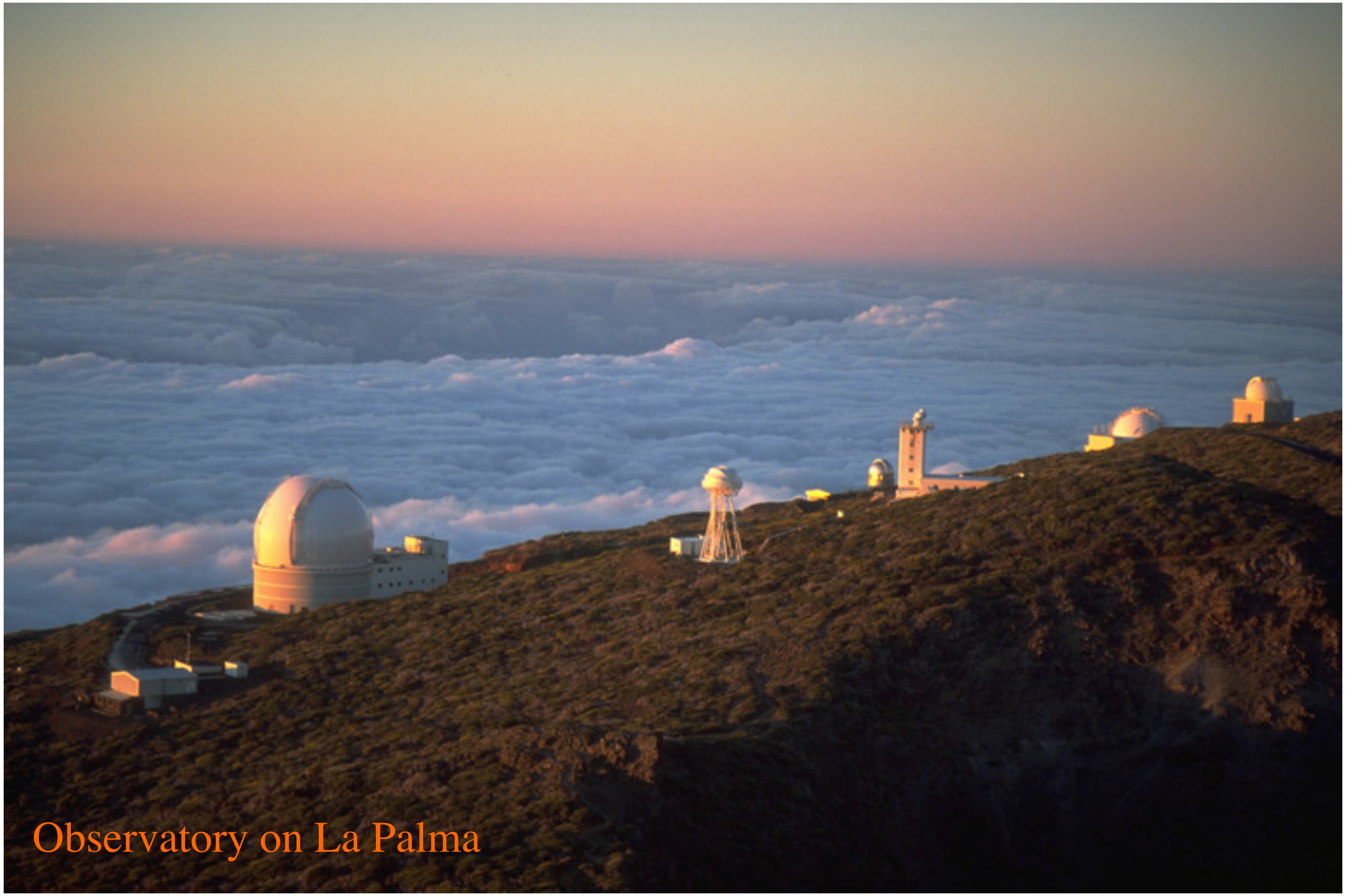
**The objective mirror of the Hobby-Eberly Telescope is 11.0 m in diameter, but in operation only an area of 9.2 m in diameter is used to collect light.*

Telescopes



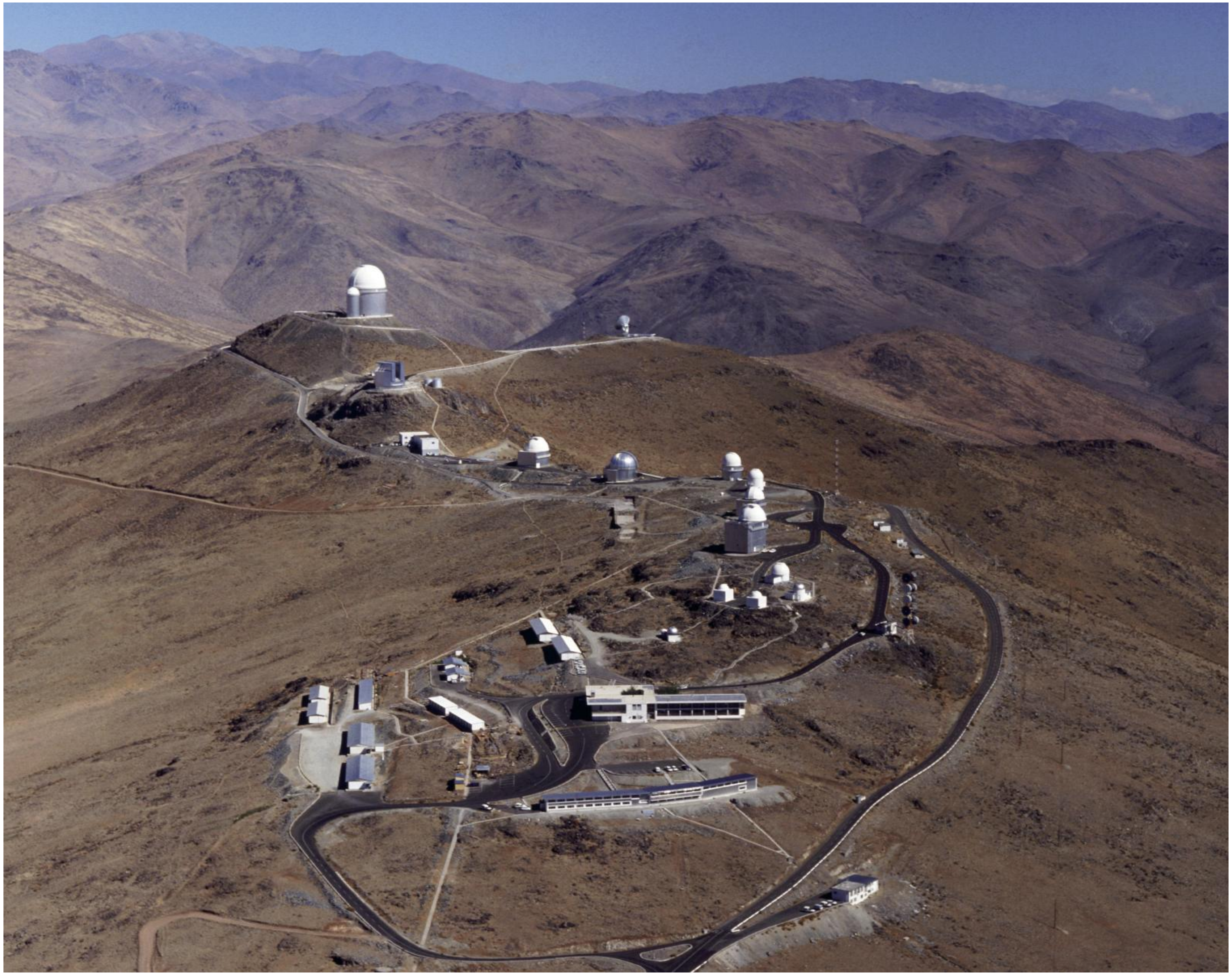
The telescopes of Mauna Kea

Telescopes



From left to right, the William Herschel Telescope, Dutch Open Telescope, the Carlsberg Meridian Telescope, the Swedish Solar Telescope, the Isaac Newton Telescope (second from right) and the Jacobus Kapteyn Telescope (far right) at Roque de los Muchachos. (Photo by Bob Tubbs)

Telescopes



La Silla Observatory in Chile operated by the European Southern Observatory (ESO)

Telescopes

Paranal Observatory in Chile operated by the European Southern Observatory (ESO)

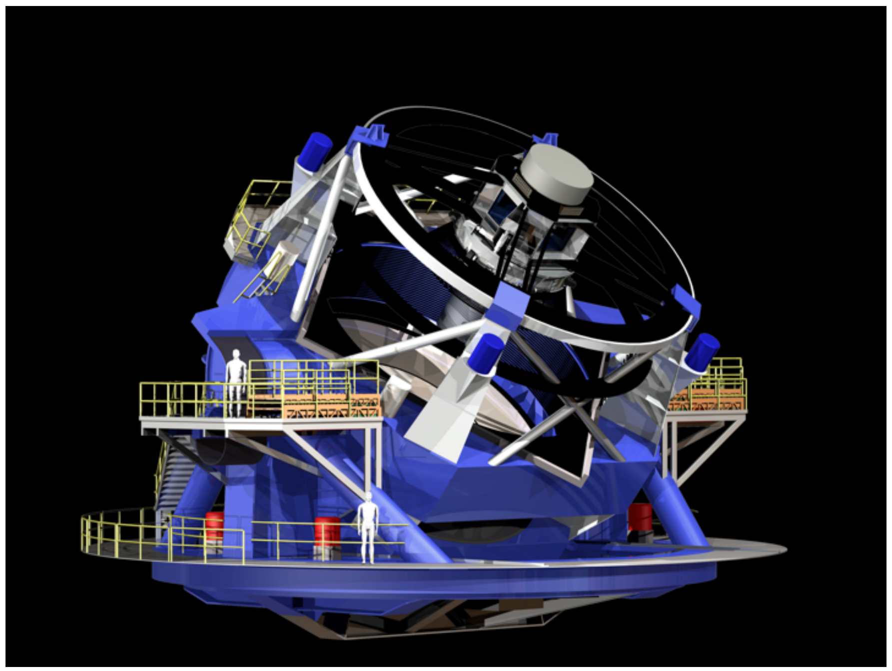
Telescopes

Find out about IIA Telescopes?

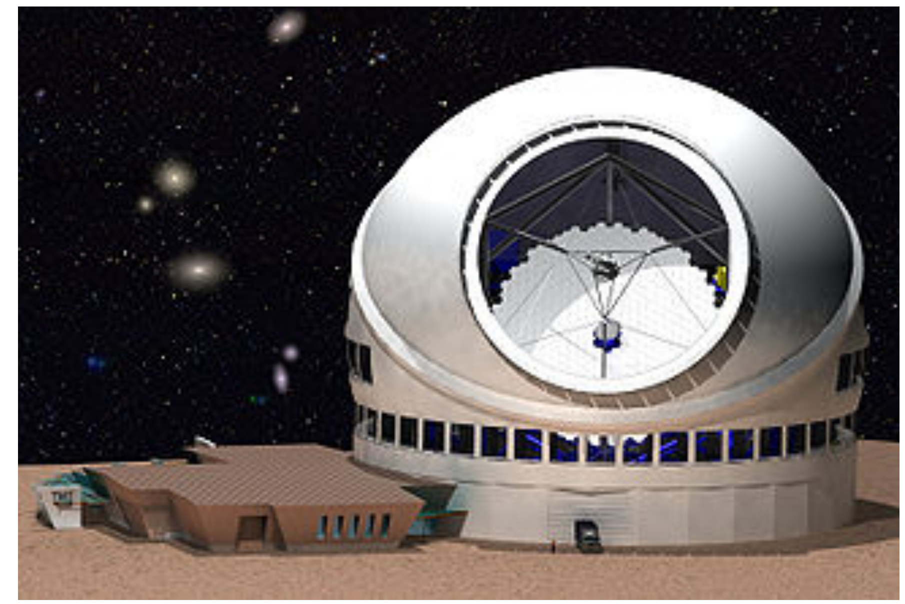
Telescopes

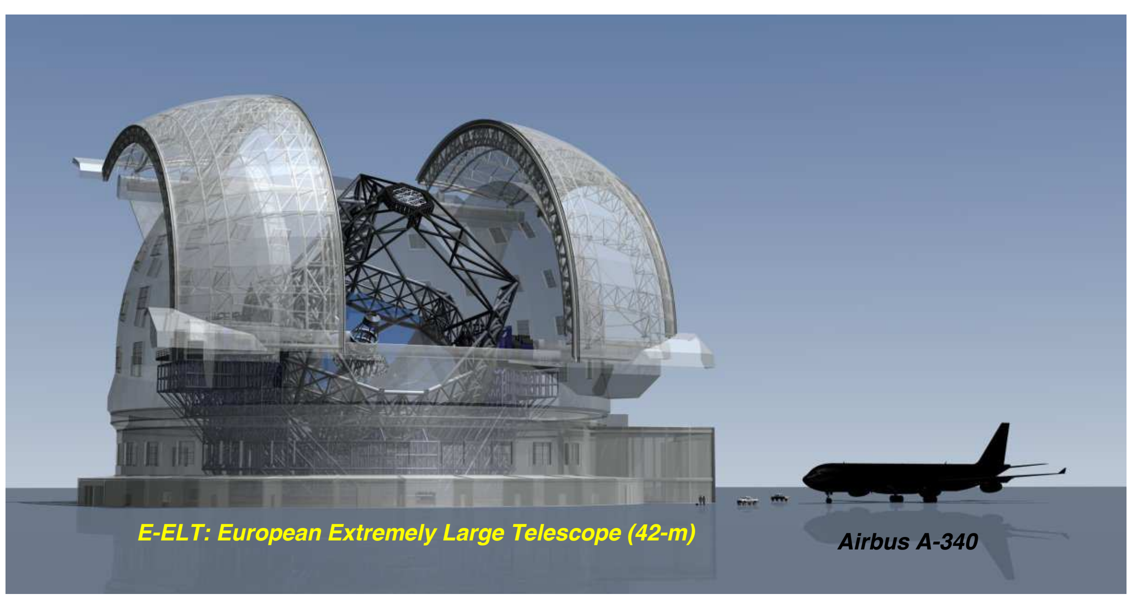
The Era of Large Telescopes

Large Synaptic Survey Telescope (LSST)

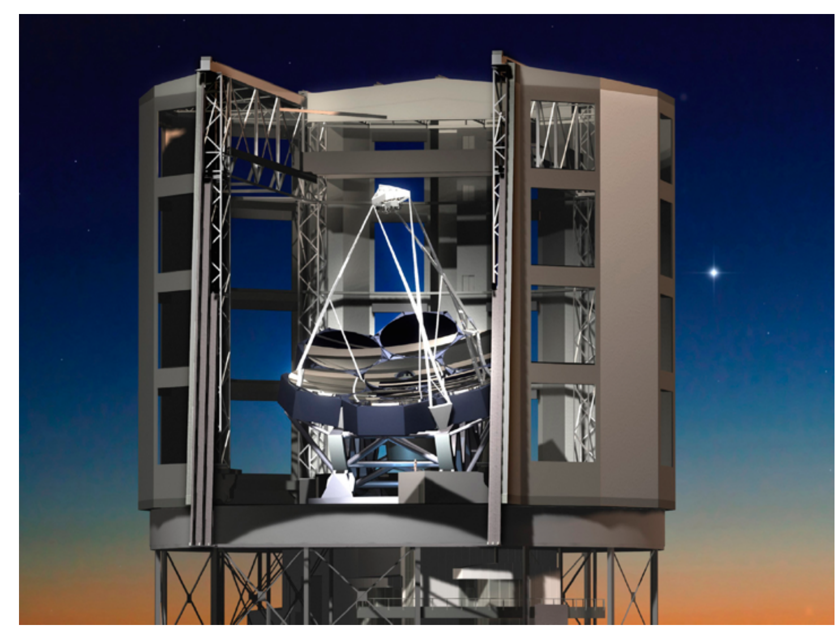


Thirty Meter Telescope (TMT)





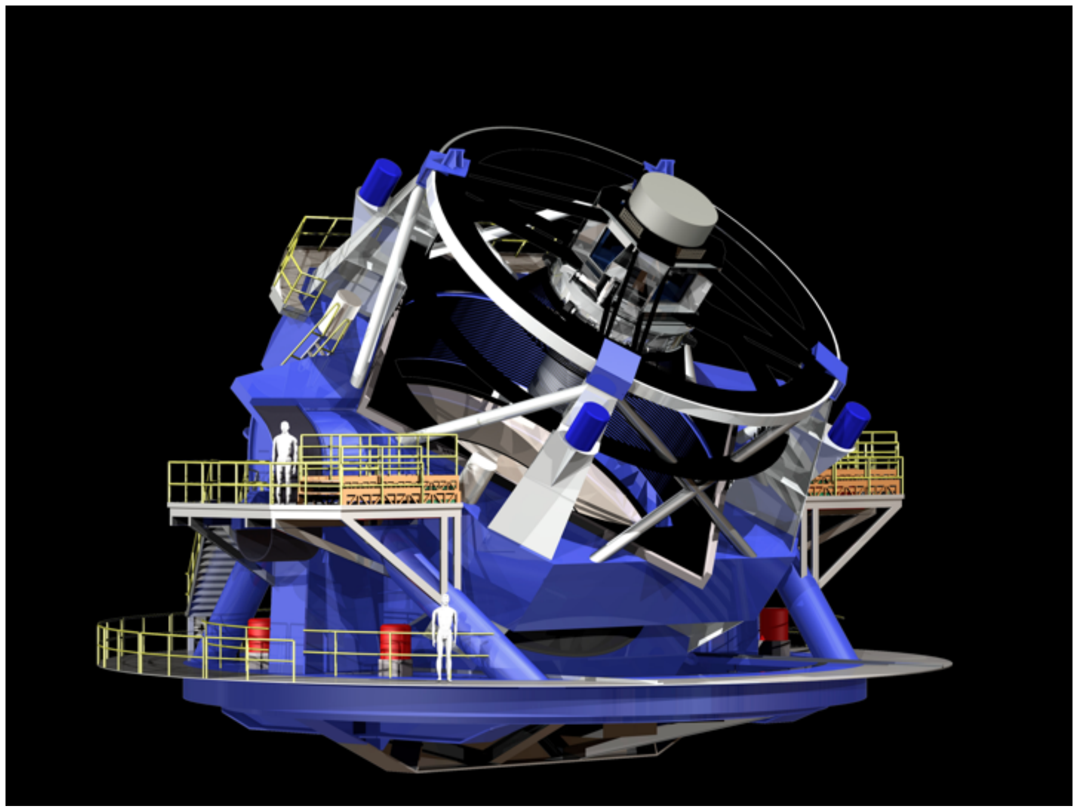
Extremely Large Telescope (ELT)



Giant Magellan Telescope (GMT)

Telescopes

The Era of Large Telescopes



Location	El Peñón, Chile
Altitude	2,662.75 m
Wavelength	320–1060 nm
Built	2014–2021
Diameter	8.360 m
Collecting area	35 m²
Camera	32 GigaPixel

LSST

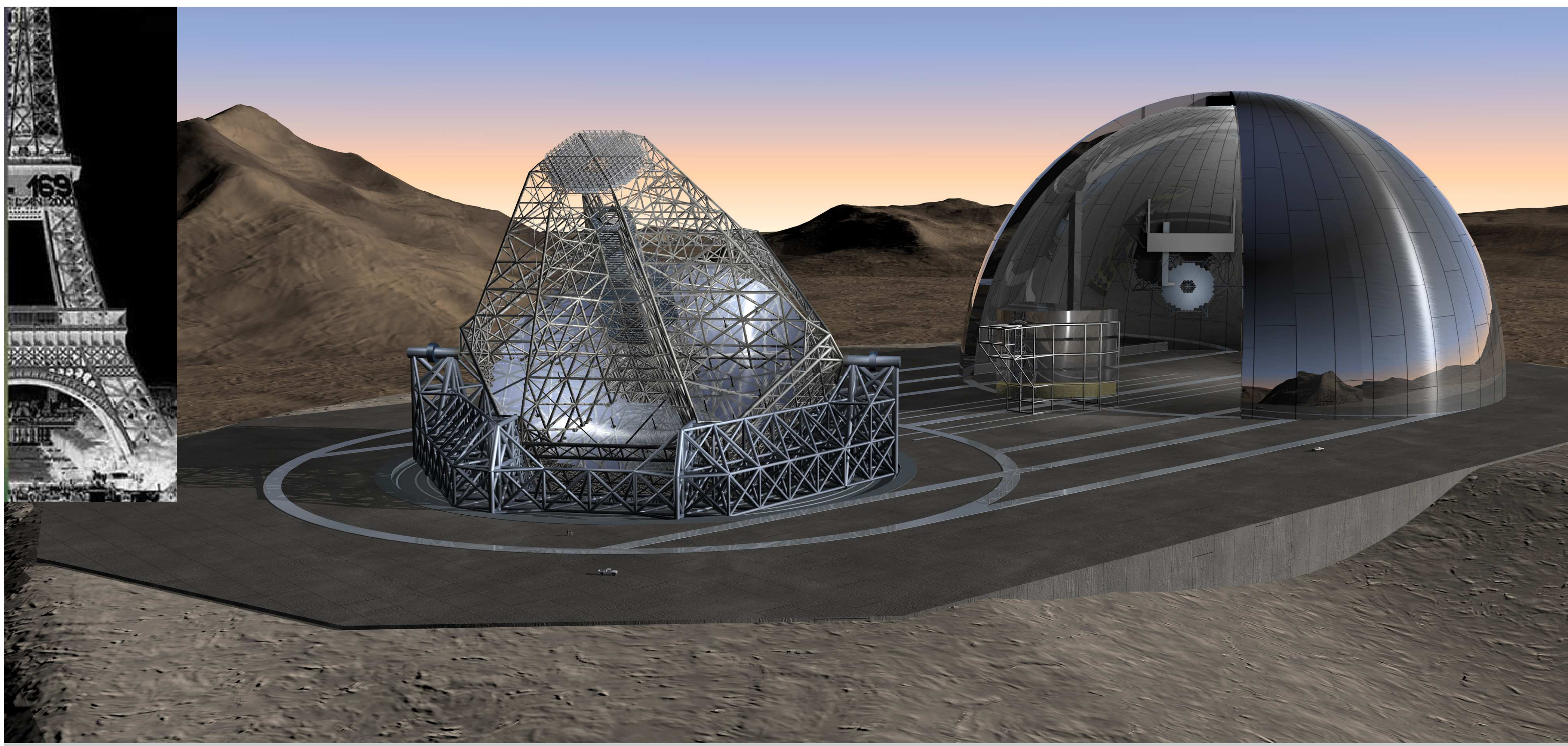
Southern Sky Survey
15-second exposure every 20 seconds
200,000 pictures = 1.28 petabytes data per year

Telescopes

The Era of Large Telescopes

The Original European 100-m OWL concept

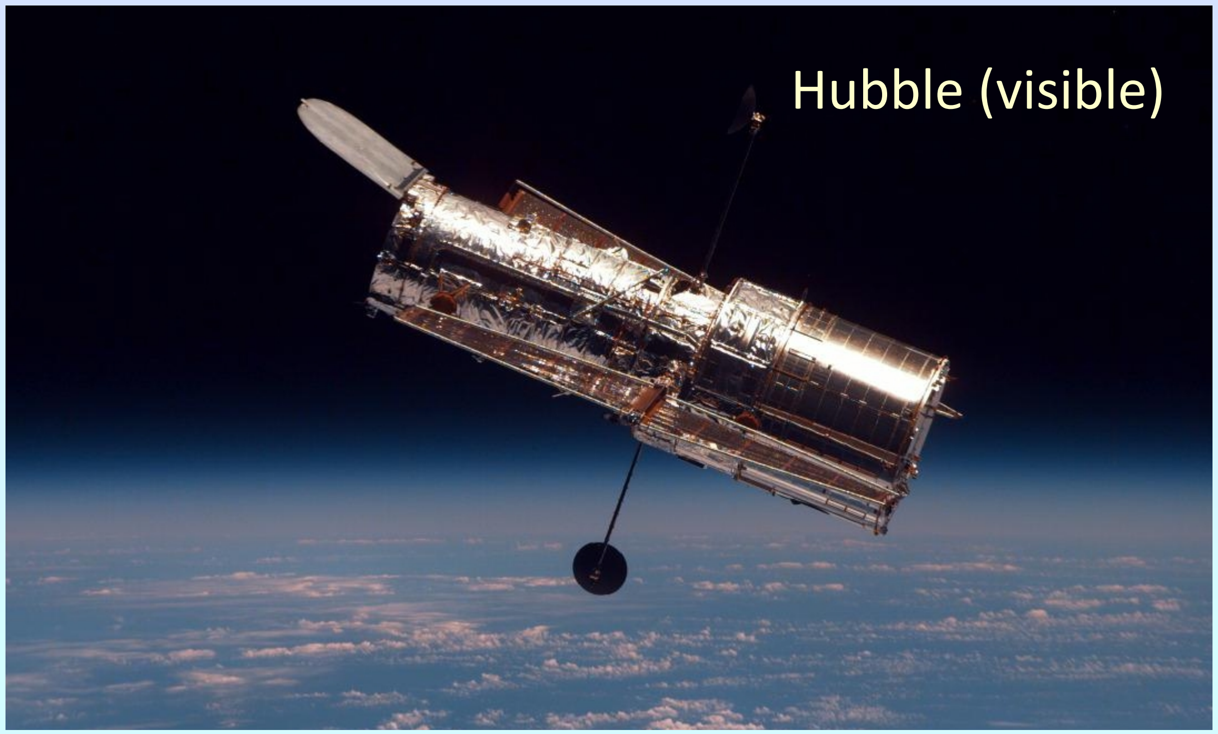
(Overwhelmingly Large Telescope)

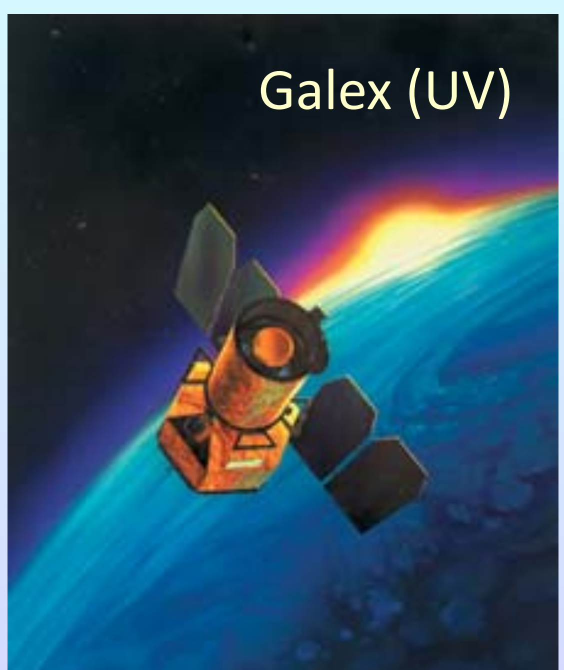


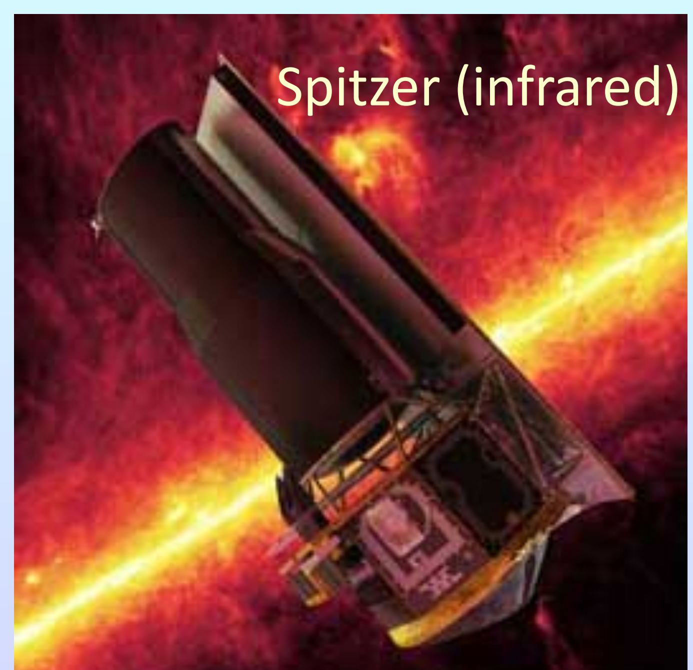
Also sometime disparagingly called the ULT: Unnecessarily Large Telescope!

Telescopes

Space Observatories







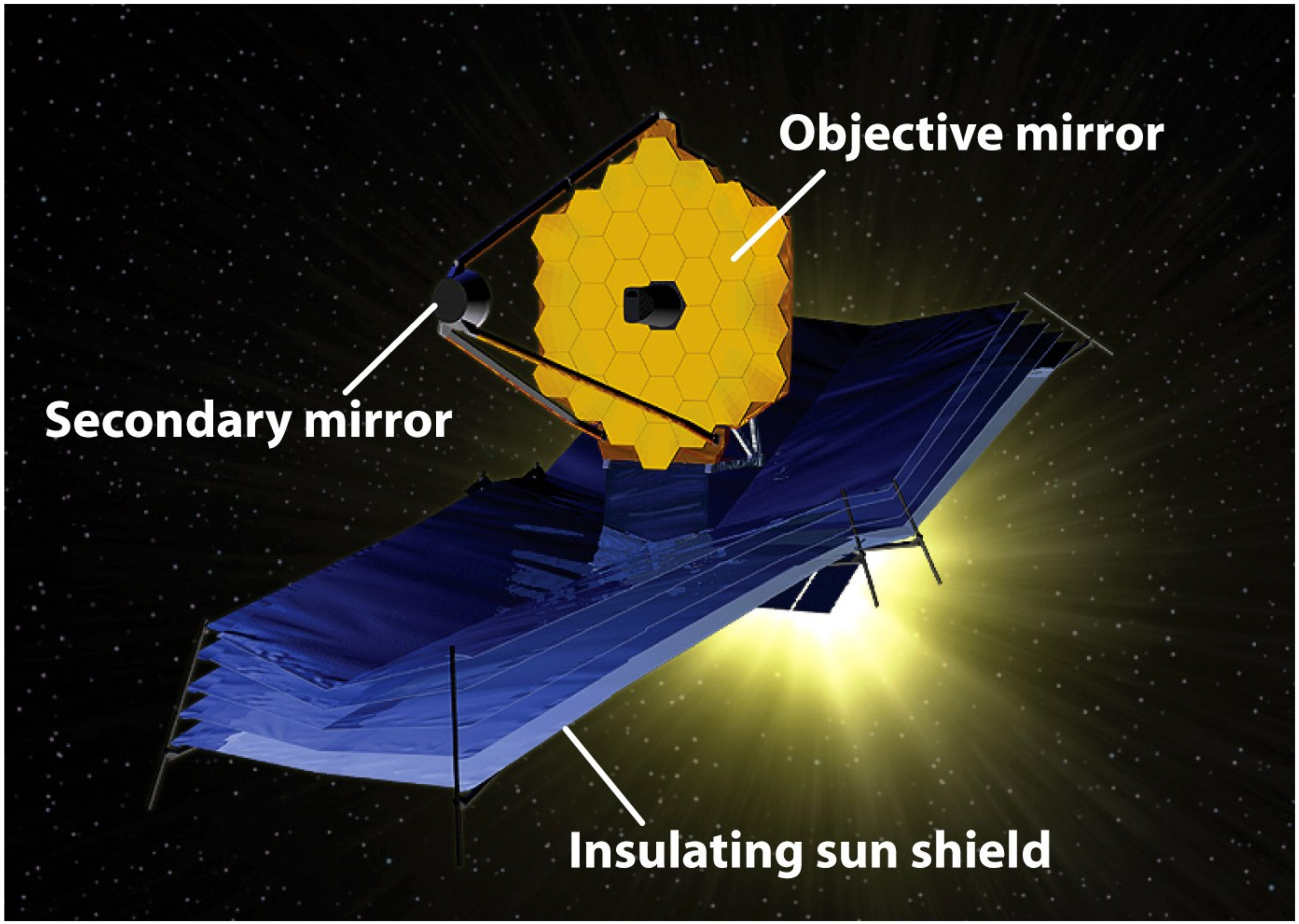
Telescopes

Hubble Space Telescope (HST)

The Hubble Space Telescope (HST) launched in 1990 had a 2.4-meter objective mirror and was designed to observe at wavelengths from 115 nm (ultraviolet) to 1μm (infrared). HST uses a CCD to record images. HST has made numerous discoveries.

Telescopes

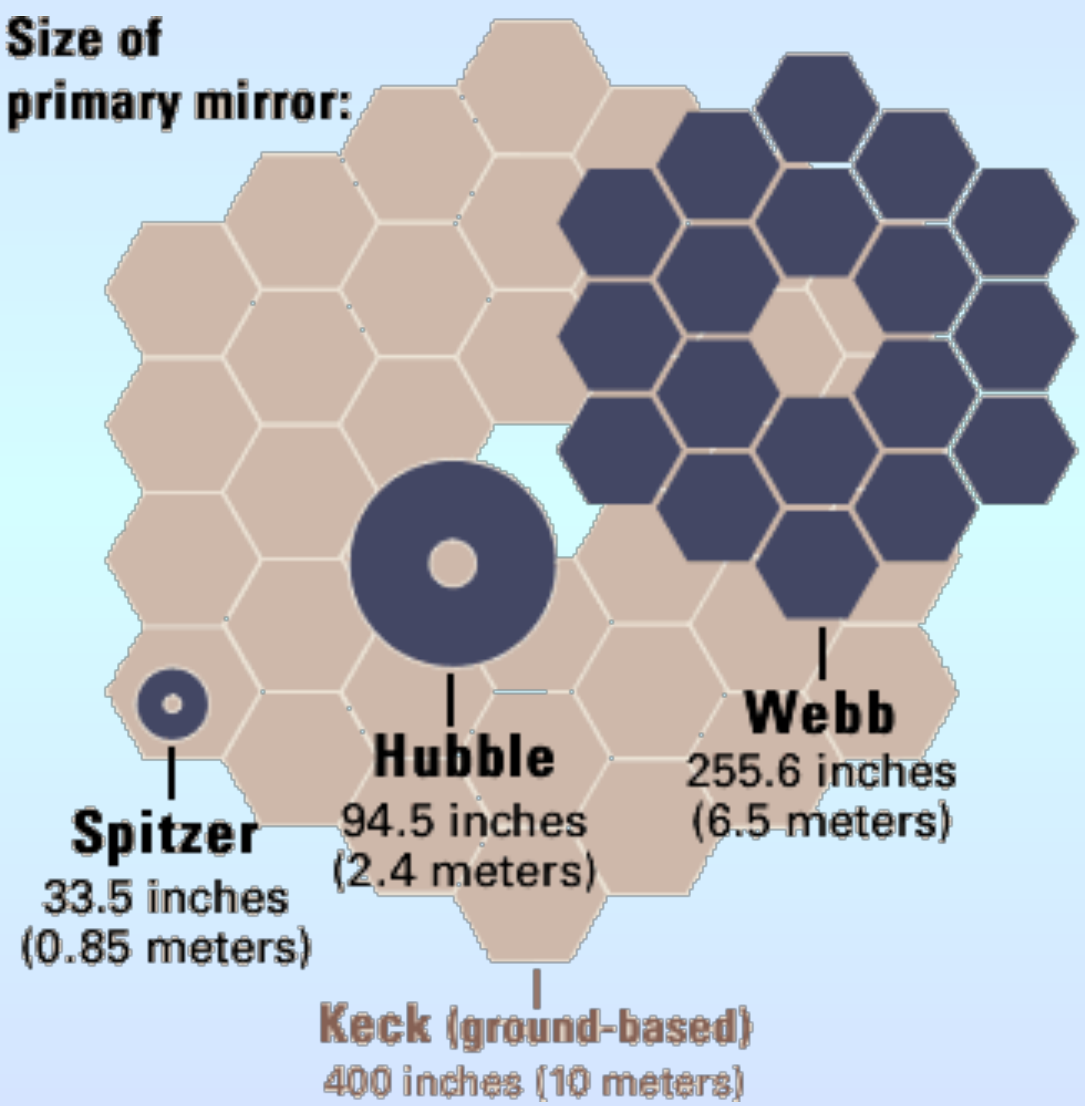
James Webb Space Telescope (JWST)

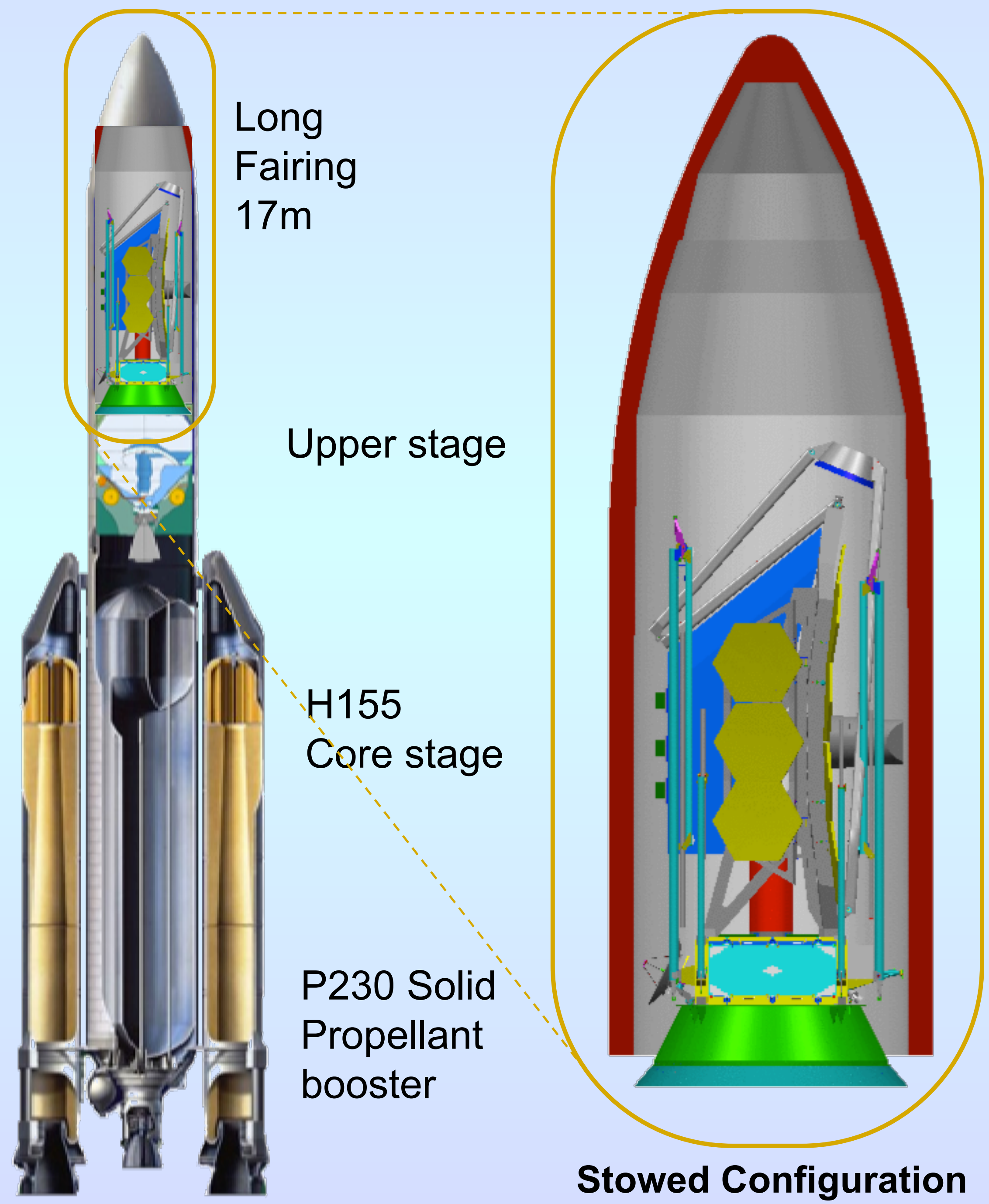


The James Webb Space Telescope (JWST) to be launched soon will have a 6.5m diameter objective mirror, and observe from 600nm to 28 μm. (http://www.jwst.nasa.gov/)

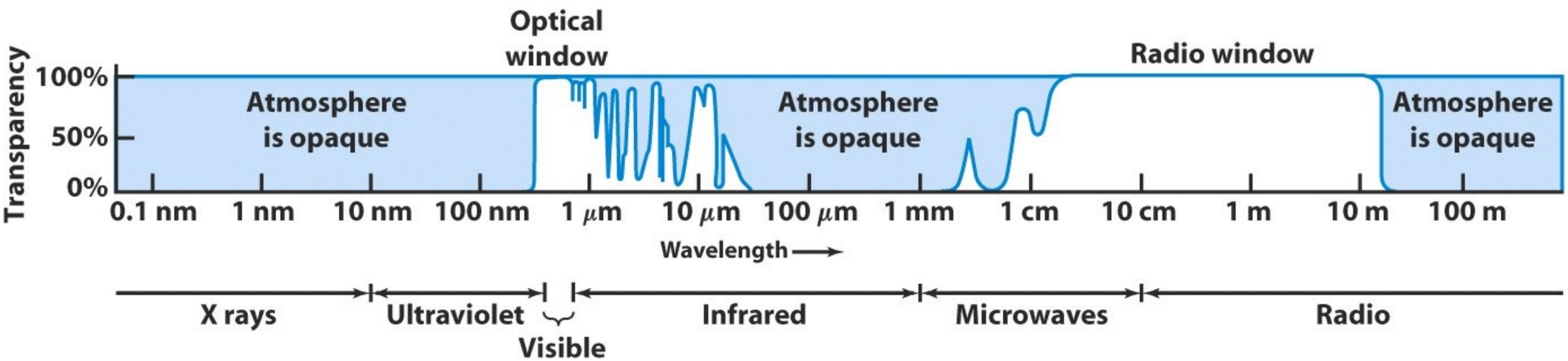
Telescopes

James Webb Space Telescope



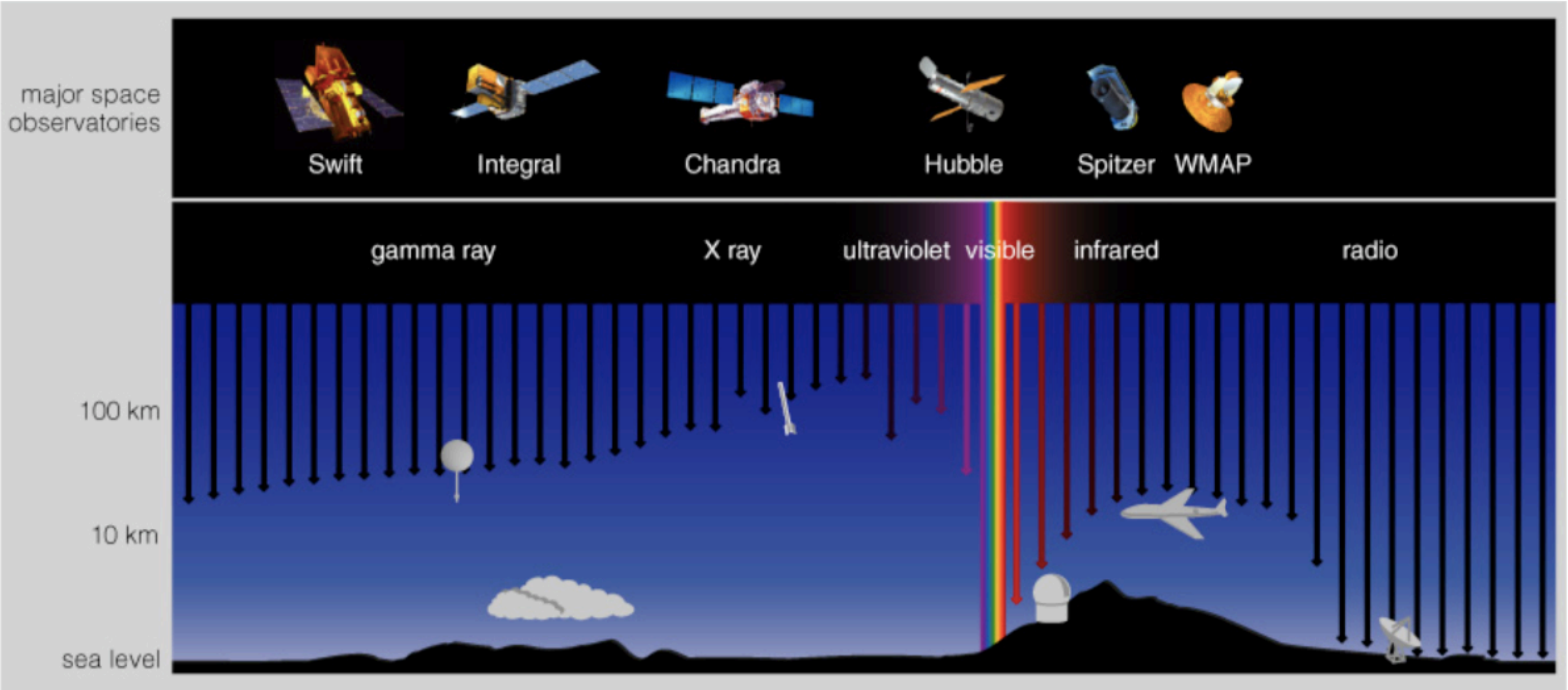


Telescopes



- Visible – Ångstrom (Å). Traditional optical range unit (10^{-10} m) – Nanometre commonly used (10^{-9} m)
- Infrared – Micron (μm). Near infrared 1 – 5 μm (1μm = 10^{-6} m)
- Radio – mm "microwave" Radio – cm. eg. 21cm line of neutral Hydrogen
- Radio – Frequency/Hertz (Hz). eg. 21cm = 1420 MHz.
- X-ray,-ray–Energy(eV).eg.1keV=2.4×10^{17} Hz=12.4×10^{-10} m

Telescopes



- Only radio and visible light pass easily through Earth’s atmosphere
- We need telescopes in space to observe other forms

Telescopes

What do astronomers do with telescopes?

- Telescopes perform key functions
  - Collect light (EM radiation) from astronomical sources
  - Record information on that light
    - Position
    - Arrival time
    - Energy
- Different telescopes & detectors optimised to measure some or all of this information

Telescopes

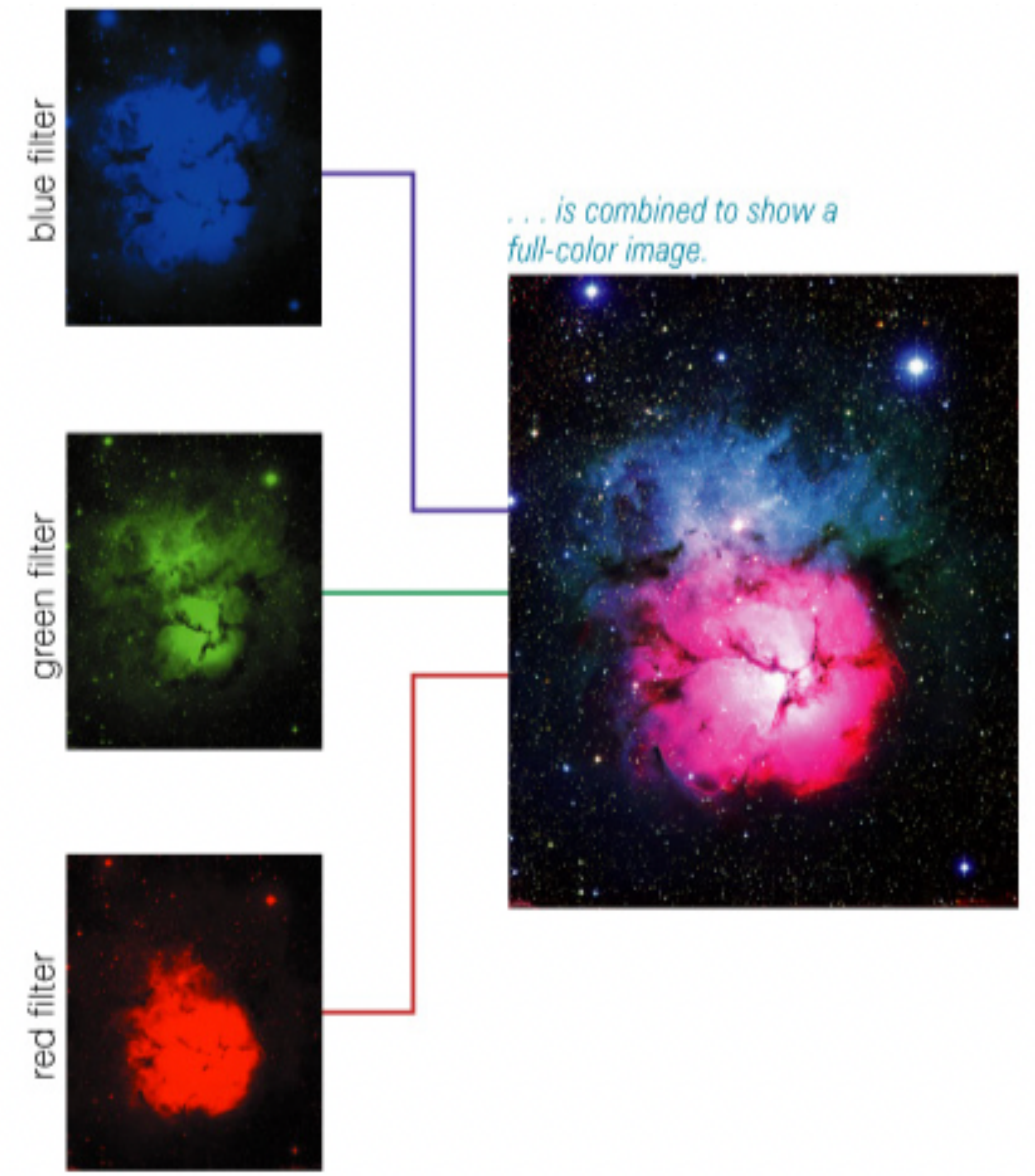
Imaging:

- If we use positional information we get an image
  - Study e.g. structure of galaxies

Telescopes

Imaging:

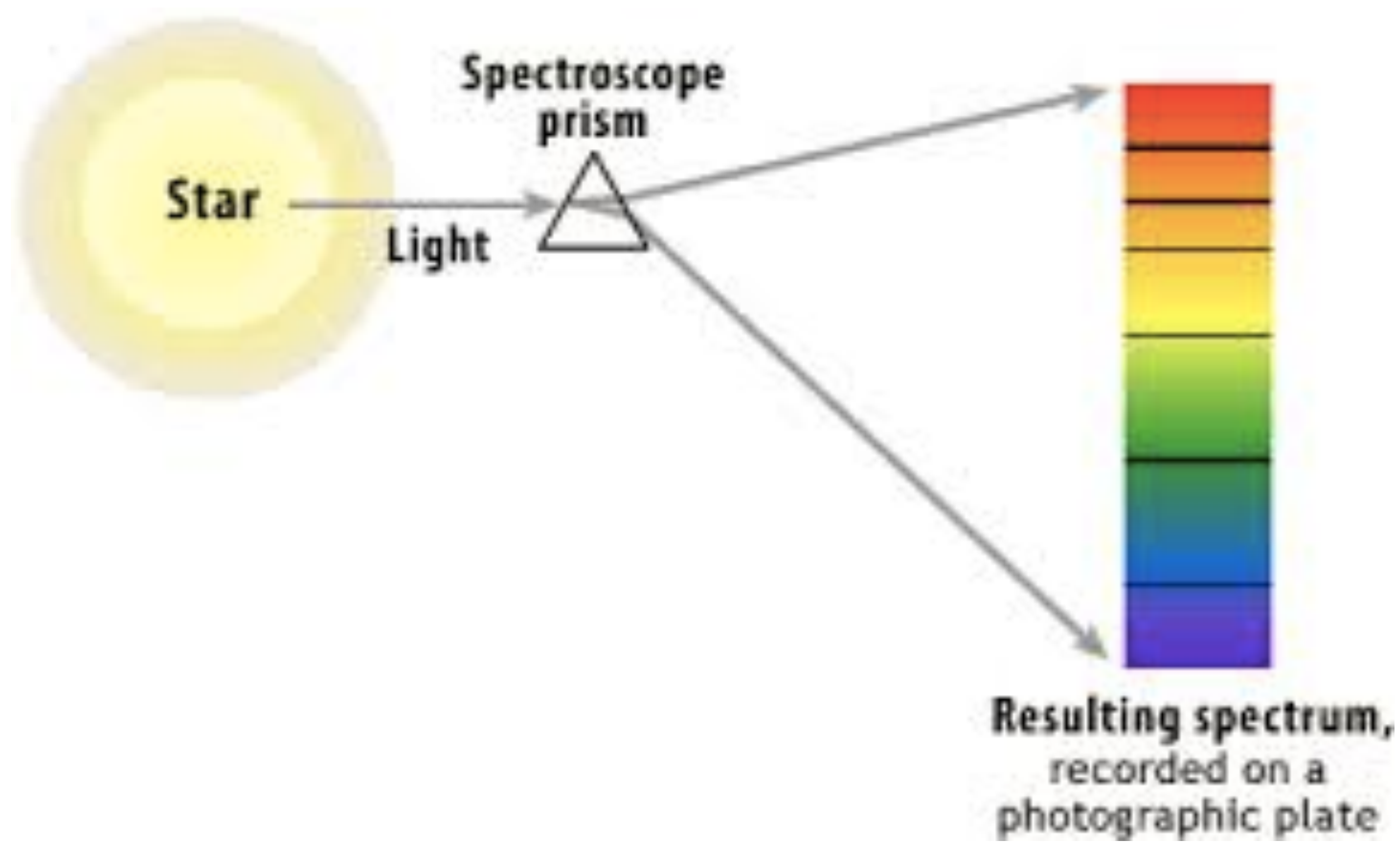
- Astronomical detectors generally record only one colour of light at a time.
- Several images must be combined to make full-colour pictures
- Astronomical detectors can record forms of light our eyes can't see
- Colour is sometimes used to represent different energies of nonvisible light



Telescopes

Spectroscopy: If we use energy information we get a spectrum

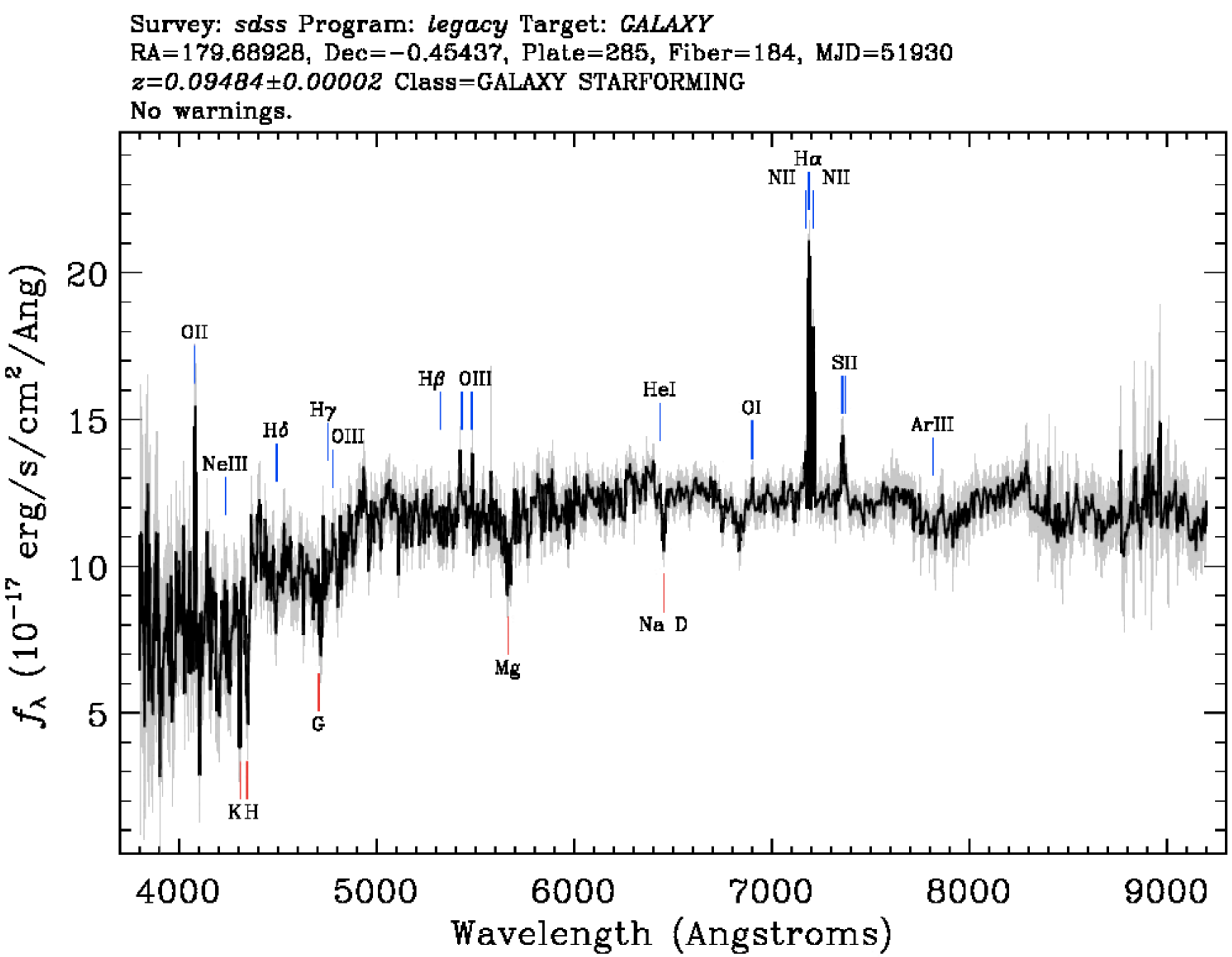
A spectrograph separates the different wavelengths of light before they hit the detector



Telescopes

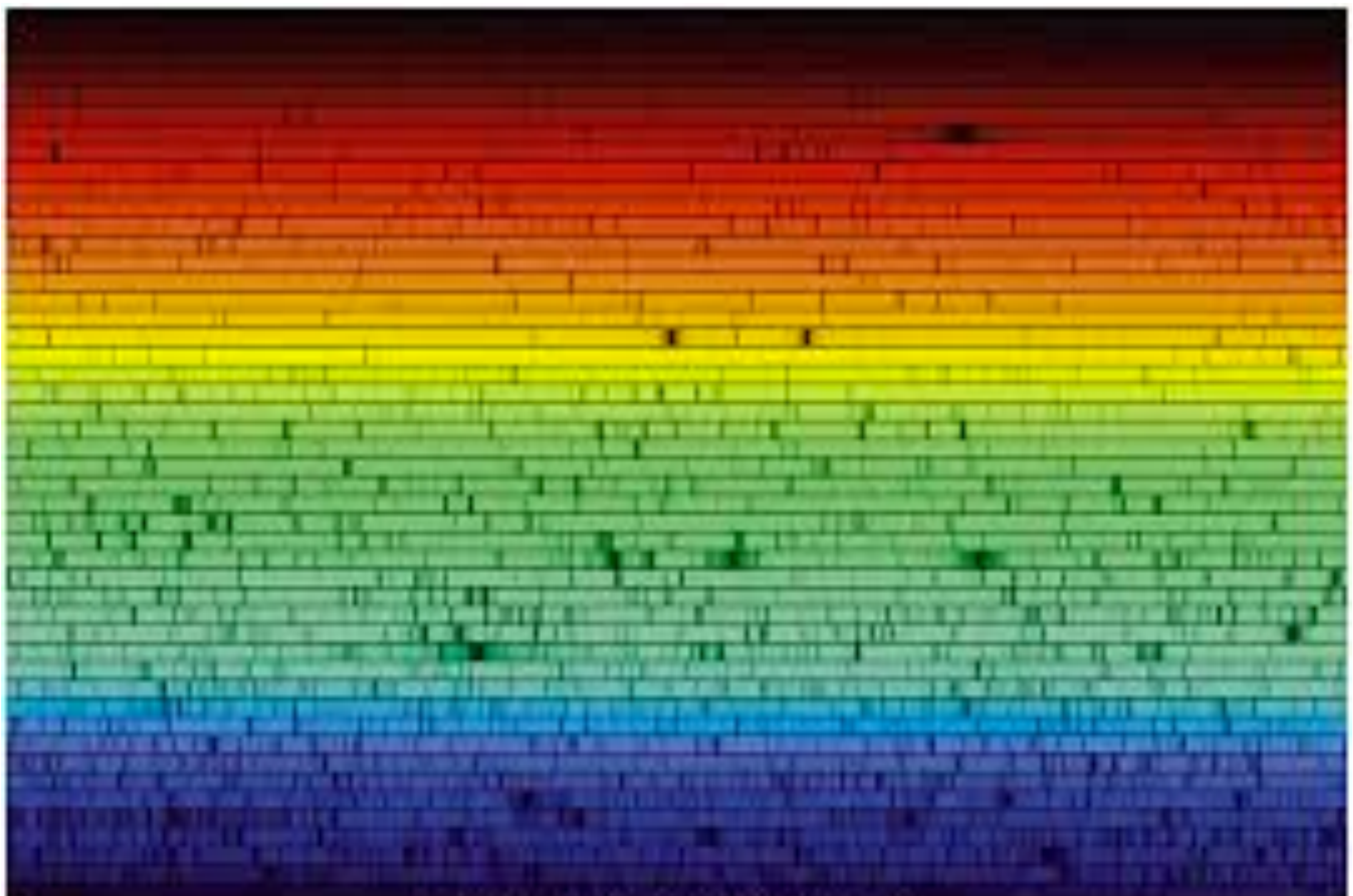
Spectroscopy: If we use energy information we get a spectrum

Graphing relative brightness of light at each wavelength shows the details in a spectrum



Telescopes

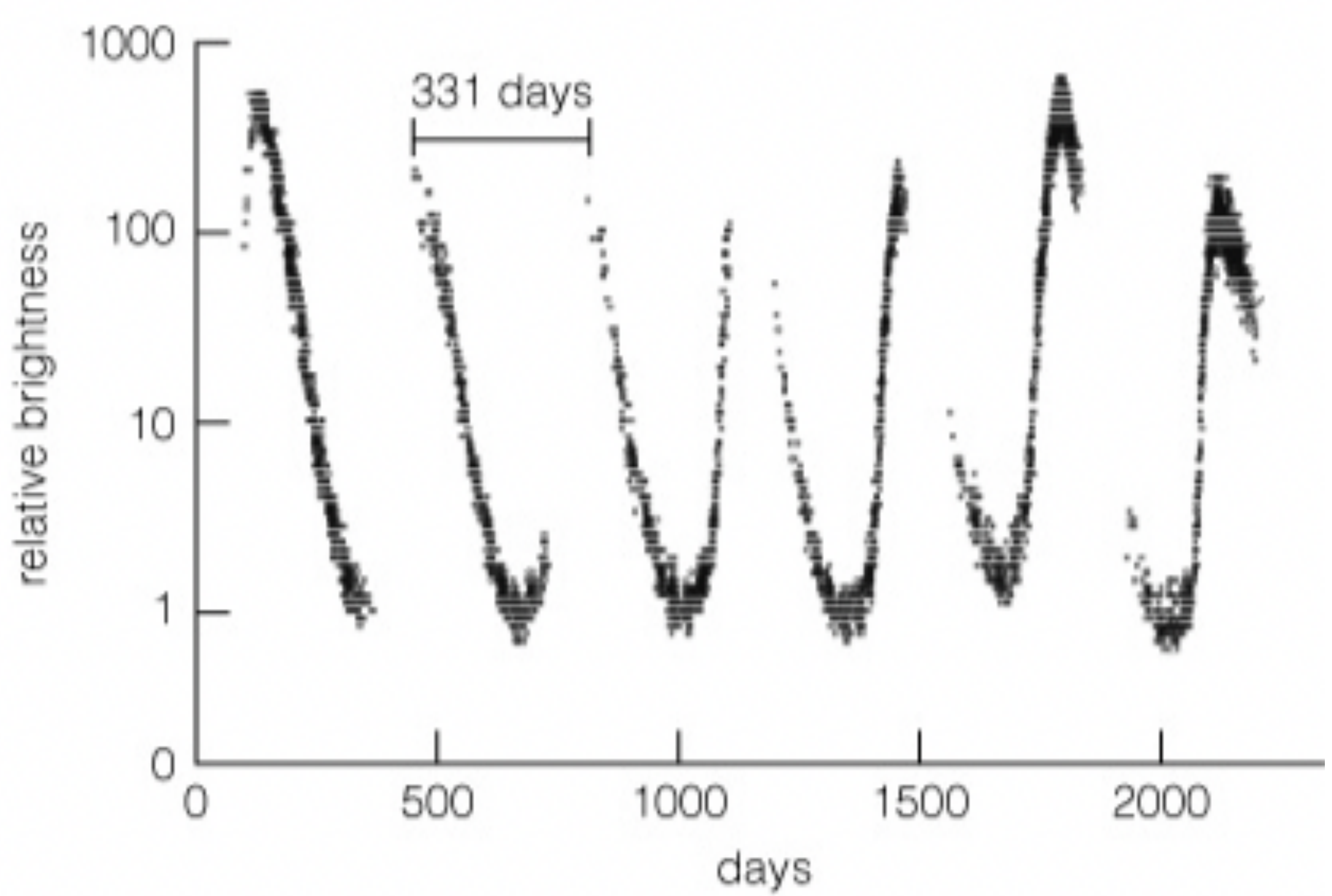
- Spectroscopy: IF we use energy information we get a spectrum
  - Study e.g. chemical abundances in stars



Telescopes

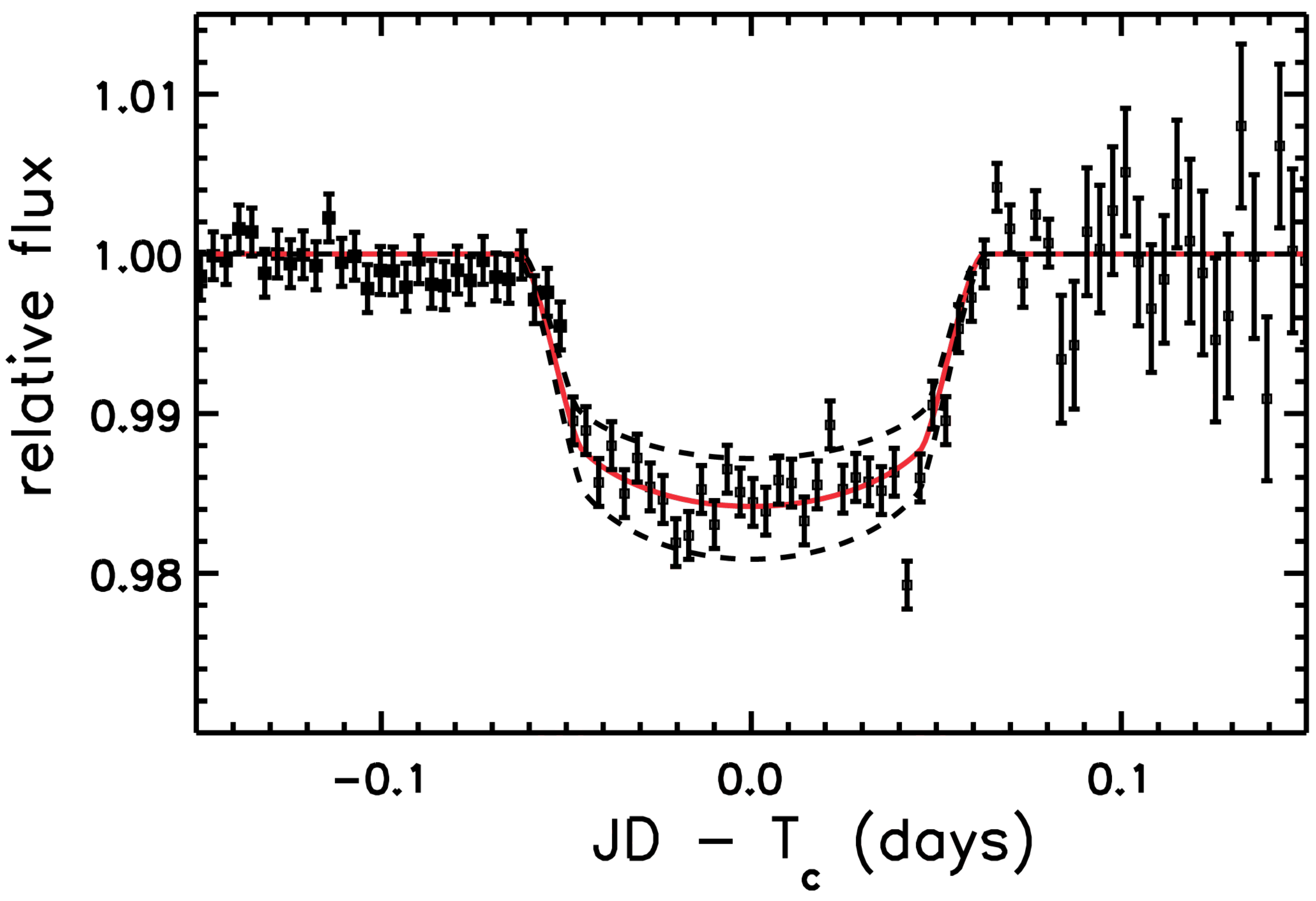
- Timing — If we use time information we get a light curve

  A light curve represents a series of brightness measurements made over a period of time



Telescopes

- Timing — If we use time information we get a light curve
    - Study e.g. transits of exoplanets



What Do Telescopes Do?

Functions of Telescopes

- Magnification (make things look bigger) — easy to make a telescope with good magnification
- Collection of large amounts of light (see fainter things) — most important feature of a telescope
- Sharp images (see more detail and structure)
- Map large areas of sky (search for rare objects)
- Detect light across the electromagnetic spectrum (see new phenomena)
- Sophisticated analysis of light (e.g., spectroscopy)
- Record images (e.g., photographs, digital pictures)

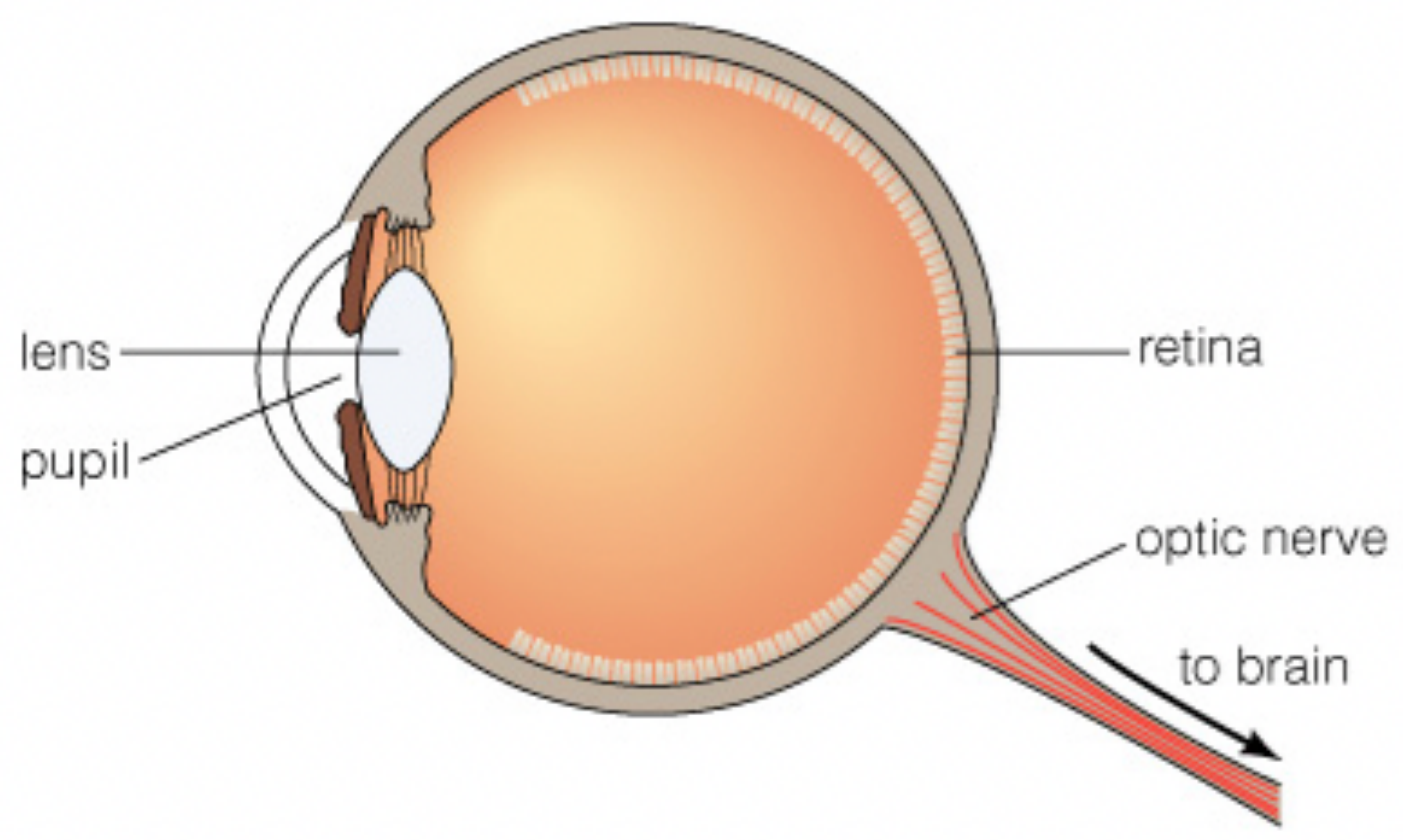
Telescopes

Type of Telescopes

- Optical ✓
- Radio
- X-Ray/Gamma-Ray

Telescopes

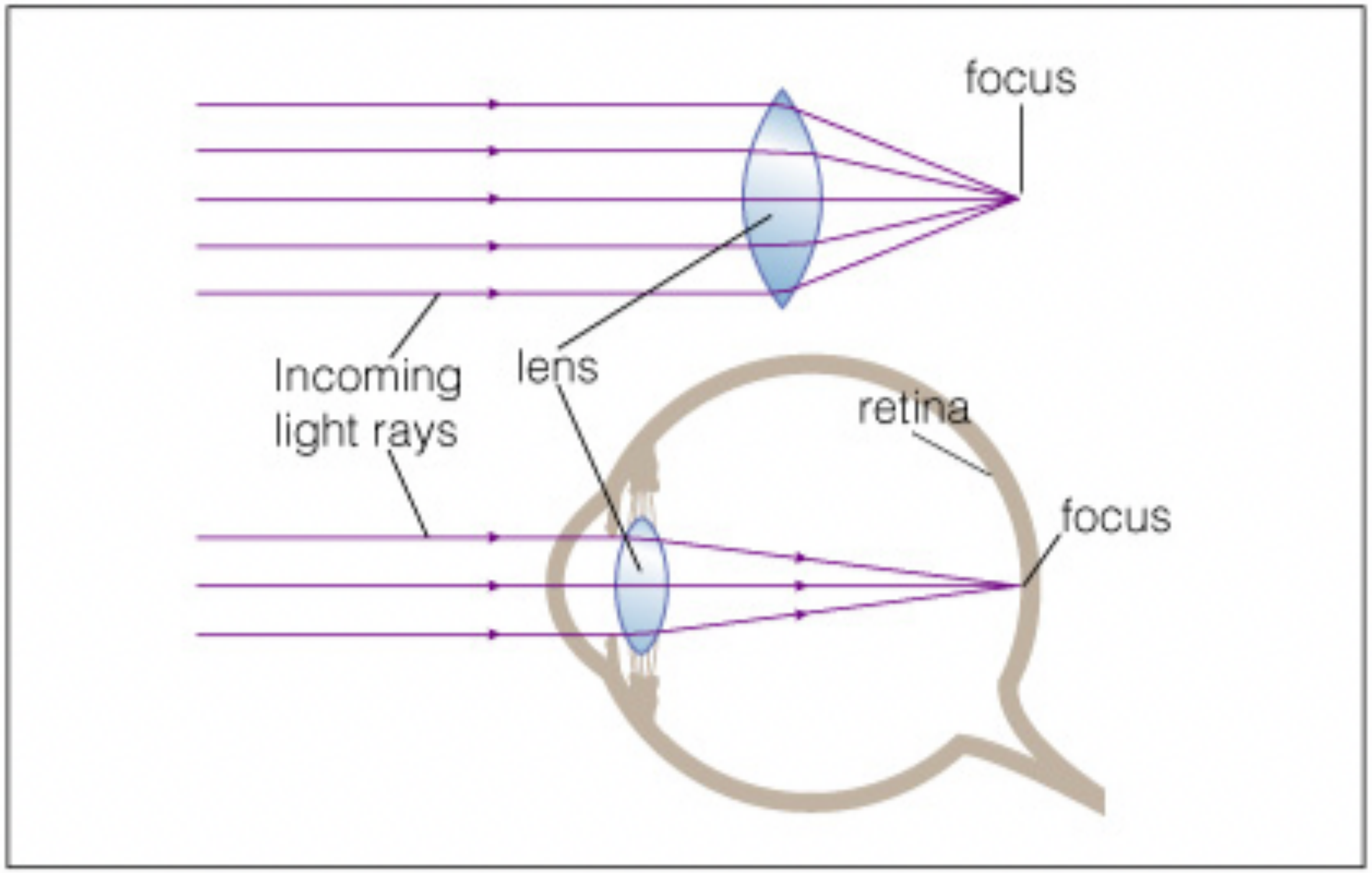
How does your eye form an image?



- Refraction is the bending of light when it passes from one substance into another
- Your eye uses refraction to focus light

Telescopes

How does your eye form an image?



Focusing Light

Refraction can cause parallel light rays to converge to a focus

Telescopes

Telescope Optics

What is a telescope system?

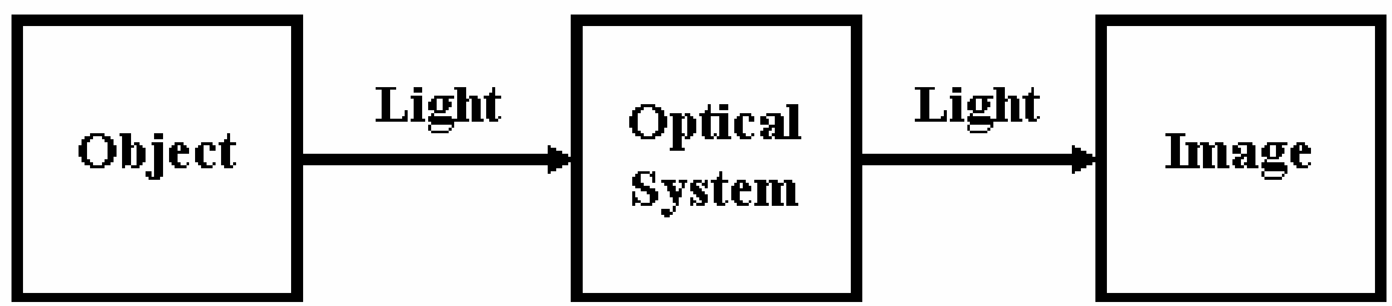
With optics (lenses or mirrors) it produces an image of an object at a distance.

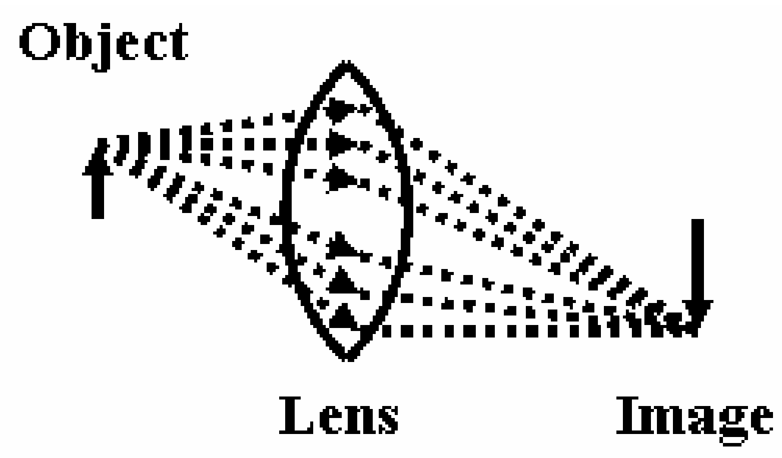
Telescopes

Telescope Optics

What is a telescope system?

With optics (lenses or mirrors) it produces an image of an object at a distance.

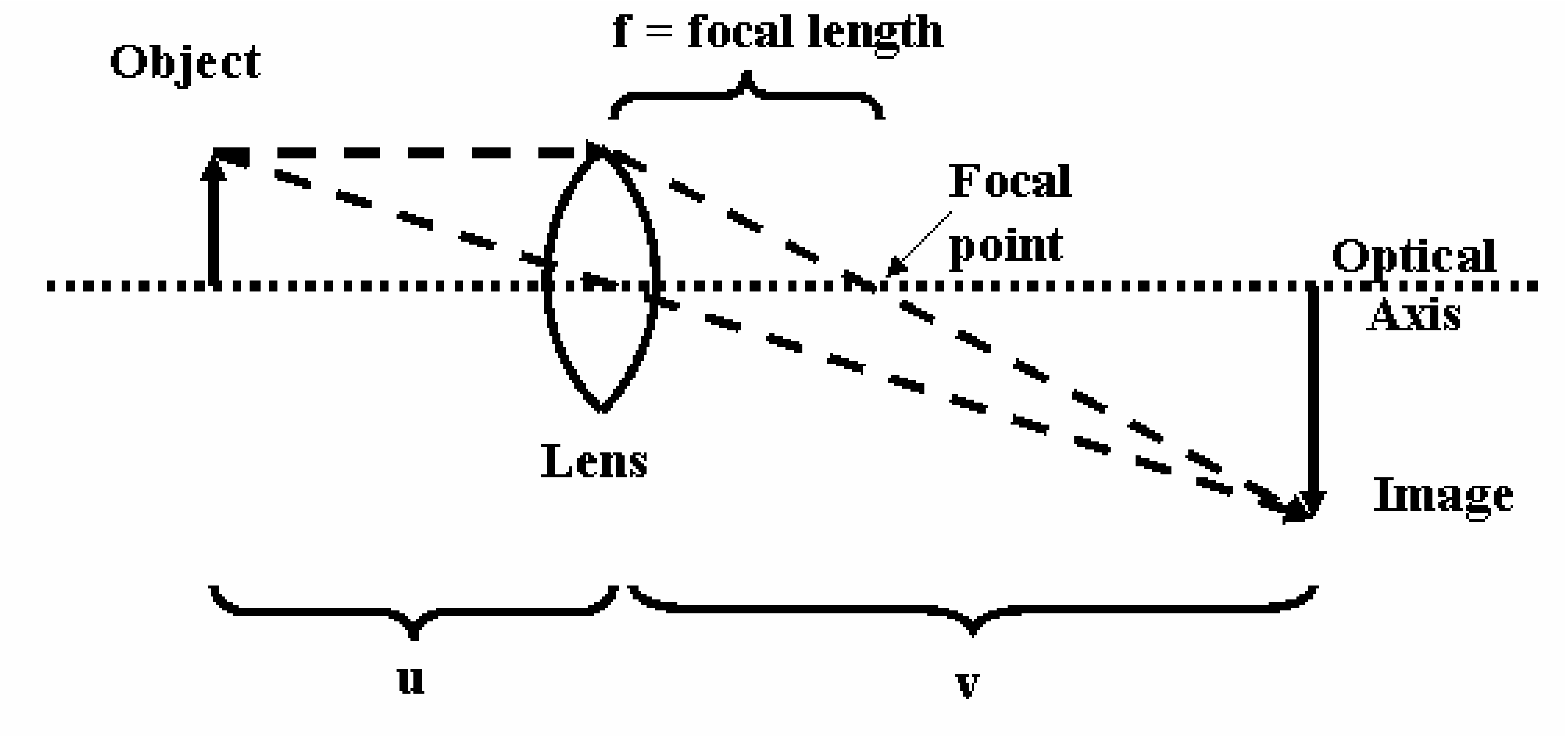




Telescopes

Telescope Optics

Review basic knowledge of geometric optics

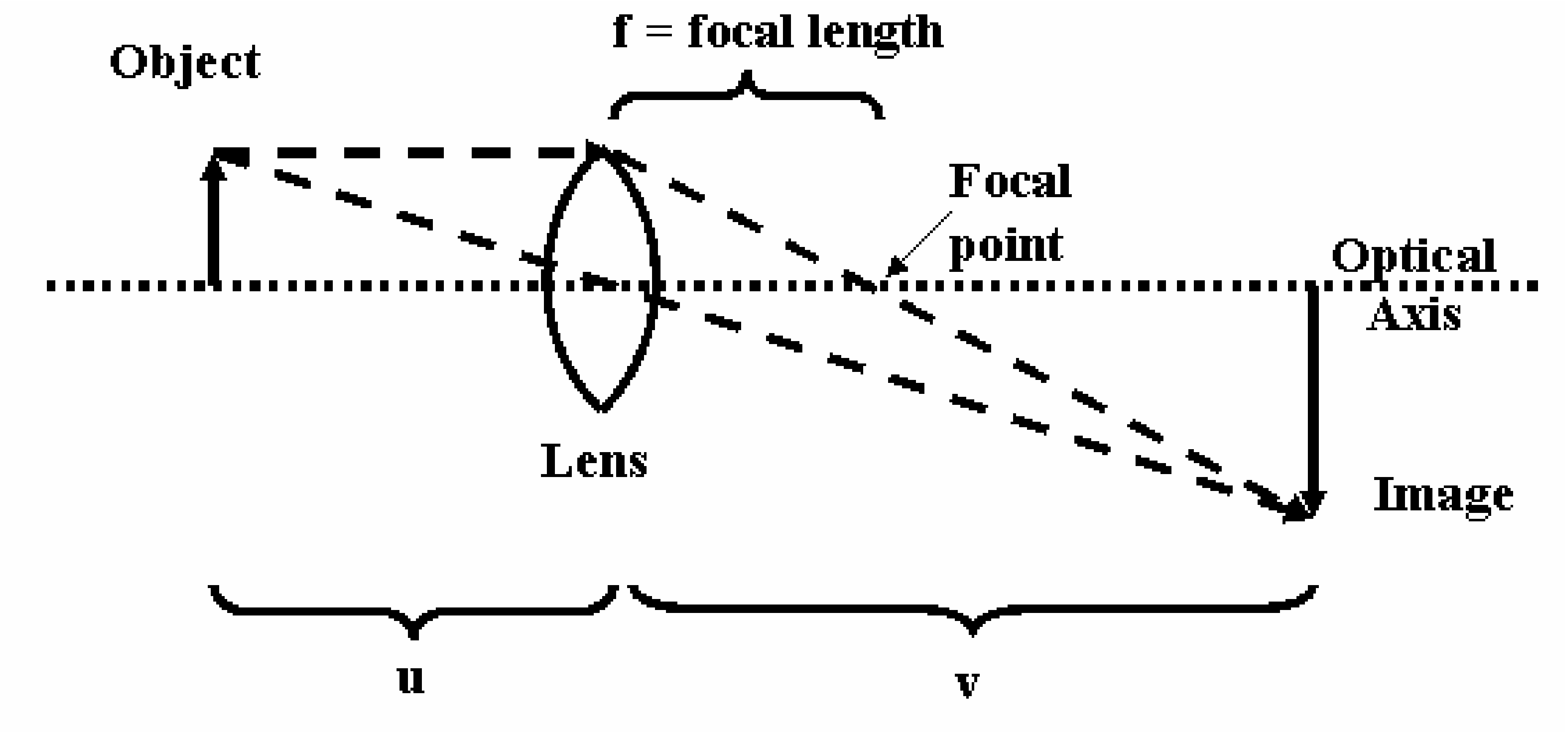


Optics equation?

Telescopes

Telescope Optics

Review basic knowledge of geometric optics

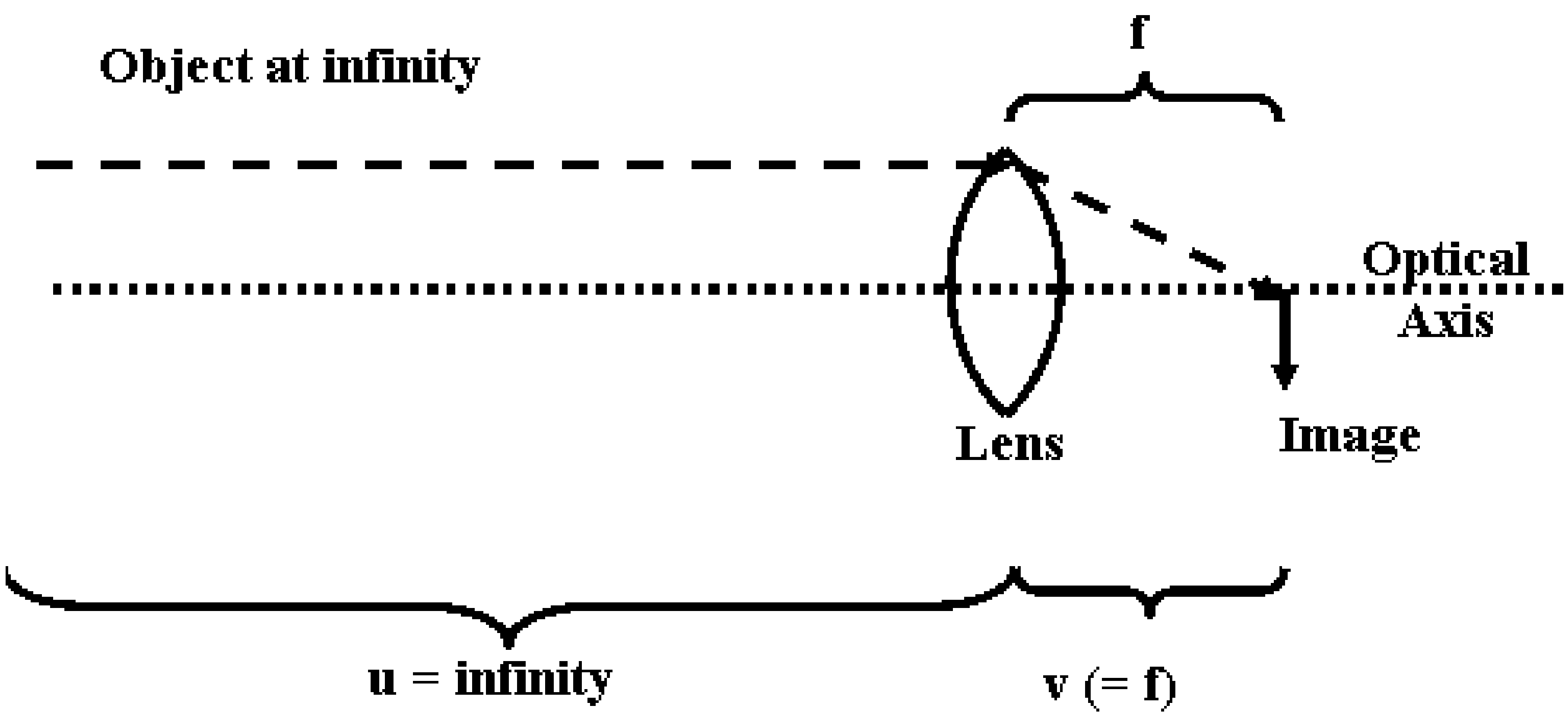


$$1/u + 1/v = 1/f$$

Telescopes

Telescope Optics

- For astronomical telescopes we can assume that the ‘object’ is at infinity ($u = \infty$)



Telescope Optics

What is a telescope system?

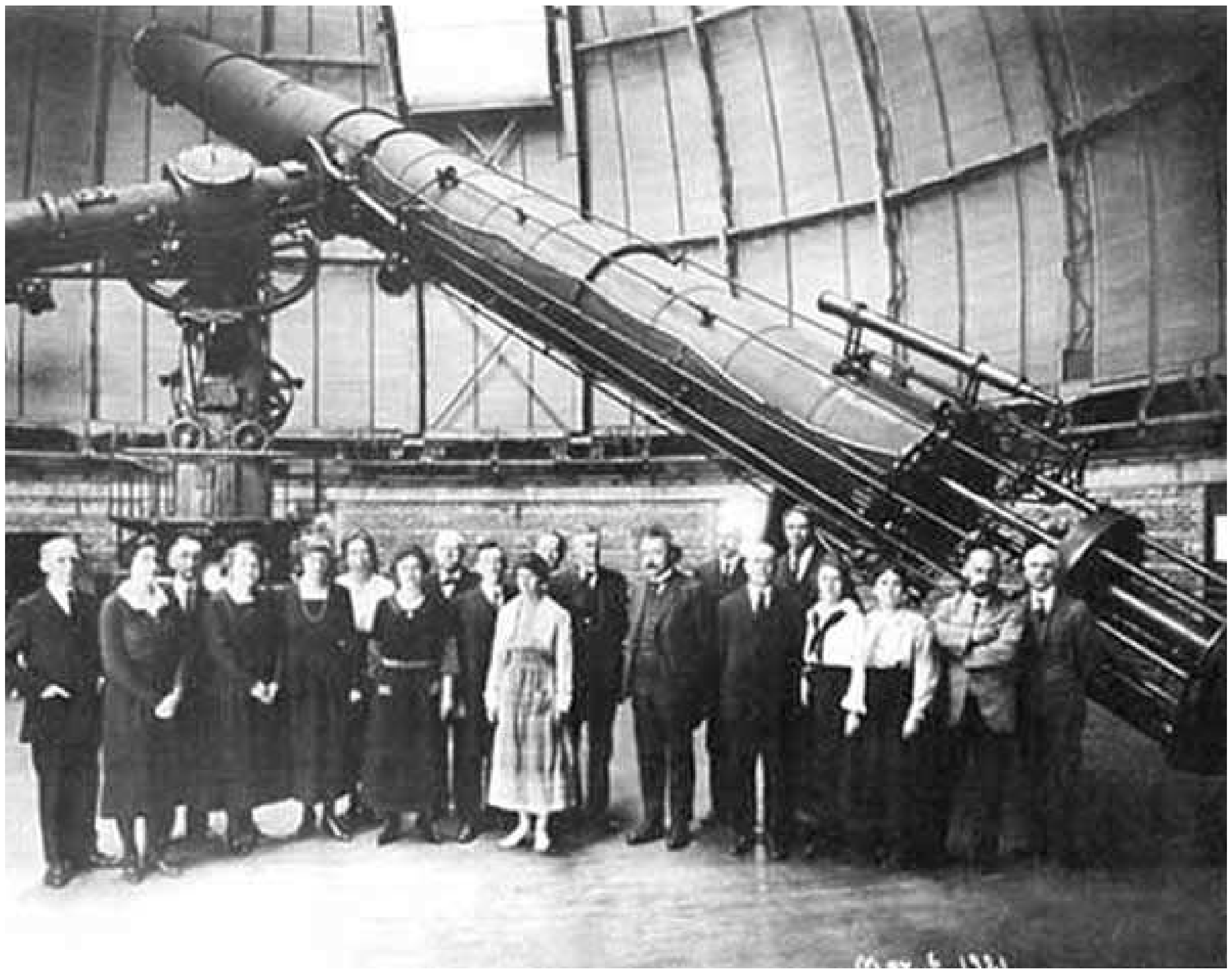
With optics (lenses or mirrors) it produces an image of an object at a distance.

What are the two basic designs of telescopes?

- Refracting telescope: Focuses light with lenses
- Reflecting telescope: Focuses light with mirrors

Telescopes

Refractors:



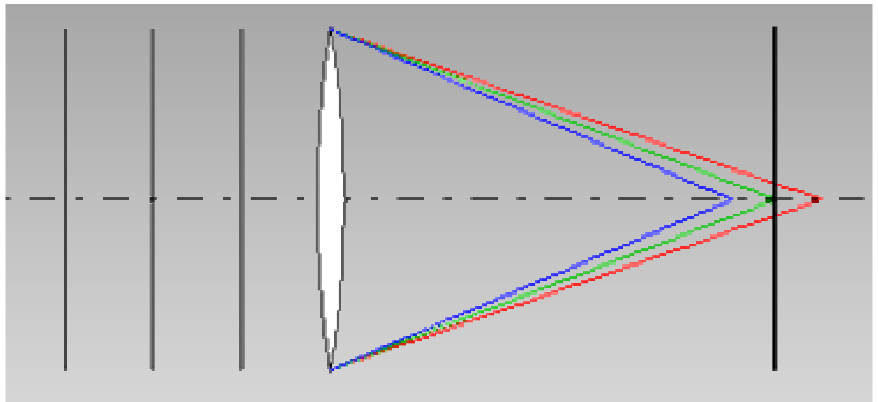
Yerkes refractor in 1895

- The lens has to be supported around the edge (like spectacles)
- As lenses become bigger (light grasp $\propto d^2$), the mass increased as the cube of the size ($m \propto d^3$)
- Supporting the lens became harder (bigger and more complex)
- Flexure (bending) of the lens itself cause ‘figure’ to change, resulting in optical aberrations
- Largest refractor ever made is the Yerkes telescope in the US (1 m diameter)

Telescopes

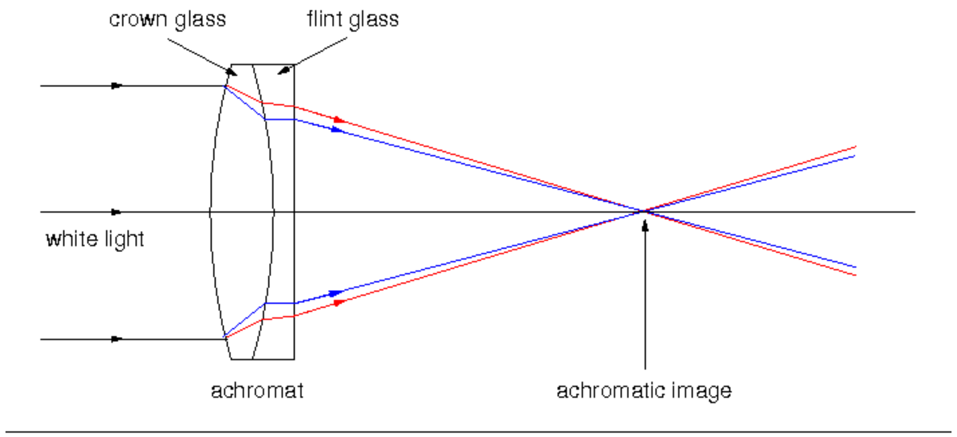
Refractors: The first telescopes built were refractors

- Lenses bend light to a focus through refraction
- Lens only can be supported at their outer edges Limited in size to ~1-m due to sagging under their own weight
- As refraction is wavelength dependent, certain chromatic aberrations occur



Different wavelengths brought to different foci

- Some corrections for this can be done by combining lenses of varying refractive index



Correction achieved with achromat doublet

Yerkes Today

Telescopes

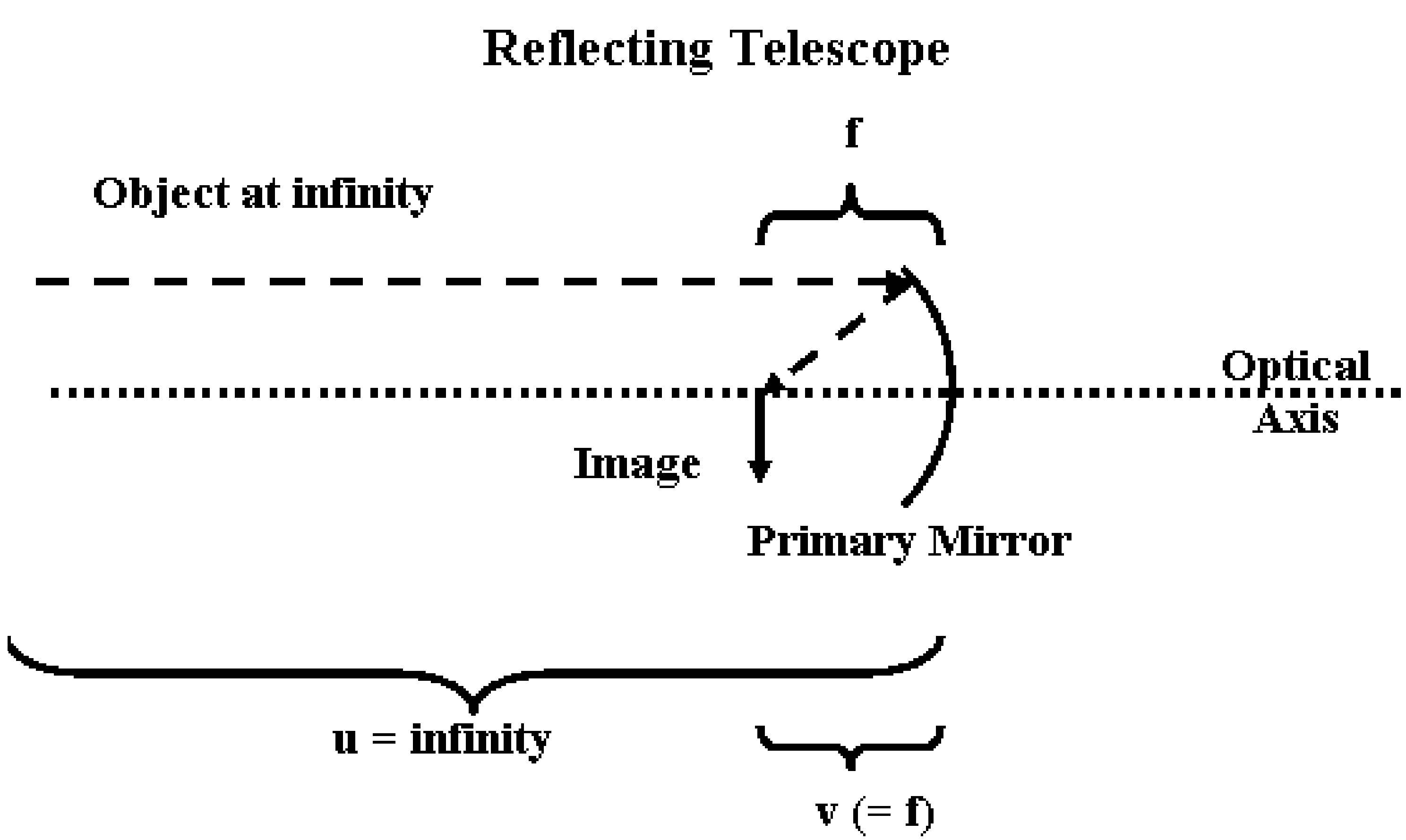
Refractors: Disadvantages

- Difficult to figure and test large lenses
- Large lenses are heavy, bend and difficult to keep aligned
- Glass absorbs light, particularly at short wavelength
- Chromatic effects — Dispersive properties of glasses

Telescopes

Reflectors:

- Reflection is wavelength independent
- Avoids chromatic effects
- Can support them from behind, so they can be much bigger than any lens (up to 8.3 m diameter current limit for single monolithic mirror)



Telescopes

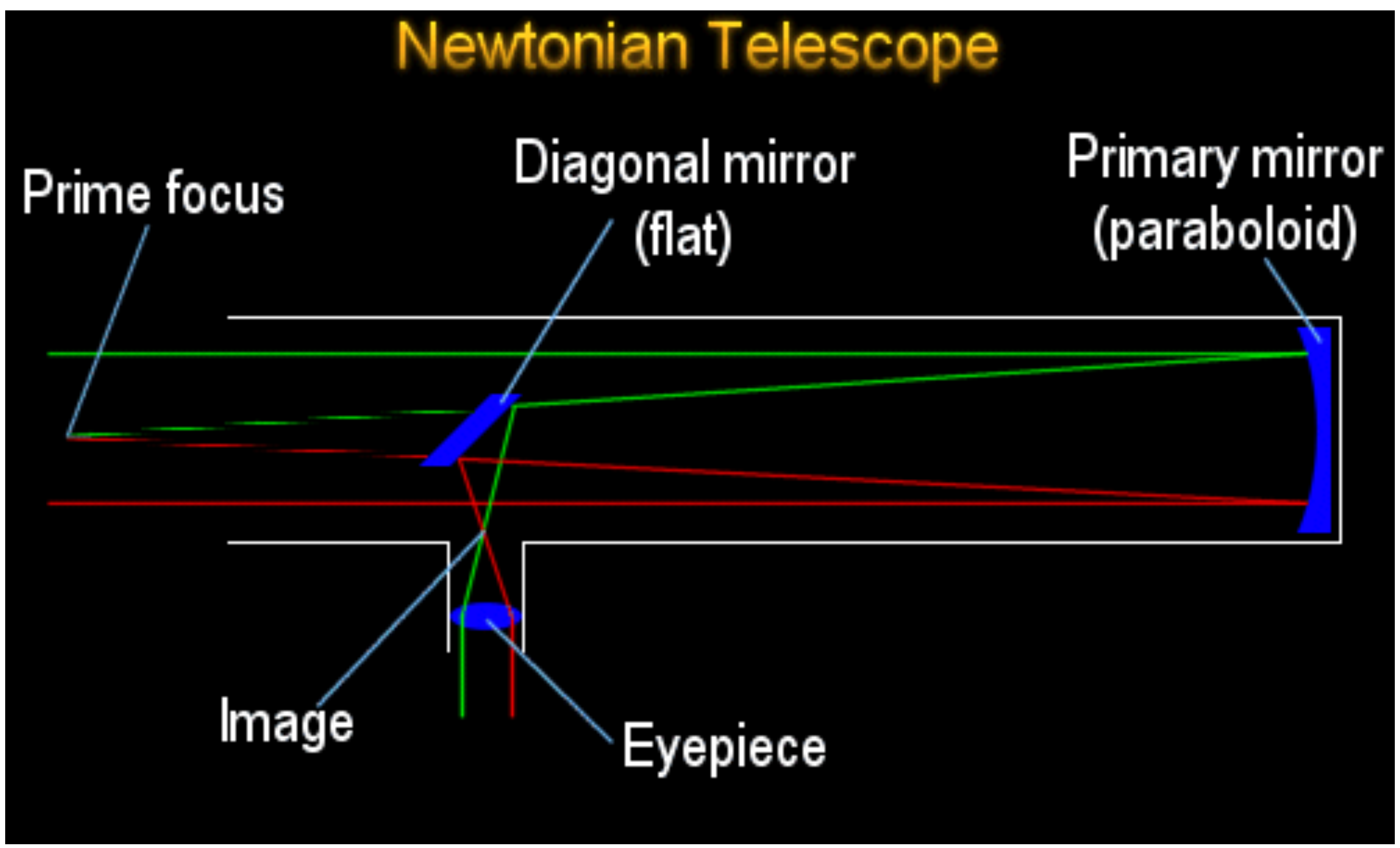
Reflectors: Types

- Newtonian
- Cassegrain
- Gregorian
- Schmidt

Telescopes

Reflectors: Newtonian telescopes

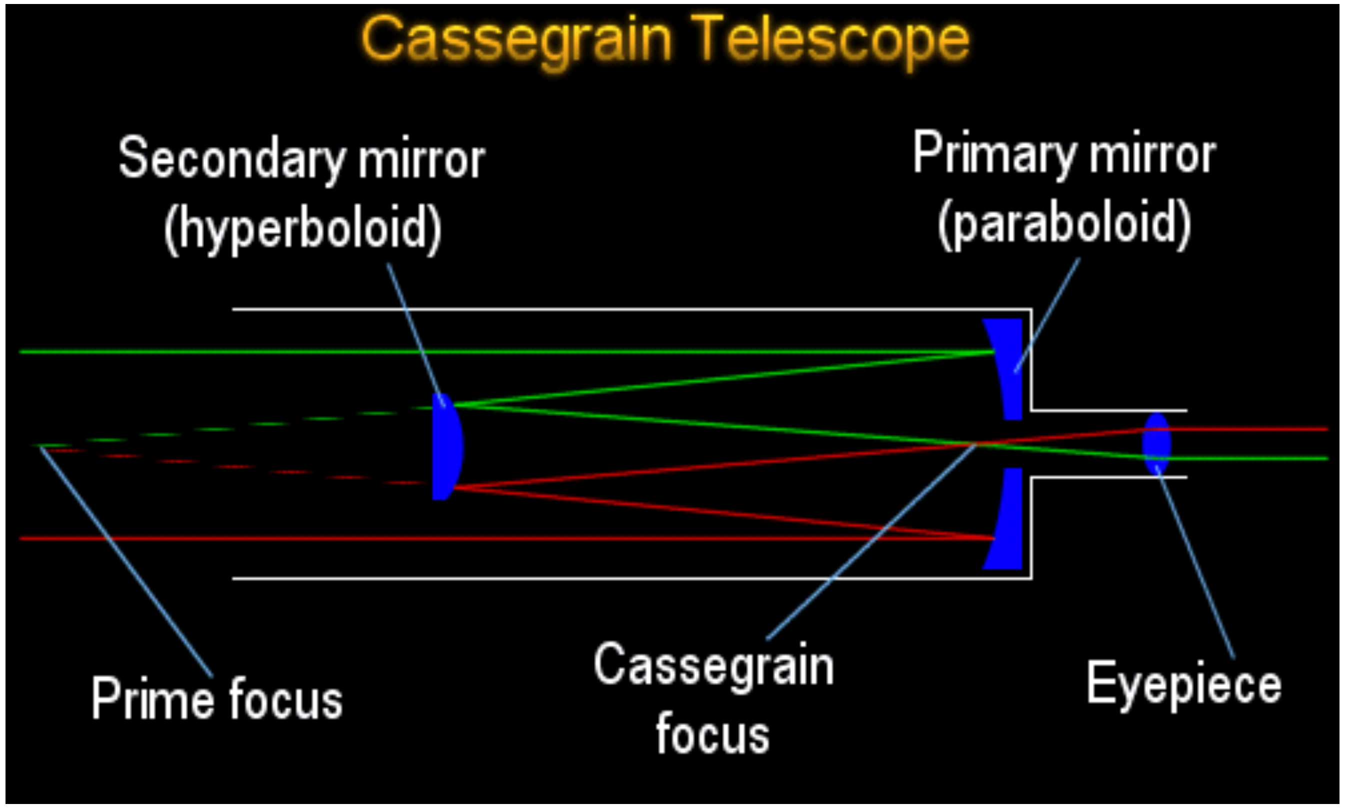
- The Mt Wilson 100 inch Hooker telescope, completed in 1917



Telescopes

Reflectors: Cassegrain telescopes

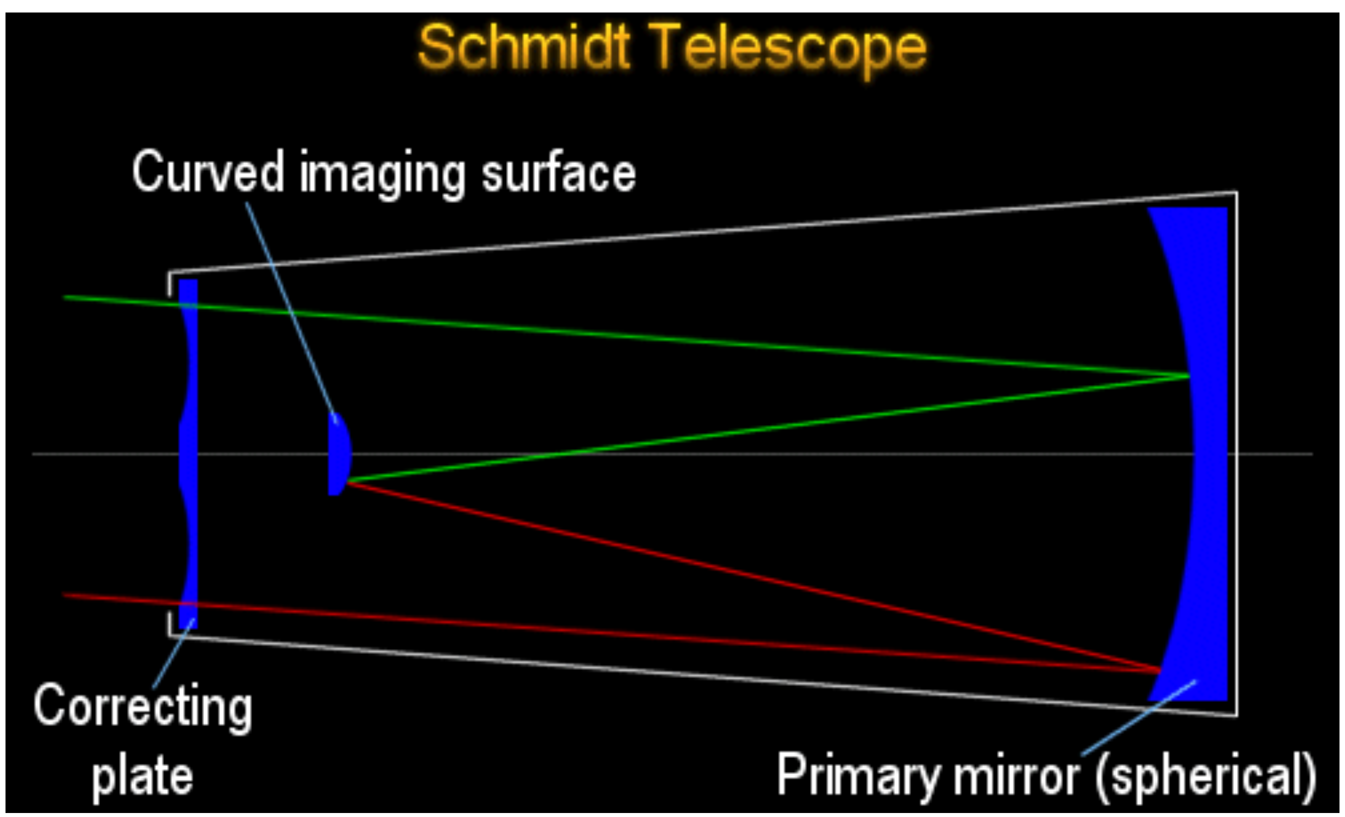
- Cassegrain reflector typically has a paraboloid primary and hyperboloid secondary
- Generally “slow” beams (~f/10- f/20)
- Typically aberrations (primarily coma & astigmatism) limit the useable field of view
- Can correct for this using addition “corrector” optics (lenses)
- Modification of Cassegrain (Ritchey-Chretian) gives larger FoV



Telescopes

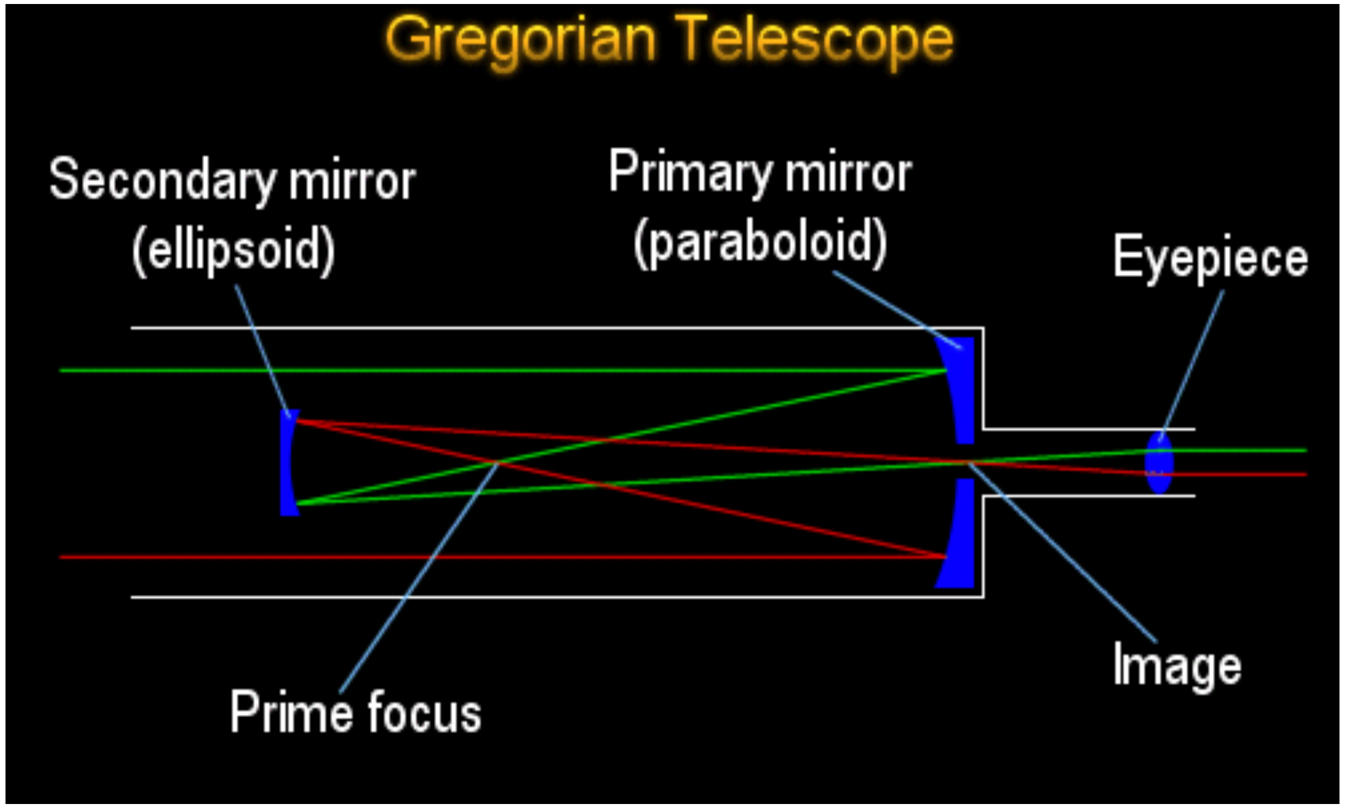
Example of a Schmidt telescope:

- The UK Schmidt in Australia
- Allows wide FoV (6 degrees) imaging and spectroscopy
- Combined with Schmidt telescope, objective prisms could be used to spectroscopically survey large areas of sky
- Multiplex advantage: area coverage and wavelength information



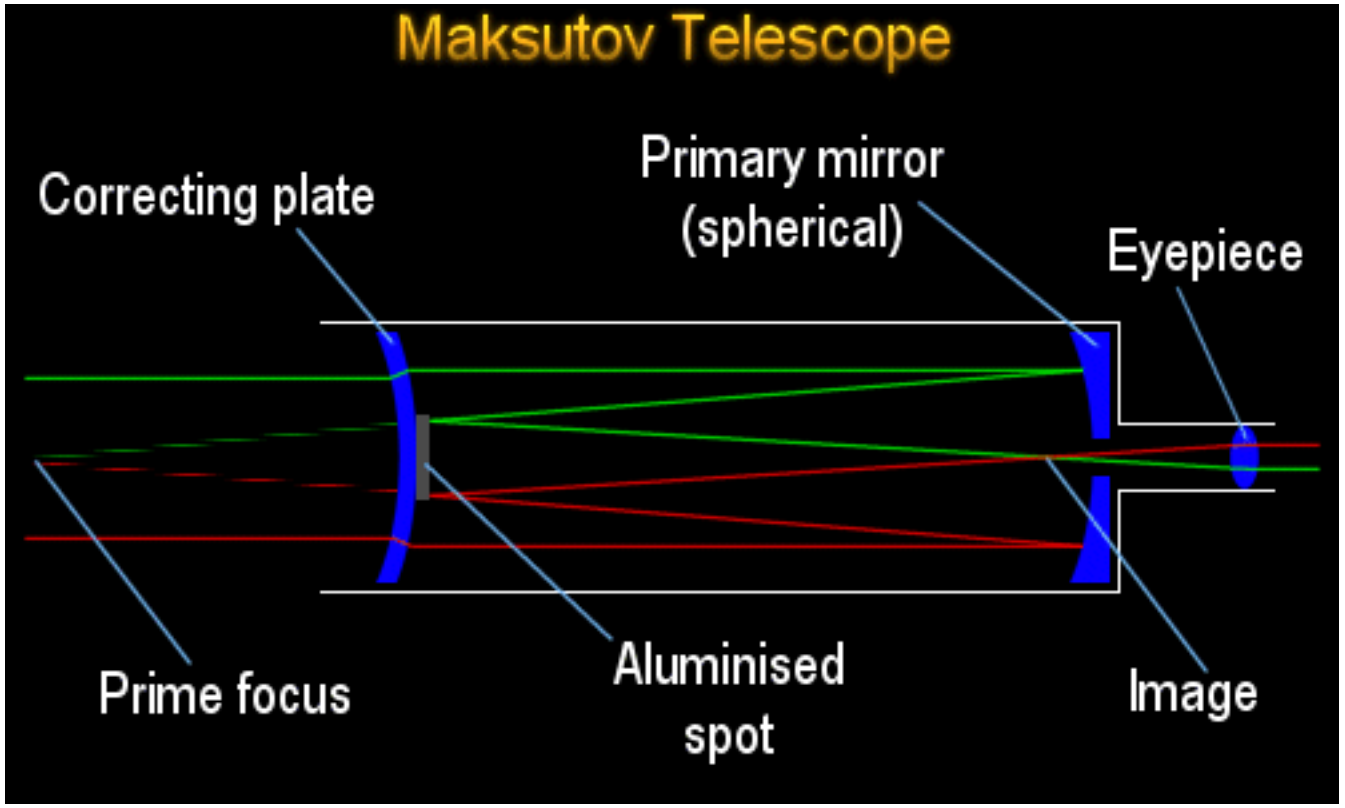
Telescopes

Gregorian telescope —



Telescopes

Maksutov telescope —



Telescopes

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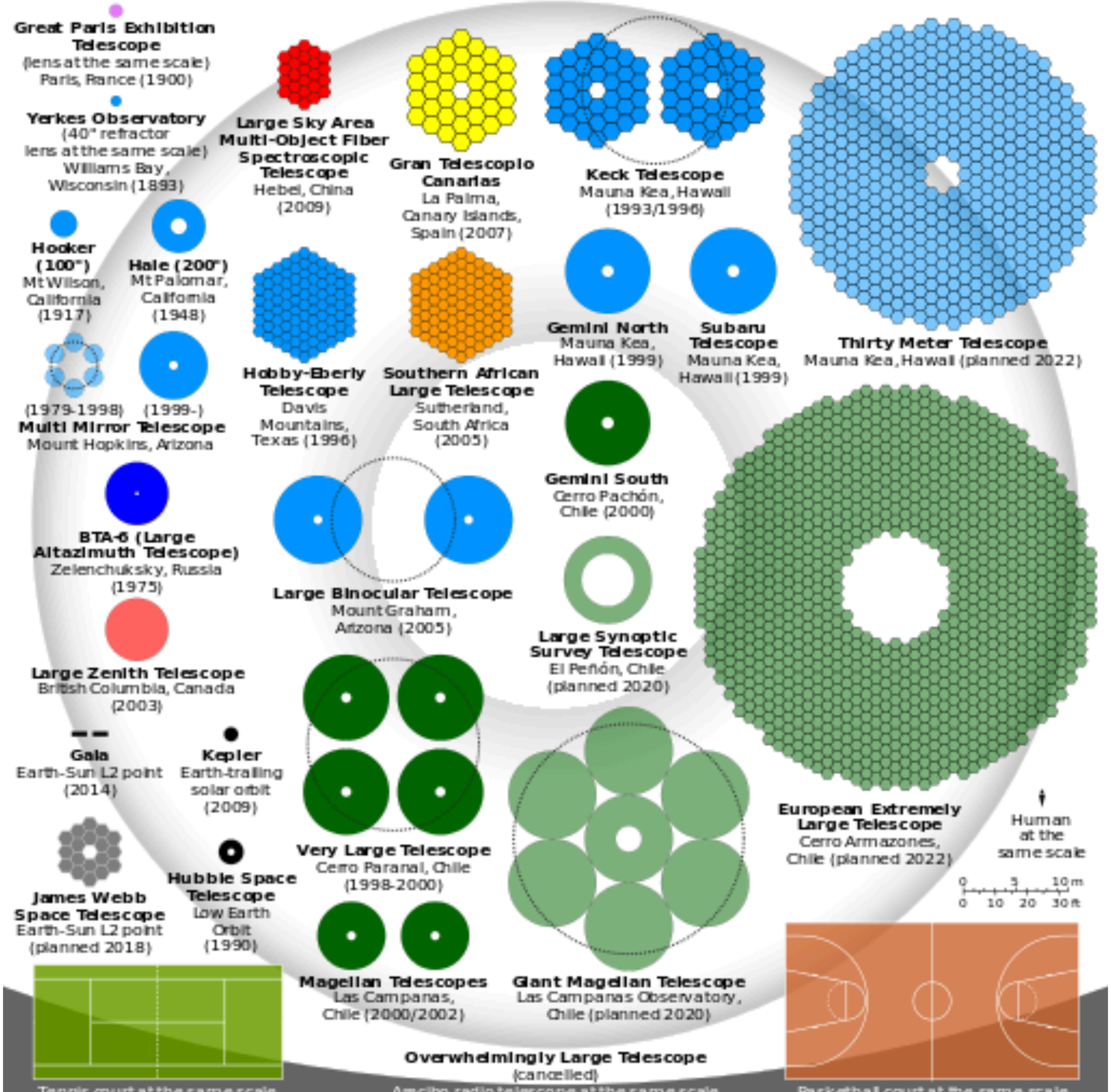
Keck II	Mauna Kea, Hawaii	1996	10.0
Keck I	Mauna Kea, Hawaii	1993	10.0
Hobby-Eberly Telescope	McDonald Observatory, Texas	1998	11.0*
South African Large Telescope	Sutherland, South Africa	2004	9.2
Large Binocular Telescope	Mount Graham, Arizona	2004–05	Two 8.4
Subaru	Mauna Kea, Hawaii	1999	8.3
VLT UT 1–Antu	Cerro Paranal, Chile	1998	8.2
VLT UT 2–Kueyen	Cerro Paranal, Chile	1999	8.2
VLT UT 3–Melipal	Cerro Paranal, Chile	2000	8.2
VLT UT 4–Yepun	Cerro Paranal, Chile	2000	8.2
Gemini North (Gillett)	Mauna Kea, Hawaii	1999	8.1
Gemini South	Cerro Pachón, Chile	2000	8.1

**The objective mirror of the Hobby-Eberly Telescope is 11.0 m in diameter, but in operation only an area of 9.2 m in diameter is used to collect light.*

The world's largest telescopes are reflectors.


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchukskiy, Russia (1975)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

Telescopes

Segmented Mirror telescopes

The Big Five

- Keck I (1993) & Keck II (1996): Hawaii, USA
- HET (1999): Texas, USA
- SALT (2005): South Africa
- GRANTECAN (2009): Canary Islands, Spain

These telescopes have the largest light grasp

Some also use adaptive optics to get sharper images, particularly at longer wavelengths (IR)

Telescopes

Key parameters for an astronomical telescope:

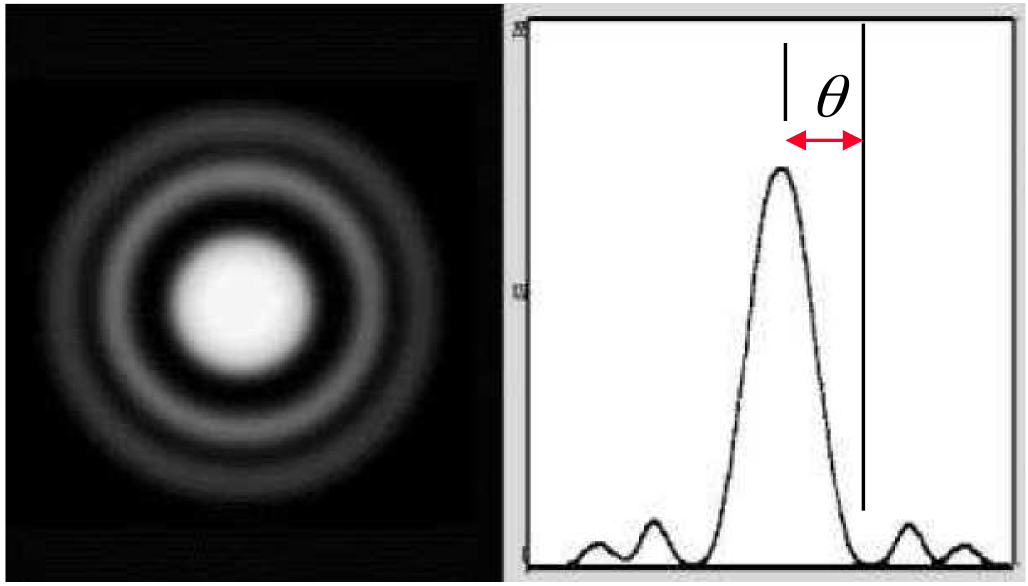
- Light gathering (grasp) power
  Determined by the area of the collecting element (objective lens of Mirror)

  $\propto$ telescope diameter^2

- Resolution

  Measure of the how much fine detail can be seen in an image

  $\propto$ telescope diameter (a)



$$\theta = 1.22 \frac{\lambda}{a}$$

Telescopes

Key parameters for an astronomical telescope:

- **Intrinsic image quality**
  Determined by the figure of the individual optical elements (how close they are to their ideal shape) and how well they are aligned.
- **Field of view (FoV)**
  Determined by the optical design. Usually expressed as field diameter.

  Information content $\propto$ area of FoV $\propto$ diameter of FoV^2
- **Throughput**

  How efficiently photons are delivered to a focus. Determined by the transmissiveness of lenses and the reflectivity of mirrors.
- **Tracking & pointing capability**
  This determines overall performance in terms of observational efficiency and how well image quality is retained during an observation.

Telescopes

Summary

- Telescopes allow us to record images, light curves and spectra of astronomical objects
- Lenses suffer from chromatic aberration – Focal length depends on λ
- Refracting telescopes impractical for astronomy
- All large telescopes are Cassegrain reflectors

Telescopes

Key parameters for an astronomical telescope:

- **Instruments**

  A telescope is only as good as the instruments that are available on it.

- **Telescope & building design**

  This can greatly affect the delivered image quality.

  Local "seeing" effects by poorly design telescope tube, dome or building can compromise the optical performance (blurring effects of air currents).

- **The *etendue* of a telescope**

Characterizes how "spread out" the light is in area and angle. This is a *figure of merit* parameter related to both the light collecting area (A) and FoV (Ω):

$$E = A.\Omega$$

[N.B. this parameter does not factor in the resolving power of the telescope, another important parameter.]

Some Important Telescope parameters

- Focal Ratio — is the focal length (F) of the telescope divided by its aperture or diameter (D), also known as F number

$$f/\# = \text{focal length/diameter} = F / D$$

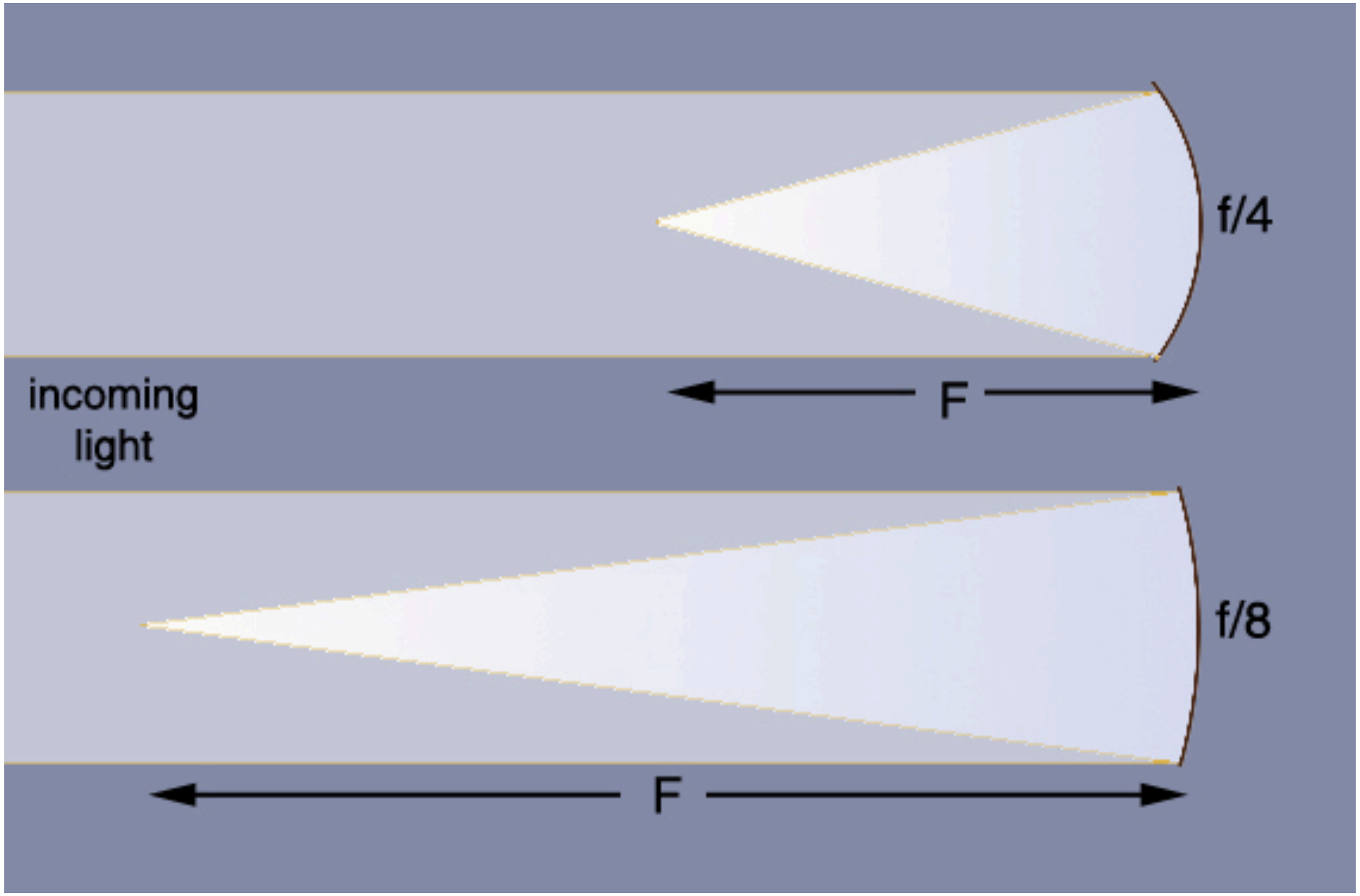
- Focal ratio for 120mm aperture (4.7") refractor with a focal length of 1 meter (1000mm) is 1000/120 = 8.3 or f/8.3

- Focal ratio determines photographic speed
    - For example —an f/5 telescope or lens requires shorter exposure times than an f/10 optics
    - Therefore higher focal ratios are called slower, and lower focal ratios are called faster
    - Slower focal ratios produce less aberrations

Some Important Telescope parameters

- Focal Ratio — is the focal length (F) of the telescope divided by its aperture or diameter (D), also known as F number

$$f/\# = \text{focal length/diameter} = F / D$$



Some Important Telescope parameters

- Focal Ratio — is the focal length (F) of the telescope divided by its aperture or diameter (D), also known as F number

$$f/\# = \text{focal length/diameter} = F / D$$

This an important feature of a telescope, and is often mentioned in the specification of an instrument.

- Telescopes with small f-numbers are short and compact, have a wide field of view and a bright image.
- Making a short focal-ratio lens or mirror is more difficult.

- Telescopes with large f-numbers are comparatively long, and have a narrower field of view but work better at higher magnification.
- Making a short focal-ratio lens or mirror is more difficult than making a longer one

Some Important Telescope parameters

- Light gathering power — Simply defined by collecting area

Light gathering power = D^2

- Bigger telescopes can collect more light
- This property determines the ability to see faint objects
- A large telescope see the faintest, nearby objects in the universe, and the most distant

Bigger is better!!

Some Important Telescope parameters

- Light gathering power — Simply defined by collecting area

$$\text{Light gathering power} = D^2$$

Thought Question

How does the collecting area of a 10-meter telescope compare with that of a 2-meter telescope?

- It's 5 times greater.
- It's 10 times greater.
- It's 25 times greater.

Some Important Telescope parameters

- Light gathering power — Simply defined by collecting area

$$\text{Light gathering power} = D^2$$

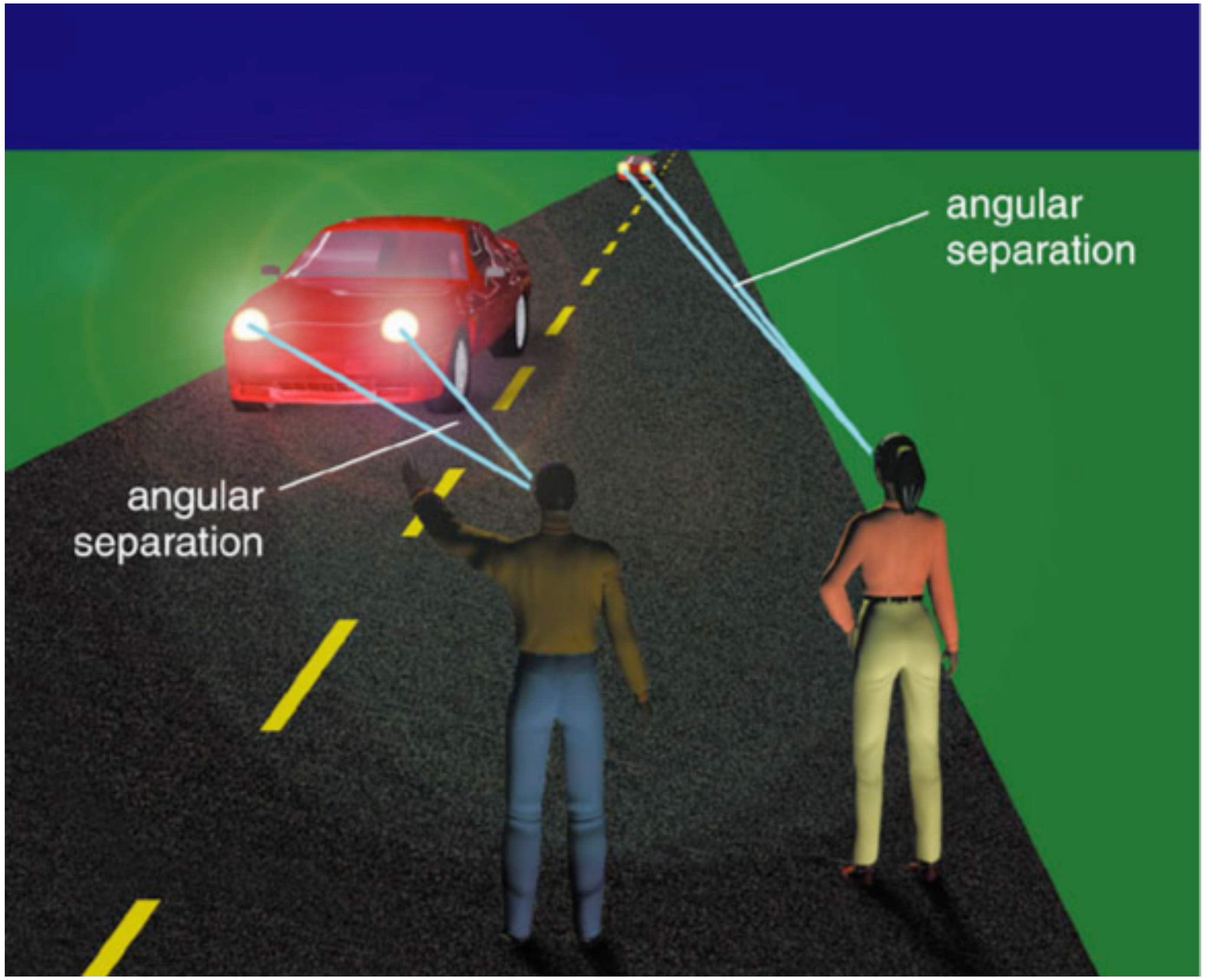
Thought Question

How does the collecting area of a 10-meter telescope compare with that of a 2-meter telescope?

- It's 5 times greater.
- It's 10 times greater.
- It's 25 times greater.

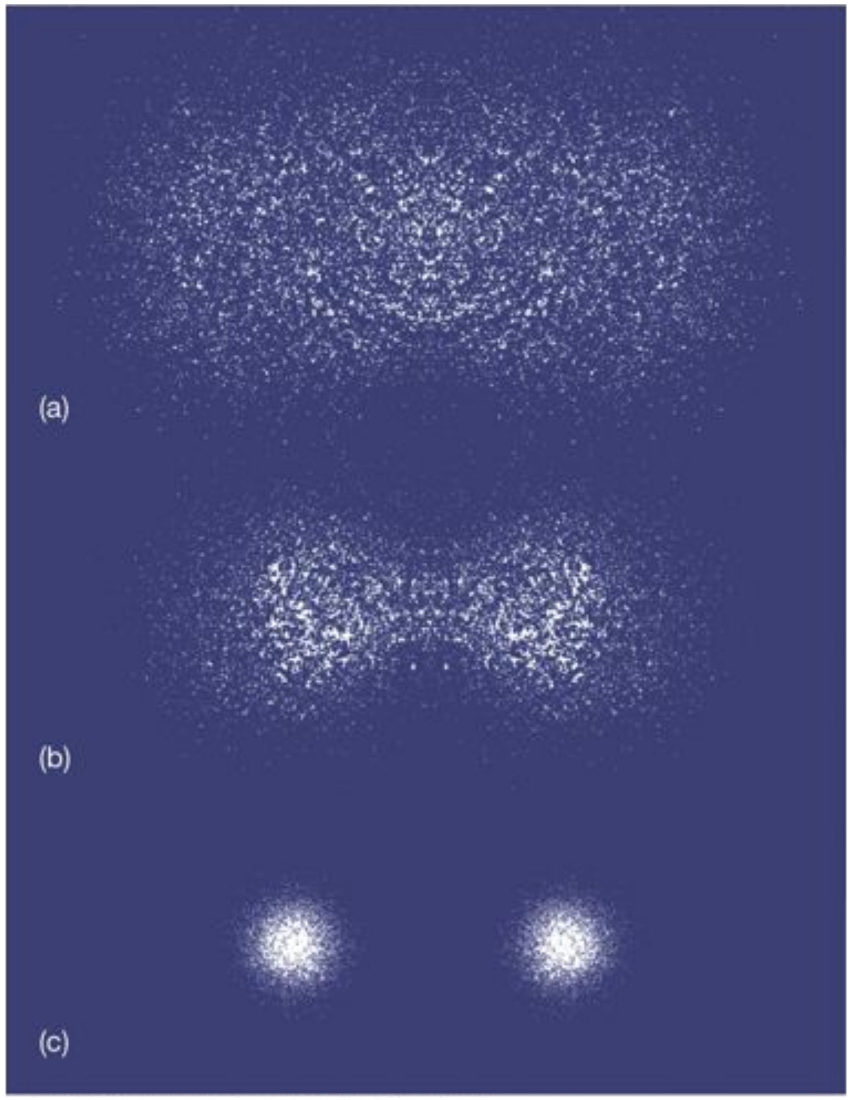
Some Important Telescope parameters

- Resolution — The *minimum* angular separation that the telescope can distinguish.
- Depends on both separation and distance to us



Some Important Telescope parameters

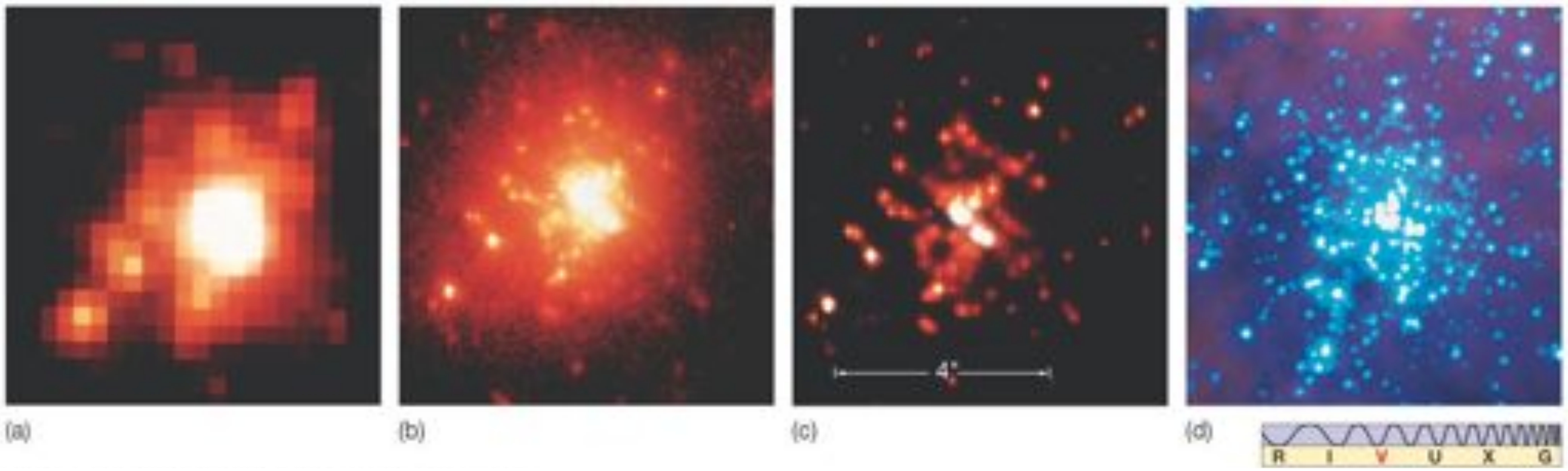
- Resolution — How well you can distinguish two objects, or detail in a single object. It is an *angle*, usually in arcseconds.



Increasing resolution from top to bottom. High resolution is good, means sharp image.

Some Important Telescope parameters

- Resolution — poor resolution means "blurry," and is equivalent of having a digital camera with only 0.2 megapixels

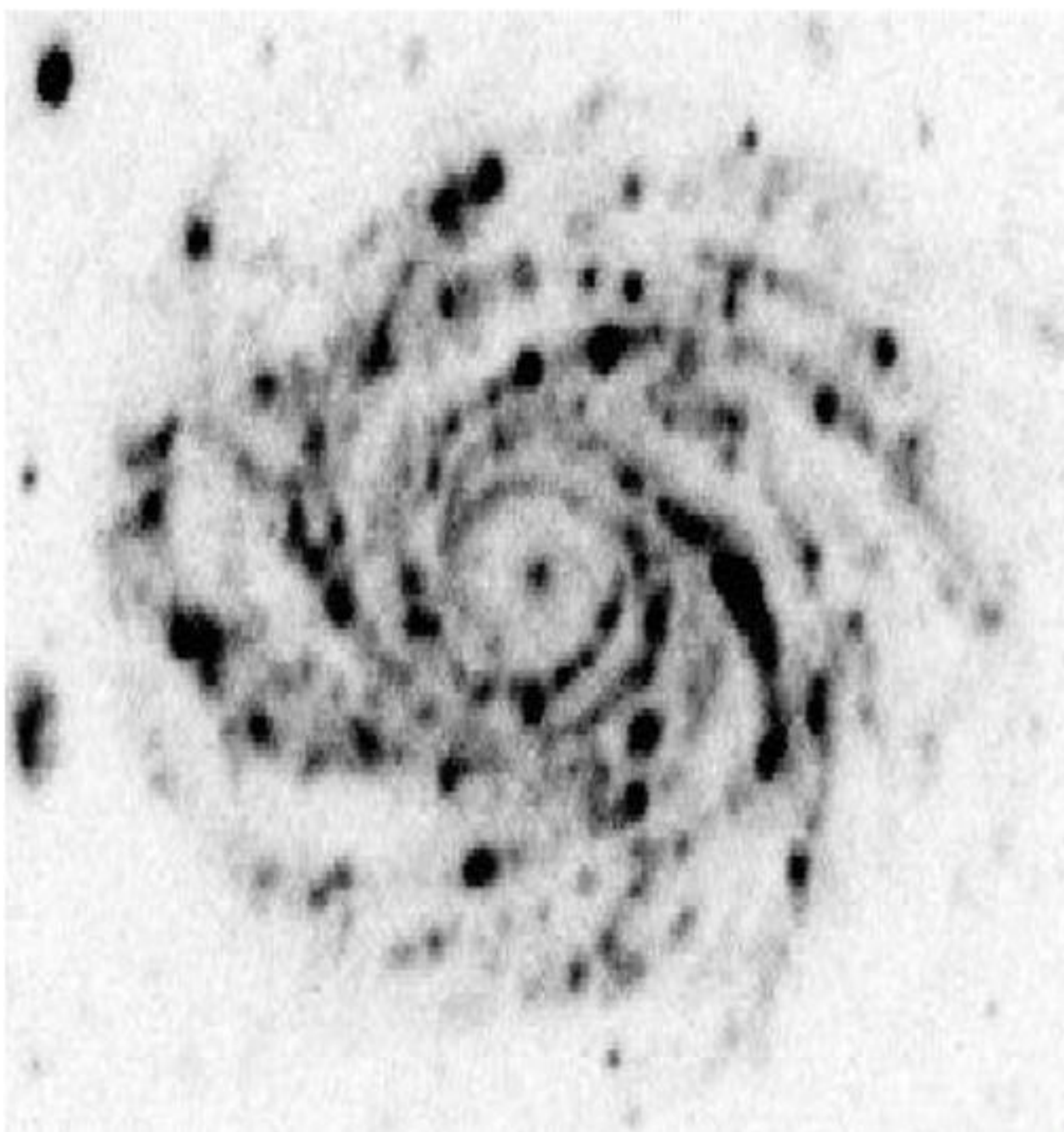


How to enhance resolution? First must understand the limitations, which are —

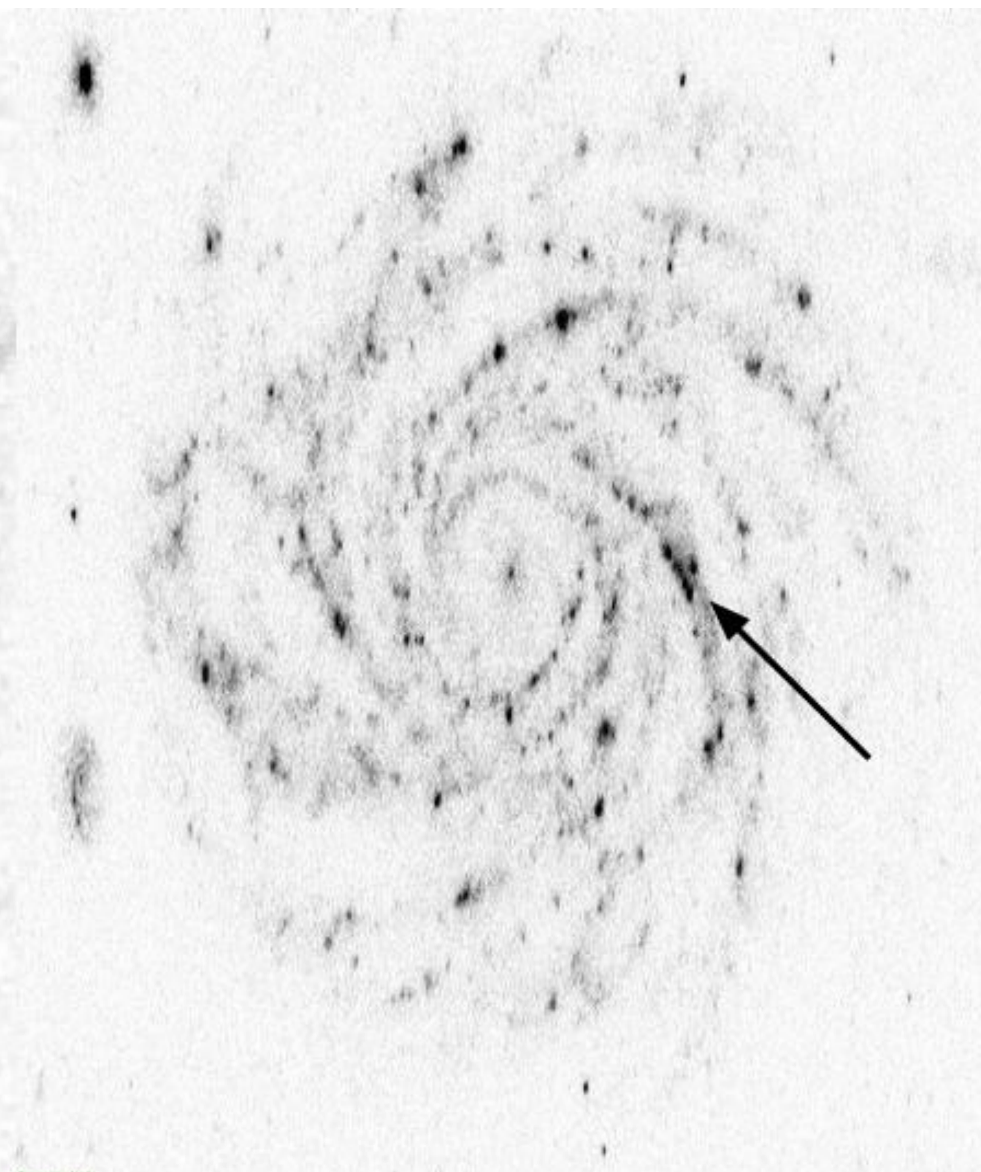
- The "seeing limit" (Earth's atmosphere), and
- The "diffraction limit" (inherent in observing through an instrument)

Some Important Telescope parameters

- Resolution — poor resolution means “blurry,” and is equivalent of having a digital camera with only 0.2 megapixels



GALEX Image



AstroSAT UVIT Image

Some Important Telescope parameters

Thought Question

Suppose two stars are separated in the sky by 0.1 arc-second. If you look at them with a telescope with an angular resolution of 0.01 arc- second, what do you see?

a) Two distinct stars.

b) One point of light that is the blurred image of both stars.

c) Nothing at all.

Some Important Telescope parameters

Thought Question

Suppose two stars are separated in the sky by 0.1 arc-second. If you look at them with a telescope with an angular resolution of 0.01 arc- second, what do you see?

a) Two distinct stars.

b) One point of light that is the blurred image of both stars.

c) Nothing at all.

Telescopes

Some Important Telescope parameters

Diffraction limit or Angular resolution or Resolvability

The minimum angular separation of two sources that can be distinguished by a telescope depends on the wavelength of the light being observed and the diameter of the telescope.

$$\theta = 1.22 \frac{\lambda}{a}$$

θ — the angular resolution (radians),
λ — the wavelength of light,
D (a) — the diameter of the lens' aperture
λ and D (or a) are expressed in the same units (centimeters, meters).

The factor 1.220 is derived from a calculation of the position of the first dark circular ring surrounding the central Airy disc of the diffraction pattern

Telescopes

Some Important Telescope parameters

Diffraction limit or Angular resolution or Resolvability

The Hubble Space Telescope is a 2.4 meter telescope. The theoretical resolution set by diffraction limit for light of wavelength 5000 A is

Diffraction limit (in radians) = 1.22 x wavelength (cm) / diameter (cm)

$$= 1.22 \times 5000 \times 10^{-8} / 2.4 \times 100$$

$$= 2.5 \times 10^{-7} \times 206265$$

$$= 0.05 \text{ arcsecond}$$

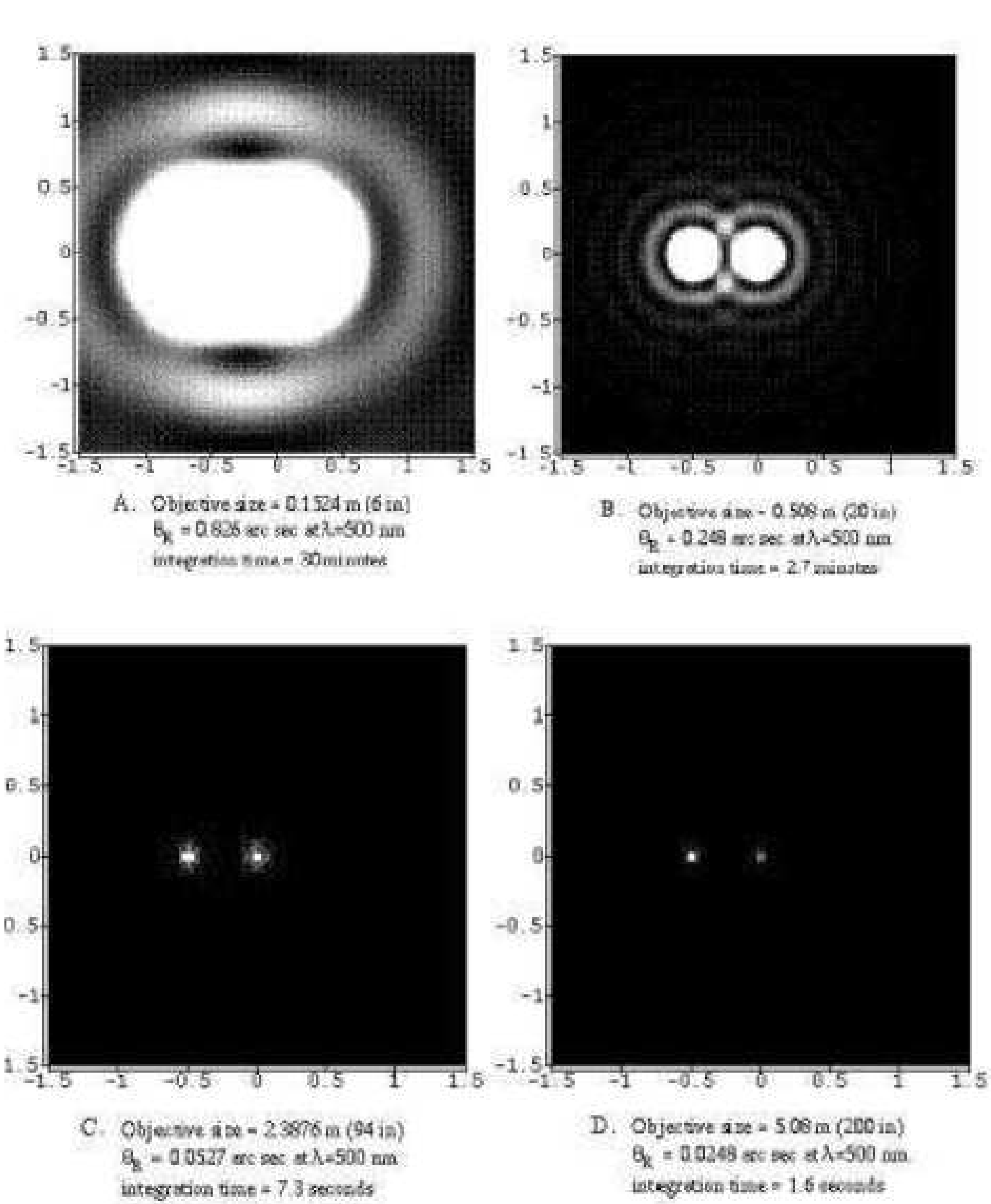
Telescopes

Some Important Telescope parameters

Resolvability —

Ignoring atmospheric effects, the resolution of an ideal telescope is just defined by its size

Examples:
D = 0.13 m, 0.50 m, 2.5m
& 5 m diameter telescopes



A. Objective size = 0.1524 m (6 in)
θ_R = 0.826 arc sec at λ=500 nm
integration time = 30 minutes

B. Objective size = 0.508 m (20 in)
θ_R = 0.248 arc sec at λ=500 nm
integration time = 2.7 minutes

C. Objective size = 2.3876 m (94 in)
θ_R = 0.0527 arc sec at λ=500 nm
integration time = 7.3 seconds

D. Objective size = 5.08 m (200 in)
θ_R = 0.0248 arc sec at λ=500 nm
integration time = 1.6 seconds

Telescopes

Some Important Telescope parameters

Plate Scale —

- This defines the scale of an image at the telescopes focal surface
- For a focal plane, with no distortion, this is just related to the focal length (F)

s (in radians/length unit) = 1 / F (length unit) So,

s (radians/mm) = 1 / F (mm)

- In more useful units for astronomers:
  - Use arcseconds (1 / 3600th of a degree; 2π radians = 360o)
  - So, 1 radian = 206,265 arcsecs

s (arcsec/mm) = 206265 / F (mm)

Telescopes

Optical Aberrations

Departures from ideal image caused by optical aberrations.

Types - Chromatic Aberrations (for lenses)

Spherical Aberrations (for mirrors)

Coma

Astigmatism

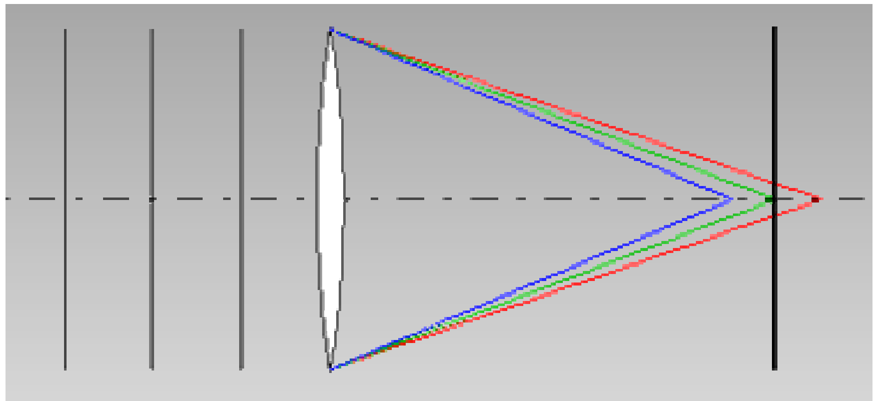
Field Curvature

Field distortion

Telescopes

Chromatic Aberrations

- As refraction is wavelength dependent, chromatic aberrations occur in lenses



Different wavelengths brought to different foci

Focal length depends on refractive index n of lens material:

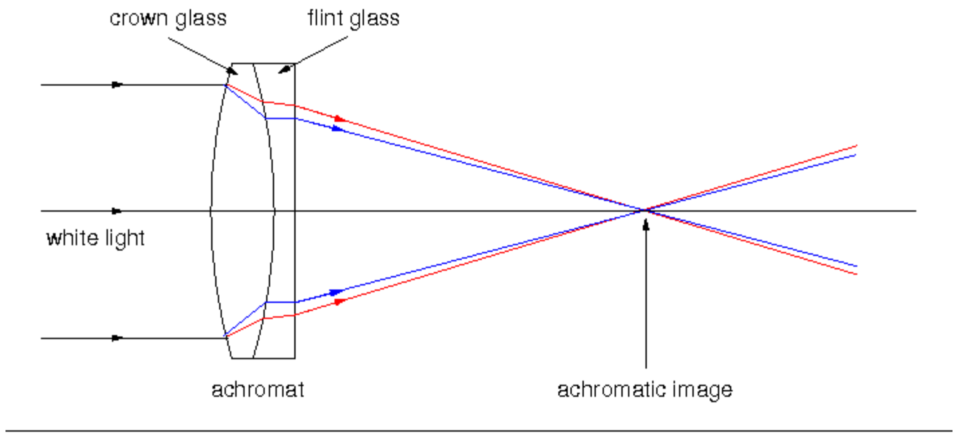
$$\frac{1}{F}=(n-1)\left(\frac{1}{r_1}-\frac{1}{r_2}\right)$$

Where r_1 and r_2 are the radii of curvature of lens surfaces

Refractive index depends on λ; $n=n(\lambda)$

F shorter for blue light than red light – Gives coloured edges to images

Telescopes



Correction achieved with achromat doublet

- Some corrections for this can be done by combining lenses of varying refractive index

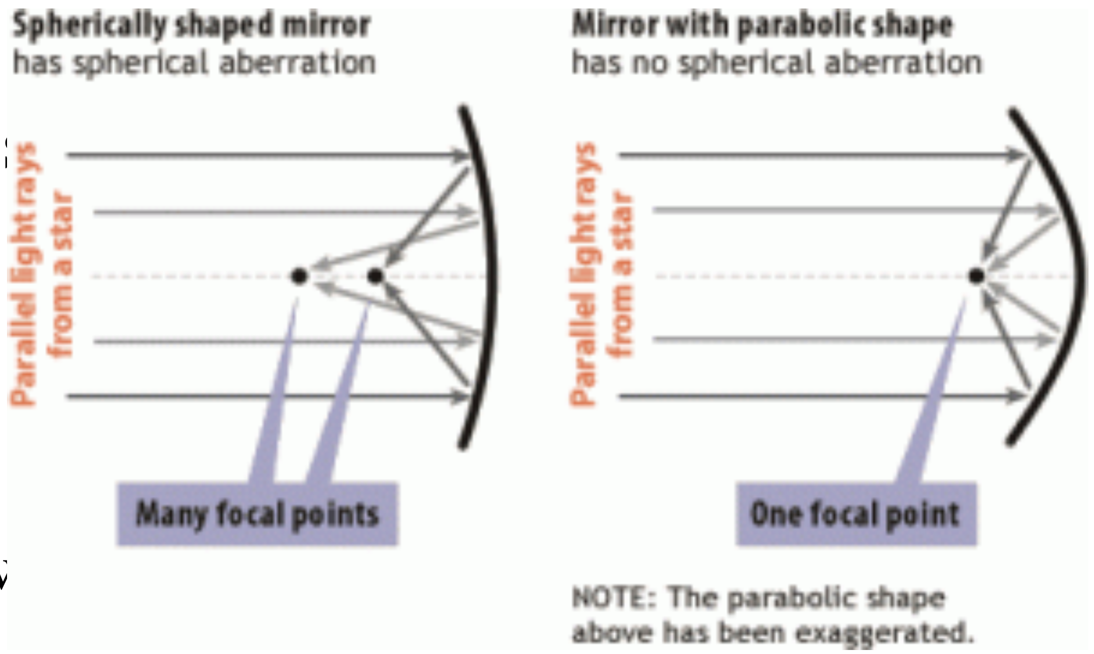
Telescopes

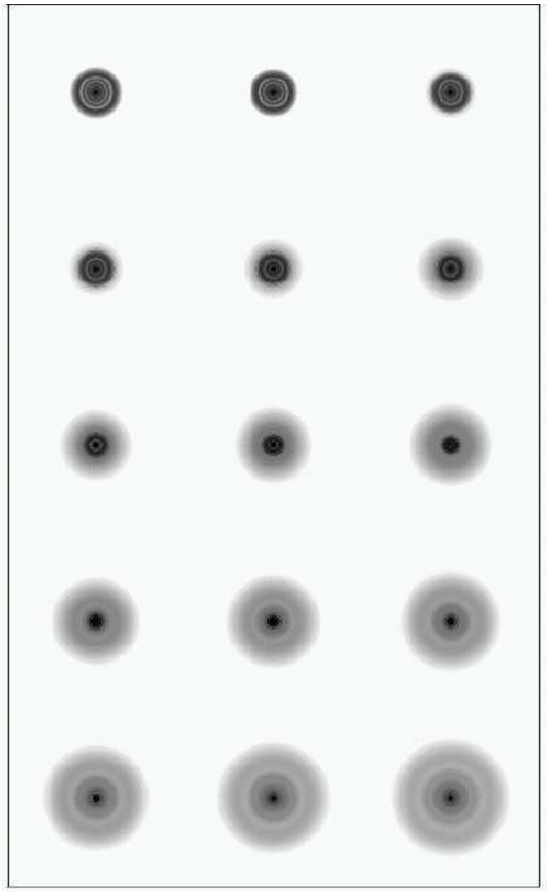
Spherical Aberrations

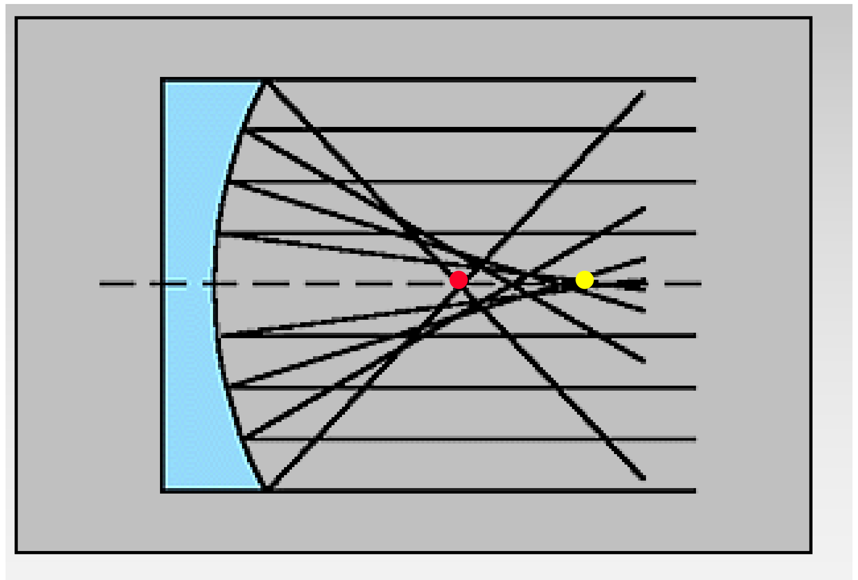
Different focus points between paraxial (passing along optical axis) and marginal (furthest from optical axis) rays.

Spherical because a sphere images just like this

- perfect image only of centre of curvature
- any optic (spherical or not) can show exhibit it
- ideal mirror to image on-axis object at ∞ is a paraboloid (as used in most telescope primary mirrors).
- SALT – Since SALT is deliberately designed to have a spherical primary mirror it suffers from severe spherical aberration



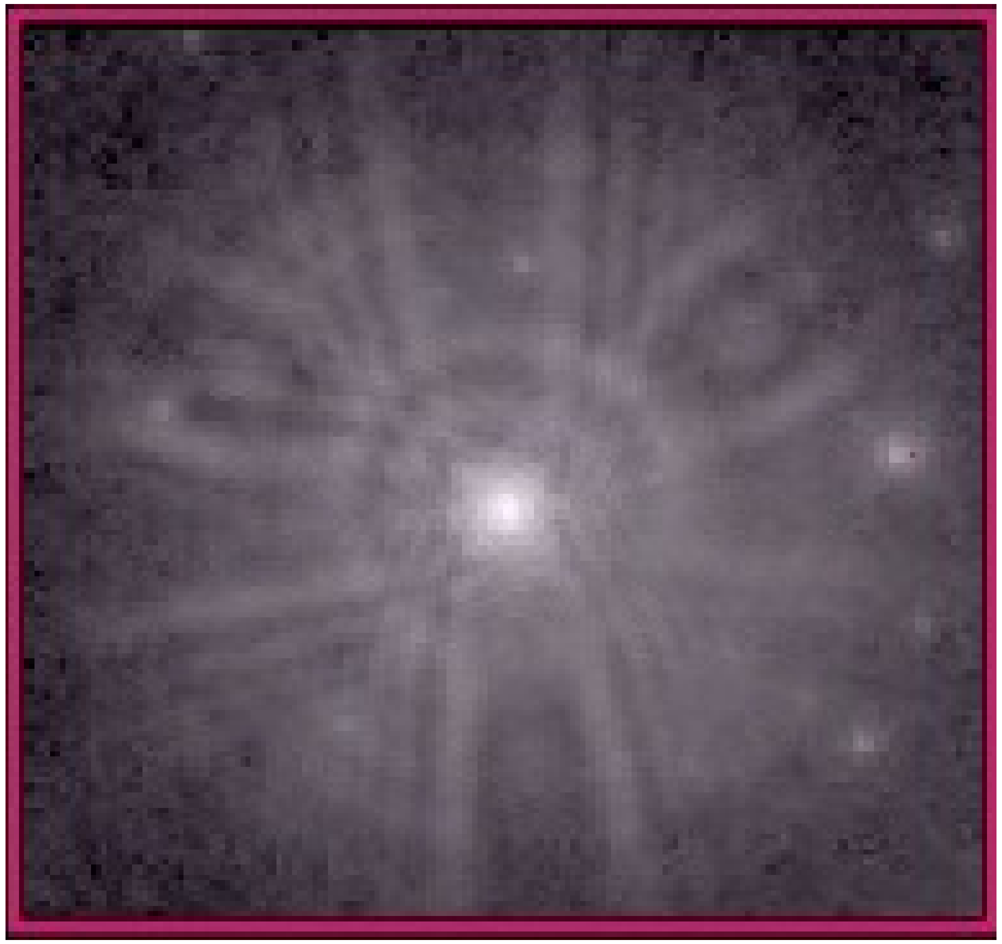




Telescopes

Spherical Aberrations

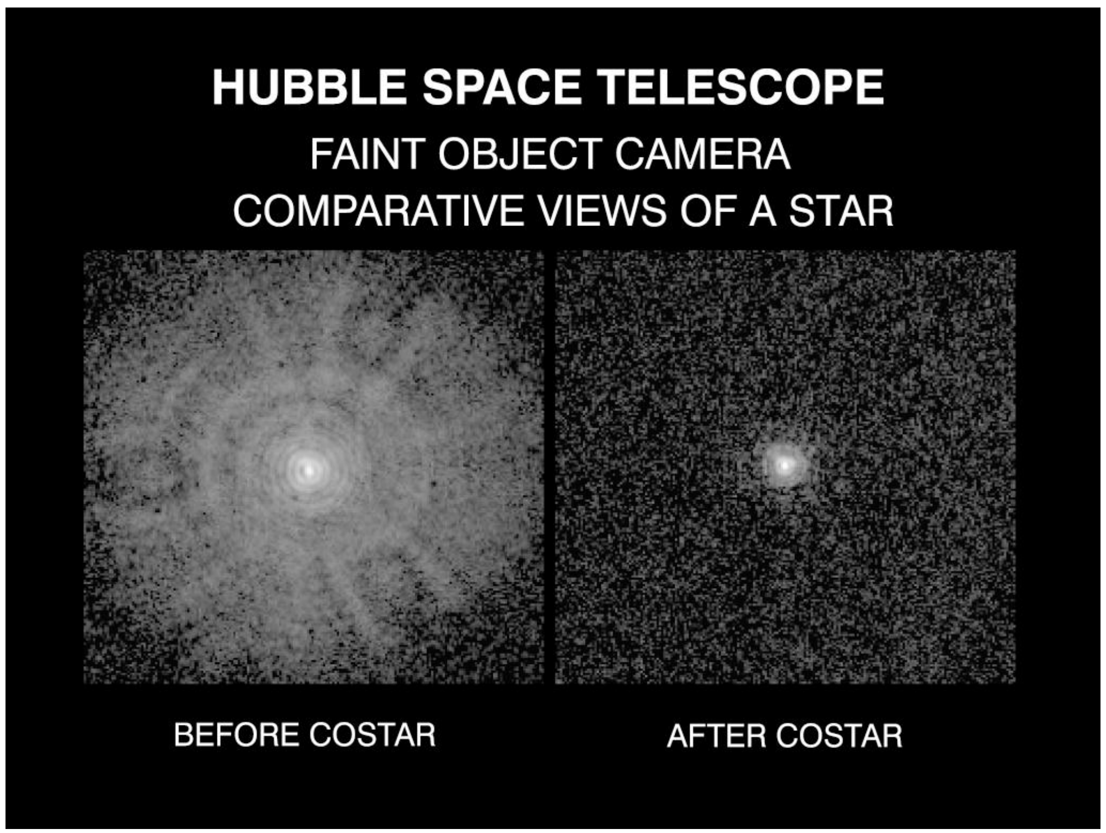
- HST suffered from spherical aberration at launch
- Mirror was most precisely ground mirror ever constructed — Variations from smooth curve ~1/20 λ
- Precise but not accurate – shape was wrong
- Company responsible assembled primary measuring device incorrectly
- 2 other devices showed shape was wrong but believed main device
- Corrective mirrors installed after 3 years One science instrument removed

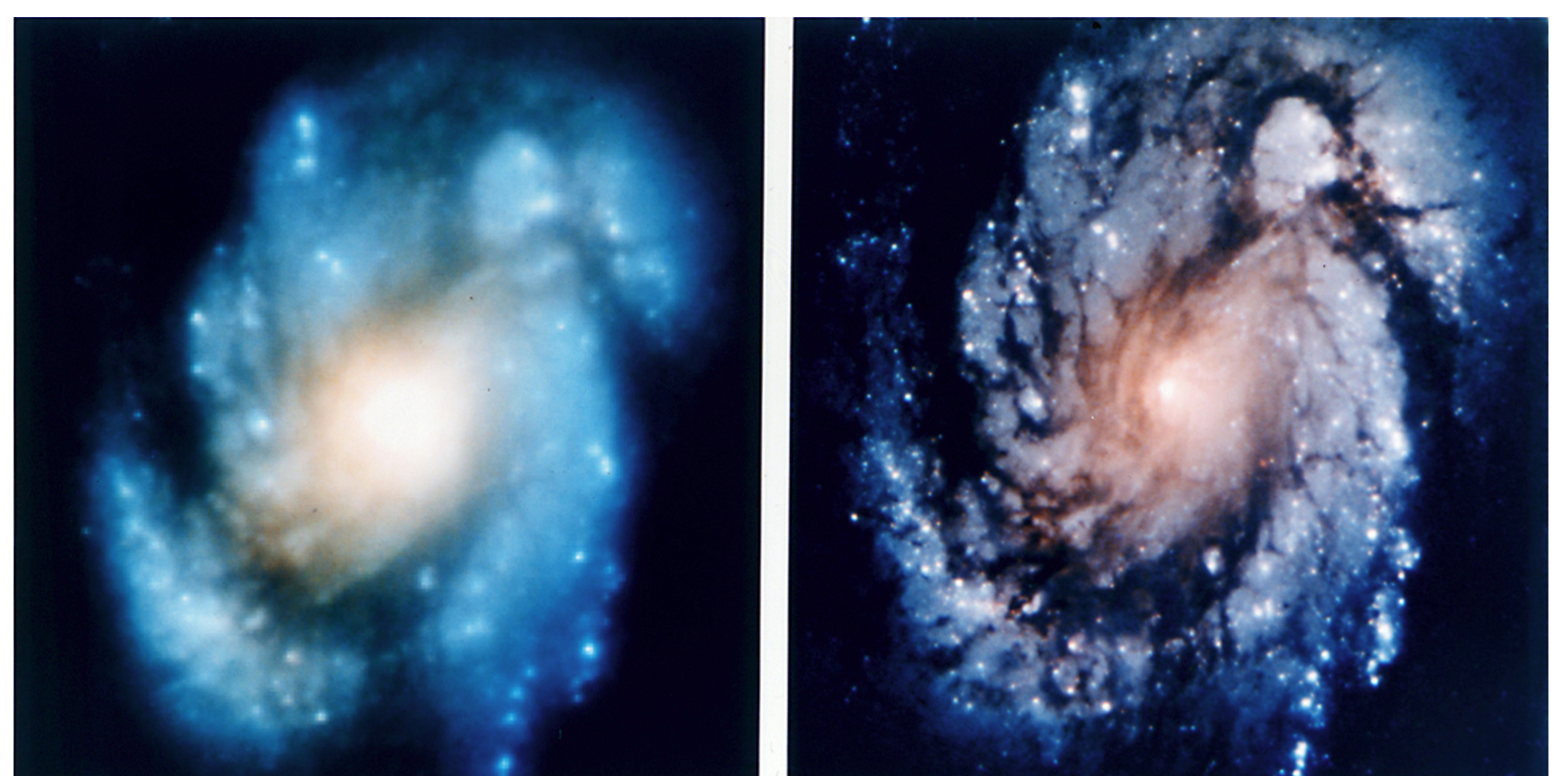


Telescopes

Spherical Aberrations

HST suffered from spherical aberration at launch





Coma

Coma is an inherent property of telescopes using parabolic mirrors.

Unlike a spherical mirror, a bundle of parallel rays parallel to the optical axis will be perfectly focused to a point (the mirror is free of spherical aberration), no matter where they strike the mirror.

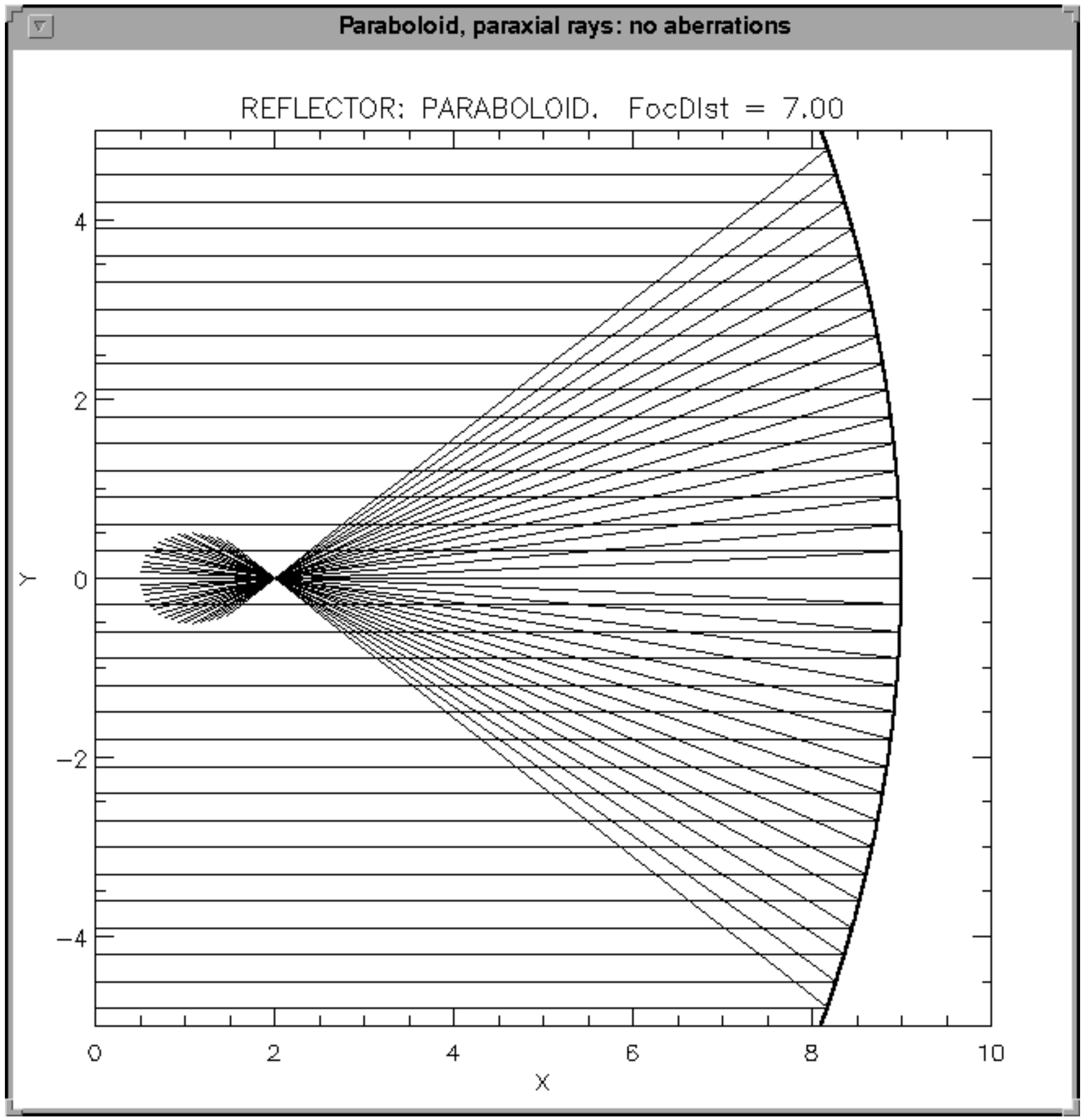
However, this is only true if the rays are parallel to the axis of the parabola.

When the incoming rays strike the mirror at an angle, individual rays are not reflected to the same point. When looking at a point that is not perfectly aligned with the optical axis, some of the incoming light from that point will strike the mirror at an angle.

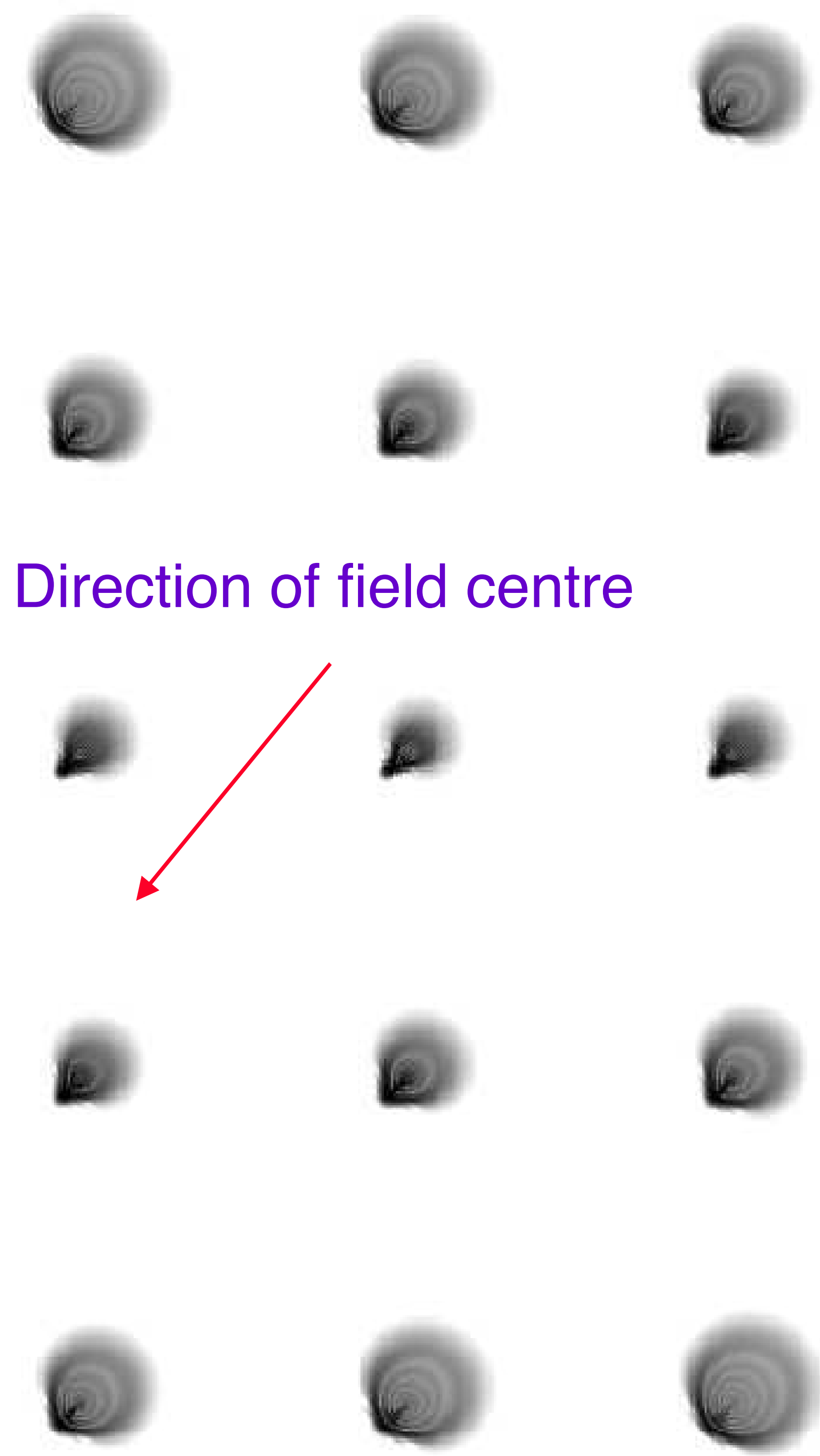
This results in an image that is not in the center of the field looking wedge-shaped. The further off-axis (or the greater the angle subtended by the point with the optical axis), the worse this effect is. This causes stars to appear to have a cometary coma, hence the name.

Telescopes

Coma

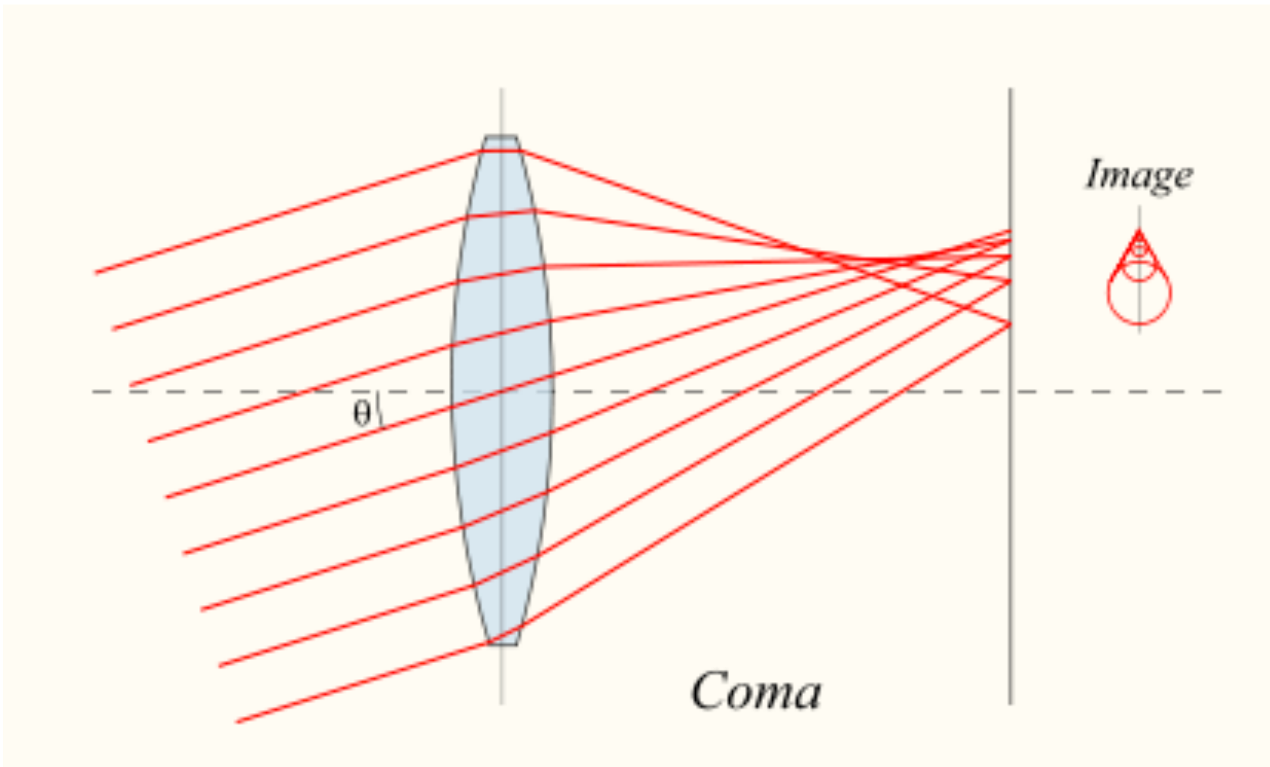


Parabolic mirror

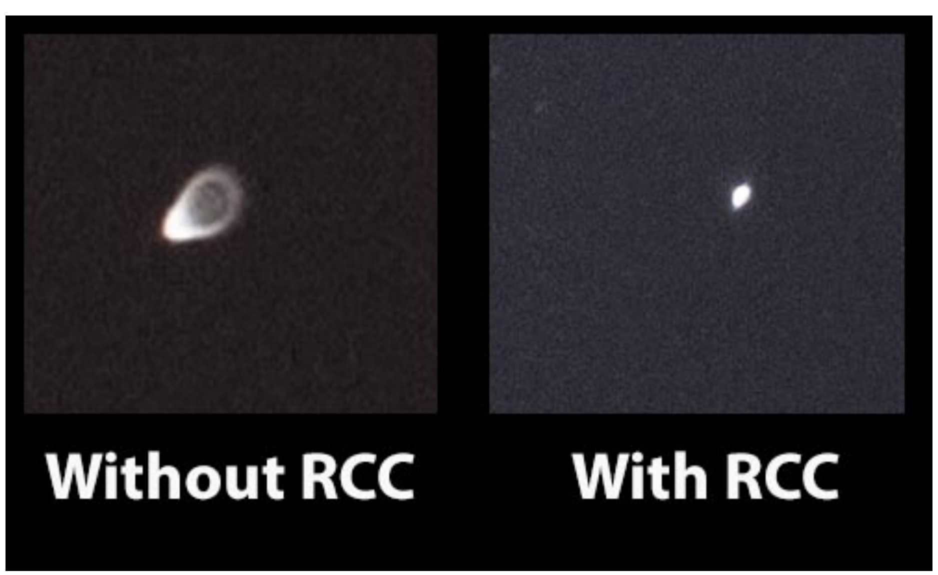


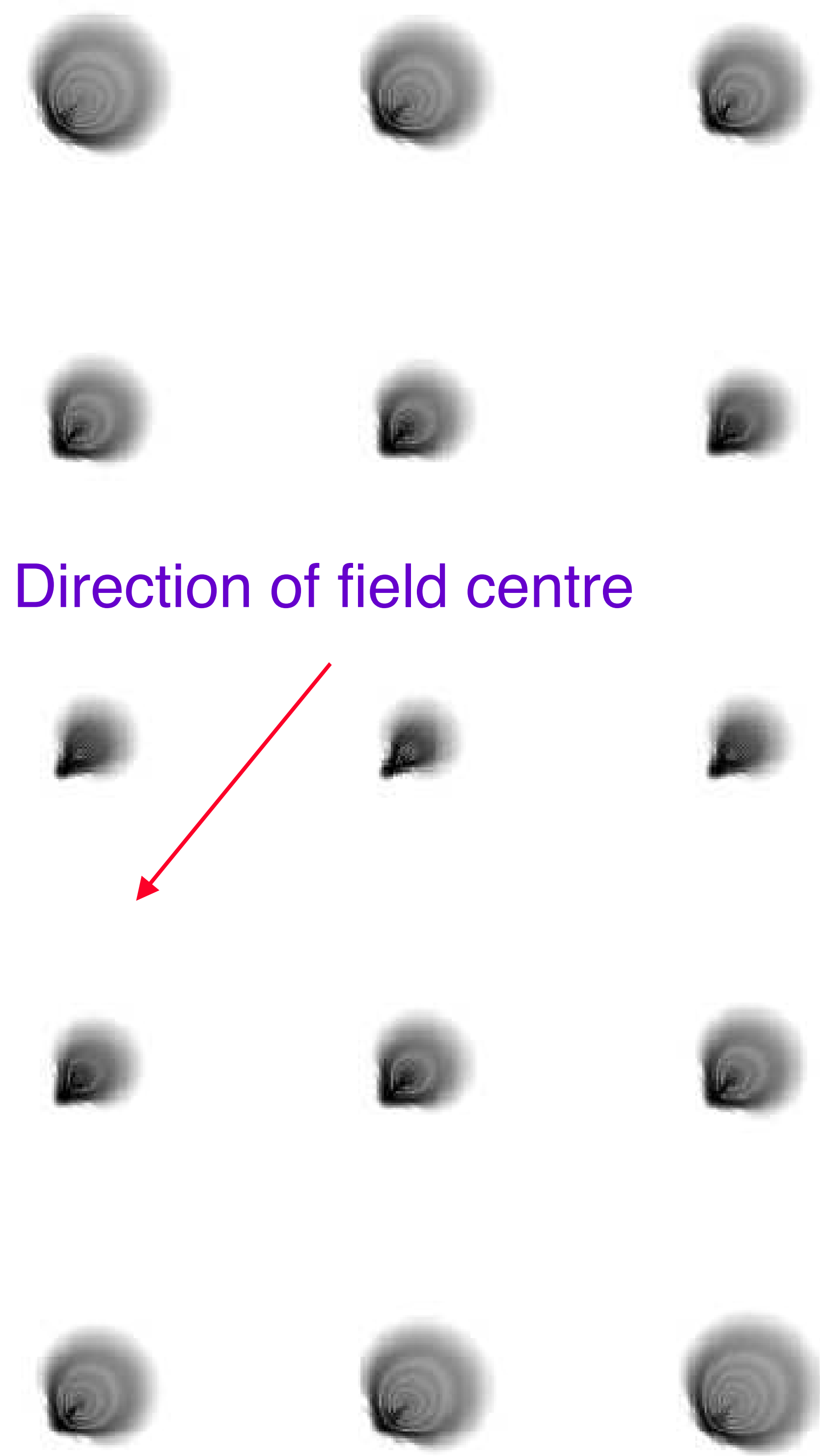
Telescopes

Coma



Single lens

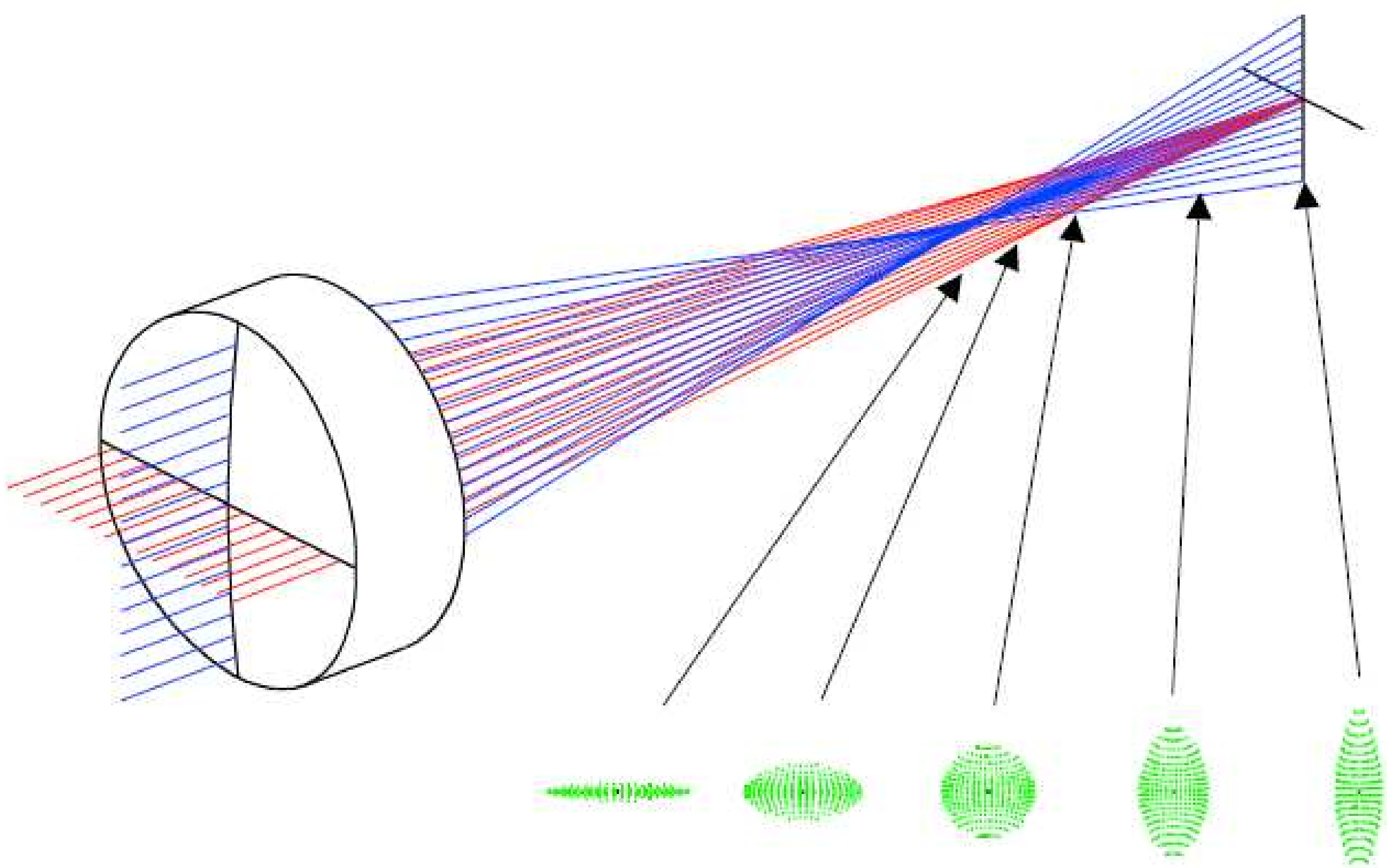




Telescopes

Astigmatism

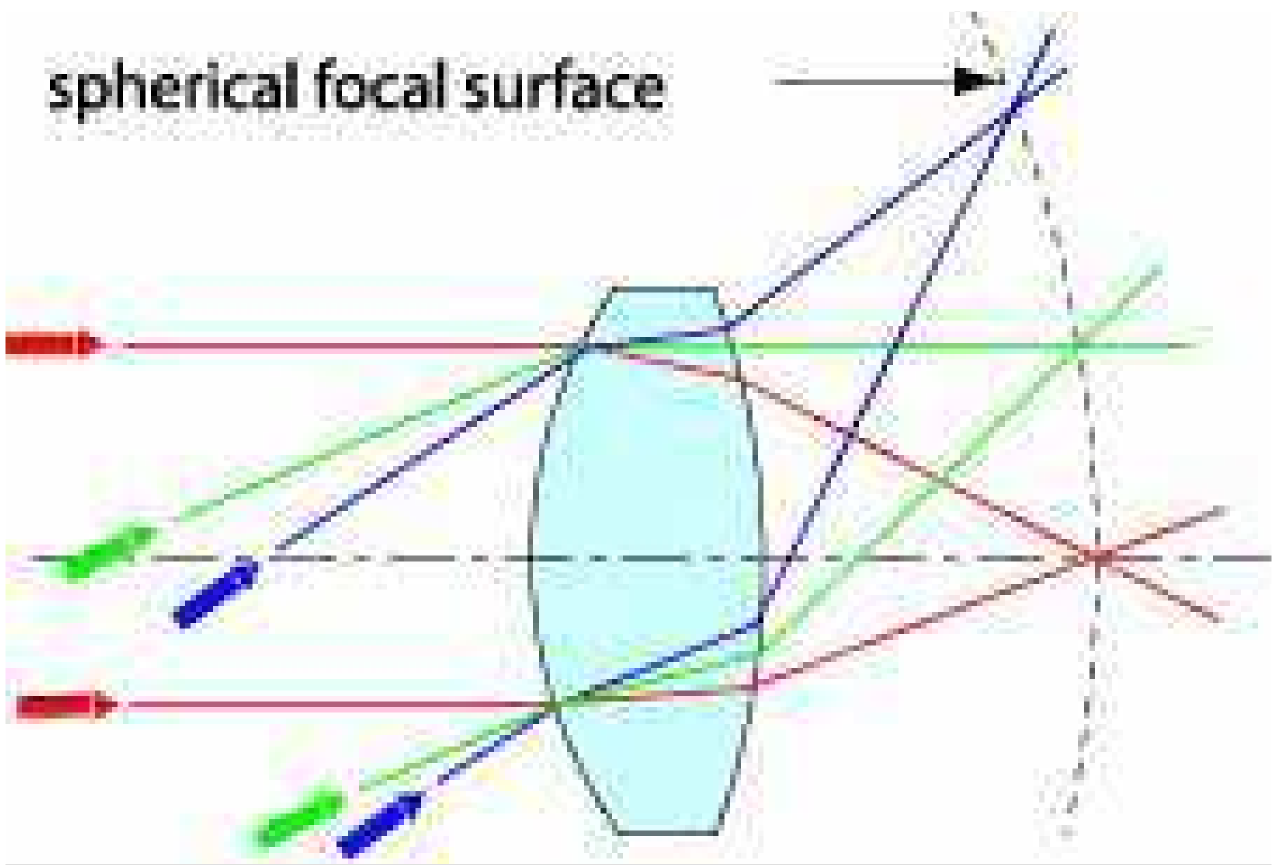
An optical system with astigmatism is one where rays that propagate in two perpendicular planes have different foci



Telescopes

Field Curvature

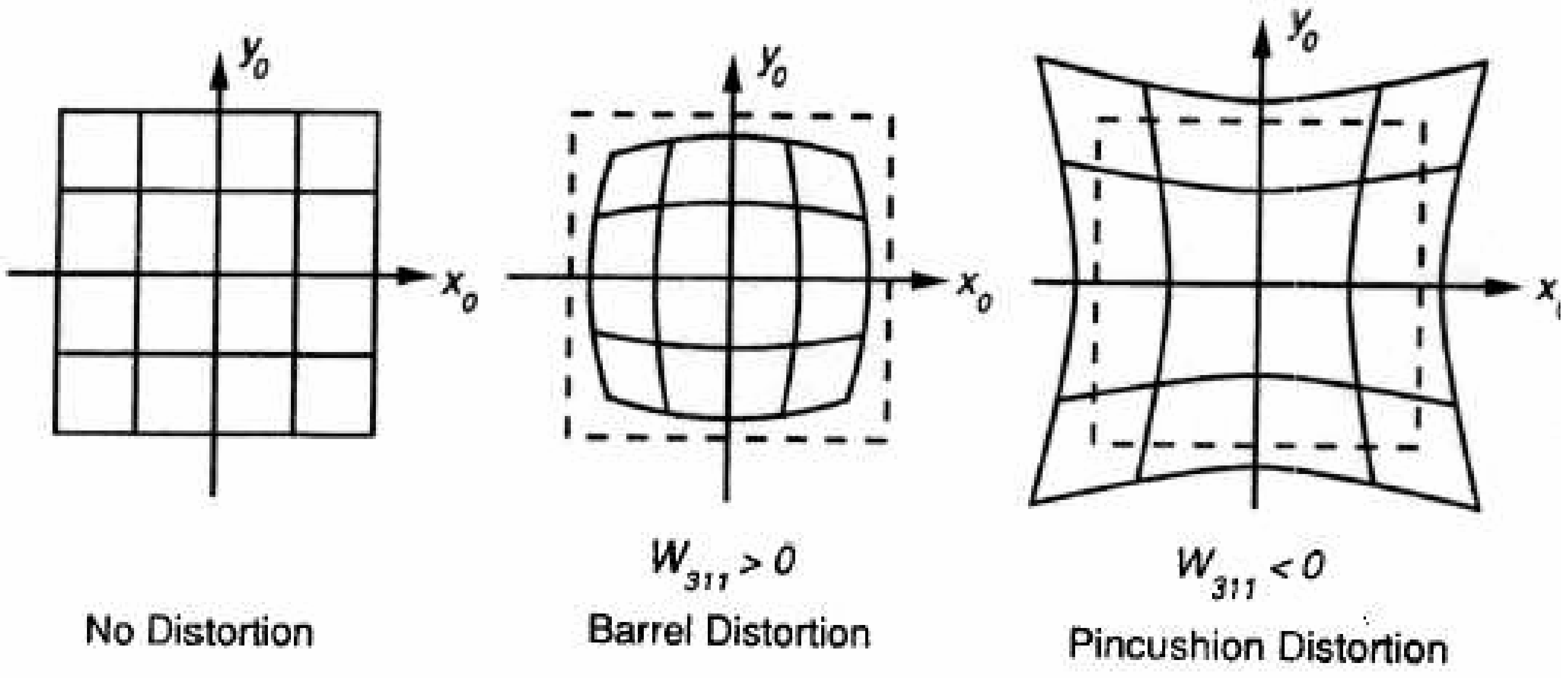
- Causes curvature of the focal plane.
- Not compatible with a flat detector (like CCD).
- In the past photographic plates could be slightly bent to accommodate
- Modern large & flat detectors require additional field-flattening optics



Telescopes

Field distortion

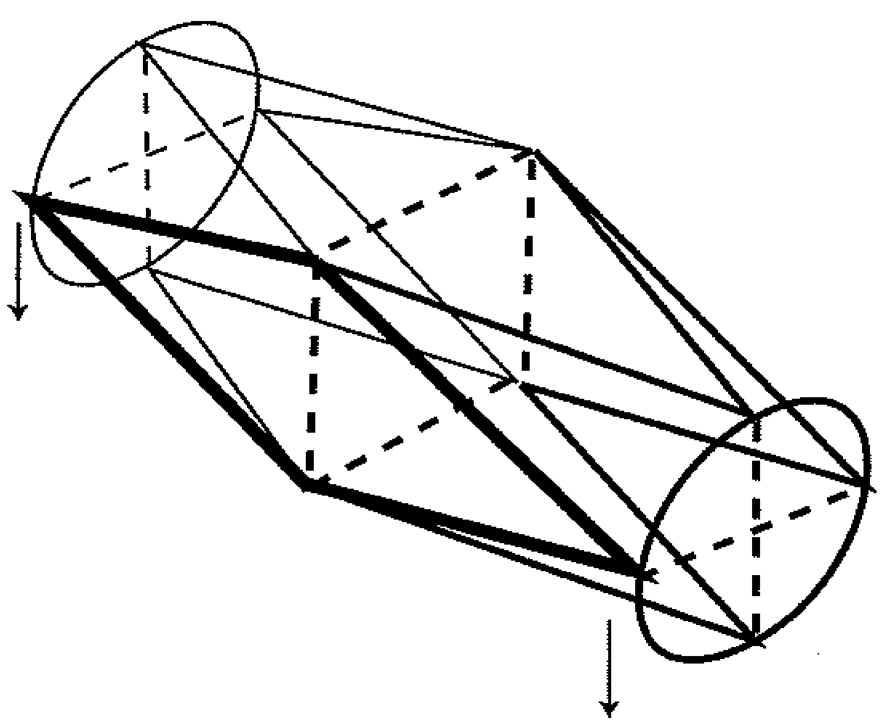
- Effectively a change of magnification across the FoV
- Can "stretch" (pin cushion) or "squeeze" (barrell) images.
- Need to map out distortion in order to do astrometry (accurate position measurement)

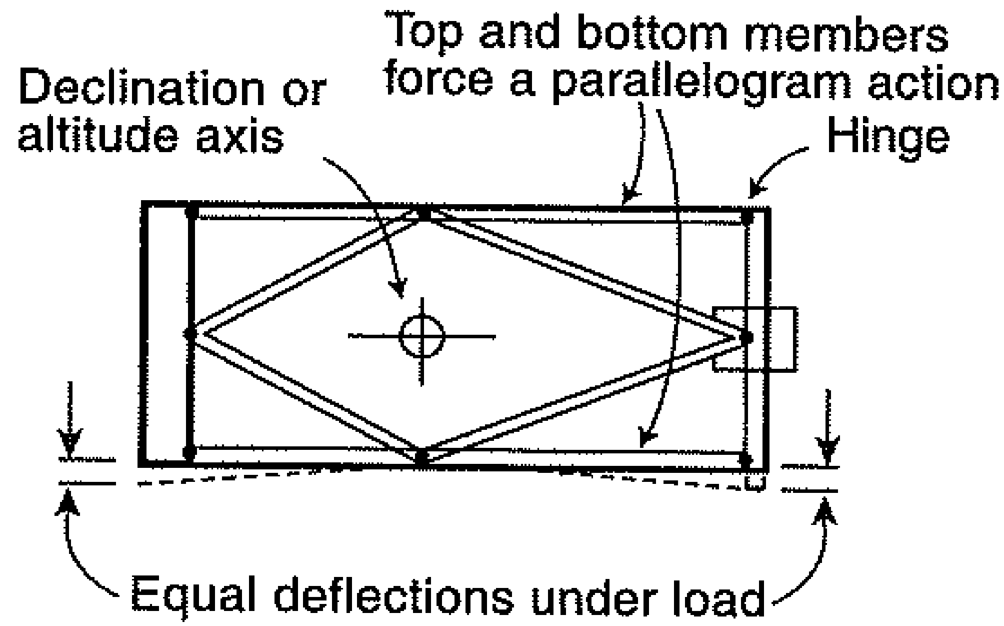


Telescopes Mounts

Telescopes Mounts

- Telescopes have to support mirrors and keep them aligned
  - "Tubes" keep mirrors & instruments co-aligned through varying gravity
  - Serrurier truss keeps primary and secondary mirrors co-aligned
    - *Relative* movement between mirror eliminated
- Telescopes need to follow objects across the sky due to Earth's rotation



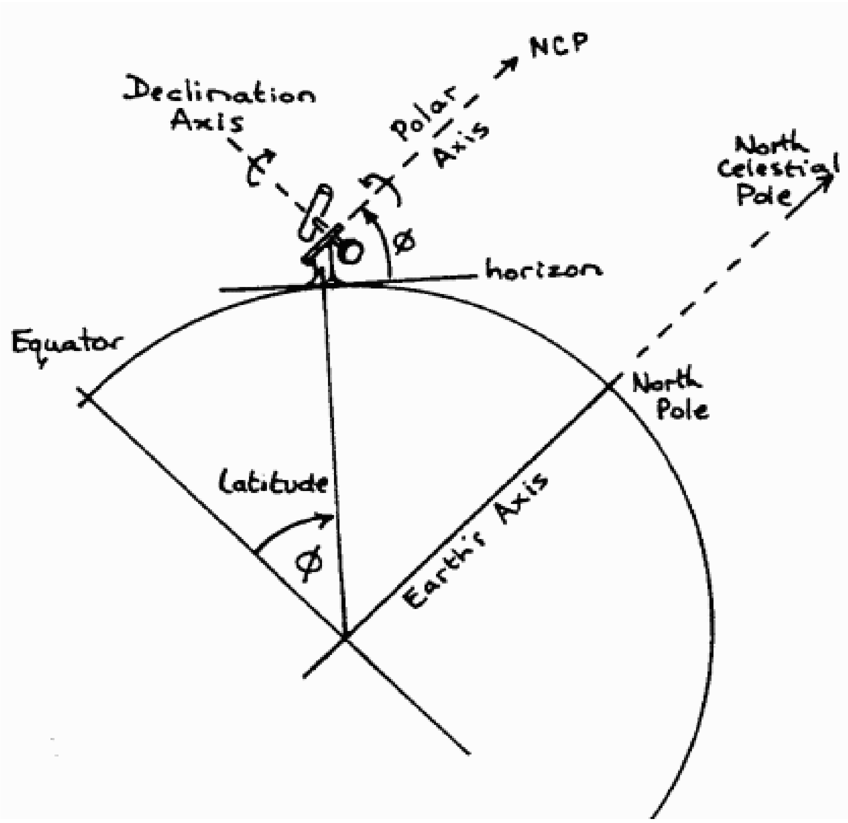


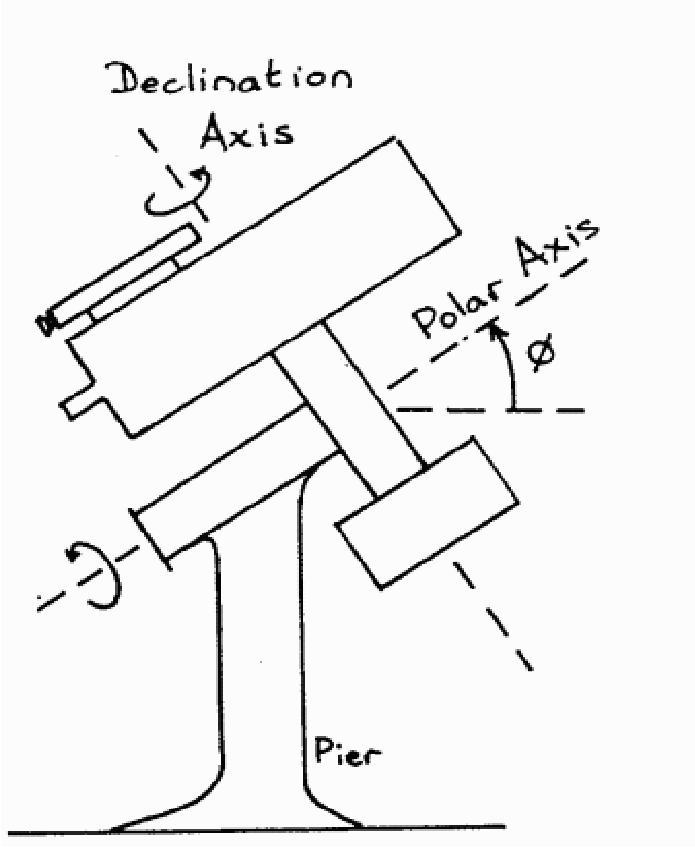
Telescopes Mounts

Telescopes need to follow objects across the sky due to Earth's rotation How?

1. Equatorial Mount

- Simplest & easiest method for tracking (used in all major telescopes pre-1980s)
- Telescope rotation axis (polar axis) is parallel to Earth's rotation axis





Telescopes Mounts

1. Equatorial Mount — Types

Fork (a)

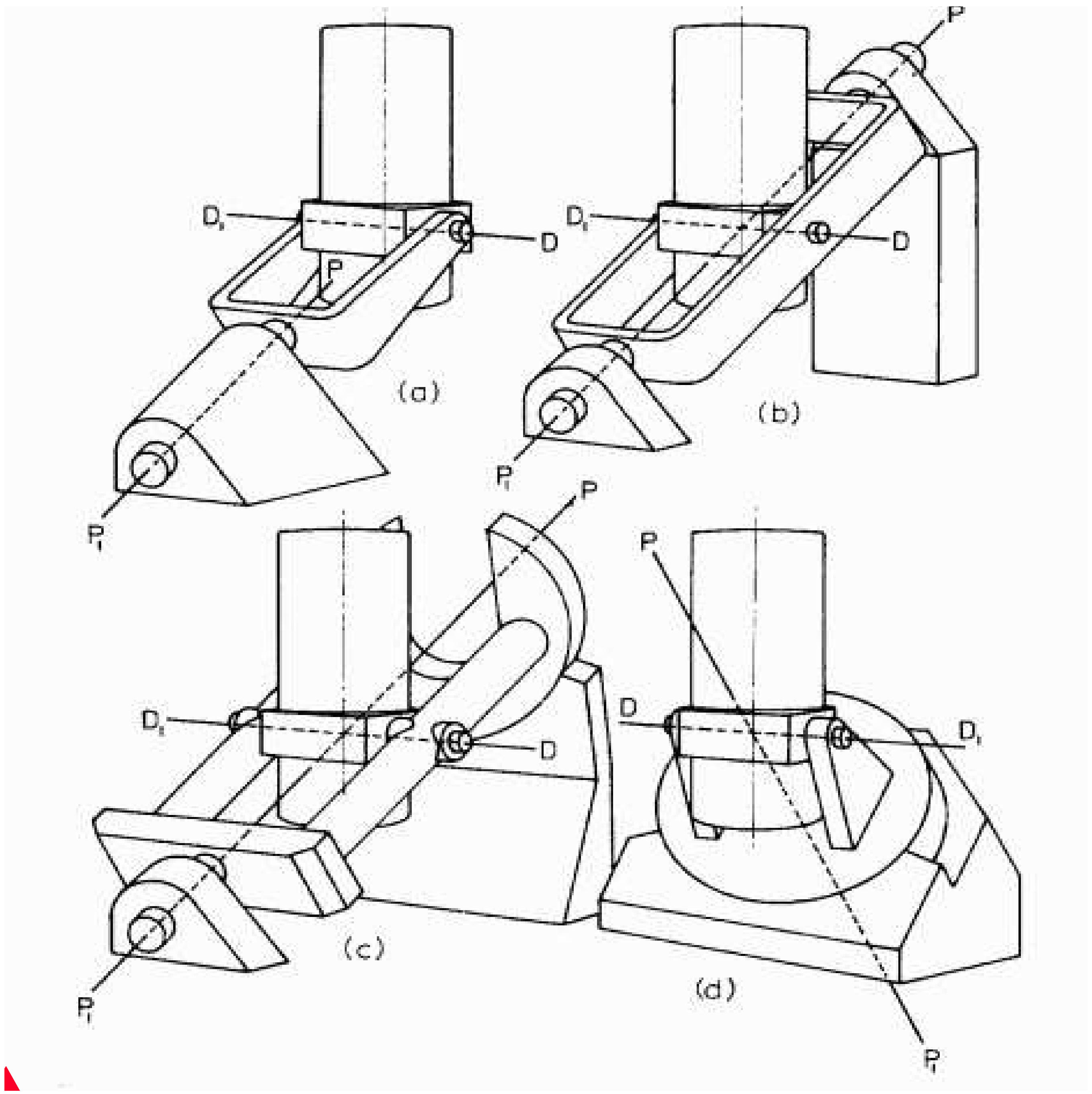
Yoke (b)

Horseshoe (c)

Polar disc (d)

English

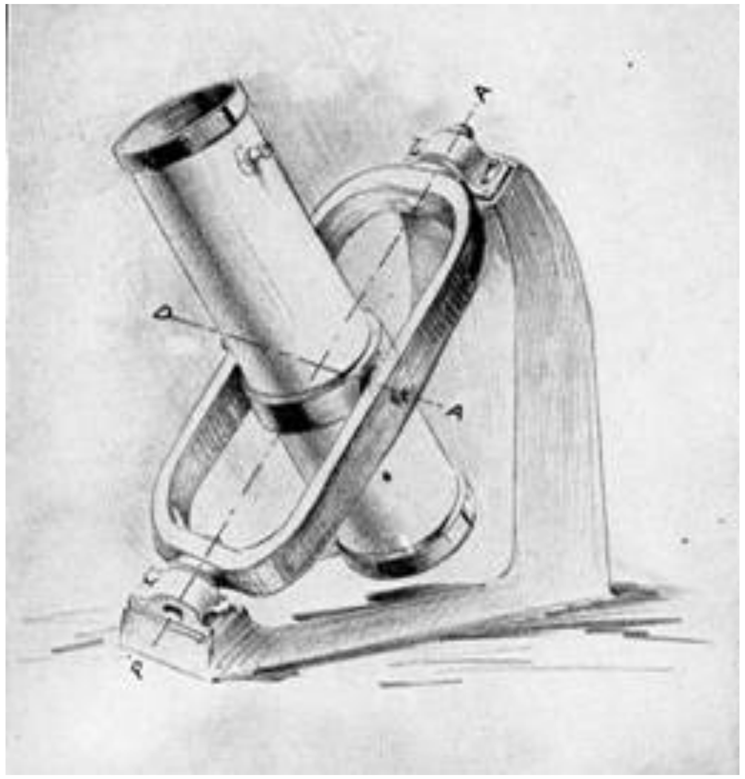
German



Telescopes Mounts

1. Equatorial Mount — Types

Fork (a)

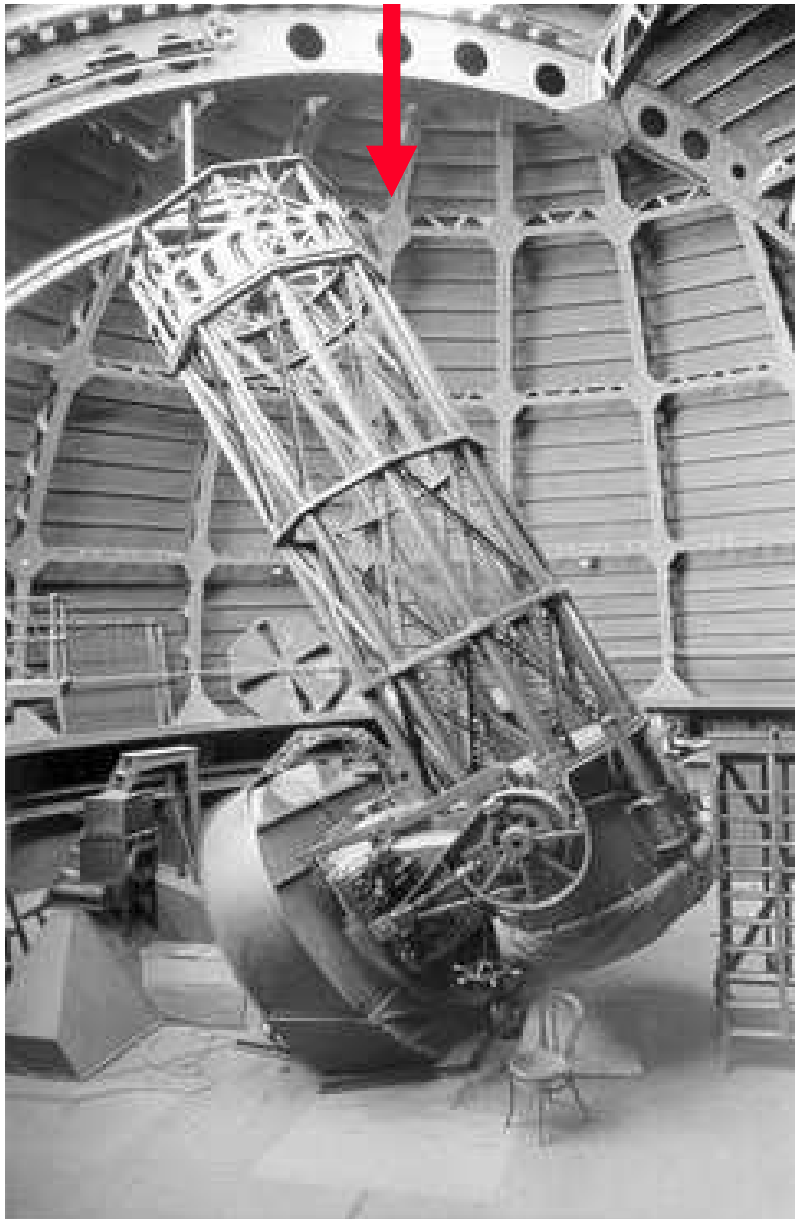


Yoke (b)

Telescopes Mounts

1. Equatorial Mount — Types

Horseshoe (c)



Polar disc (d)

Telescopes Mounts

1. Equatorial Mount — Types

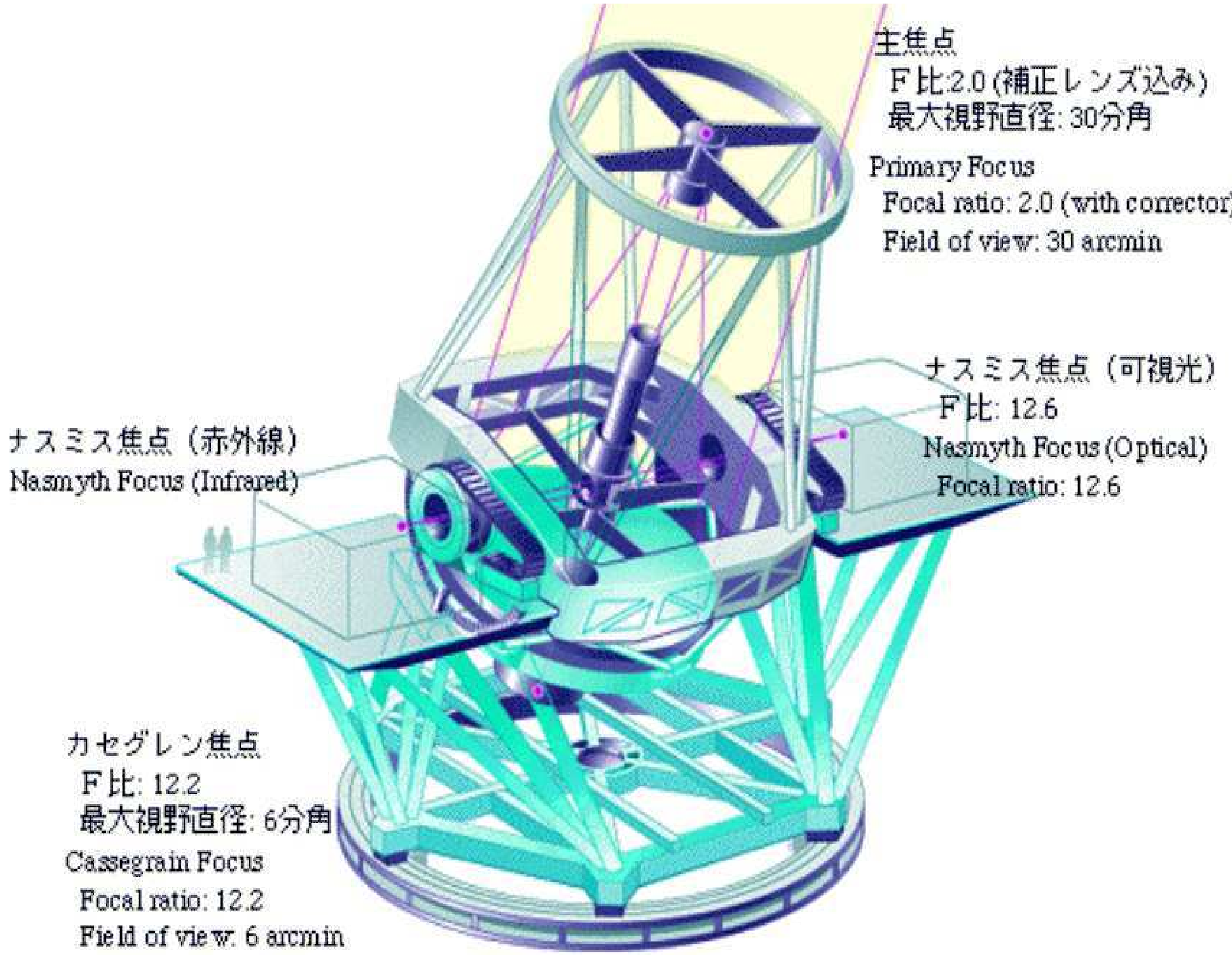
English

German

Telescopes Mounts

1. Alt-Az Mount

- Two axes are Altitude & Azimuth
- Mechanically easier to build
- More complex to track
    - Both axes have to move at differing rates
    - Field rotates, so instruments or images de-rotate

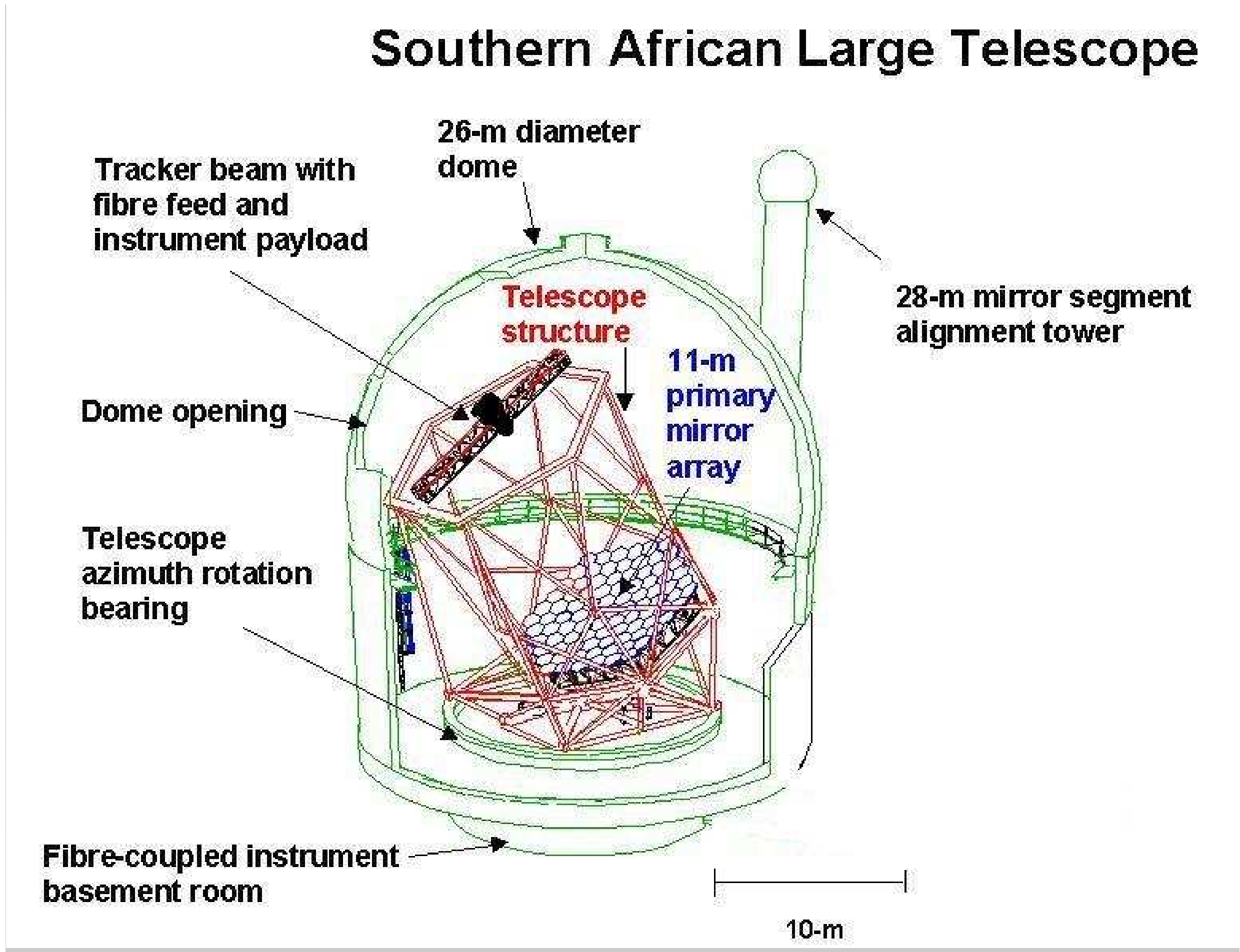


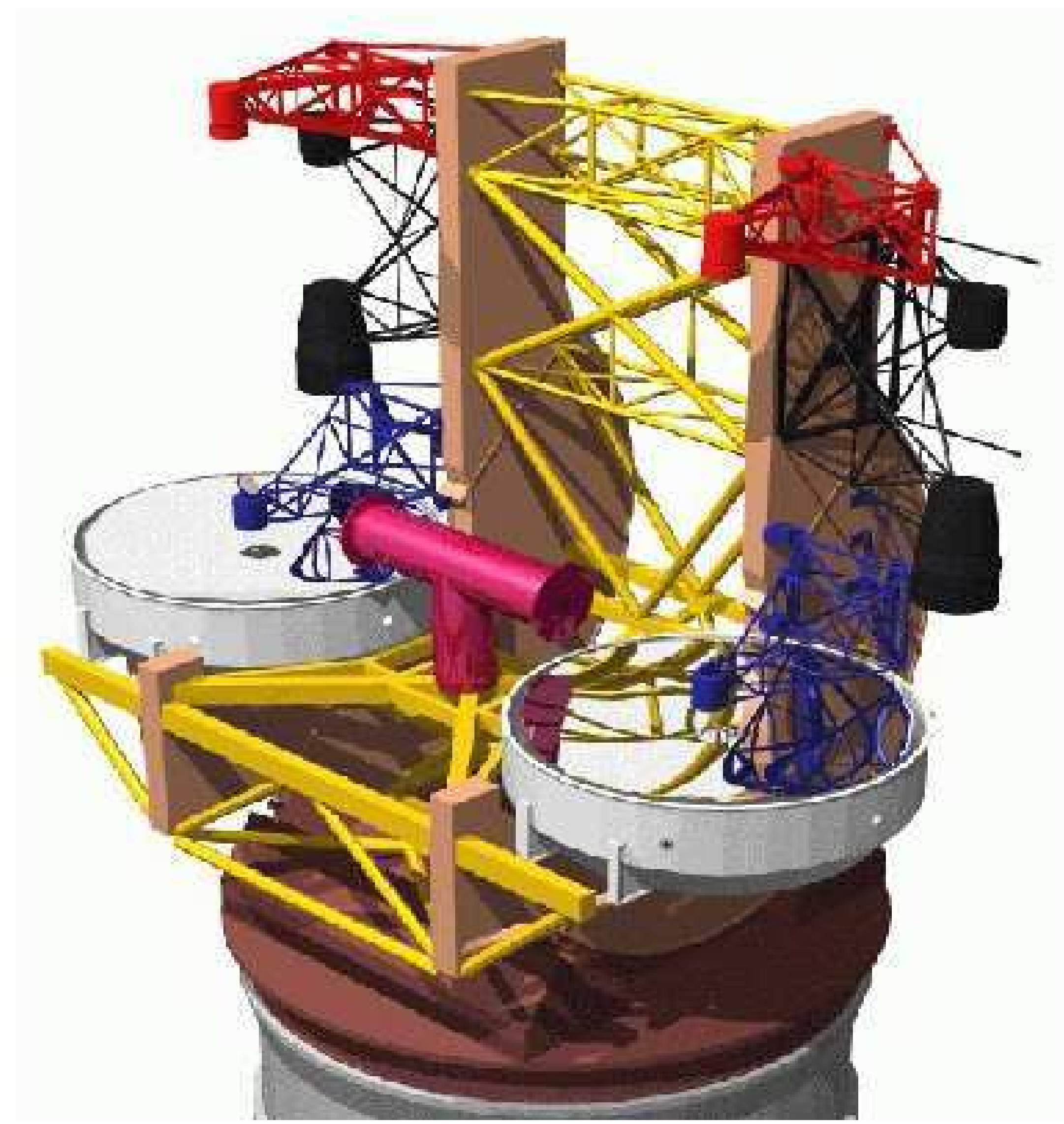
8.3-m Subaru telescope (2000)

Telescopes Mounts

New types of Alt-Az mounts

- Large Binocular Telescope (LBT)
- SALT & HET





SALT (2005)

Twin 8.4-m LBT (2006)

Telescopes

Telescope Configurations

The Nasmyth focus

- For any reflector, can add a third mirror (tertiary flat) to deflect the beam perpendicular to optical axis
- Allows for heavy instrumentation to be easily supported

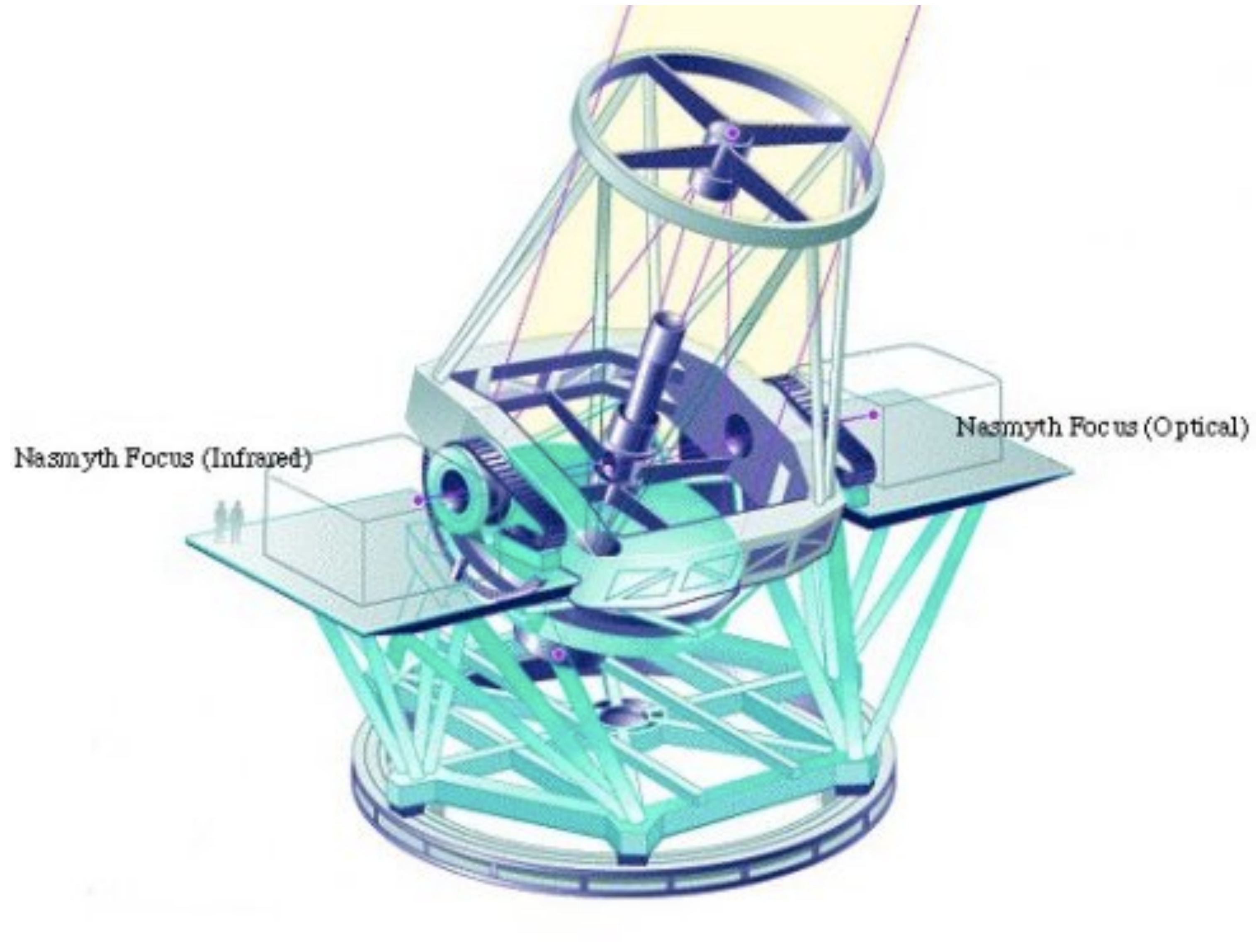


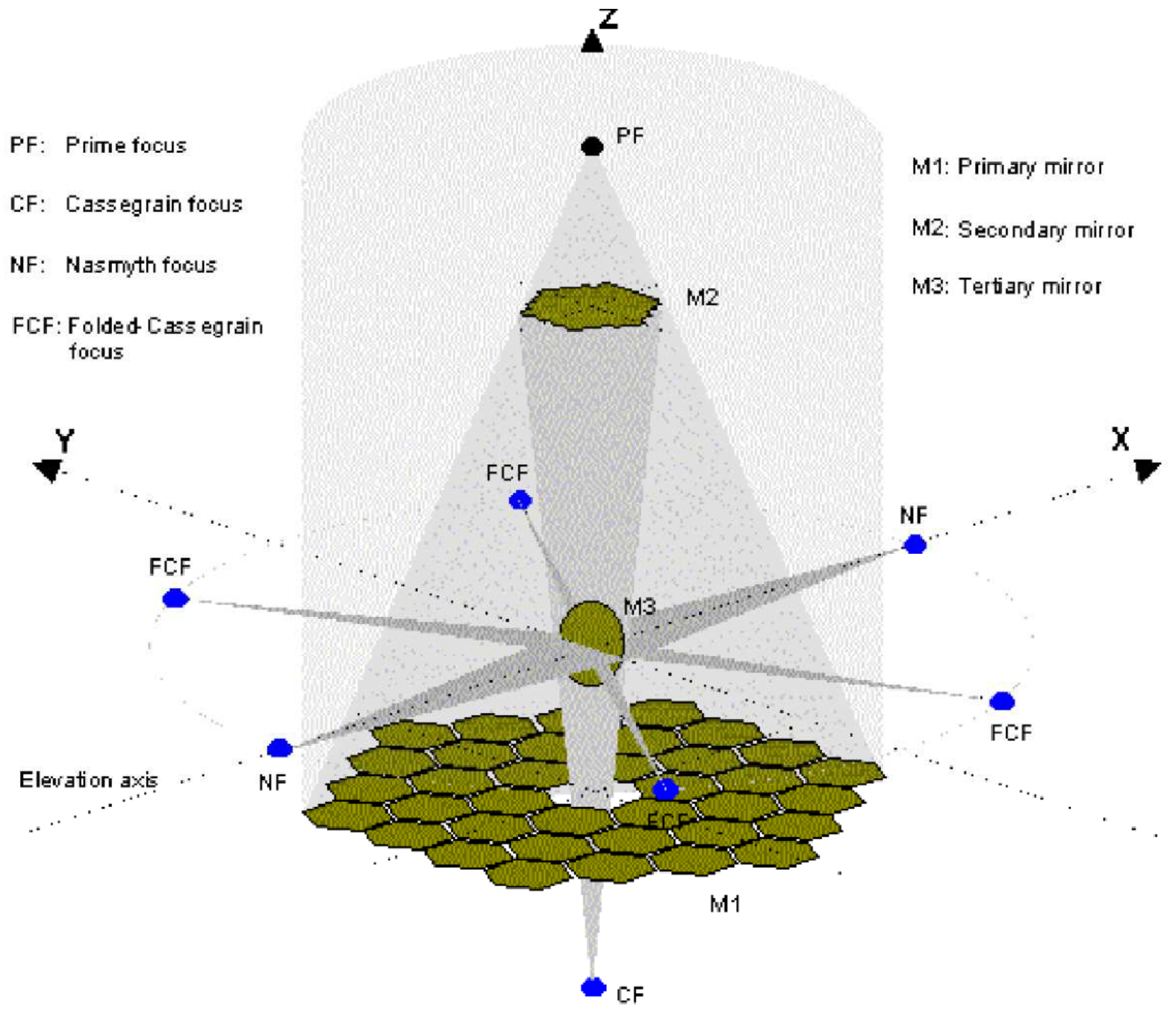
Illustration by Takaetsu Endo, taken from Nikkei Science 1996

Telescopes

Telescope Configurations

The Nasmyth focus - Example Keck Telescope

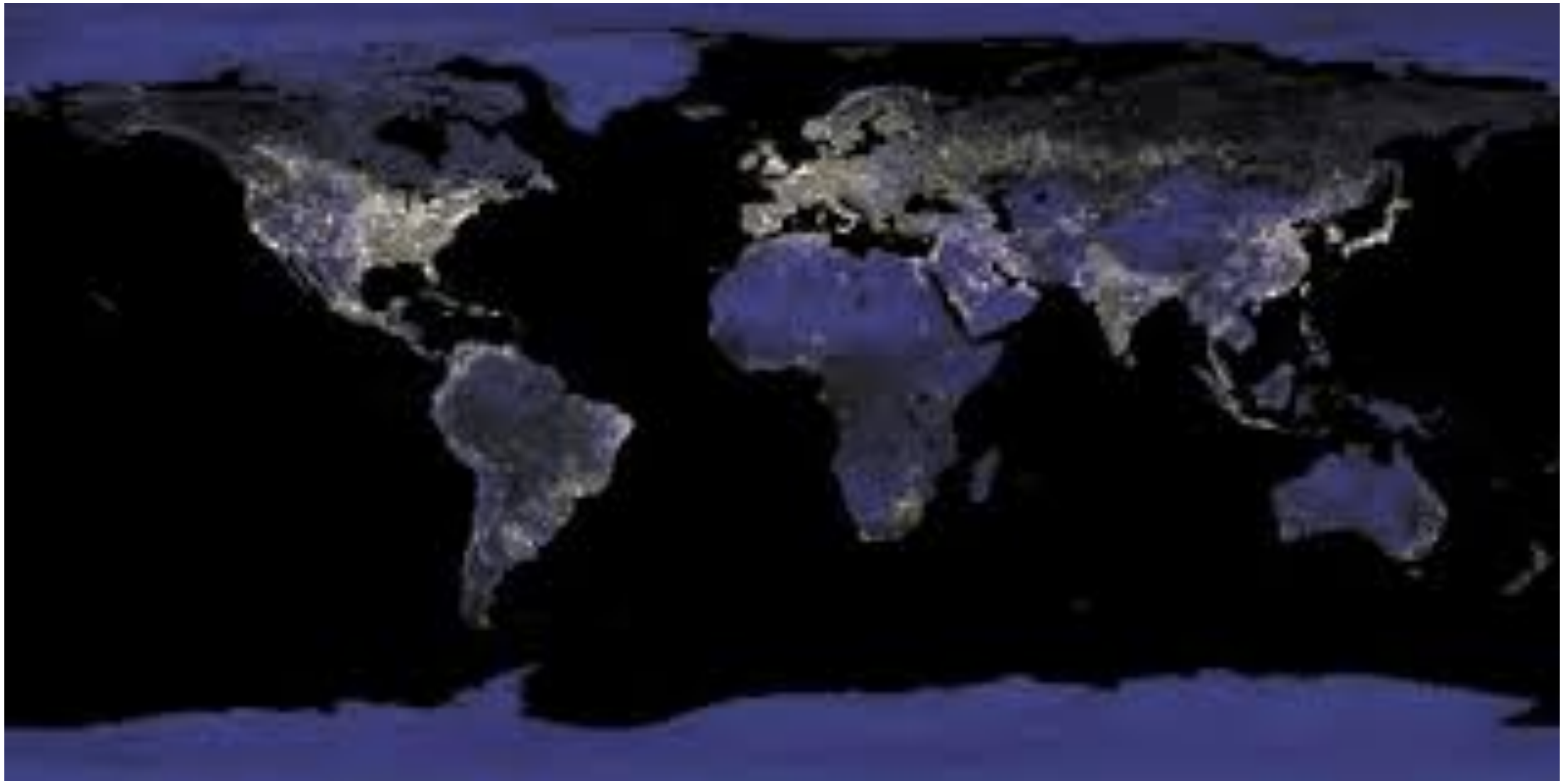
- Many foci are supported
- Multiple instruments accommodated
- Don't need to keep changing instruments



Telescopes

How does Earth’s atmosphere affect ground-based observations?

Light Pollution

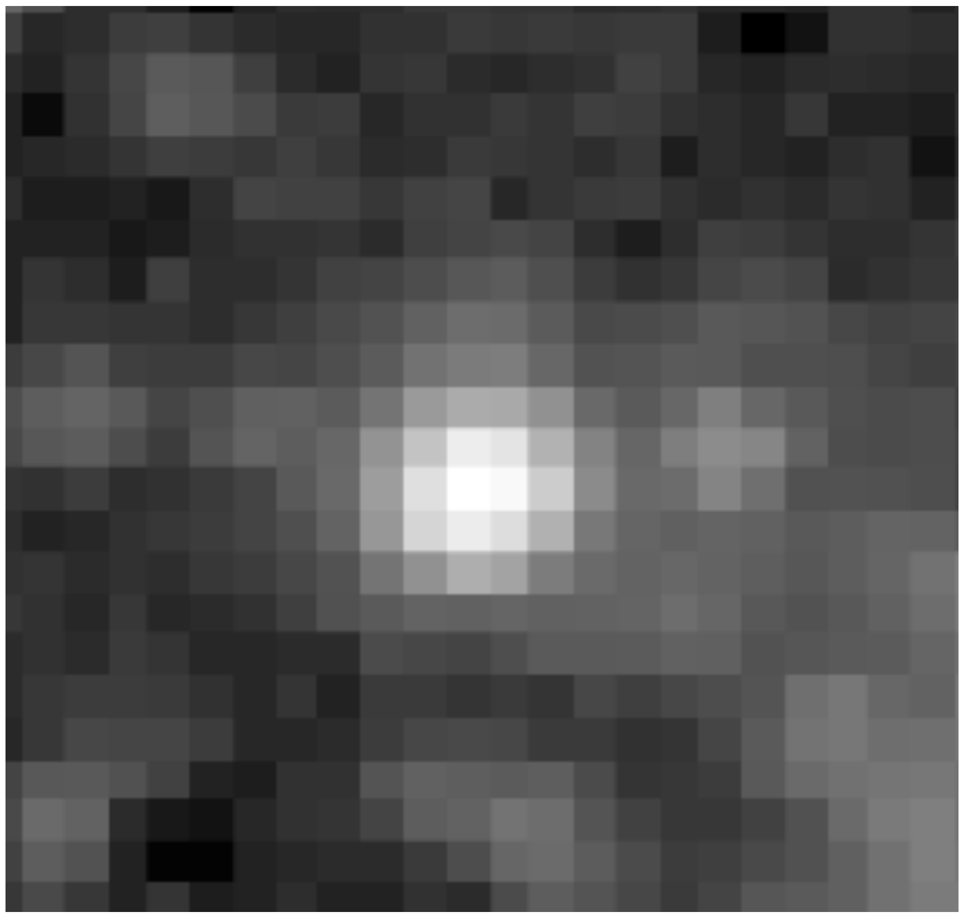


Scattering of human-made light in the atmosphere is a growing problem for astronomy

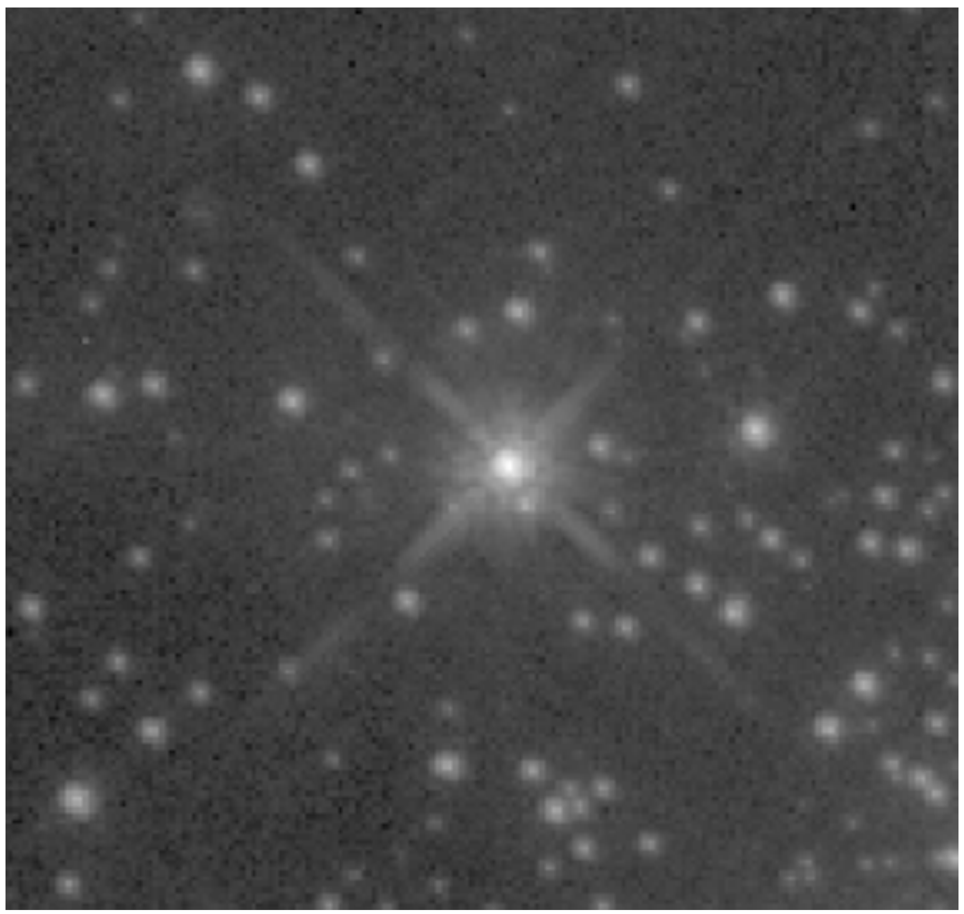
Telescopes

How does Earth's atmosphere affect ground-based observations?

Twinkling and Turbulence



Star viewed with ground-based telescope



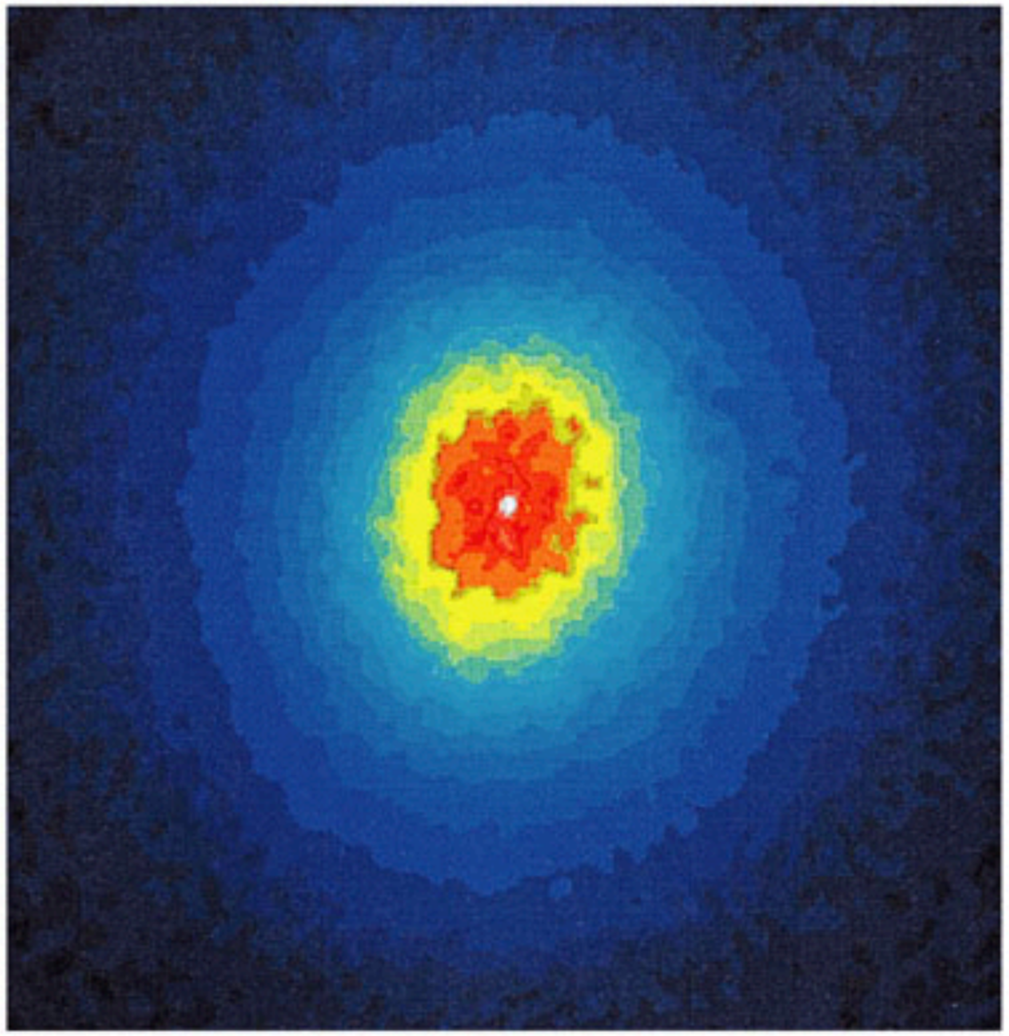
Same star viewed with Hubble Space Telescope

Turbulent air flow in Earth's atmosphere distorts our view, causing stars to appear to twinkle

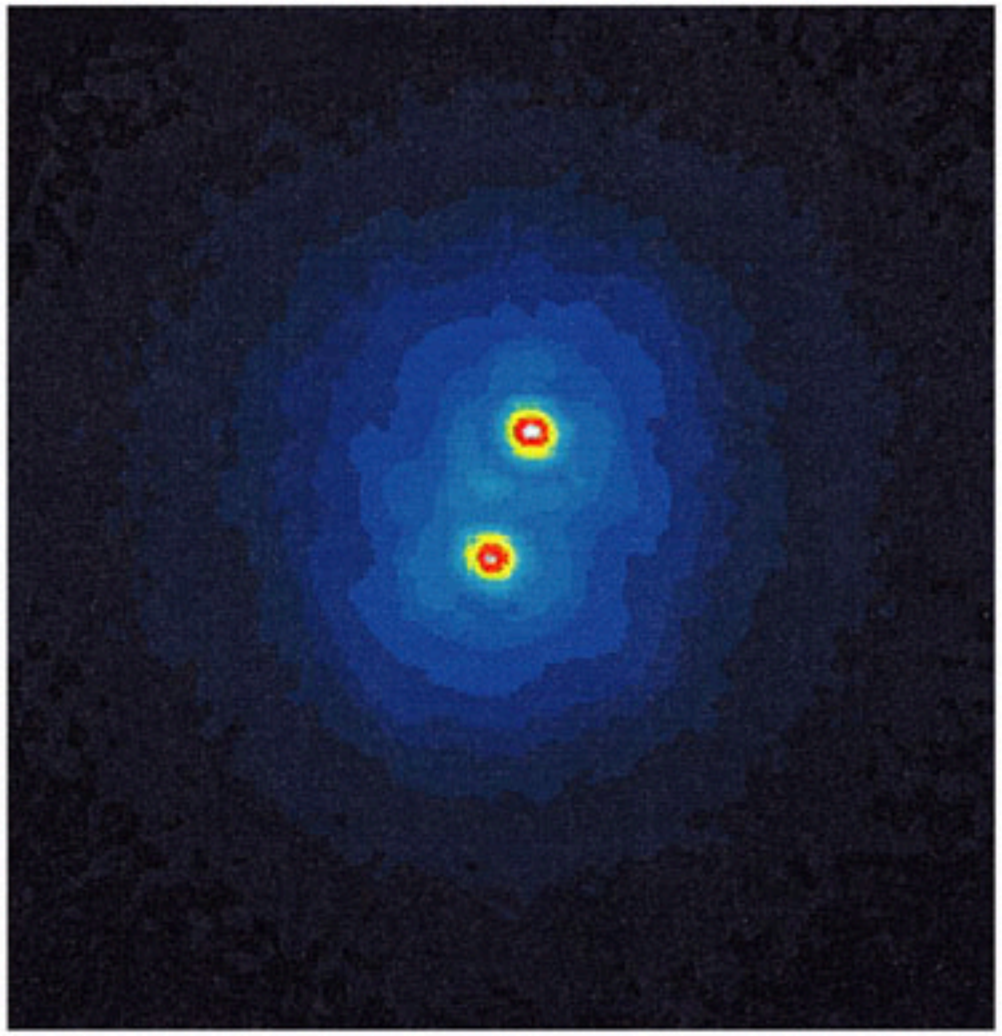
Telescopes

How does Earth's atmosphere affect ground-based observations?

Adaptive Optics



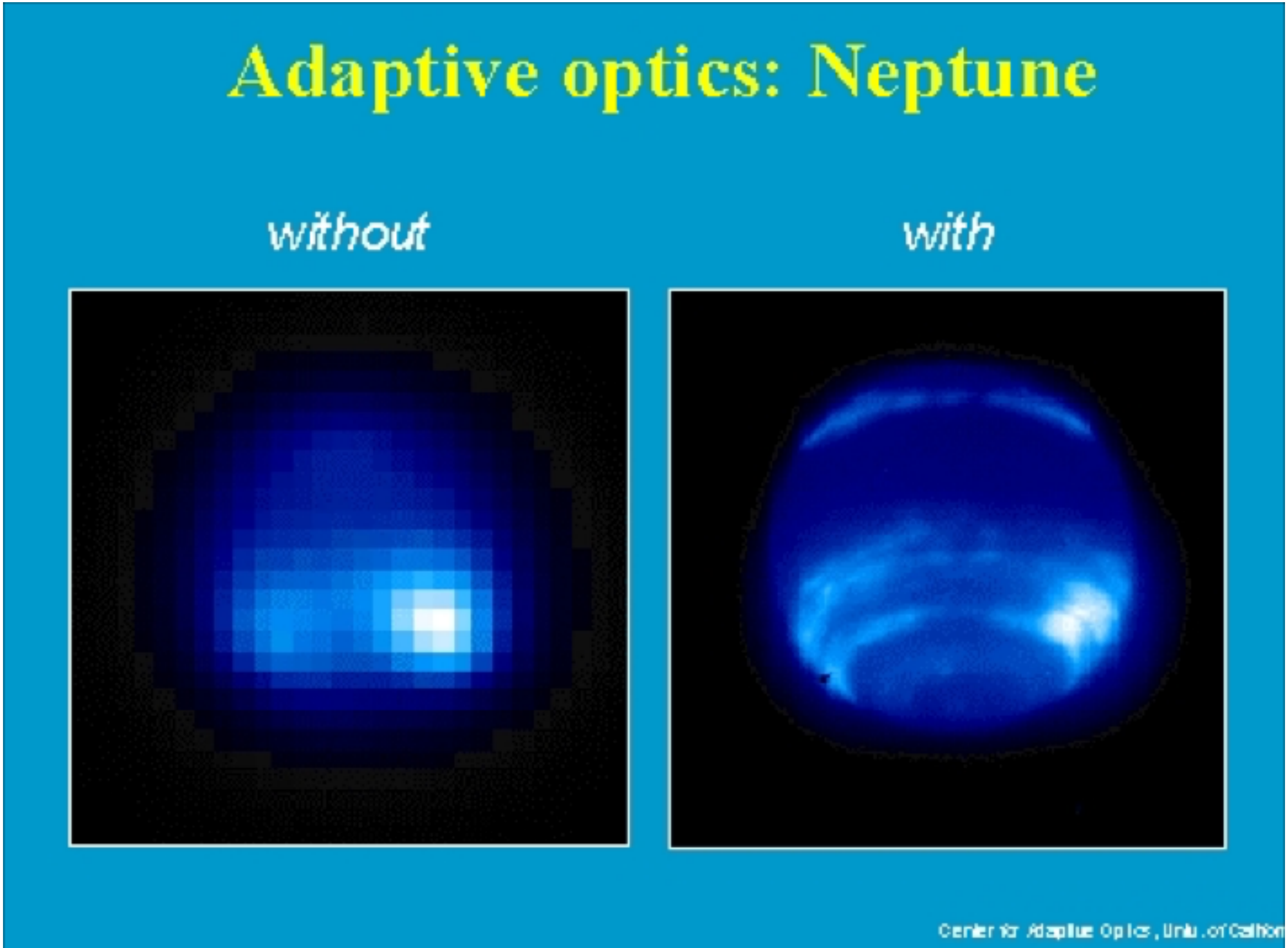
Without adaptive optics



With adaptive optics

Rapidly changing the shape of a telescope's mirror compensates for some of the effects of turbulence

Telescopes



Adaptive optics: Neptune
without
with
Center for Adaptive Optics, Univ. of Californ

Telescopes

Where should we build telescopes?

The best ground-based sites for astronomical observing are:

– Calm (not too windy)
– High (less atmosphere to see through) – Dark (far from city lights)
– Dry (few cloudy nights)

ie: atop remote mountains

Summit of Mauna Kea, Hawaii

Telescopes

Why do we put telescopes into space?

- Escape from atmospheric distortion (seeing)
- Escape from atmospheric airglow and light pollution
- Observe other regions of electromagnetic spectrum

Telescopes

How can we observe nonvisible light?

A standard satellite dish is essentially a telescope for observing radio waves

Telescopes

How can we observe nonvisible light?

- A radio telescope is like a giant mirror that reflects radio waves to a focus
- Wavelengths of light much longer than visible light
- Irregularities should be less than 1/5 the wavelength of light being focused

Telescopes

How can we observe nonvisible light?

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Telescopes

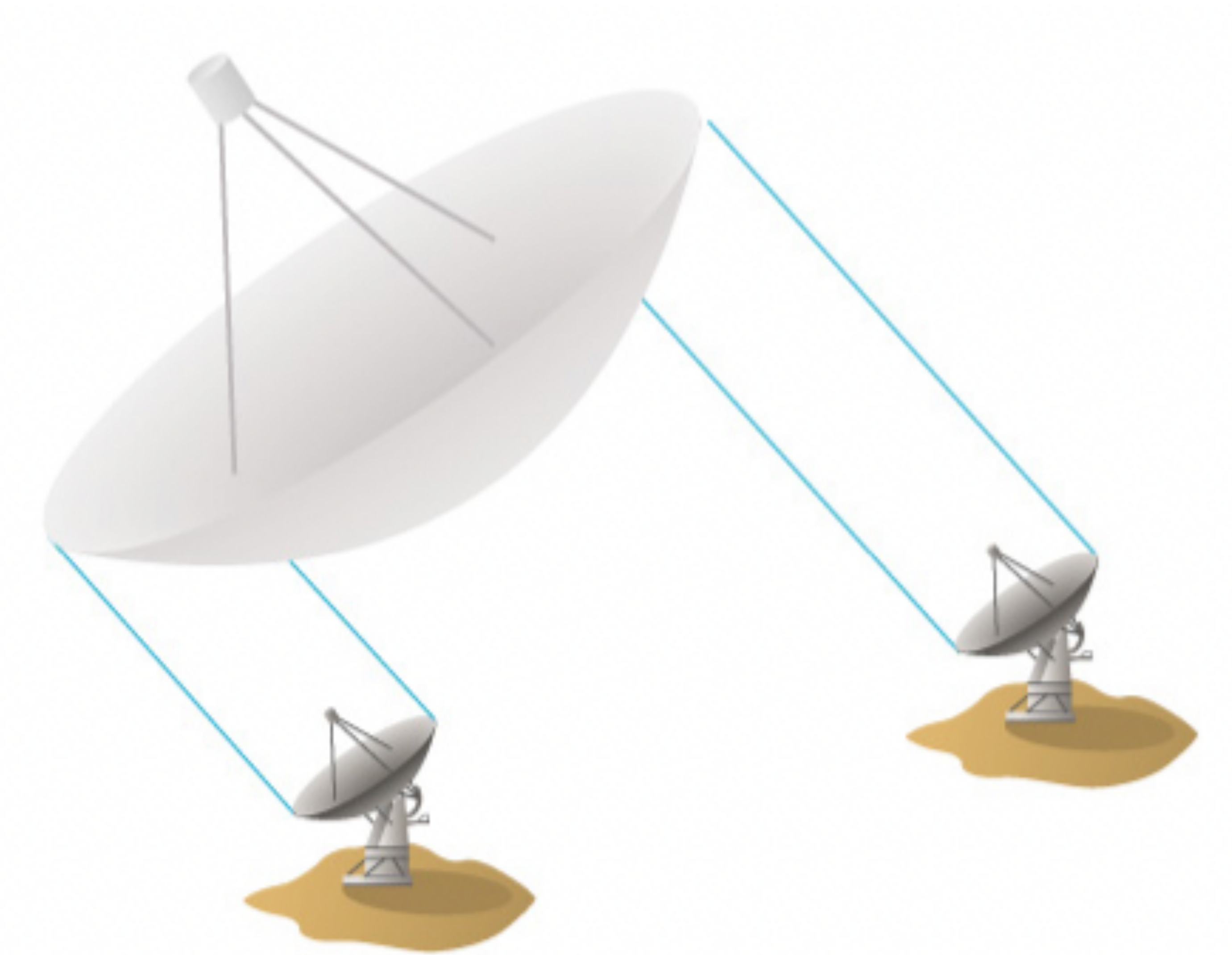
How can we observe nonvisible light?

Interferometry

Telescopes

How can we observe nonvisible light?

Interferometry

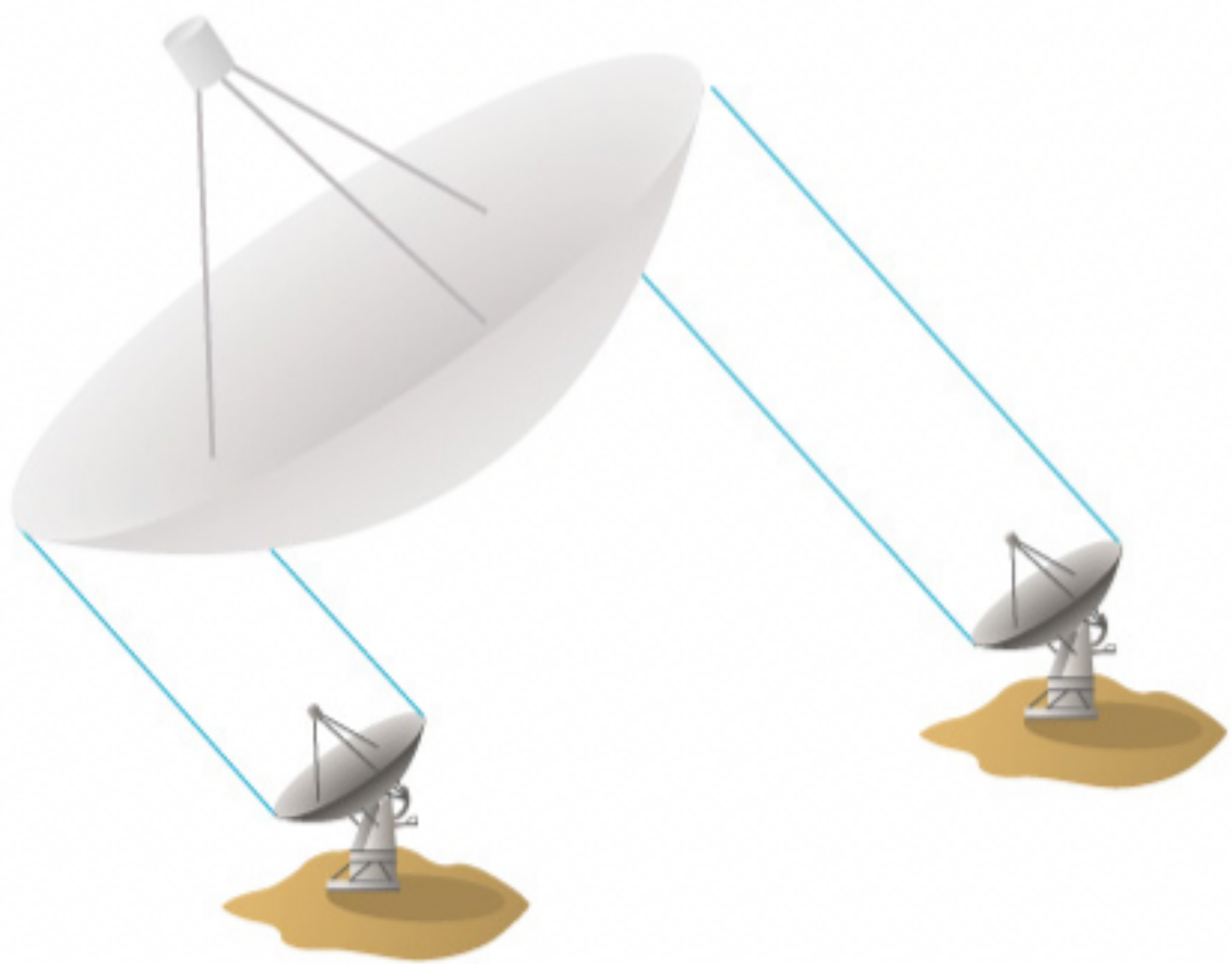


Interferometery is a technique for linking two or more telescopes so that they have the angular resolution of a single large one

Telescopes

How can we observe nonvisible light?

Interferometry



Interferometery is a technique for linking two or more telescopes so that they have the angular resolution of a single large one

Telescopes

How can we observe nonvisible light?

Interferometry

Very Large Array (VLA)

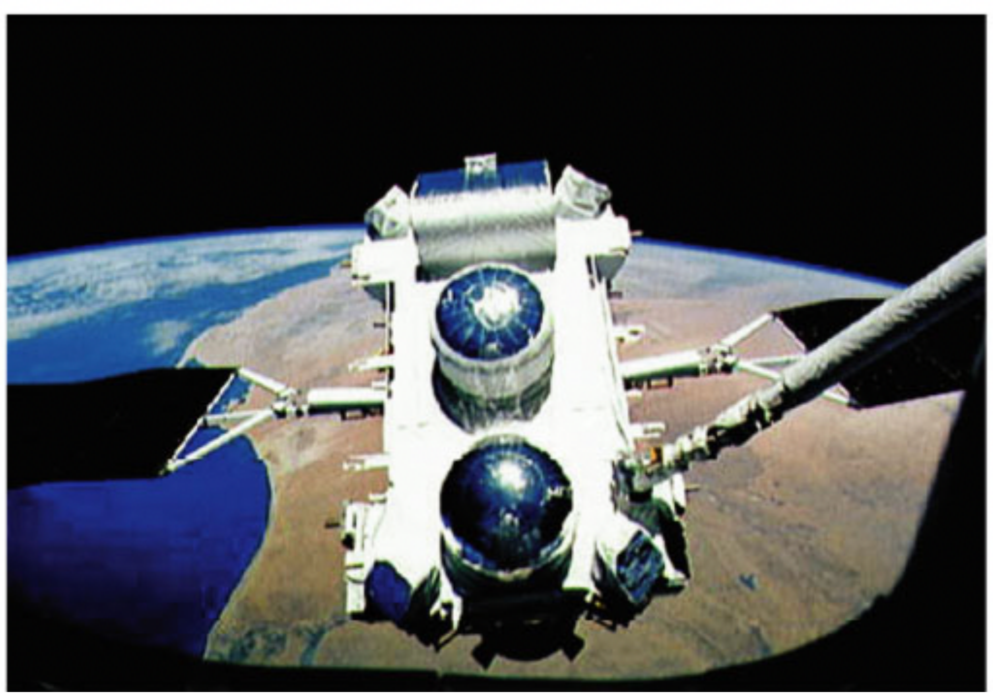
- Easiest to do with radio telescopes
- Now becoming possible with infrared and visible-light telescopes

Telescopes

How can we observe nonvisible light?

X-Ray and Gamma Ray Telescopes

- X-ray telescopes also need to be above the atmosphere



- As do Gamma Ray telescopes

Telescopes

Summary

- Primary function is to collect light (more than the human eye can)
- A telescope also magnifies objects, the magnification depending upon the eyepiece / backend instrument. However, stars are still point sources.
- Telescope systems : reflectors (catoptric), refractors (dioptric), or a combination of both (catadioptric)
- Field-of-View (FoV) and plate scale (spatial resolution) are the important characteristics of a telescope
- Fast beam – typically f/1 to f/3 – large FoV – used for surveys.
- Slow beam – typically f/20 to f/30 – small FoV – used for high resolution imagers or spectrographs.

Detectors

Detectors

Detecting Photons

- Once a telescope has collected the EM radiation from an astronomical source and brought it to a focus, those photons must be recorded
- This is achieved by a detector – a device that turns EM radiation into a usable signal e.g.
  - The Eye
  - Photographic plates
  - Photomultiplier tubes
  - Micro-channel Plate (MCP) Detectors
  - Charge Couple Devices (CCDs)
- Type of detector depends on part of the EM spectrum being observed
- The energy of the photons depends on their wavelength

$$E = h\nu = hc/\lambda$$

- If the photon energy is less than the thermal energy (kT) of the particles in the detector

$$hc/\lambda < kT$$

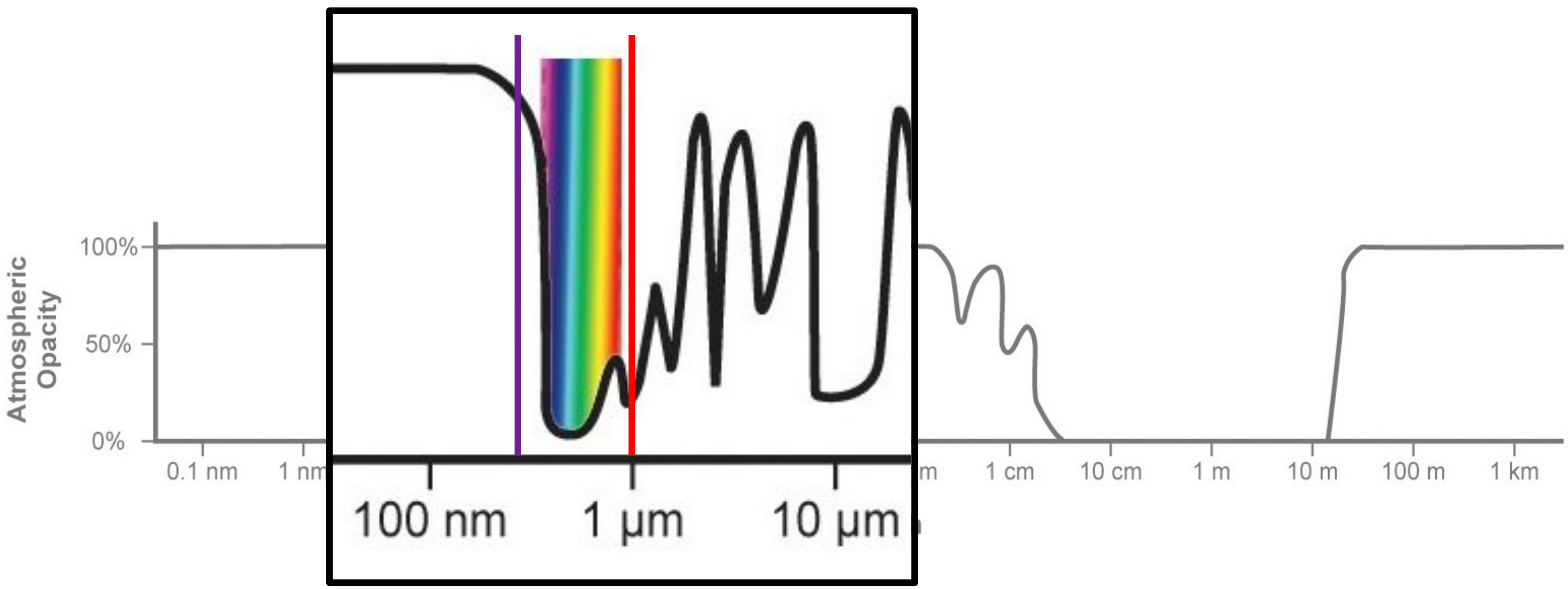
it is difficult to detect individual photons

Detectors

Optical and IR Astronomy

Optical refers to part of EM spectrum around the visible where atmosphere is transparent

Near UV		Visible		Near Infrared
300 – 400nm	+	400 – 700nm	+	700 – 1000nm



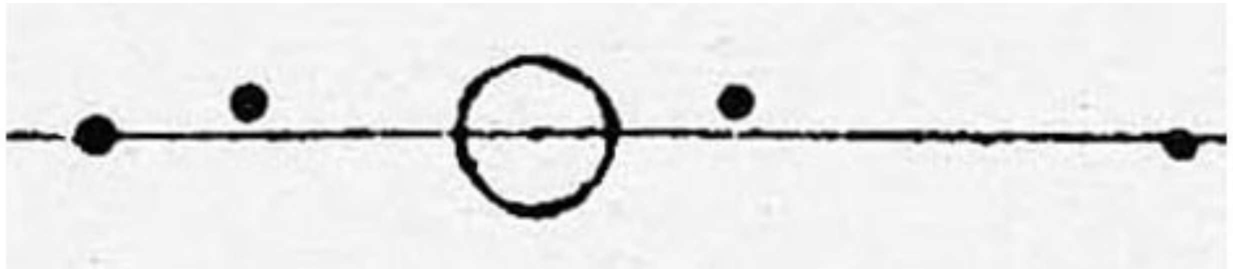
Detectors

Optical Detectors

Need a permanent record of the photons detected by telescope

Galileo – first astronomer to use a telescope

– drew results



Jupiter's moons

Detectors

Optical Detectors

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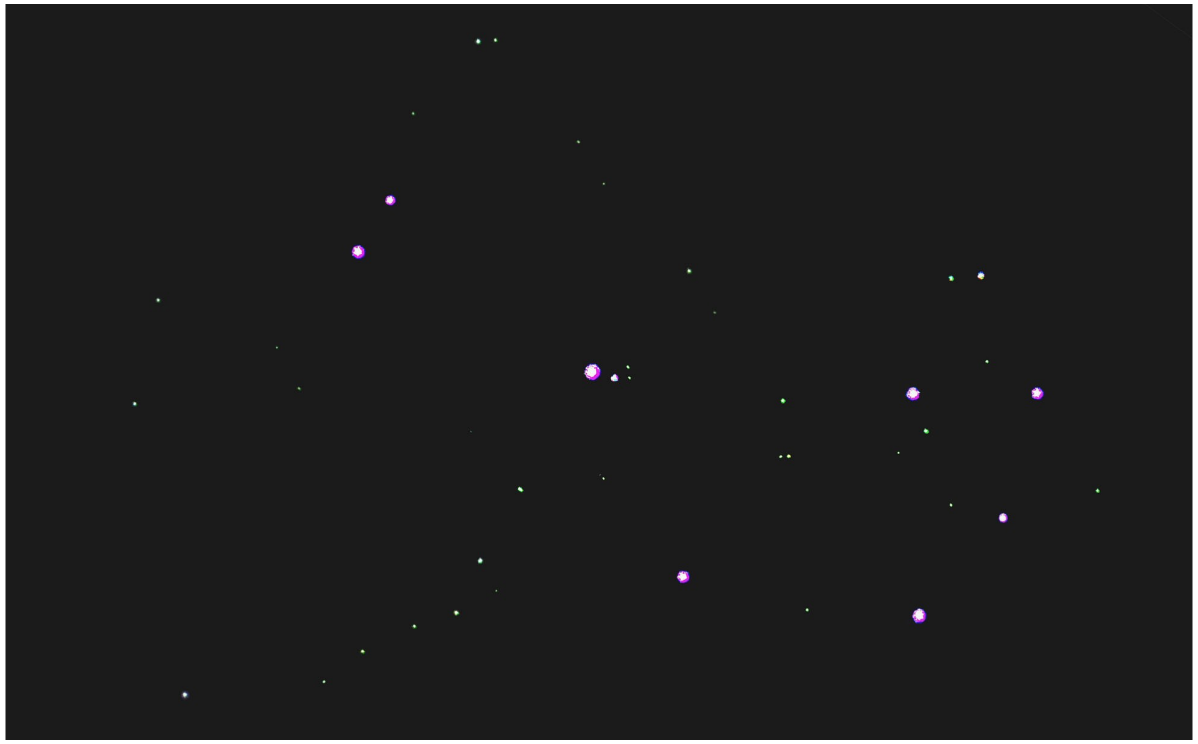
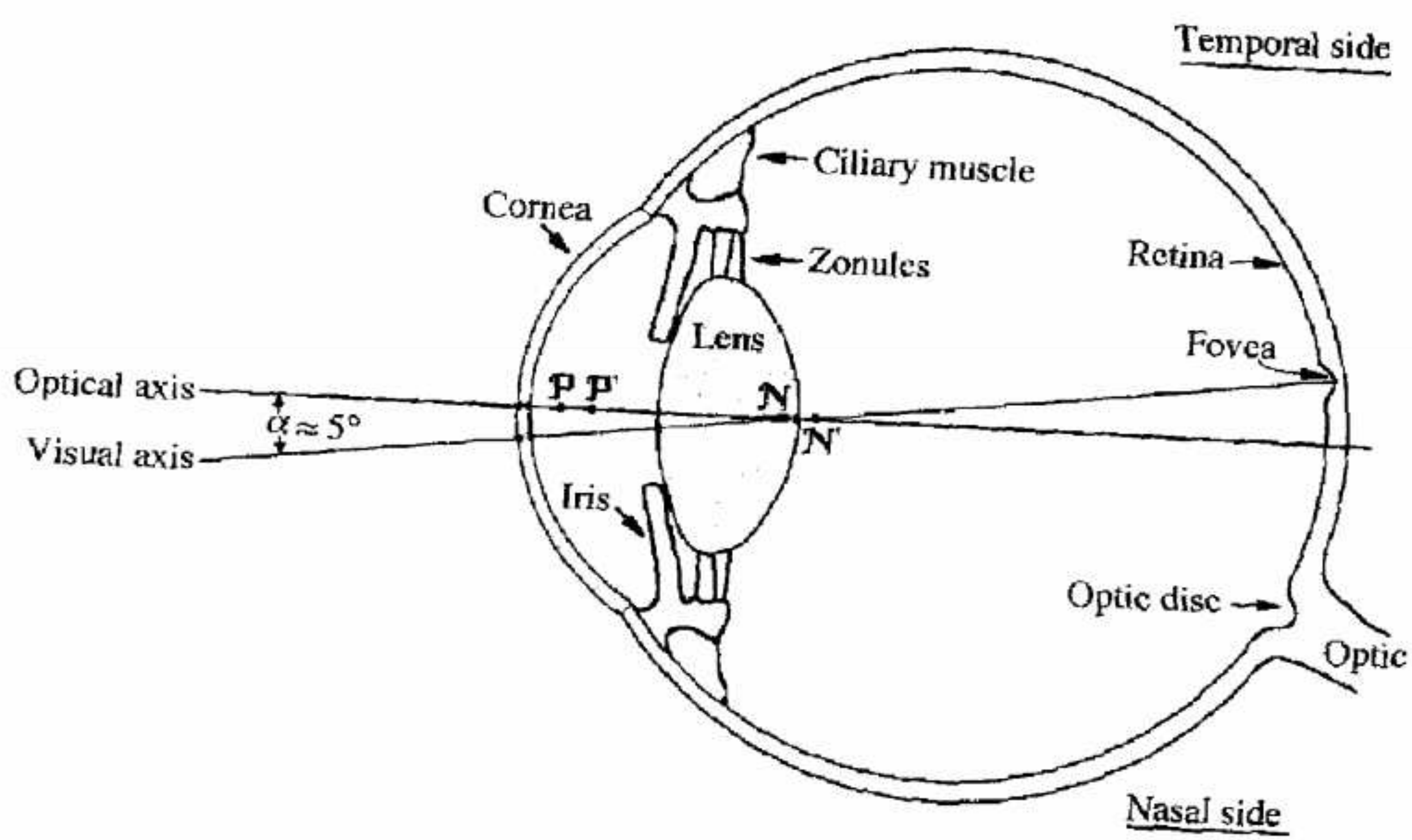


Detectors

How we (mostly) perceive the Universe

First perceptions were by eye by our ancestors

- The “visible” region of the electromagnetic spectrum
- Human eye sensitive over a small range of wavelength: 390 - 780 nm
- An optical imaging system — Cornea & lens combine to form a curved focal surface on the retina



Detectors

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Eye-brain is an amazing detector

- Removes aberrations (clever image processing; stereoscopic; scanning)
- Capable of a 10^9 dynamic range (< 10^6 for CCDs), ~0.6 arcmin resolution
- Equivalent to a 576 megapixel digital video camera!

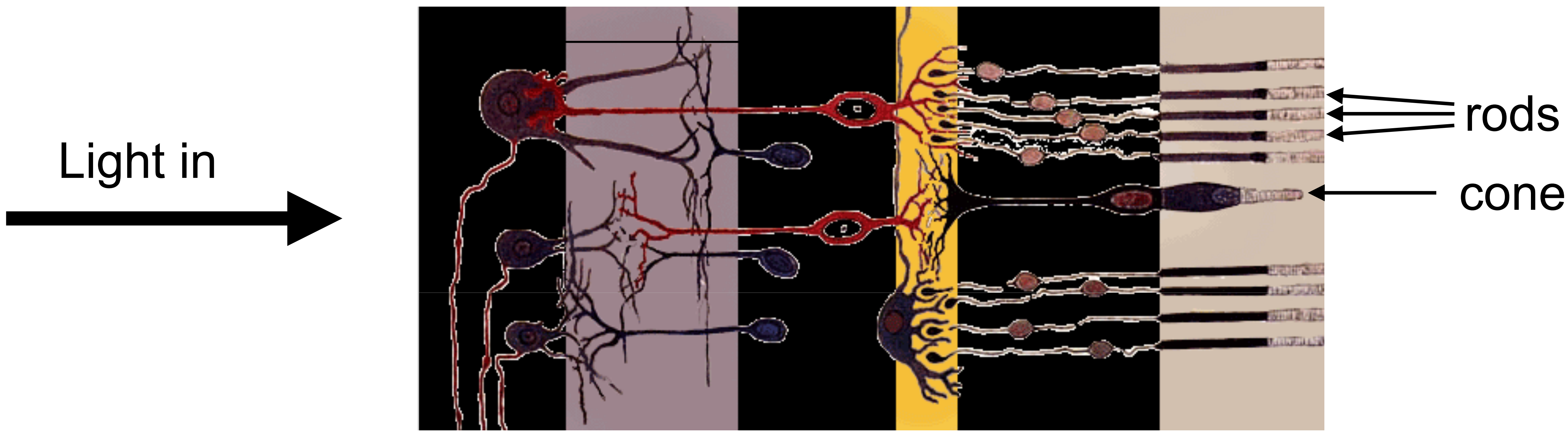
The first astronomical detector was the human retina

- Capable of resolving objects of ~1 arcmin in size (pupil diameter = 6mm for fully dilated)
- A two-dimensional (2-D) video detector (~30 frames / sec)
- Capable of photometry: measuring the brightness and colour of stars

Detectors

The Eye

Cross section of the retina —



How it works —

- Retina consists of photo-receptor cells (rods & cones)
  - In rods rhodopsin (visual purple; 40,000 amu molecule) absorbs photons
    - Fragments into retinadehyde (286 amu; a chromophore vitamin A derivative) & opsin
    - Results in changing electrical properties of cell ⇒ signal
- In cones, similar mechanism with molecule odopsin
  - But 3 different variants S, M & L(in ratio1:4:8)

The Magnitude Scale

The stellar “magnitude scale” – based on range of star brightness that the eye perceives – was invented around 120 BC by Hipparchus (the same guy who discovered precession)

- He devised 6 “steps” of brightness between the brightest and faintest stars seen by the eye (where smaller magnitudes implies brighter stars!)
- The eye perceives the same ratio changes in brightness as equal intervals of brightness
- Magnitude difference are related to the ratio of intensities —

$$\boxed{m_1 - m_2 = -2.5\ log \frac{I_1}{I_2}}$$

Or

$$\boxed{\frac{I_2}{I_1} = 2.512^{m_1 - m_2}}$$

- So the difference in apparent magnitude of two stars, one of which has 100x the intensity of the other, is Δm = 2.5 log (100) = 5 magnitudes.
- The conversion between magnitudes and intensity is given as: $m = -2.5\ log\ I$ + constant
- The constant is referred to as the zero point of the system, and is determined for a specific telescope-instrument-detector combination.

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$m_1 -$ … I_2 … I_1

More about this topic in Photometry lecture

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Detectors

How we perceive the Universe

- Improvements came with the invention of new detection methods, other than just the human eye, to record light. This improved the faintness limit of telescopes, since the new techniques were more sensitive by >10 than the eye.
- The end of the 19th Century saw the invention of *photography.*
- Light causes chemical reactions in silver halide salts bonded into a gelatin layer, which converts them to metallic silver. "Developing" results in permanent changes: the film negative is black (due to silver metal) where light was absorbed and transparent where there was no light.
- Next revolution in optical astronomy was astrophotography.
- Pioneered at the Royal Observatory, Cape of Good Hope (Sir David Gill)

Detectors

Astrophotography

A huge leap forward in astronomy!

Detectors

Astrophotography

A huge leap forward in astronomy!

Led to mapping the skies —

- “Astrographic Catalogue” and the Carte du Ciel” atlas (late 19th C), initiated at Paris Observatory in 1887
- Catalogue and map postions of all stars down to m_V = 11-12
  - 5,176,000 positions from 22 observatories around the world
  - From 22,000 glass photographic plates
  - Split up into different Dec zones
  - Cape Observatory produced the largest single number of positions from observations taken between 1897 & 1912
    - 540,000 in the zone -41º<Dec<- 51º
- “Cape Durchmusterung” catalog of astrometric positions and magnitudes

Astrophotography

A huge leap forward in astronomy!

- Able to record – permanently – positions of thousands of objects at a time
- More sensitive than the eye: QEs of ~5-10% compared to 2-3%
- Could be large
  – e.g.350 x 350 mm for UKSchmidt: 6º x 6º
- Lots of information content
  – Fine photographic emulsions could have resolutions of ~10μm, implying a UK Schmidt plate is ~35,000 x 35,000 pixels, or 1.2 x 10^9 pixels (= 1.2 Gpixels)!
  – Digitize to 6 bits, i.e. 2^6 = 64 intensity levels
  ⇒ 8 x 10^{10} bits of information per plate (= 5GB!)

But there are disadvantages —

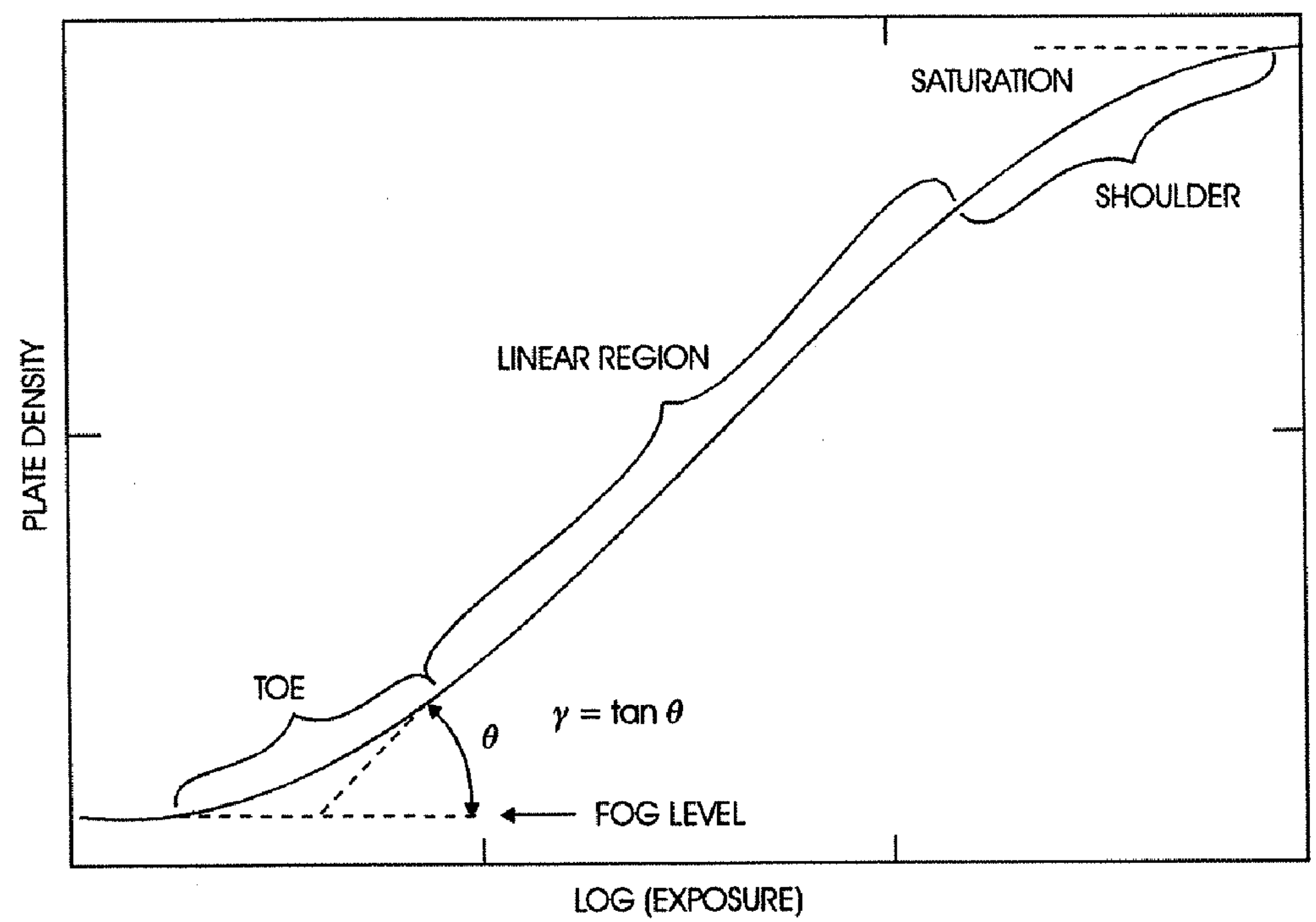
- They are analogue devices
  – Have to be digitized by scanning: a time consuming process
- They do deteriorate over timescales of decades
  – Chemical degradation (“gold spot disease”)
- They are non-linear in their response

Detectors

Astrophotography

Major disadvantage — Typical non-linear response of a photographic emulsion

- Only linear in the regime where the signal increases linearly with log of exposure time.
- Slope is termed ‘Gamma’ (γ), and is a measure of the contrast of the emulsion.
- Below the ‘toe’ signal lost in the ‘fog’ of the background.
- In the ‘toe’ faint stars dominated by fog, hence non-linear.
- In the ‘shoulder’, bright stars saturate.

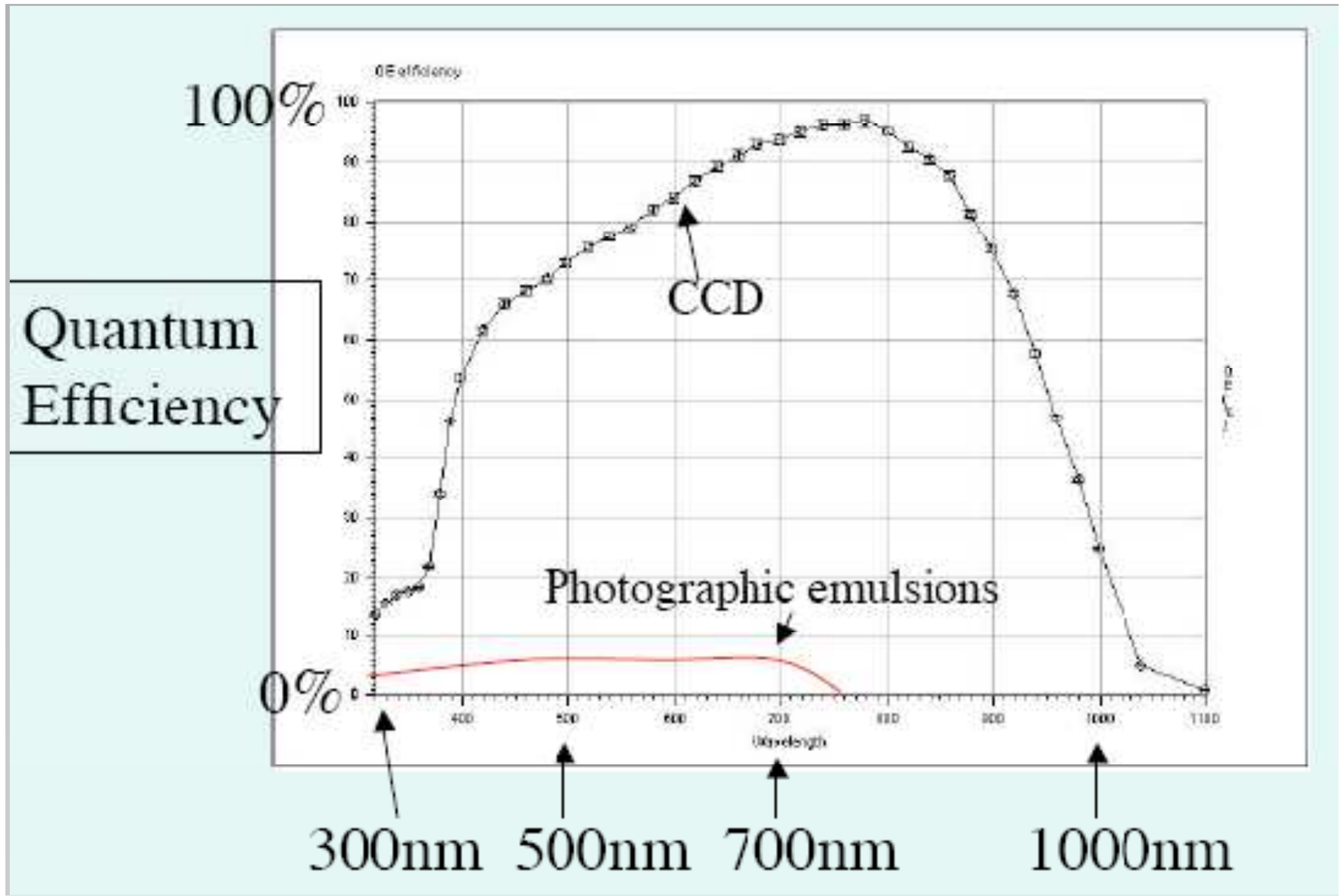


Detectors

How we perceive the Universe

- The 20th Century has seen the invention of devices that record photons by absorbing and recording their energy
- The quantum and wave theories of radiation have impacted on all areas of detection of electromagnetic waves

- Harnesses the photoelectric effect
  - Photomultiplier tubes
  - QEs typically of 20-30% max
- Development of semi-conductor devices, with much higher QE
  - Charge Coupled Devices (CCDs) can now reach QEs of ~90%



These devices spelled the end of photographic plates, although CCDs still don’t have the area coverage of the largest photographic plates.

Detectors

Photomultiplier Tube (PMT)

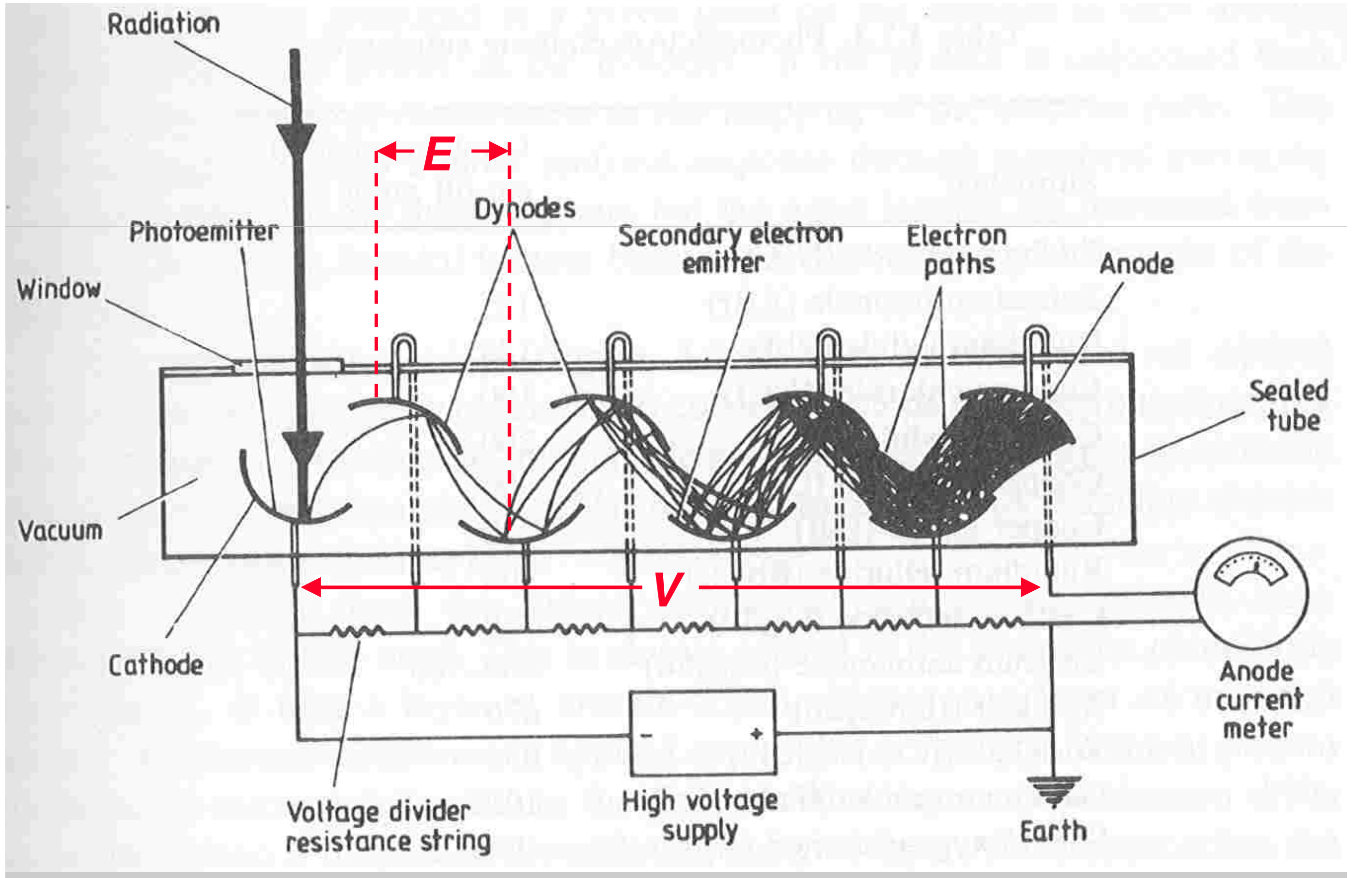
- Based on the photoelectric effect: a photoemissive cathode (at a -ve voltage) emits a photoelectron on absorption of a photon
- Amplification from a series of n dynodes at increasing +ve voltage
- Results in a gain (g) each time electrons collide with dynodes (& final anode)
  - $g = 3–5$; $n = 10–12$, typically
  - Total gain of tube $G = g^n$
  - $G = 10^5$ to 10^8
  - $g \propto E^\alpha$, where $\alpha = 0.7 – 0.8$ (E is the dynode Δvoltage)
  - Total cathode-anode voltage V $\Rightarrow E = V / (n+1)$

    $\Rightarrow g \propto V^\alpha$

    $\Rightarrow G \propto V^{\alpha n}$
  - $\alpha n = 7–10$

    $\Rightarrow$ gain highly dependent on V

    $\Rightarrow$ need to have very stable V
  - V typically 10kV

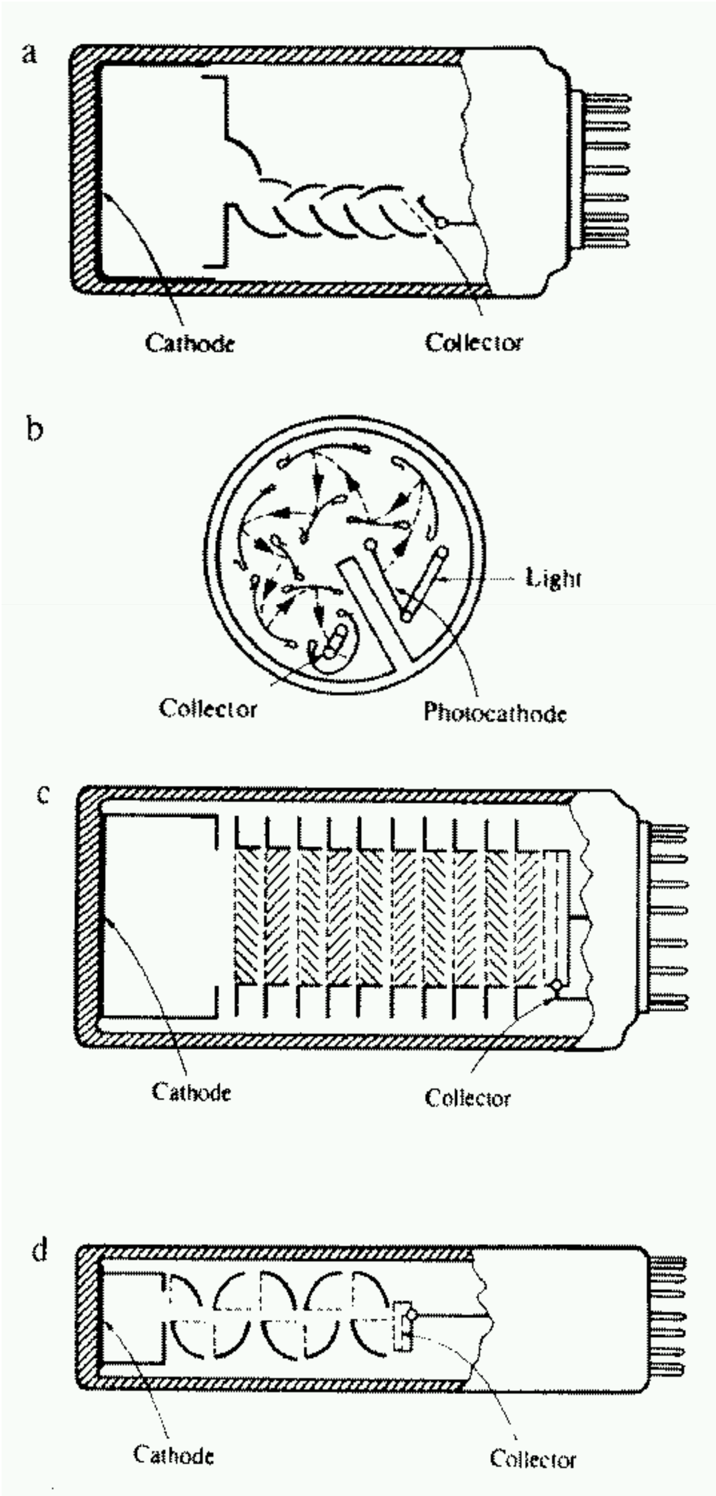


Detectors

Photomultiplier Tube (PMT)

Different dynode architectures for different purposes

- (a) Focussed tubes for fast response
- (b) “squirrel cage” for compactness
- (c) “Venetian blind” for large photocathode area



Photocathode material metallic-like designed to work in the UV-Visible range (200-900nm)

Detectors

Photomultiplier Tube (PMT)

- Low noise photon counting devices
- “Dark current” present from thermal excitation of electrons from photocathode & dynodes
  - Reduce effect by cooling tubes
  - A GaAs tube cooled to -20C will reduce dark current by factor of several 1000
- But only single channel
  - Single photocathode
  - No “multiplex advantage”
  - Like a single cell in the retina

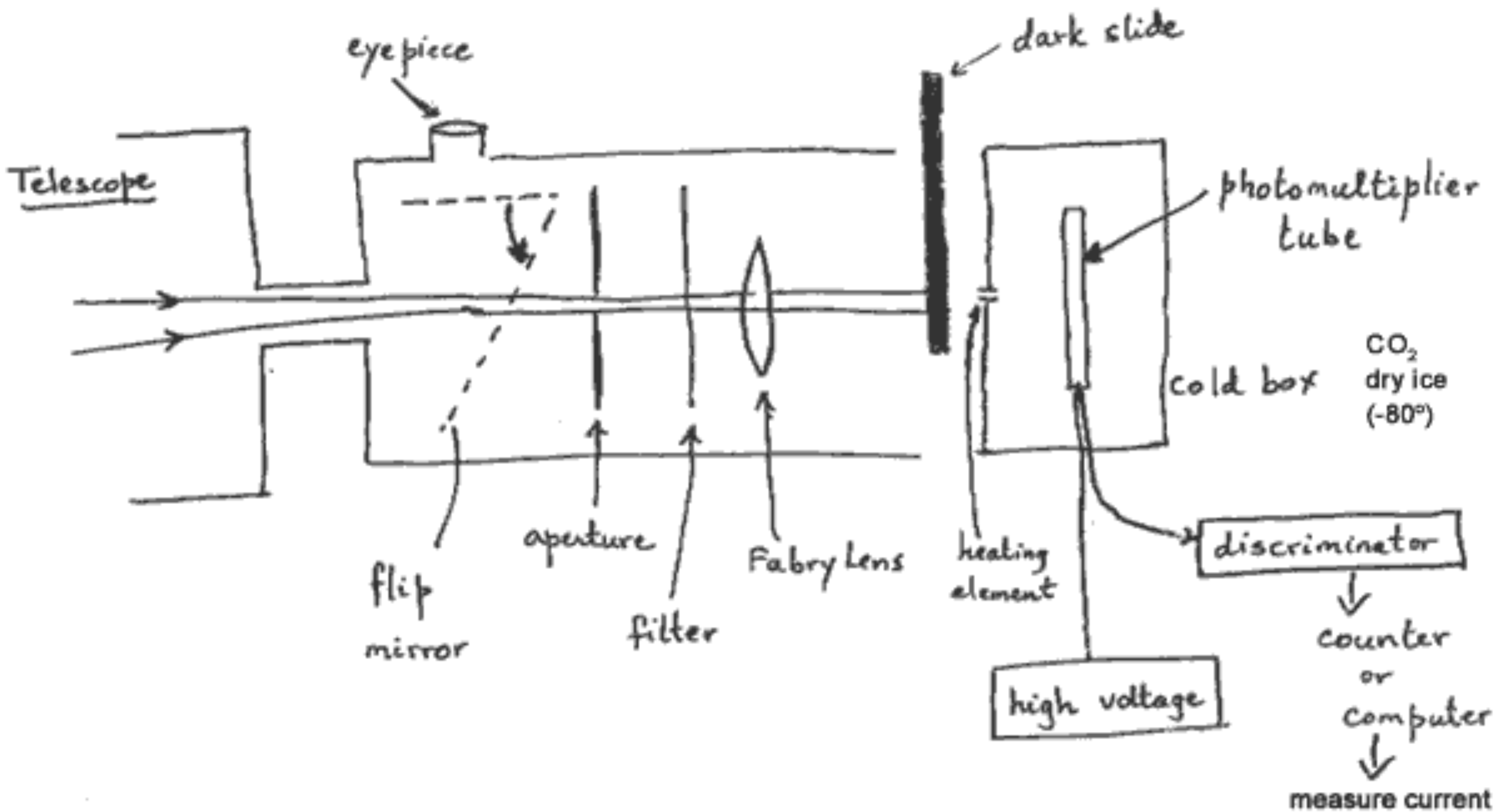
Well, not quite accurate!

- Arrays of PMTs can do crude imaging by combining signals
- Focal plane detector for Cerenkov gamma ray telescopes
- Liquid tank detectors for neutrinos

Detectors

The Single Channel Photometer

Photometry used to be done with a single channel, photoelectric photometer, generally a photomultiplier tube (PMT)

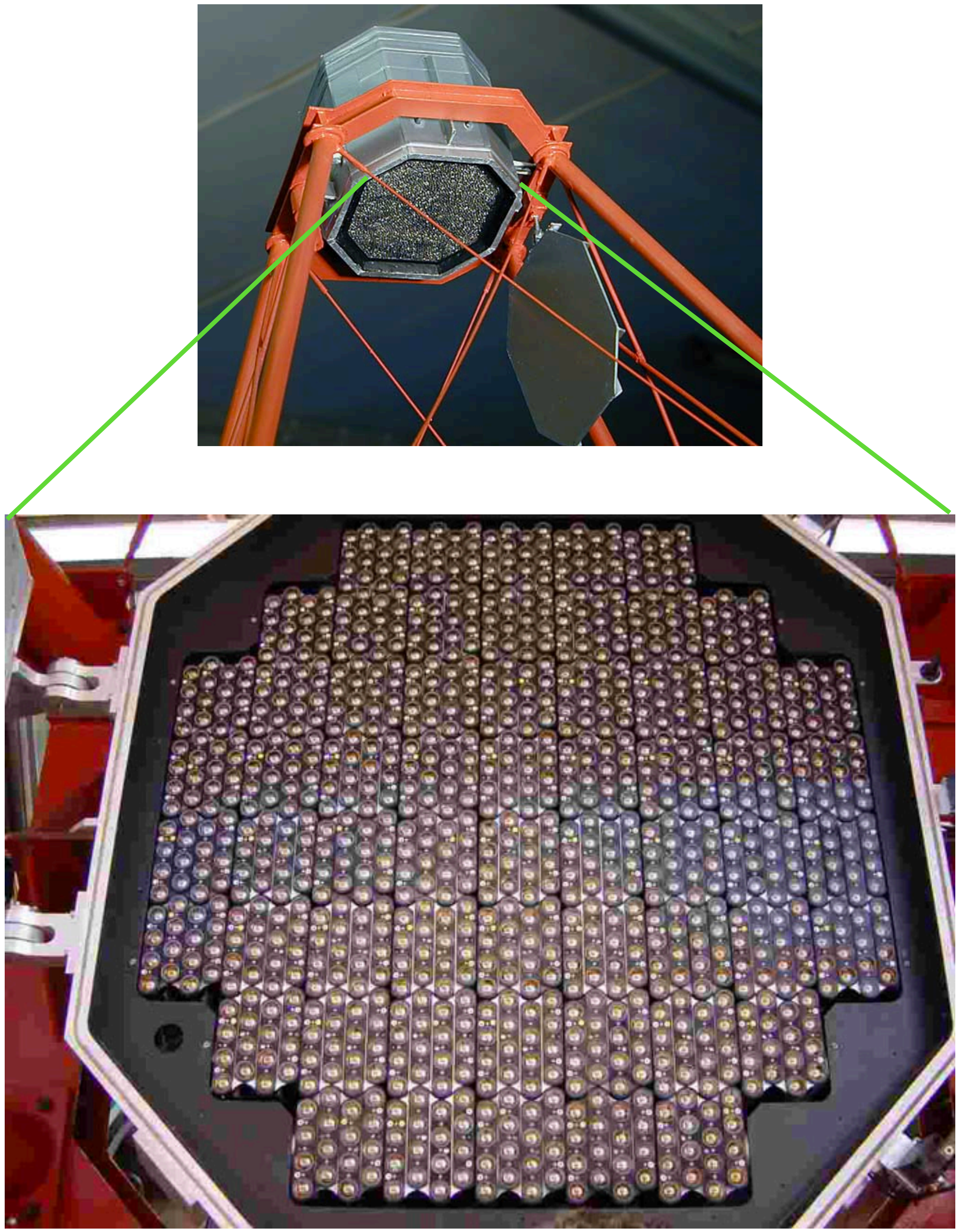


Detectors

The Single Channel Photometer

Detectors

Photomultiplier Tube (PMT)



960 PMTs

Cherenkov Telescope

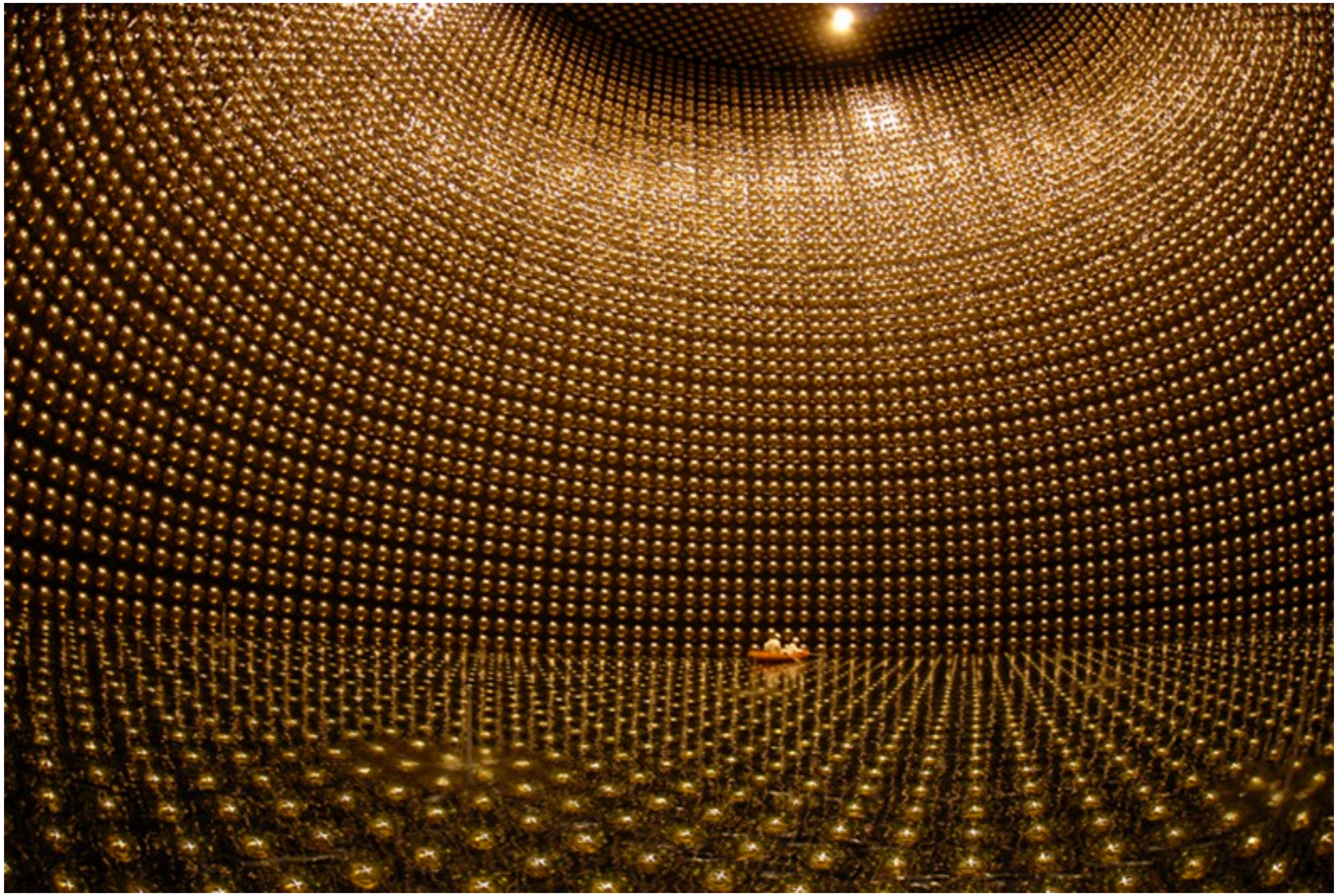
HESS in Namibia

Detectors

Photomultiplier Tube (PMT)

Super Kamiokande neutrino “telescope” in Japan

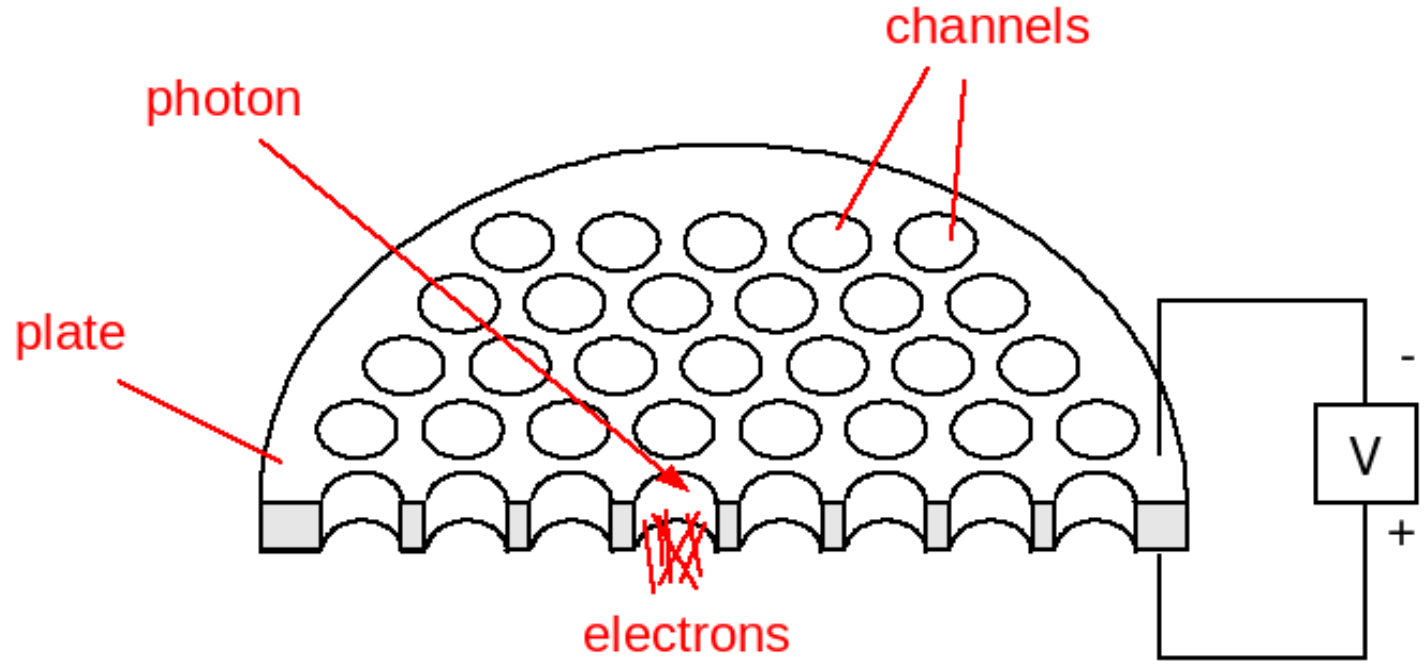
- 11,200 50cm diameter PMTs
- Inside a 40-m high tank
- 50,000 tons of water!
- 1 km underground



Detectors

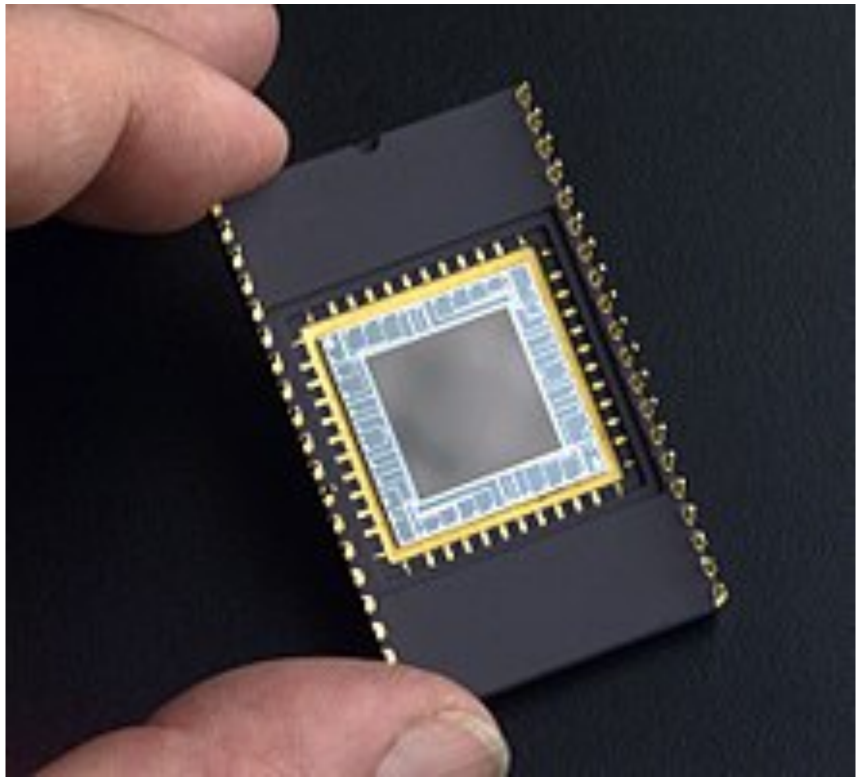
Micro-channel Plate (MCP) Detectors

- Detectors using micro-channel plates have been used in several successful space missions
- A micro-channel plate (MCP) is a planar component used for detection of particles (like photons).
- Plate of high resistance material with ~10 μm channels
- Incident photon strikes wall of channel liberating electron (photoelectric effect)
- Electrons accelerated by V
- Subsequent collisions with walls generate cascade of electrons and Detected at end of channel
- Used as UV detectors — GALEX mission

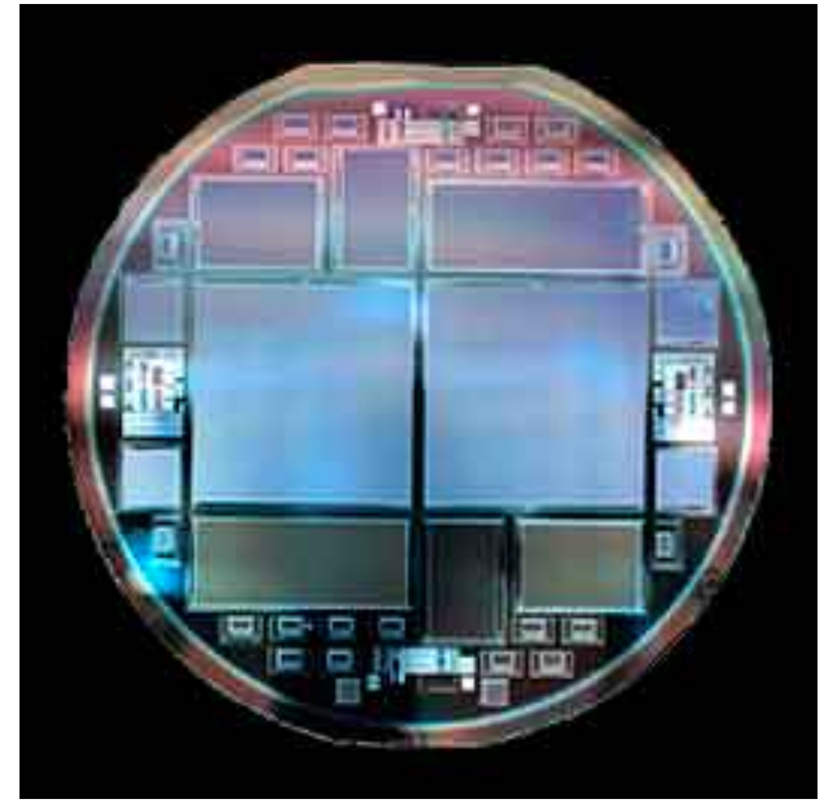


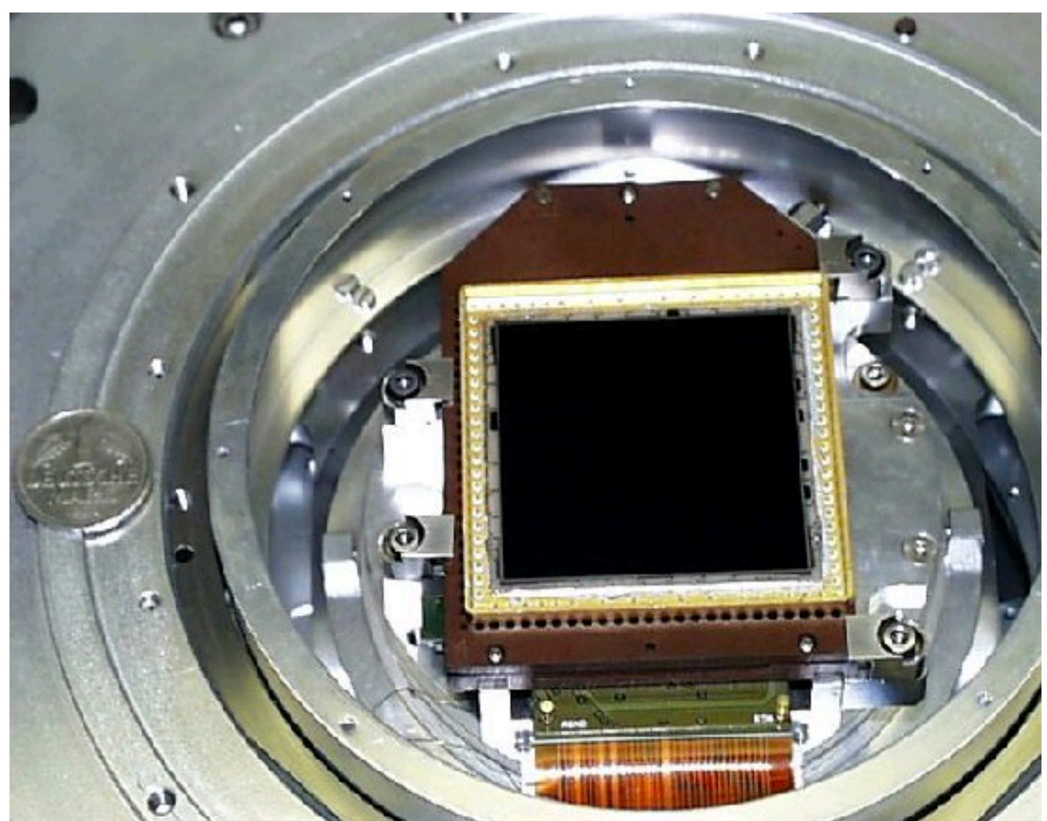
Detectors

The Next Revolution: Charge Couple Device Detectors (CCDs)



- Integrated semi-conductor detector.
- From photon detection (pair production) to final digitization of signal.
- Manufactured from a Si wafer, as in ICs.





Detectors

Charge Couple Device Detectors (CCDs)

Major advantages of CCDs

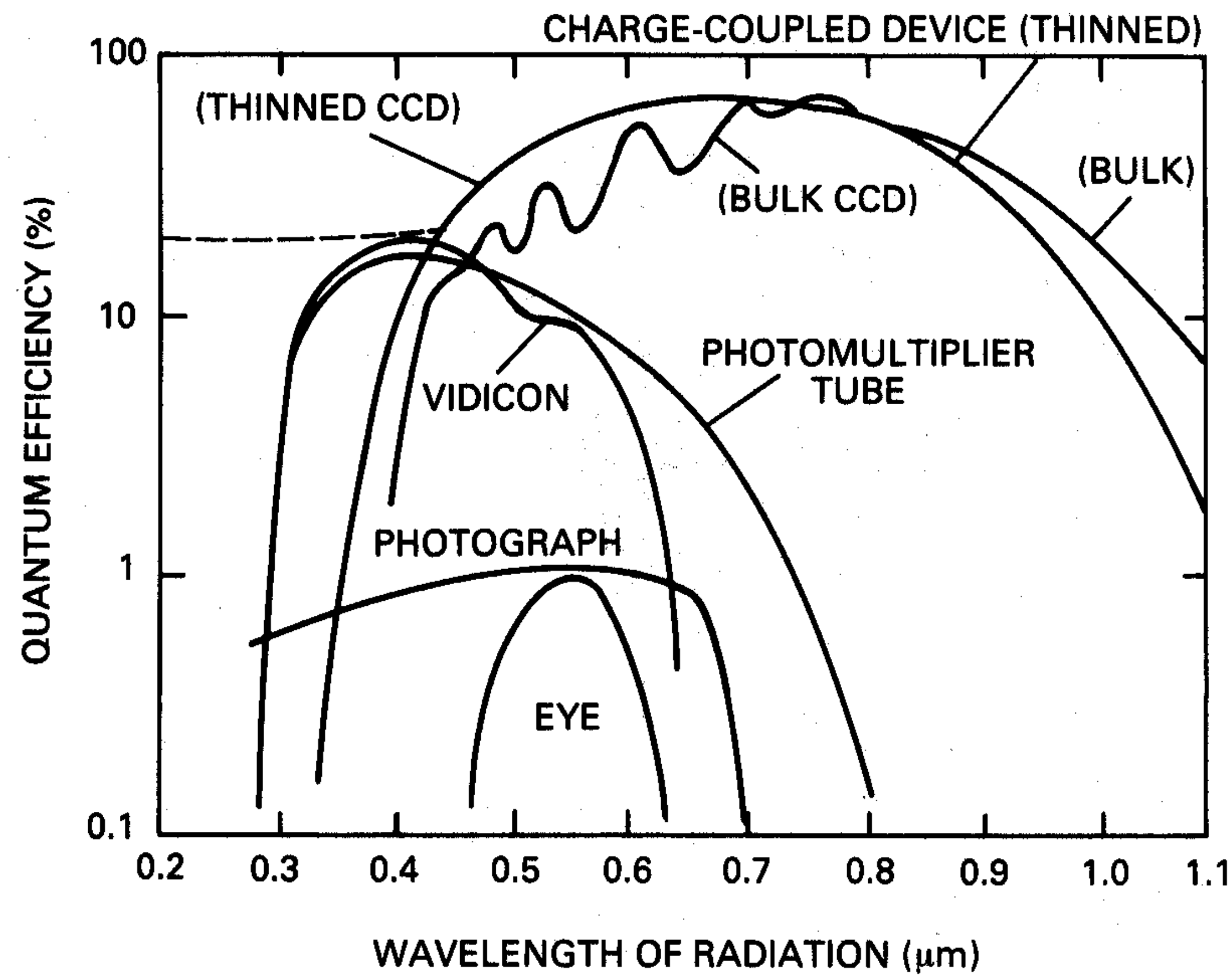
1. Compact, rugged, stable, durable, low-power (using 10's instead of 1000's of volts)

2. Excellent stability and linearity

3. No image distortion (direct image onto a Si array fixed in fabrication process

4. Relative ease of operation, and reasonable cost due to mass production

5. Unprecedented sensitivity (i.e. quantum efficiency) over wide range λ



Detectors

Charge Couple Device Detectors (CCDs)

History of the invention of CCDs

The CCD was invented by Willard S. Boyle and George E. Smith of Bell Labs (where the transistor was invented) in 1969

They were jointly awarded the Nobel Prize for Physics in 2009

Detectors

Charge Couple Device Detectors (CCDs)

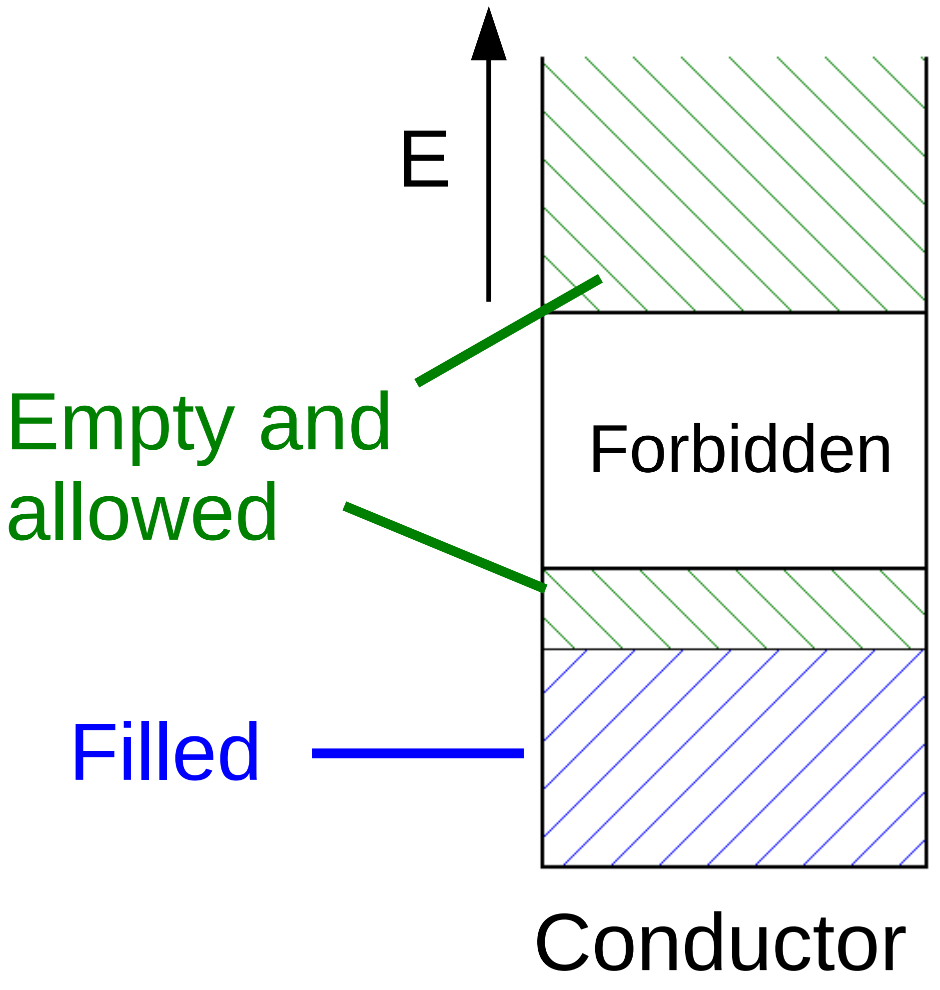
- Standard detector type in astronomy
- Used from optical to near infra-red to X-rays
- Constructed from semi-conductors
- In a solid, electrons have allowed and forbidden bands of energy, not well defined energy levels as in atoms
- Size of forbidden gap between bands and completeness with which lower energy band is filled determine if solid is
    - Conductor
    - Insulator
    - Semi-conductor

Detectors

Charge Couple Device Detectors (CCDs)

In a conductor

- Lower energy band not completely filled
- Electrons may travel freely in this unfilled part and conduct electricity

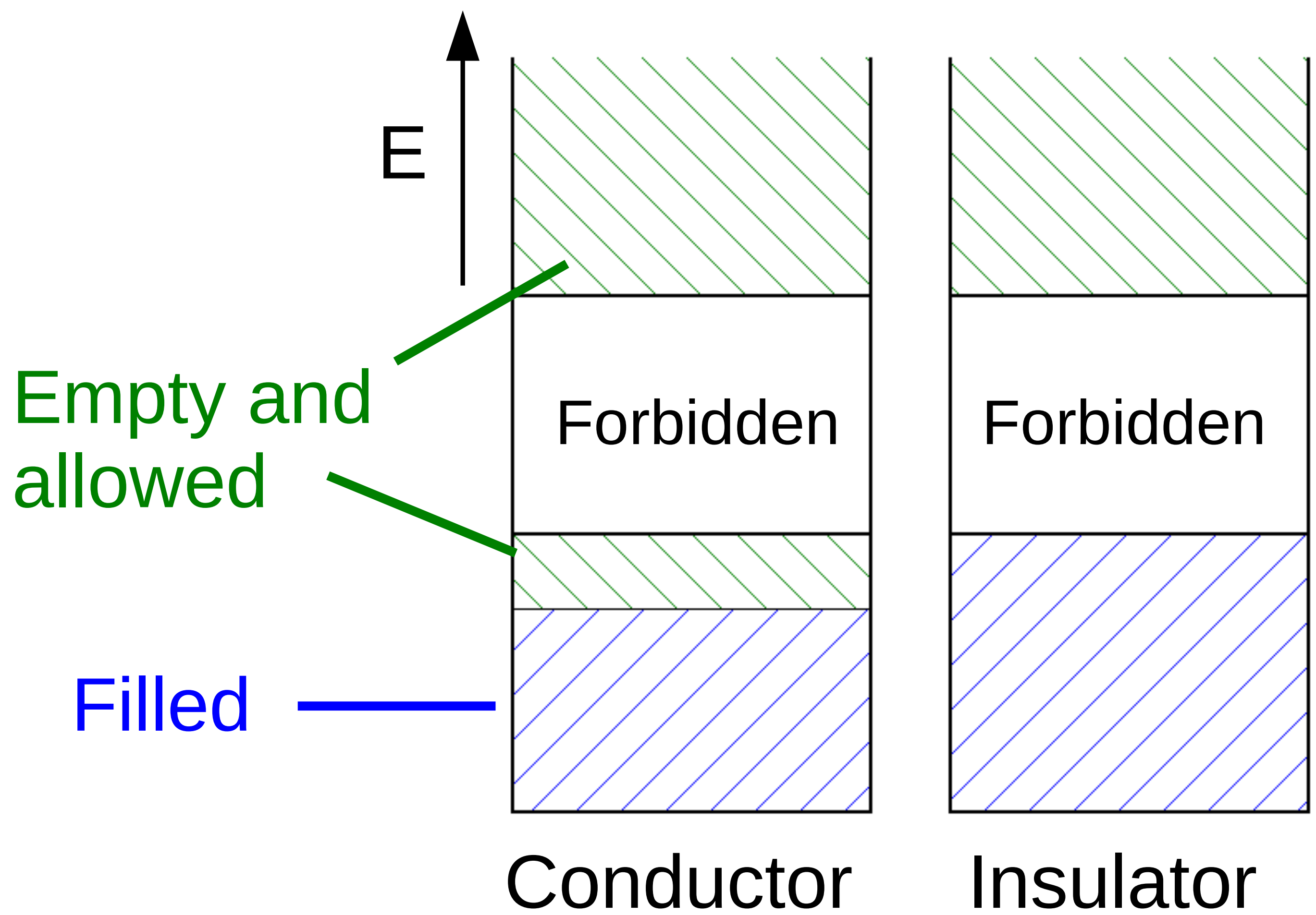


Detectors

Charge Couple Device Detectors (CCDs)

In an insulator

- Lower energy band is full
- Electrons require great deal of energy to move into upper allowed band and conduct

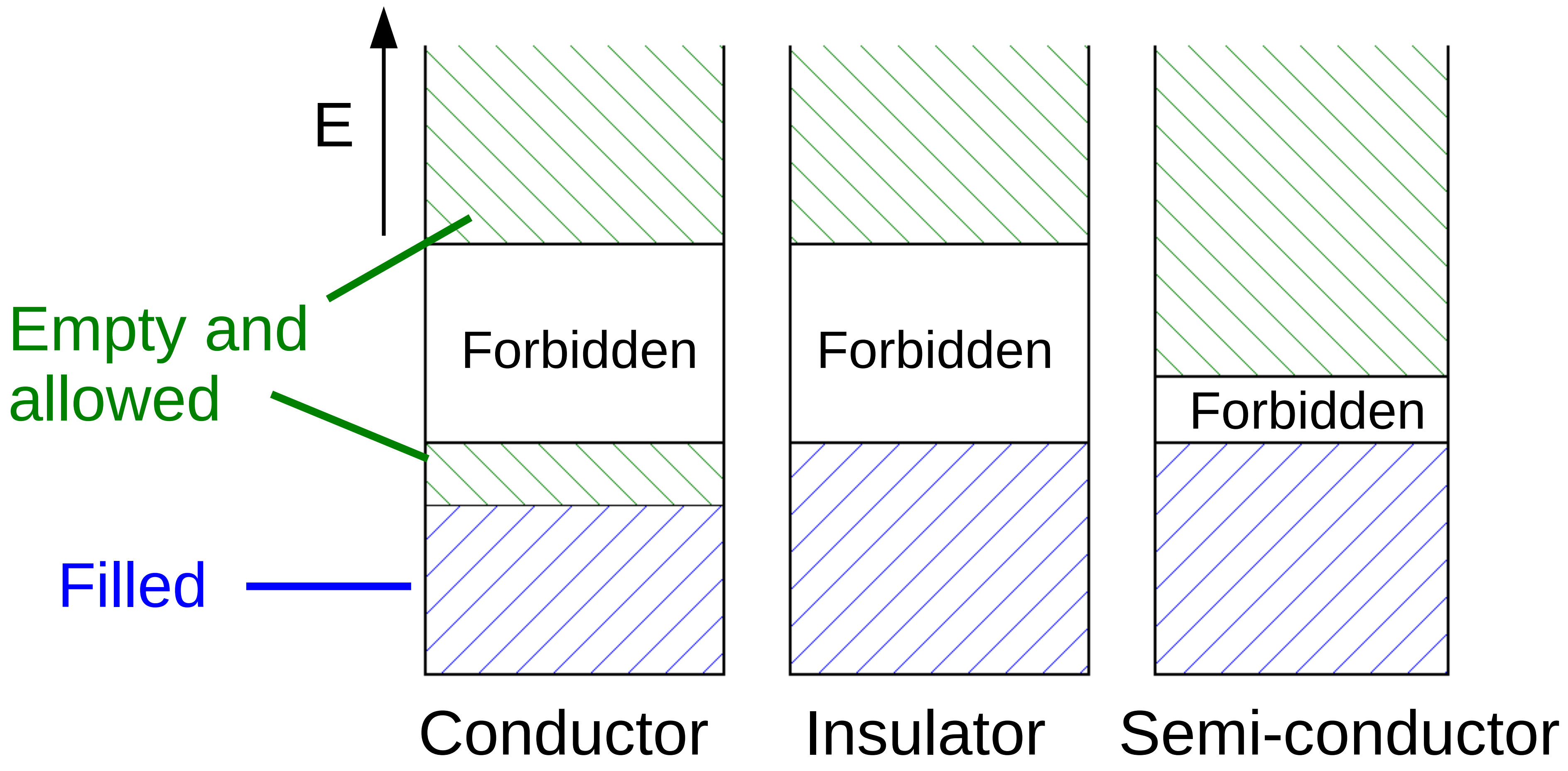


Detectors

Charge Couple Device Detectors (CCDs)

In a semi-conductor (e.g. Silicon)

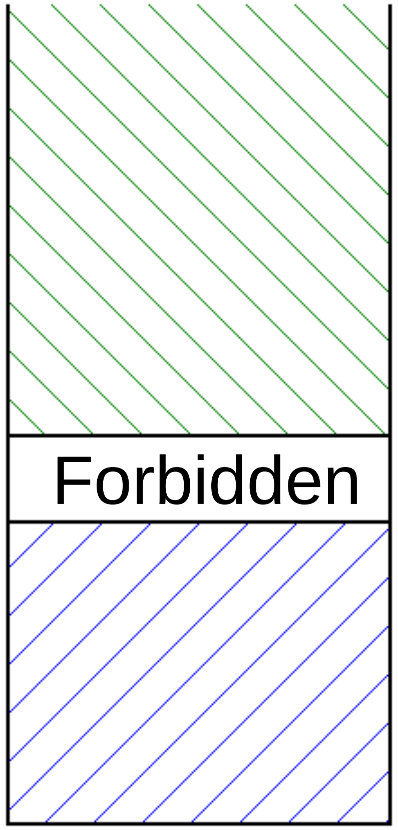
- Lower energy band is full
- Forbidden gap is small enough that electron may be excited across it thermally or by absorbing a photon
- Produces an electron-hole pair, both of which contribute to conductivity



Detectors

Charge Couple Device Detectors (CCDs)

- CCDs make use of this property of semiconductors
- Photons striking the semiconductor free electrons (photoelectric effect) which are then stored
    - Record the number of photons
- Size of forbidden band in Silicon fixes the infra-red limit for CCD use at ~1.1μm
    - At longer λ not enough energy to free electrons
- Cooling detector reduces background
    - Fewer electrons thermally excited through forbidden ban

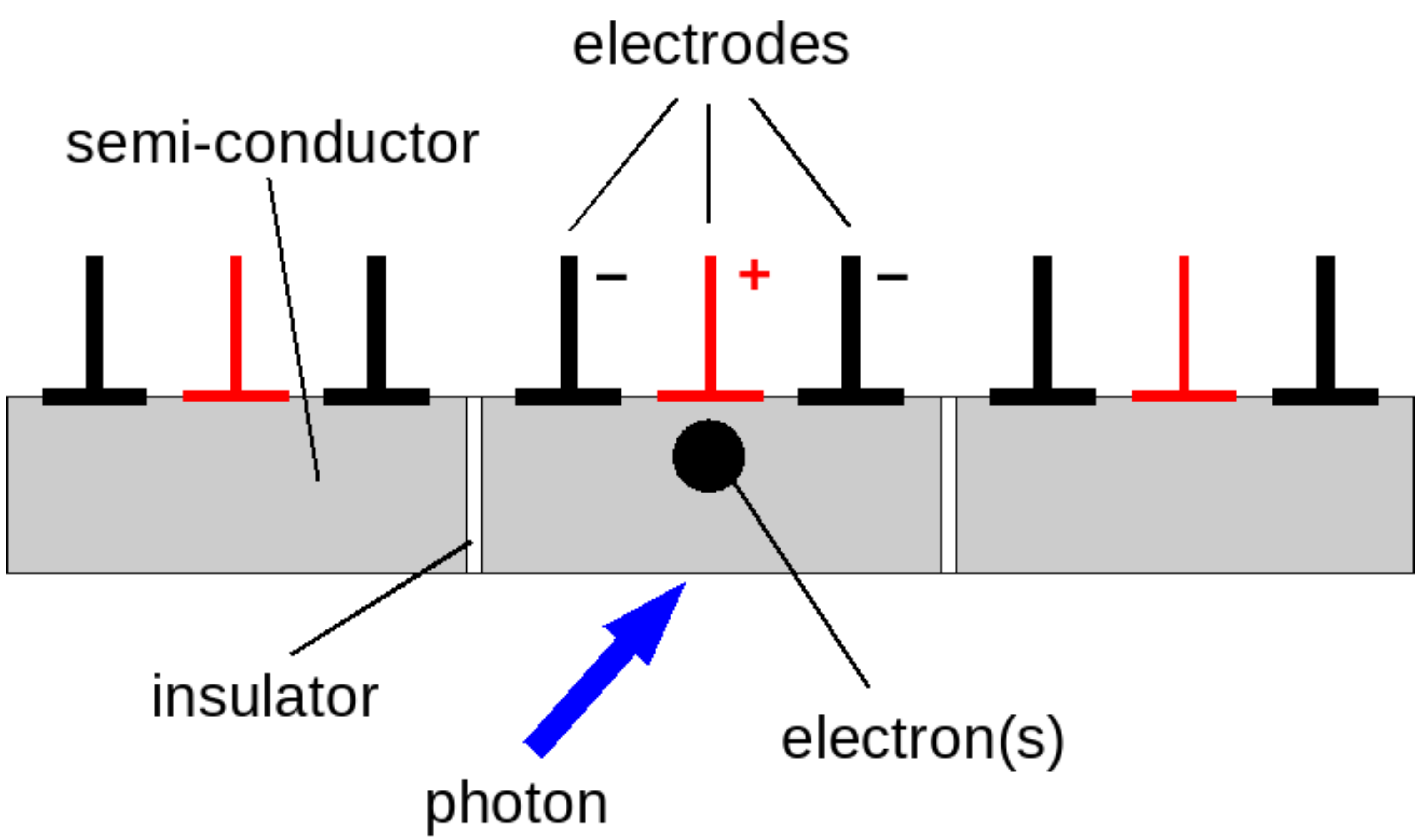


Semi-conductor

Detectors

Charge Couple Device Detectors (CCDs)

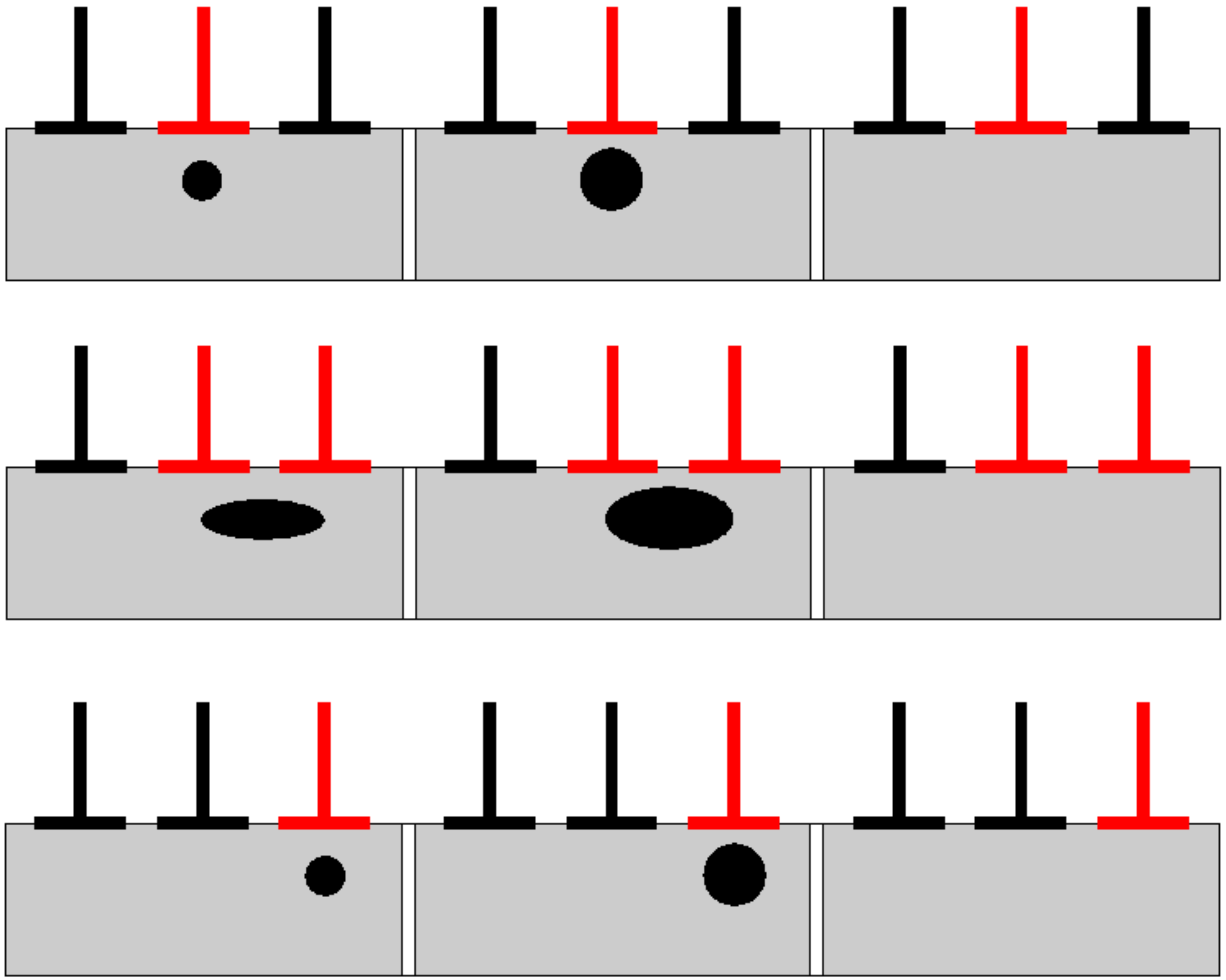
- CCDs divided into pixels ~20μm square by thin layers of insulator
- Incident photon liberates electron which is collected in electric field near +ve electrode
- Charge held and more electrons added (if more photons arrive) until readout



Detectors

Charge Couple Device Detectors (CCDs)

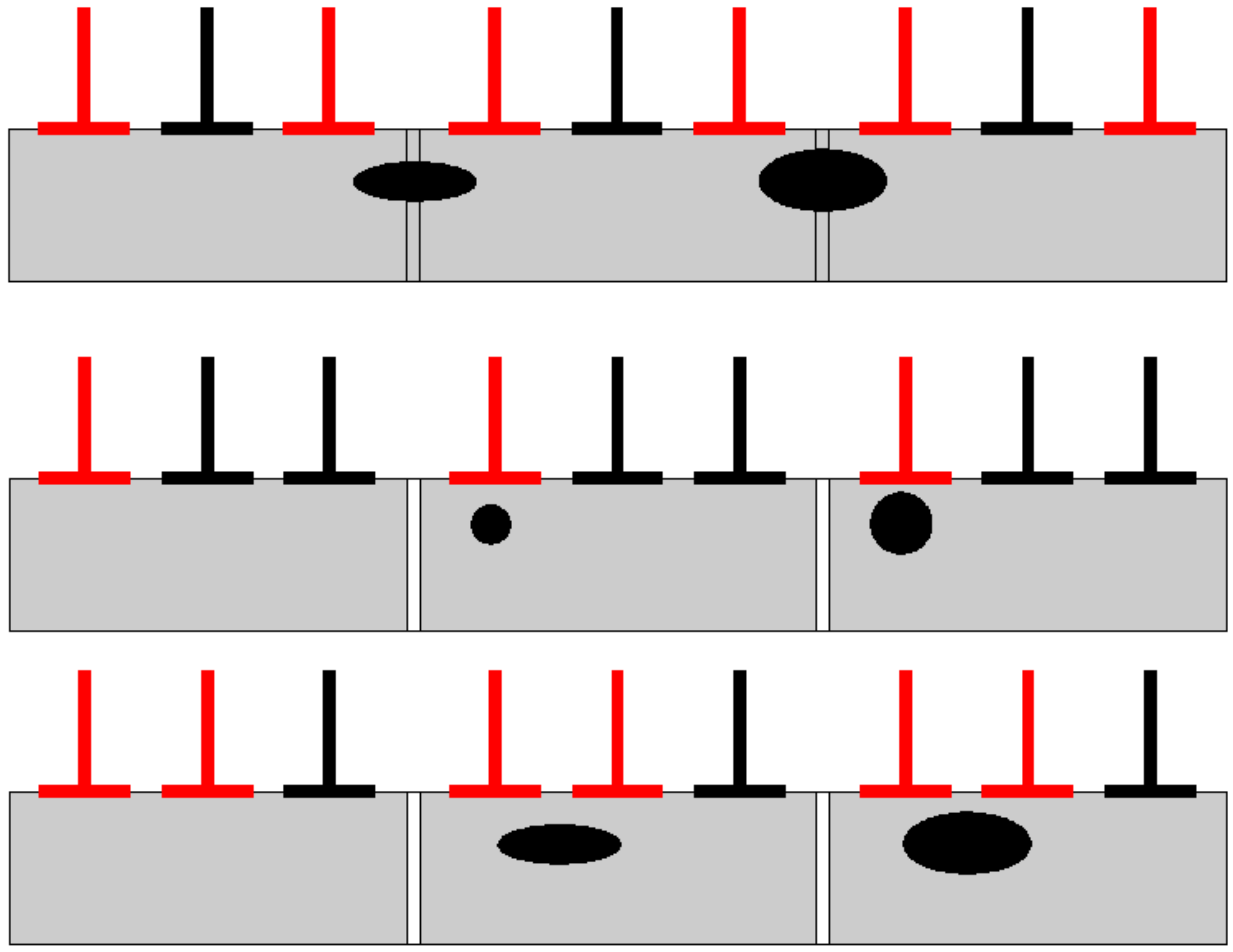
During read-out, voltages on electrodes are cycled to transfer charge from pixel to pixel



Detectors

Charge Couple Device Detectors (CCDs)

During read-out, voltages on electrodes are cycled to transfer charge from pixel to pixel

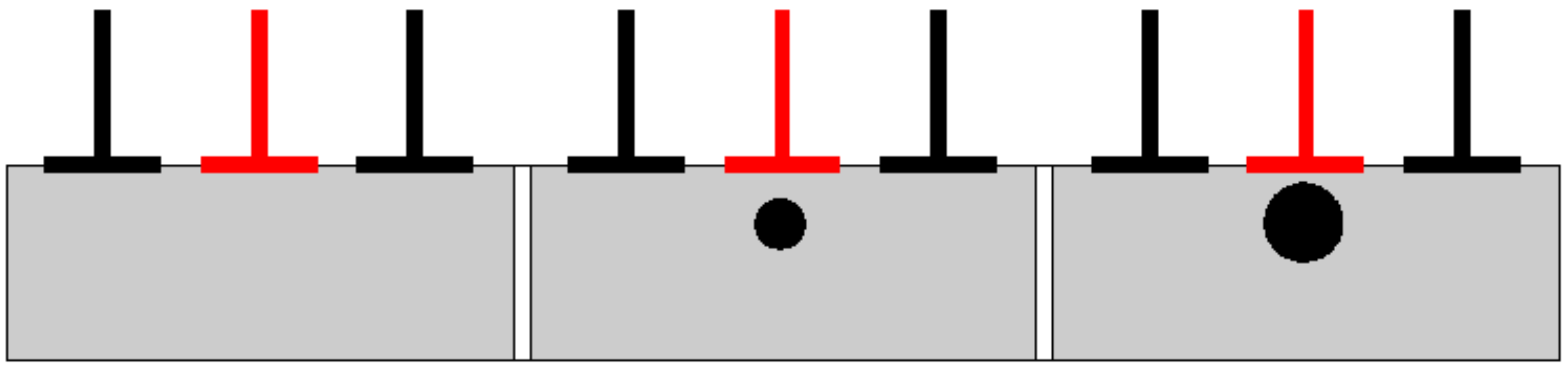


Detectors

Charge Couple Device Detectors (CCDs)

During read-out, voltages on electrodes are cycled to transfer charge from pixel to pixel

In read out direction, insulators are actually electrode gates on which the voltage can be varied to allow charges to pass

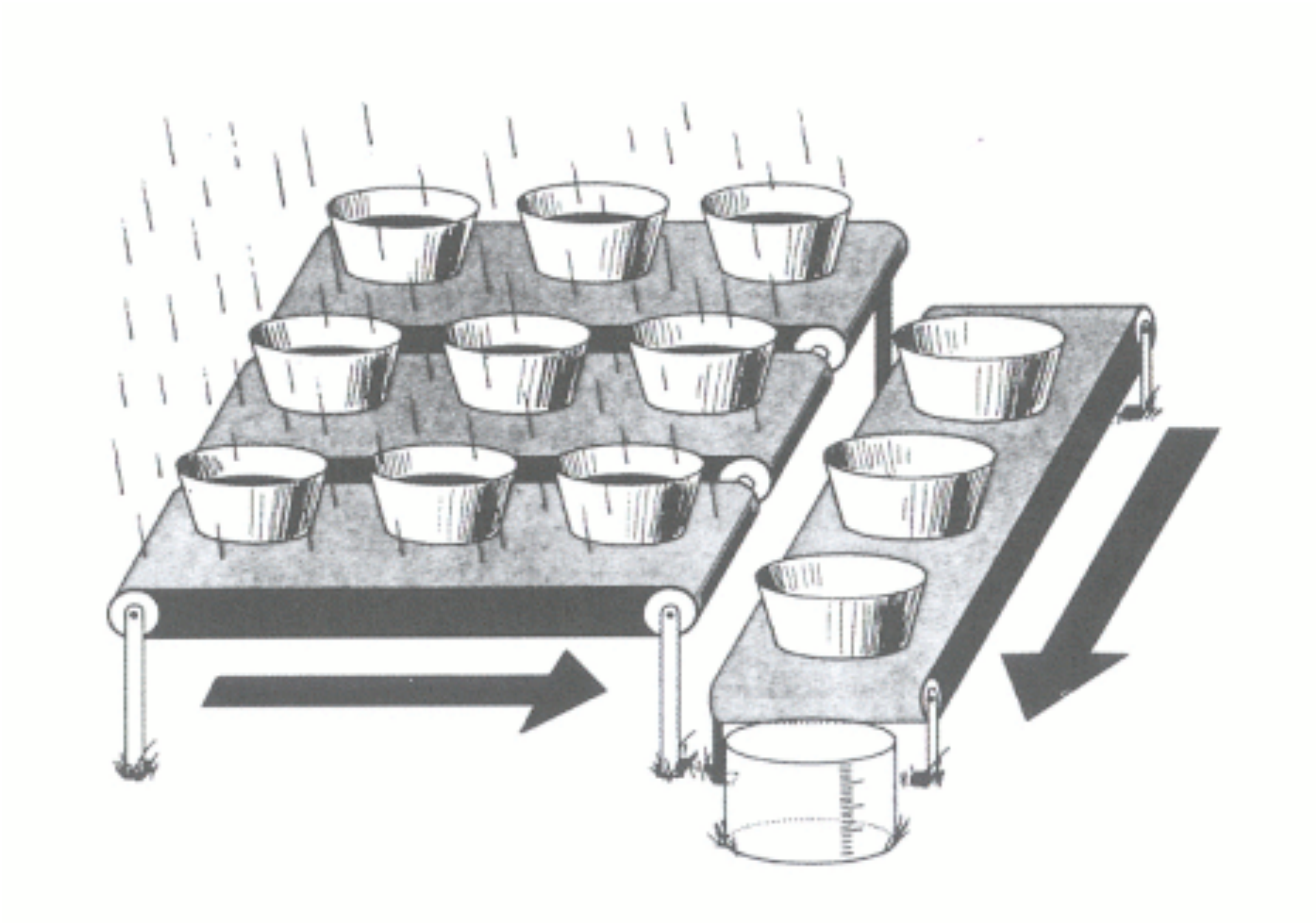


Detectors

Charge Couple Device Detectors (CCDs)

Rain Bucket analogy for a CCD

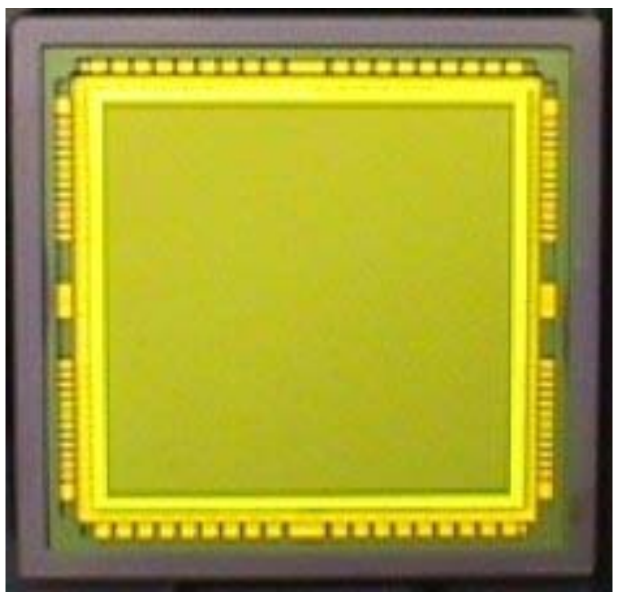
- Charge is transferred along a row and read out
- Then the next row is transferred down to the readout row and the process repeats



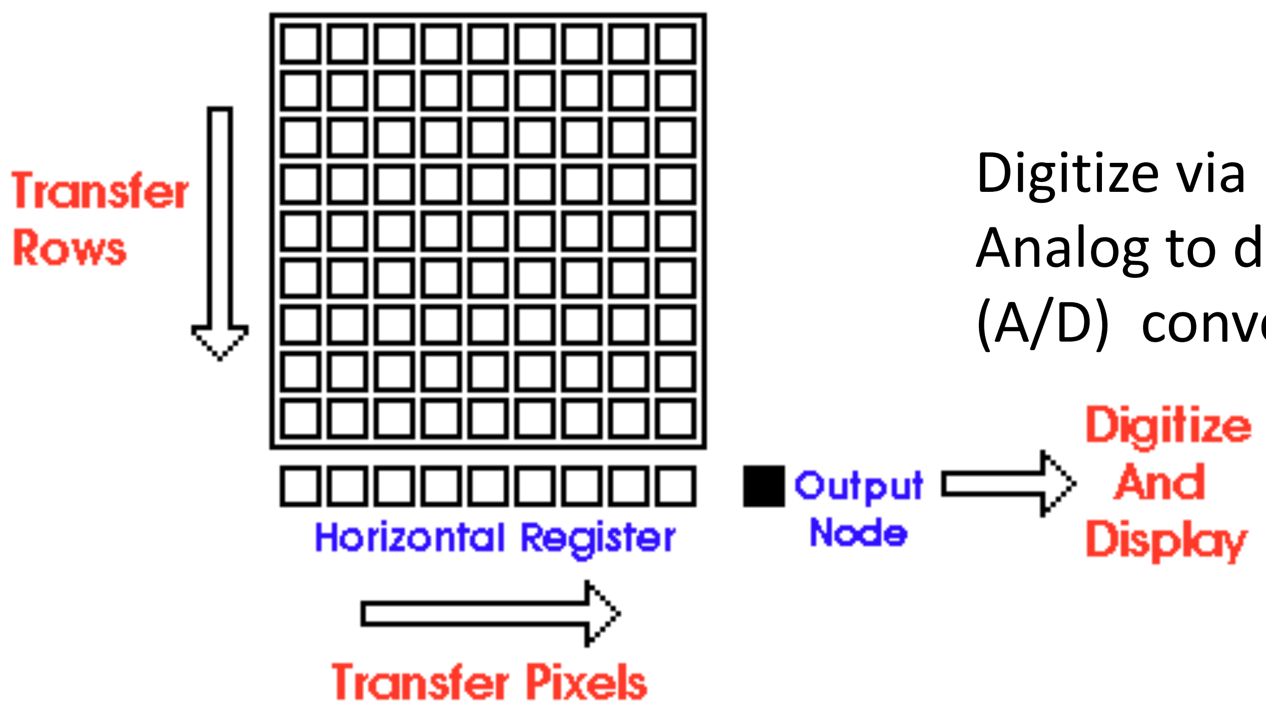
Detectors

Charge Couple Device Detectors (CCDs)

CCD Readout



Thomson
2048 X 2048
CCD



Digitize via Analog to digital (A/D) converter

Horizontal register = Serial register

Detectors

Charge Couple Device Detectors (CCDs)

Basic definition of a CCD

- CCD is a metal oxide structure (MOS), consisting of a transparent metal electrode separated by a ~0.1μm of SiO_2 insulator from a layer of p-type Si. Thus it is a simple capacitor, capable of storing electrical charge.

- CCD behaves as a two dimensional array of Si p/n junctions. The whole array is essentially a giant p/n junction, but individual 'picture elements', or pixels, are created using insulating 'channel stops' and electrodes.

- Individual 'rows' of pixels are isolated by channel stops (stopping charges being able to diffuse vertically).

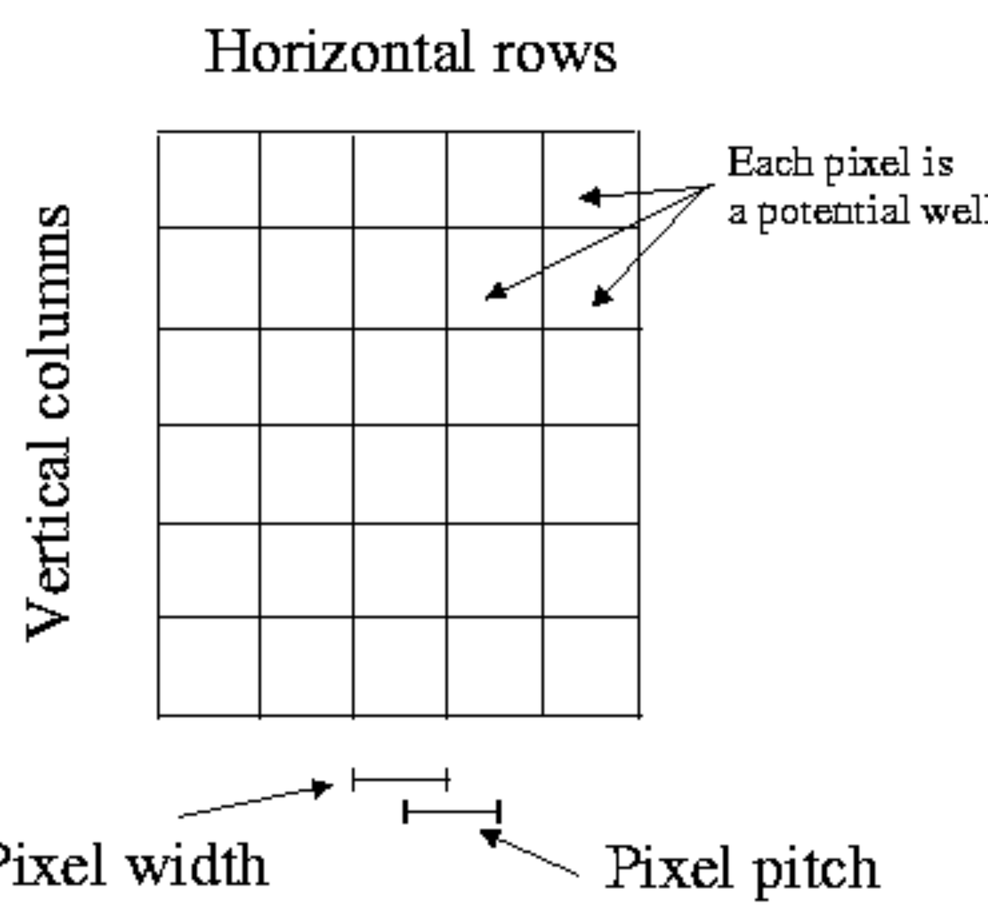
- Individual 'columns' of pixels are created by voltages applied to control electrodes.

- Charges are accumulated in pixels during exposure to light and remain there due to applied voltages.

Detectors

Charge Couple Device Detectors (CCDs)

- An actual CCD will consist of a large number of pixels (i.e, potential wells), arranged horizontally in rows and vertically in columns.
- The number of rows and columns defines the CCD size, typical sizes are 1024 pixels high by 1024 pixels wide.
- The resolution of the CCD is defined by the size of the pixels, also by their separation (the pixel pitch).
- In most astronomical CCDs the pixels are touching each other and so the CCD resolution will be defined by the pixel size, typically 10-20μm. Thus, a 1024x1024 sized CCD would have a physical area image size of about 10mm x 10mm.



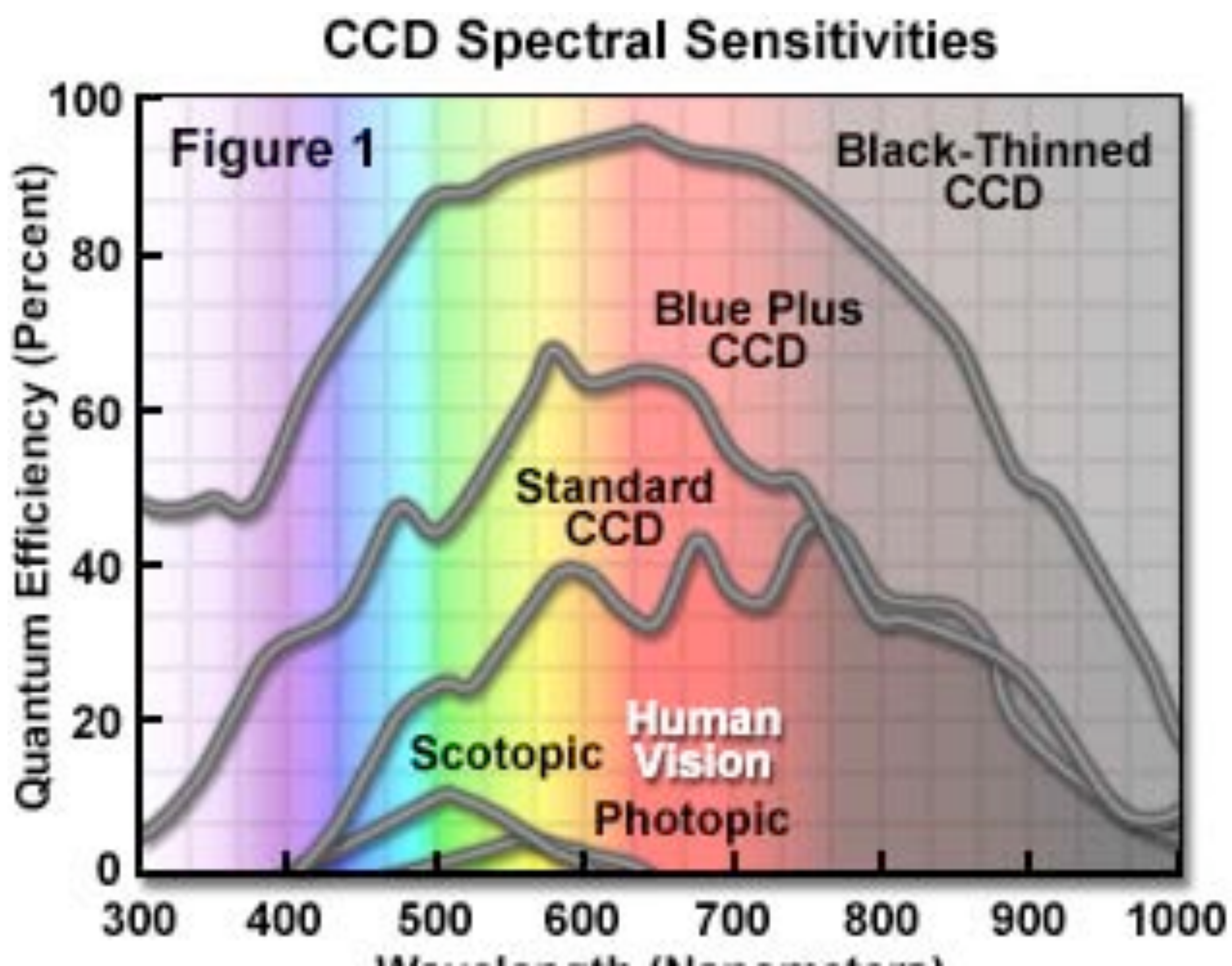
Detectors

Some aspects of CCD behaviour

Quantum Efficiencies (QEs) are one of the most important parameters of a CCD.

Quantum Efficiency (QEs) is the percentage of photons striking the CCD that are actually collected. OR

The *quantum efficiency* (QE) of a detector is the fraction of incident photons which produce photo-electrons.

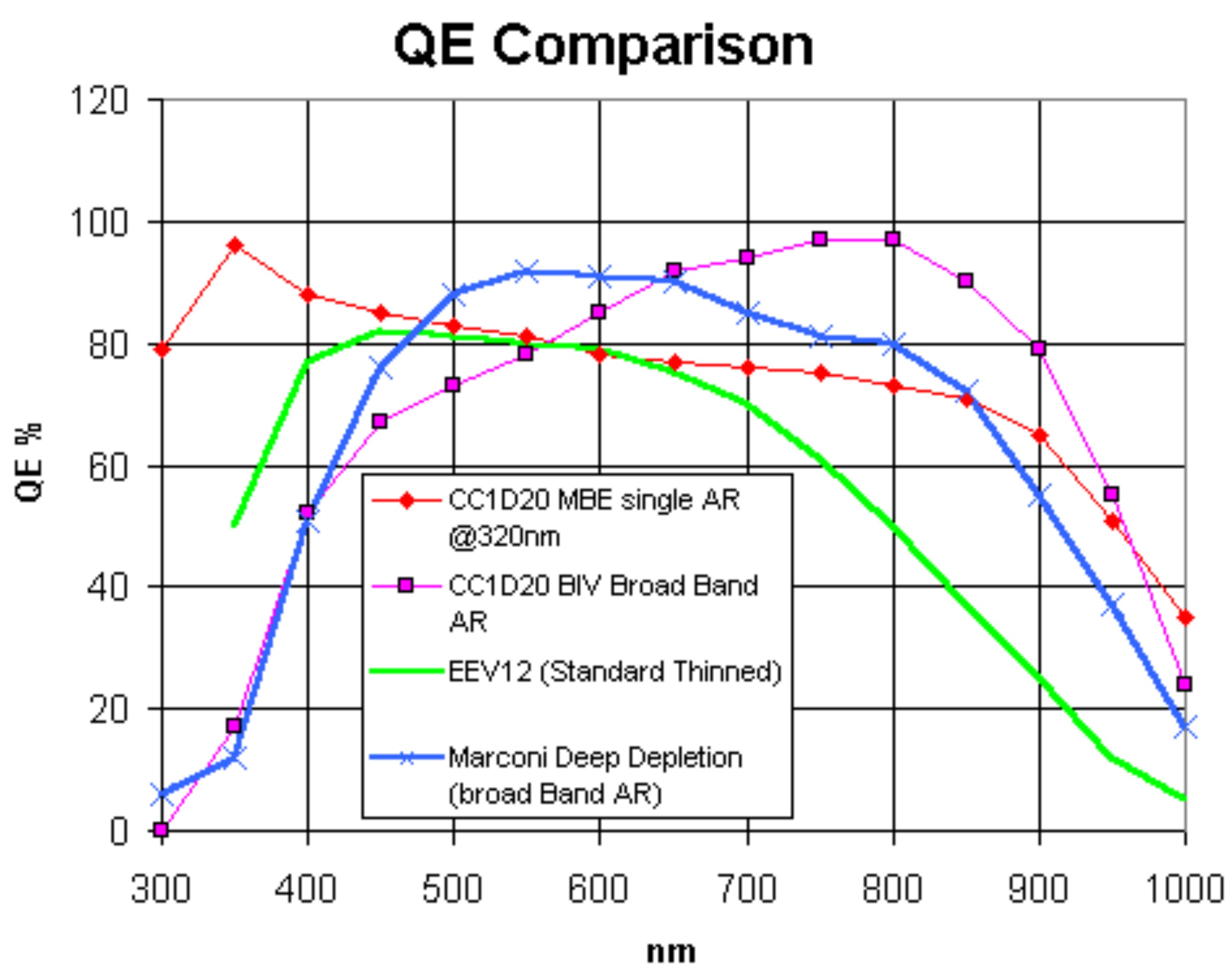


Detectors

Some aspects of CCD behaviour

CCD Quantum Efficiency is determined by CCD type (front/back side, resistivity of Si, and temperature of operation) and CCD coating.

Through clever design, the QE of CCDs can reach 90% at optical wavelengths. For comparison, the quantum efficiency of photographic film is around 10%, making it easy to see why CCDs have become the dominant detector in optical astronomy.



Some aspects of CCD behaviour

Charge transfer efficiency (CTE)

Charge transfer efficiency (CTE) is a measure of how effective the CCD is at moving charge from one pixel location to the next when reading out the chip.

A perfect CCD would be able to transfer 100% of the charge as the charge is shunted across the chip and out through the serial register.

In practice, small traps in the silicon lattice compromise this process by holding on to electrons, releasing them at a later time. (Depending on the trap type, the release time ranges from a few microseconds to several seconds).

For large charge packets (several thousands of electrons), losing a few electrons along the way is not a serious problem, but for smaller (~100 e^- or less) signals, it can have a substantial effect.

CTE is typically measured as a pixel transfer efficiency, and would be unity for a perfect CCD.

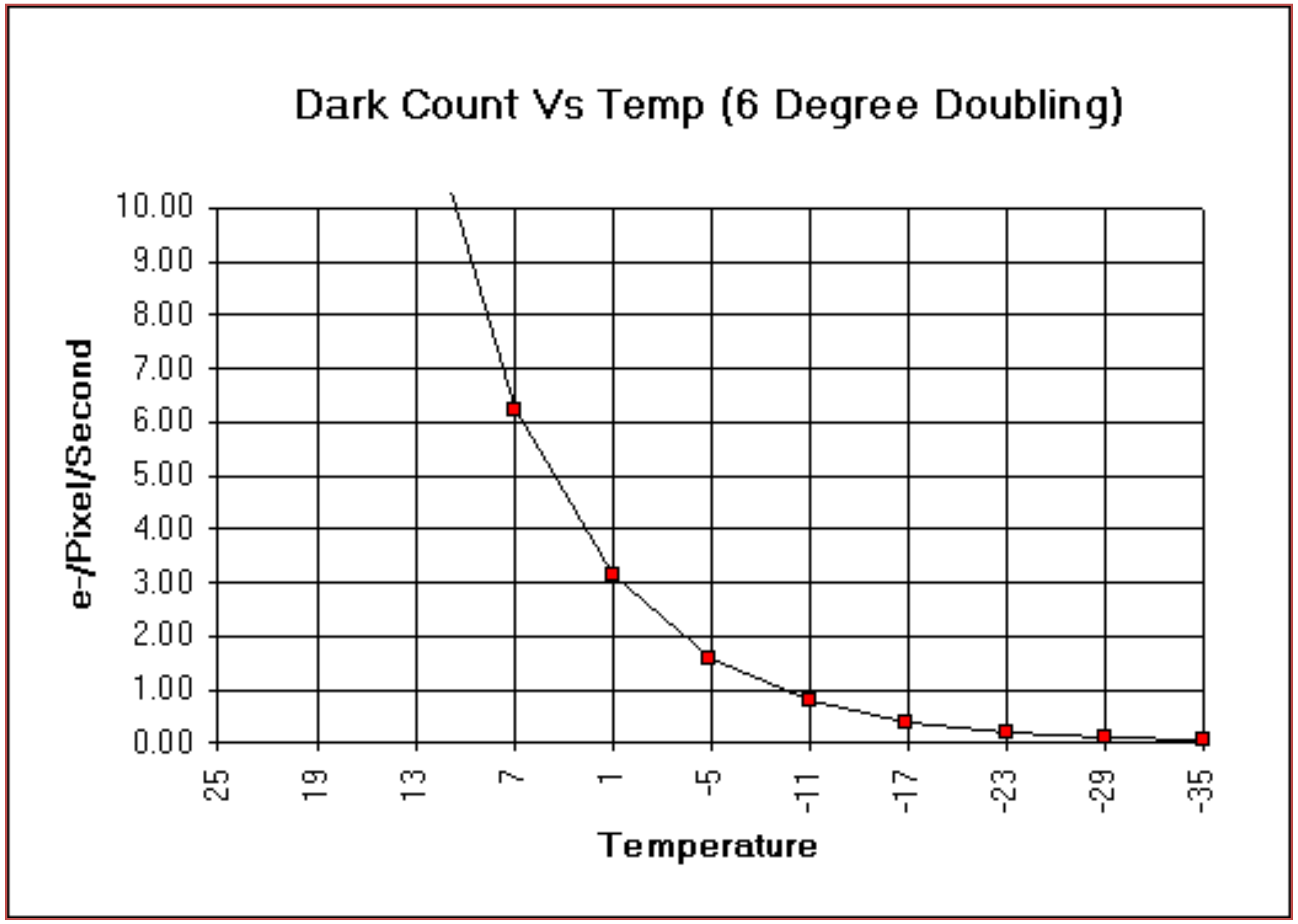
Detectors

Some aspects of CCD behaviour

Noise

Dark Current

- Thermal noise (Thermal electrons)
- Strong function of temperature
- Essentially zero in research quality CCDs operated near -100 C



Some aspects of CCD behaviour

Noise

- Read Noise
  - The level of noise present in a “no exposure” readout of the electronics
  - Use a zero second “Bias” or “Zero” exposure to measure
  - 3-10 electrons per pixel per read are typical today

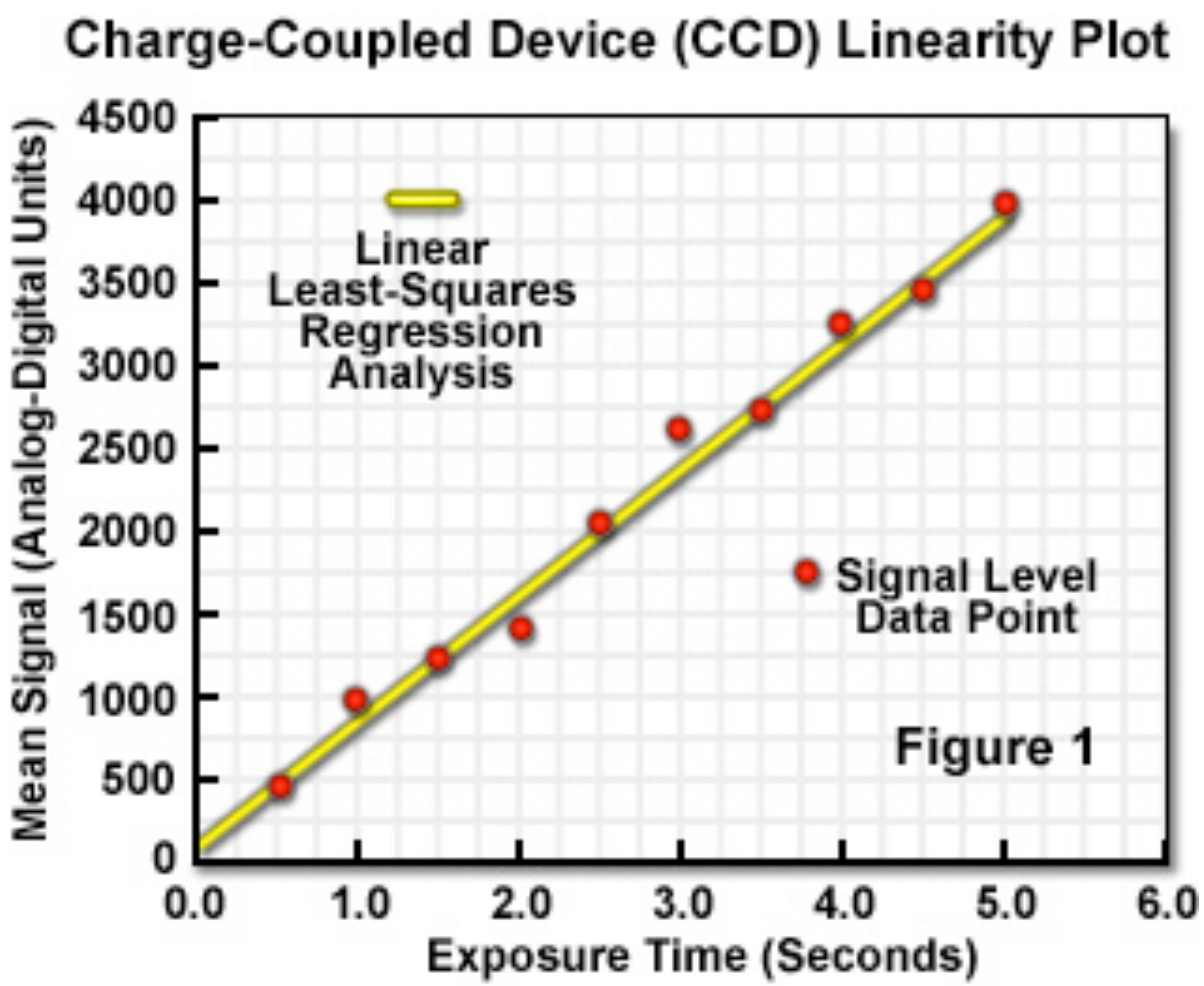
Read Noise acts as a shot noise, that is it enters the noise budget as R^2

Detectors

Some aspects of CCD behaviour

Linearity

- Relationship between photons in and DN out
- In-Out related by Gain of CCD (e.g., 3 electrons/ADU)
- <1% deviation over full range is good
- Depends on CCD and A/D



Useful CCD Stuff

- CCD pixel scale (Plate scale)
  - given in arcsec/pixel
- CCD Binning
  - How many pixels are co-added on-chip prior to readout. (e.g., 2X2, 3X1)
- CCD windowing
  - What rectangular region of the CCD is in use
- Full well capacity
  - How many photoelectrons can a single pixel hold before saturation (charge spills out to nearby pixels)

Infrared Detectors

Thermal Considerations

- In IR, photon energies close to thermal energy in detector (kT) at atmospheric temperatures
    - Detector cooling required
    - Near-IR: cool to 77K (liquid nitrogen)
    - Mid-IR: cool to 4K (liquid helium)
    - Far-IR: as low as possible, down to 100 mK (using e.g. ^{3}He)
- Wein's law for blackbody: $\lambda_{peak} = b/T$
    - At ~300K we are all glowing at ~10μm
- Telescope and atmosphere glowing in IR – Background subtraction is vital
    - Background level varies with time
    - On/off source switching used to provide real time background

Infrared Detectors

Infrared arrays

The band gap for silicon is too large to detect light at wavelengths greater than about 1.1 μm, and materials with a narrower band gap need to be used. Common materials:

- Mercury cadmium telluride (HgCdTe): 0.8-5 (25) μm
- Indium antimonide (InSb): 1-5.5 μm
- Silicon Arsenic (Si:As): 6-27 μm
- Germanium Gallium (Ge:Ga): < 70 μm, < 160 μm (depending on stress)

For Example — In HgCdTe (mercury cadmium telluride)

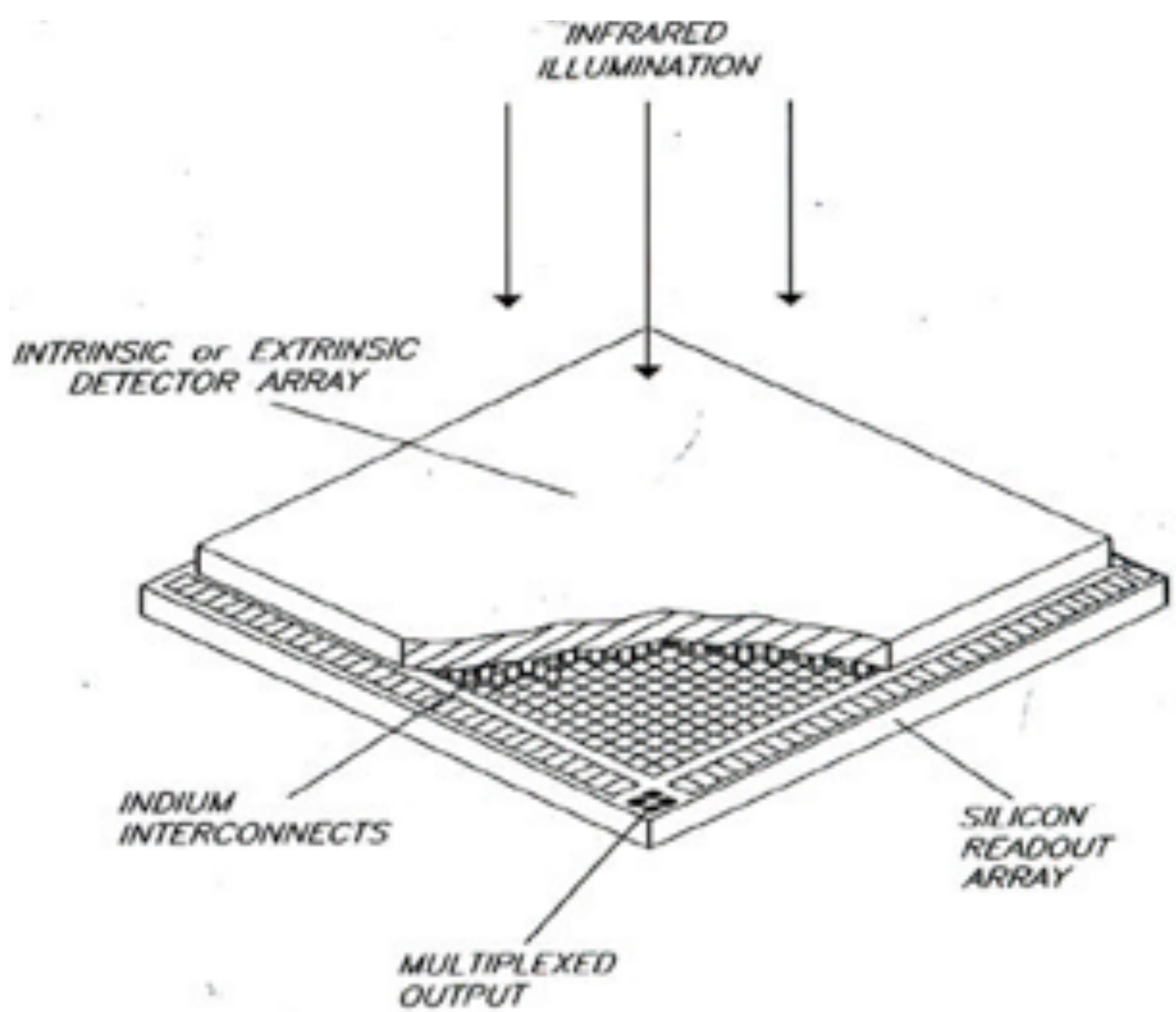
- CdTe is semiconductor with forbidden gap of 1.5eV
- HgTe has no forbidden gap
- Mixing allows “tuning” of band gap of 0 – 1.5 eV for IR

Narrower gap means more thermal noise

Infrared Detectors

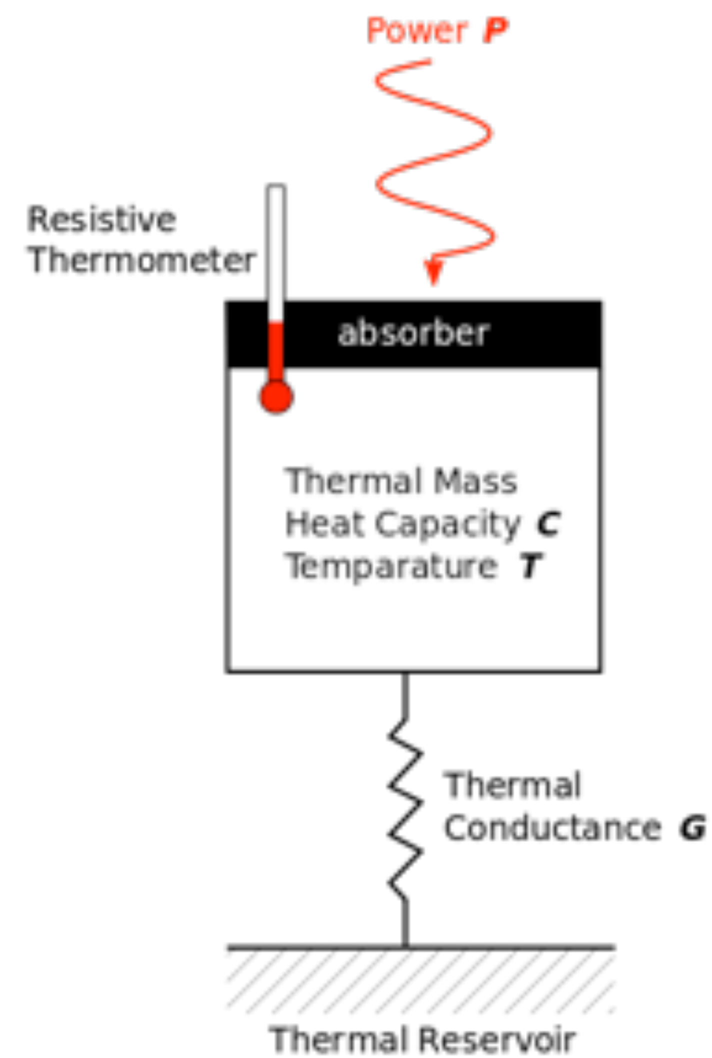
Infrared arrays

In IR arrays — detector layer (HgCdTe, etc.) mechanically bonded to a (silicon) multiplexed readout array. Unlike CCDs pixels can be readout individually; individual amplifier readouts are used.



Infrared Detectors

Bolometers: used in far-IR and submm range. In bolometers photons are thermalized raising the temperature of the material (such as Ge). This change in energy is detected with a sensitive resistive thermometer.



Infrared Detectors

Infrared arrays

- Bond detector material to a silicon readout to measure the charge in each pixel
  - Hybrid array
- Differences in thermal properties cause layers to break apart
- Difficult to build large arrays
- Expensive to produce

Infrared Astronomy

Sources of IR emission

Dusty regions (i.e. star forming regions)

- emission from warm dust (for typical temperature of galaxies, dust emission peaks ~100 μm)
- transparency of dust to IR radiation, longer wavelengths not scattered like visible radiation

Cool objects

- small cool stars, red giants, brown dwarfs
- planets, comets, asteroids
- nebulae, interstellar dust, protoplanetary disks

Cool stars energy peak ~ 1μm
Giant planets ~ 6-15μm
Dust re-radiation ~ 20-200μm

Infrared Astronomy

Sources of IR emission

High-redshift objects

- can select high-z galaxies based on breaks in the spectrum leading galaxies to appear in red bands but not bluer bands (4000 Å z~2, Lyman limit at 912 Å z>7)

Molecular vibrational and rotational lines

- lines for CO, CO2, H2, H2O, silicates
- PAH features (polycyclic aromatic hydrocarbon)

Infrared Astronomy

Sources of IR emission

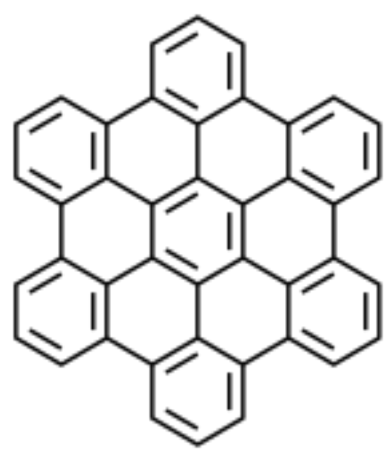
NIR emission lines

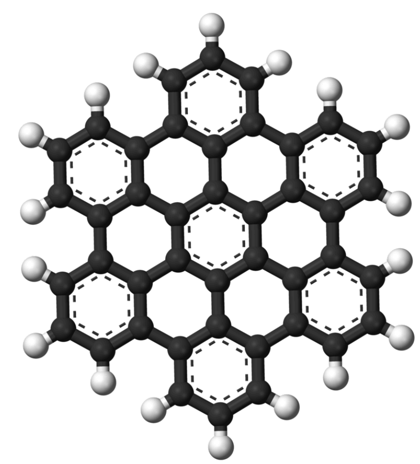
- Paschen-Beta 1.28 μm >> Recombination
- [FeII] at 1.64 μm >> shock-excited tracer of energic phenom
- H2 at 2.12 μm >> direct measure of molecular hydrogen; shocks
- Br-g at 2.17 μm >> recombination (lower extinction)
- CO bands at >2.2 μm >> ISM & circumstellar dust

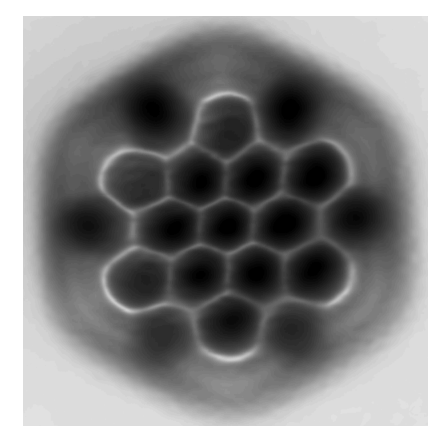
Infrared Astronomy

Molecules in the Infrared

- Emission and absorption lines of most molecules and many atoms
- Primary detection method for elements in space
- Polycyclic aromatic hydrocarbons (PAHs, also polyaromatic hydrocarbons or polynuclear aromatic hydrocarbons) are hydrocarbons —organic compounds containing only carbon and hydrogen).







Polycyclic = multiple loops
Aromatic = strong bonds
Hydrocarbons = hydrogen and carbon

- emission bands 3 - 20 microns (3.2, 6.2, 7.7, 11.3 μm)
- thought to originate in star forming regions
- linked to dust formation (precursors?)

Infrared Astronomy

Sources of IR emission

SPECTRAL REGION	WAVELENGTH RANGE (microns)	TEMPERATURE RANGE (degrees Kelvin)	WHAT WE SEE
Near-Infrared	(0.7-1) to 5	740 to (3,000-5,200)	Cooler red stars Red giants Dust is transparent
Mid-Infrared	5 to (25-40)	(92.5-140) to 740	Planets, comets and asteroids Dust warmed by starlight Protoplanetary disks
Far-Infrared	(25-40) to (200-350)	(10.6-18.5) to (92.5-140)	Emission from cold dust Central regions of galaxies Very cold molecular clouds

Detectors

Useful CCD Stuff

Signal-to-Noise is a quantitative measurement of data quality. Observers desire high signal and low noise. S/N values are quoted as a number such as S/N = 100 or S/N = 3.

For a zero noise observation of an astronomical object, the S/N = SQRT(N) where N is the total signal received (i.e., total photons from source). [Poisson Statistics]

In reality,

$$S/N = \frac{R_* \times t}{[(R_* \times t) + (R_{sky} \times t \times n_{\rm pix}) + (RN^2 + (\frac{\mathcal{G}}{2})^2 \times n_{\rm pix}) + (D \times n_{\rm pix} \times t)]^{1/2}}$$

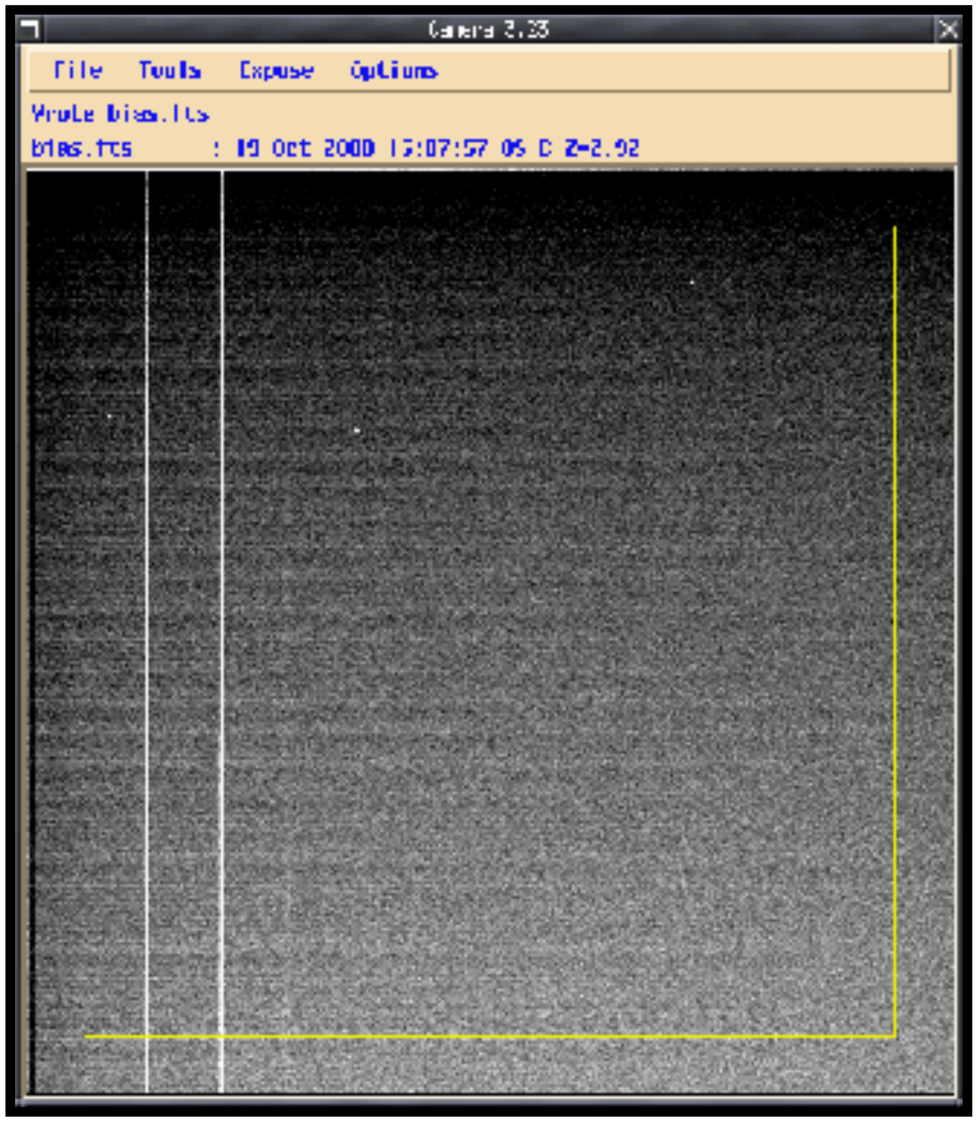
Detectors

CCD Observations

- CCDs are used in astronomy for three major applications:
  - **Imaging**
  - **Photometry**
  - **Spectroscopy**
- Used in optical and outside optical bands (e.g., x-ray, UV, EUV)

Detectors

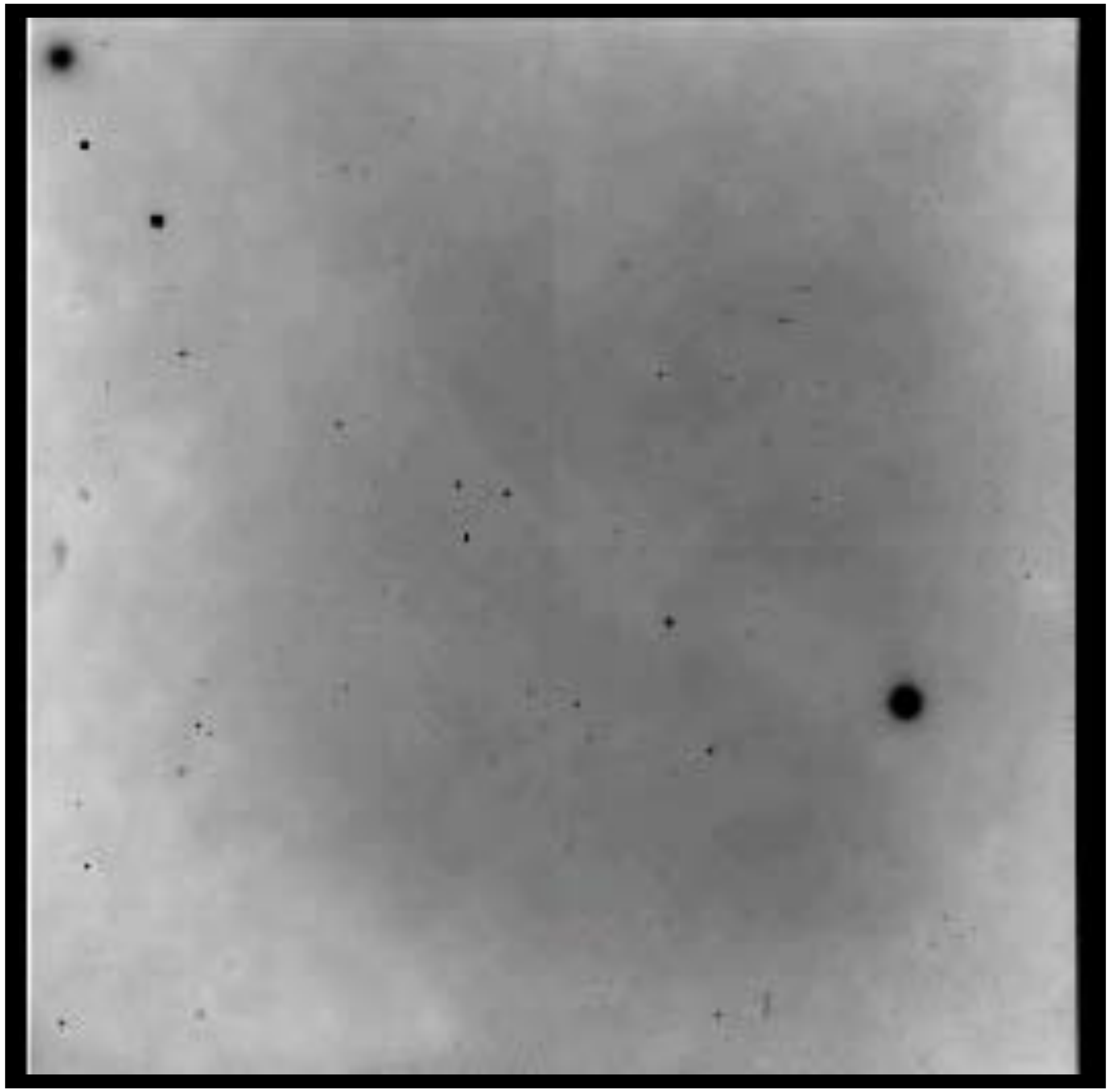
CCD Image Types



- BIAS - calibration
  - A bias (or zero) is a zero second exposure used to measure the "no signal" noise level of the detector.
  - Note the two bad columns in this CCD and cosmic rays

Detectors

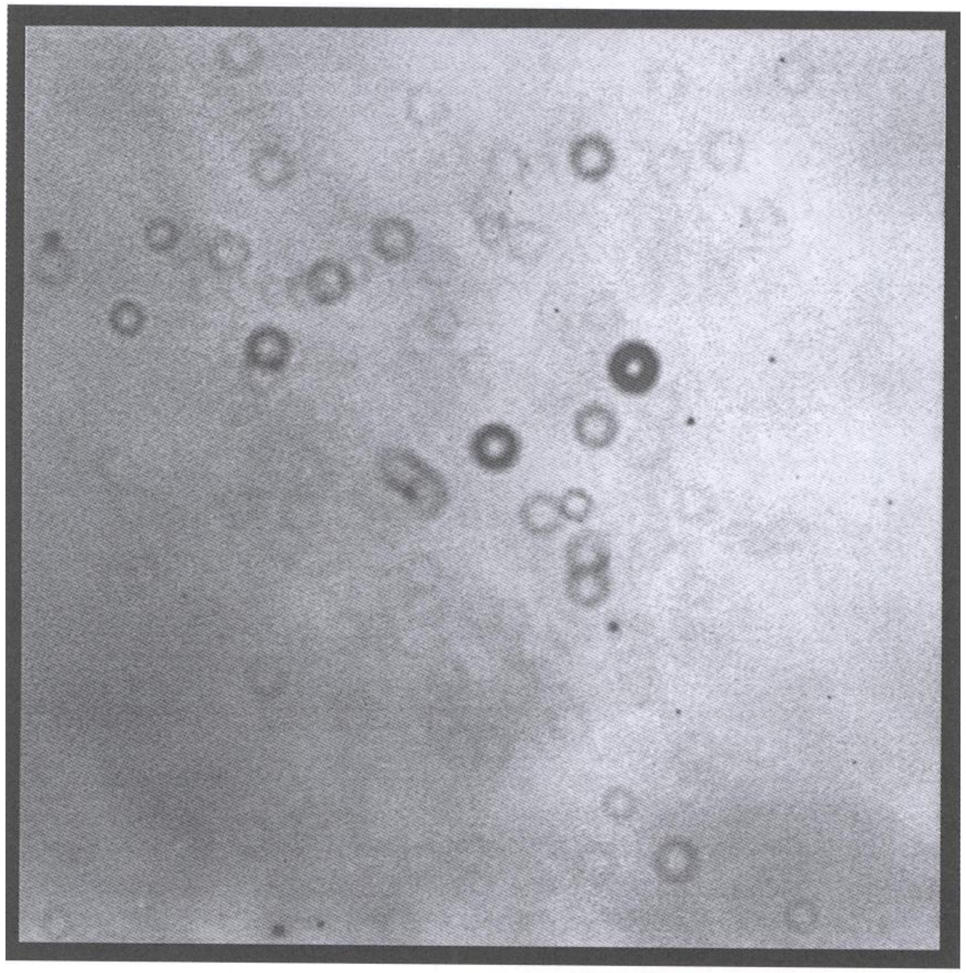
CCD Image Types



- **FLAT FIELD - calib.**
  - A flat field image is used to determine the relative QE of each pixel in the array
  - Flat field images are obtained from dome screens, the sky, or quartz lamps projected in to a spectrograph

Detectors

CCD Image Types

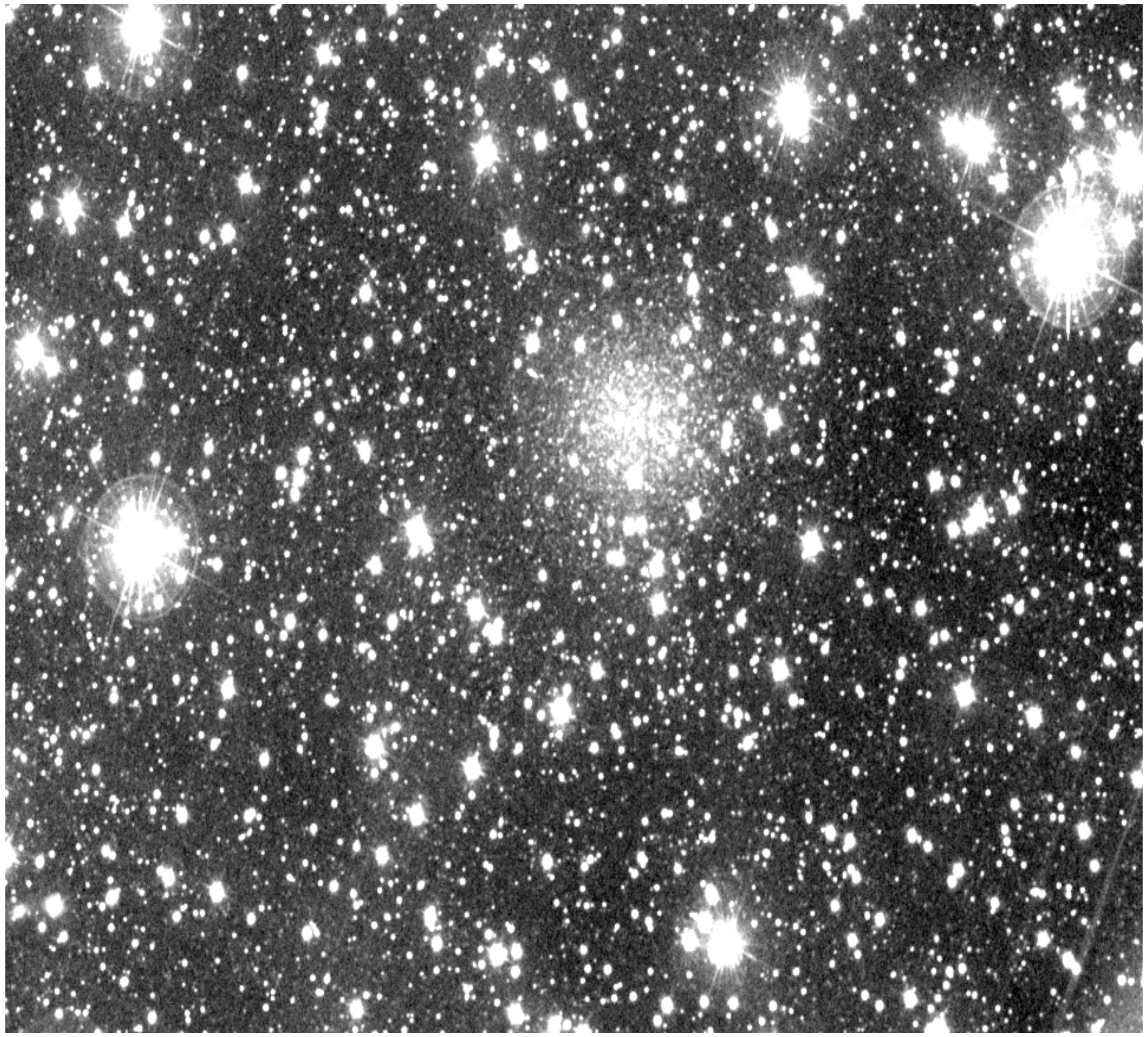


Dust & dirt (!)

- Optical elements in the light path (e.g. filters, windows) can accumulate small dust spot
- These are 'imaged' as out-of- focus spots ('doughnuts')
- Generally stable over timescale of a night (unless in a dust storm)
- Will appear on every CCD frame
- Remove using 'flat field' techniques

Detectors

CCD Image Types



Object

- CCD images are grey scale representations of the collected and stored ADUs.
- To perform imaging or photometry, observers use these types of CCD data.

Detectors

Basic CCD data reduction

- Minimal set of images: bias, flat, and object
- Darks needed if dark current an issue
- All frames include overscan
- Additional steps needed for specific CCDs and specific observations – instrument manuals should provide details
- Basic reduction
  - (Object – Mean Zero) / Mean Flat

Detectors

Summary

- Photographic plates historically important but obsolete
- CCDs based on photoelectric effect in semiconductor chips
- Charge transferred from pixel to pixel in readout
    - ★ High charge transfer efficiency required
    - ★ CCDs have linear response and high quantum efficiency
- Optical observatories study almost all types of astronomical objects
- In UV use micro-channel plate detectors

Photometry

and

The Magnitude System

UV/Optical/IR Photometry

Photometry —

Direct measure of integrated flux (counts per unit time per unit area) received from a celestial target.

UV/Optical/IR Photometry

- How do you measure the flux from an object?
- Few terminologies that you need to know
- What are potential challenges?
- Does it matter what type of object you are studying?

UV/Optical/IR Photometry

Probably the most fundamental measurement we can make in observational astronomy is how light we receive from an object (i.e. how bright it is)

Light

In astronomy, we generally deal with the amount of light emitted in terms of luminosity, L, intensity/surface brightness, I, flux, F

Beware: this terminology is astronomy-specific and other fields, e.g., engineering, use the same names with different meanings!

flux = energy/unit area/unit time

In general, these will be function of wavelength

F_ν=flux per unit frequency F_λ=flux per unit wavelength

UV/Optical/IR Photometry

For historical reasons, fluxes in the UV/Optical and IR are measured in magnitudes:

$m = -2.5 \log_{10} F + \text{constant}$ (Zero point)

UV/Optical/IR Photometry

The Magnitude Scale

- The stellar "magnitude scale" – based on range of star brightness that the eye perceives – was invented around 120 BC by Hipparchus
- He devised 6 "steps" of brightness between the brightest and faintest stars seen by the eye (where smaller magnitudes implies brighter stars!)

Modern definition —

- Early photometric measurements demonstrated that first magnitude stars are about 100 times brighter than sixth magnitude stars.
- In 1856 Norman Pogson of Oxford proposed that a logarithmic scale of $\sqrt[5]{100} \approx 2.512$ be adopted between magnitudes, so five magnitude steps corresponded precisely to a factor of 100 in brightness.
- A first magnitude star is about 2.5 times brighter than a second magnitude star, 2.5^2 brighter than a third magnitude star, 2.5^3 brighter than a fourth magnitude star, and so on.

The Magnitude System

The Magnitude Scale

$$\boxed{m_1 - m_2 = -2.5\ log\frac{I_1}{I_2}}$$

Or

$$\boxed{\frac{I_2}{I_1} = 2.512^{m_1 - m_2}}$$

- So the difference in apparent magnitude of two stars, one of which has 100x the intensity of the other, is $\Delta m = 2.5 \log (100) = 5$ magnitudes.
- The conversion between magnitudes and intensity is given as:

  $m = - 2.5 \log I + \text{constant}$; $I = \text{flux}$
- The constant is referred to as the zero point of the system, and is determined for a specific telescope-instrument-detector combination.

The Magnitude Scale

Two of the main types of magnitudes distinguished by astronomers are:

- Apparent magnitude - the brightness of an object as it appears in the night sky.
- Absolute magnitude - which measures the luminosity of an object; it is the object's apparent magnitude as seen from a specific distance, conventionally 10 parsecs.

The Magnitude System

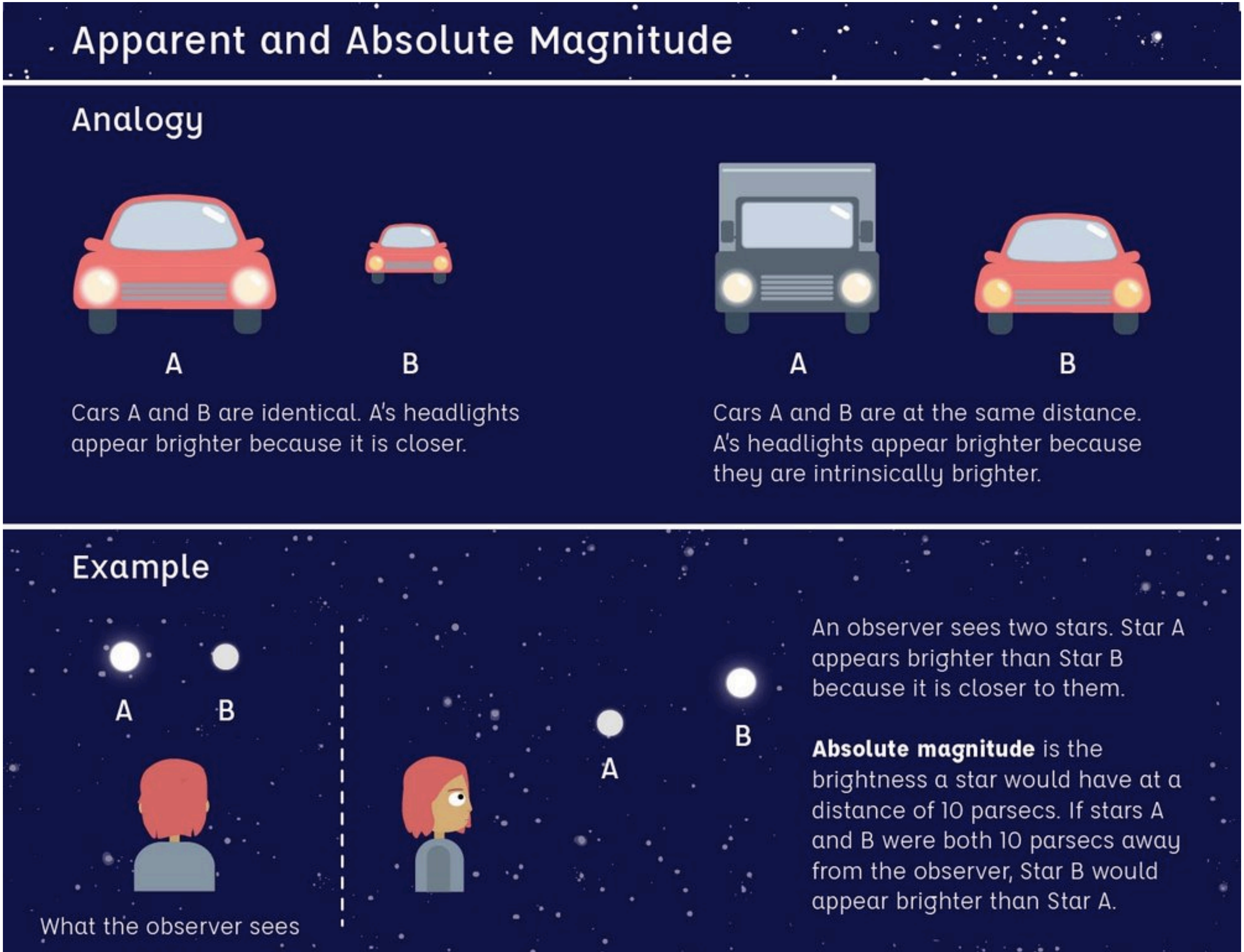
The Magnitude Scale

- Absolute magnitude - Absolute magnitude is a concept that was invented after apparent magnitude when astronomers needed a way to compare the intrinsic, or absolute brightness of celestial objects.

- The apparent magnitude of an object only tells us how bright an object *appears* from Earth. It does not tell us how bright the object is compared to other objects in the universe. For example, from Earth the planet Venus appears brighter than any star in the sky. However, Venus is really much less bright than stars, it is just very close to us. Conversely, an object that appears very faint from Earth, may actually be very bright, but very far away.

- Absolute magnitude is defined to be the apparent magnitude an object would have if it were located at a distance of 10 parsecs. So for example, the apparent magnitude of the Sun is -26.7 and is the brightest celestial object we can see from Earth. However, if the Sun were 10 parsecs away, its apparent magnitude would be +4.7, only about as bright as Ganymede appears to us on Earth.

The Magnitude System



The Magnitude Scale

Interesting magnitudes values (in the V-band filter which approximates the human eye response)

- Sun: $m = -26.7$ (1.2×10^{10} brighter than the brightest naked eye star)
- Full moon: $m = -12.6$
- Sirius (brightest star at night): $m = -1.5$
- Naked eye limit: $m = 6$
- Brightest stars in Andromeda galaxy: $m = 19$
- Present day limit for biggest telescopes: $m \sim 29$ (6×10^{-9} fainter than faintest naked eye star)
- Night sky brightness: $m = 21.5$ / arcsec^2 (best sites, dark Moon time)
- Night sky: $m = 18$ / arcsec^2 (bright Moon time)

The Magnitude System

- Apparent magnitude of Vega is 0.
- Absolute magnitude of the Sun is +4.74.
- Magnitudes in different bands – photometric systems. Example : UBVRI.
- Colours $U - B$, $B - V$ etc. Vega : zero magnitude in all bands. So, zero colour. Vega is an A0 V star ; 10000 K.
- Hotter than Vega : more flux at shorter wavelengths : -ve colour.
- Cooler than Vega : more flux at longer wavelengths : +ve colour.

Distances

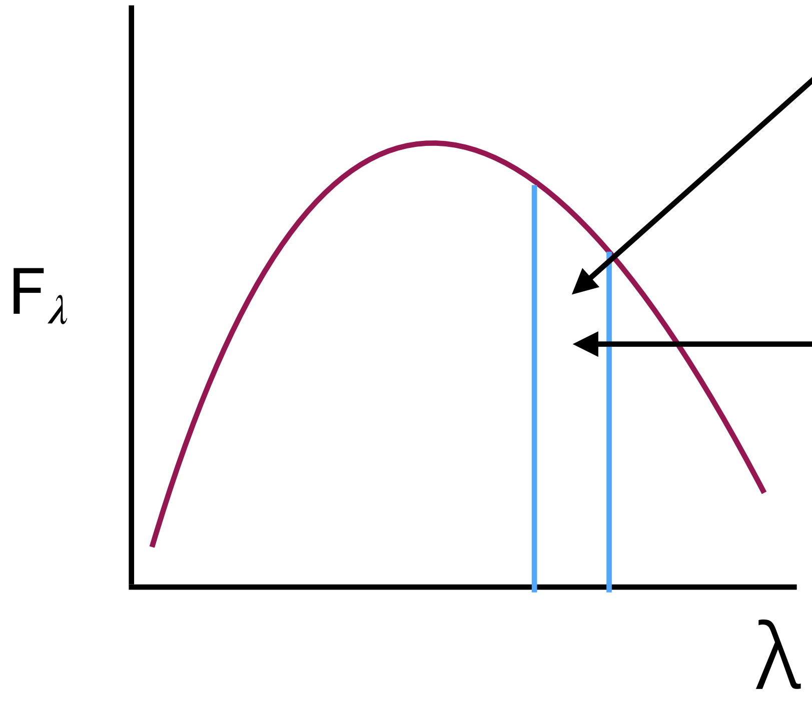
- Distance modulus: m-M=5logD-5 ; M = m + 5 log (D/10)pc +5
- Frequently used to determine D when M is known. Famous example : Period-luminosity relation (P-L) for Cephids.
- Astronomical Unit = mean distance between the Sun and Earth. 1 AU = 1.495×10^{11}m.
- Light year is the distance traversed by light in one year. 1 LY = 6.324×10^4 AU.
- 1 parsec (pc) = 3.262 LY.
- Proxima Centauri, the closest star to us, is 4.225 LY away.

UV/Optical/IR Photometry

If F is the total flux, then m is bolometric magnitude.

Usually instead consider a finite bandpass (or filter), e.g., in V band (λ ~550nm)

$m_V = -2.5 \log_{10} F$ + constant (Zero point)



Flux integrated over the range of wavelengths for this band

UV/Optical/IR Photometry

Astronomical Photometric System

A **photometric system** is a set of well-defined passbands (or filters), with a known sensitivity to incident photons.

UV/Optical/IR Photometry

Astronomical Photometric System

Photometric systems are usually characterized according to the widths of their passbands:

- Broadband (passbands wider than 30 nm, of which the most widely used is Johnson-Morgan UBV system)
- Intermediate band (passbands between 10 and 30 nm wide)
- Narrow band (passbands less than 10 nm wide)

UV/Optical/IR Photometry

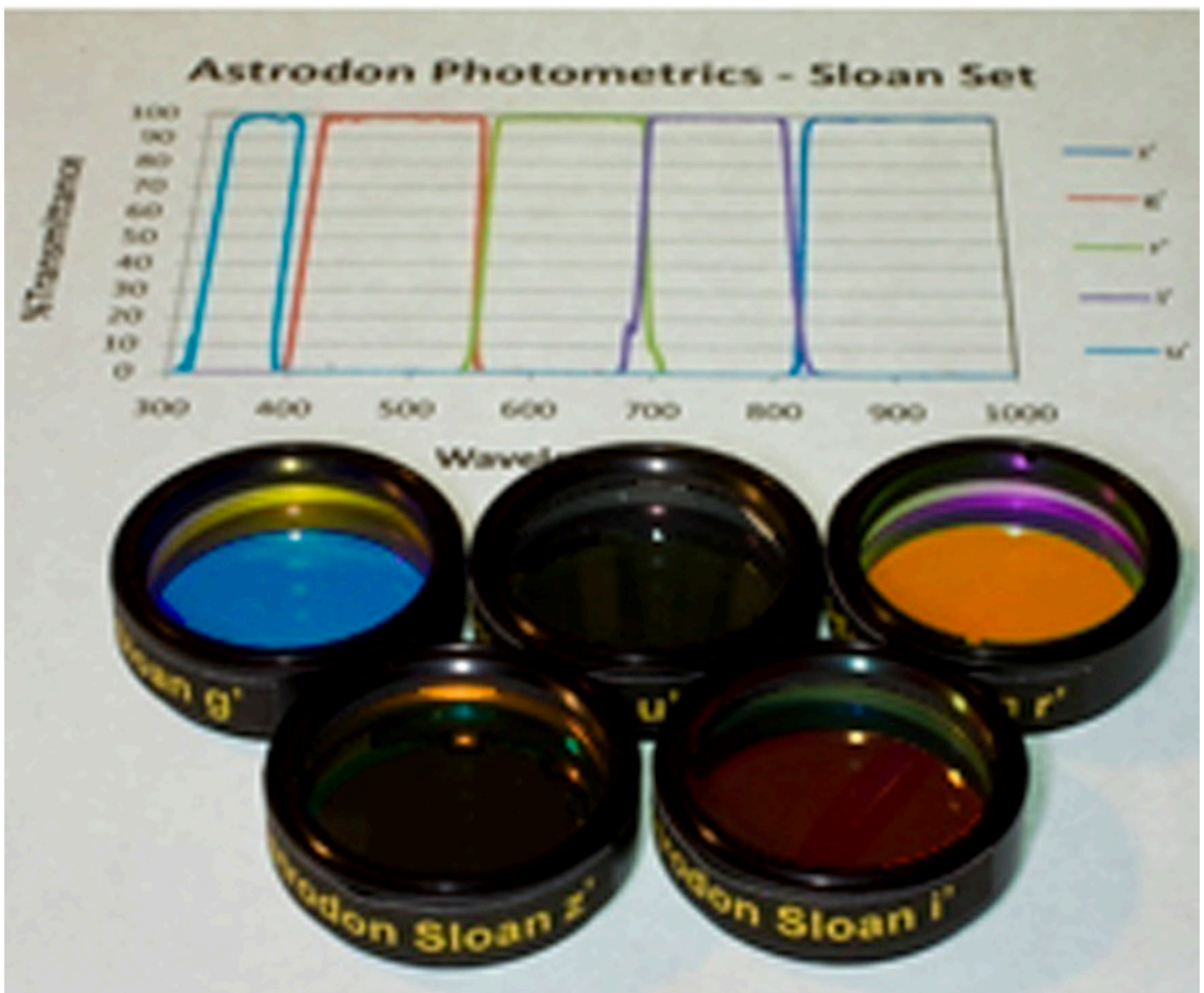
Astronomical Photometric System

- **Johnson** - U, B, V, R, I, expanded to near-IR by J, K, L.
- **Kron-Cousins/Cousins** - Rc, Ic are better behaved at the red end; better positioned with respect other filters.
- **Stromgren** - u, b, v and y. Medium band filters, designed for stellar astrophysics. u and b straddle the Balmer and Ca H+K break at 4000 Å.
- **Washington system** - C, M, T_1, T_2 designed for metallicity studies in old stars.
- **2MASS filters J, H, Ks (“K-short”)** - shifts K to an effective wavelength of 2.15 μm, avoiding the strong OH bands at the red end of Johnson K.
- **Gunn** - u, g, r, i, z have steeper cut-off. Precursor of HST and Sloan filters
- **Sloan filters** - u’, g’, r’, i’, z’ with square filter *transmission curves* and minimal gaps between filters. Optimal board-band filter for photometric redshifts

UV/Optical/IR Photometry

Filter Systems

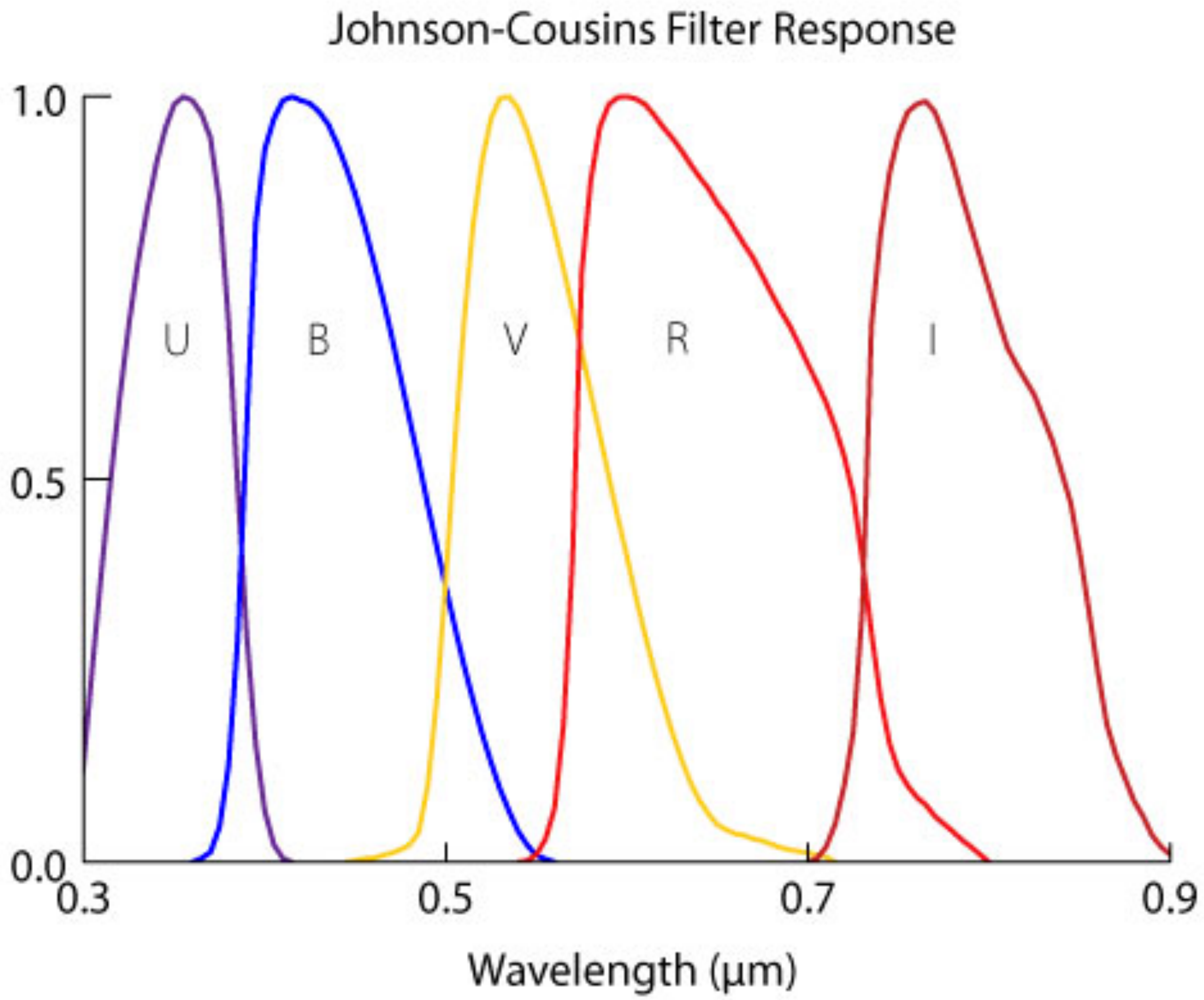
A number of filter systems has been developed since the original Johnson UBV system. Some are expansions of the Johnson system, like Johnson UBVRIJKL, others are completely new. just a few examples:

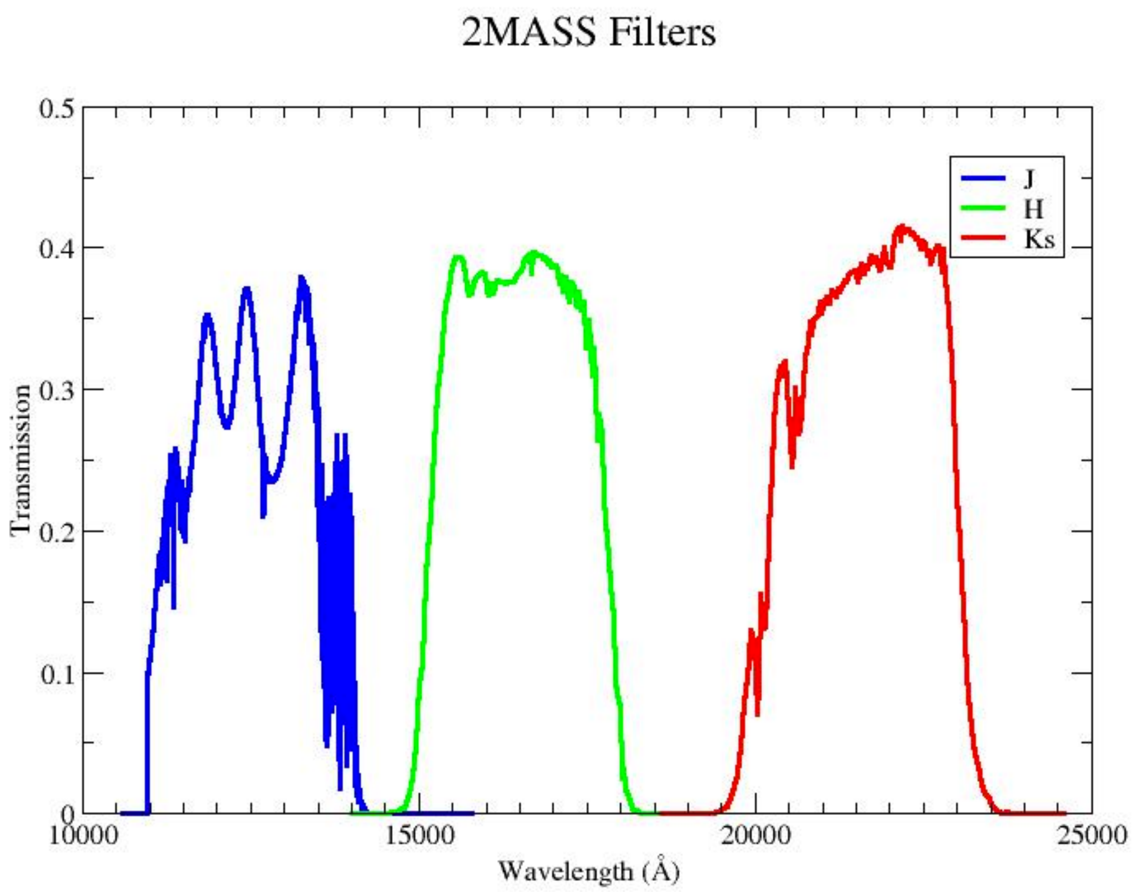


UV/Optical/IR Photometry

Filter Systems

The transmission curve or transmission characteristic is the mathematical function or graph that describes the transmission fraction of an optical (or electronic) filter as a function of frequency or wavelength.





UV/Optical/IR Photometry

Filter Systems

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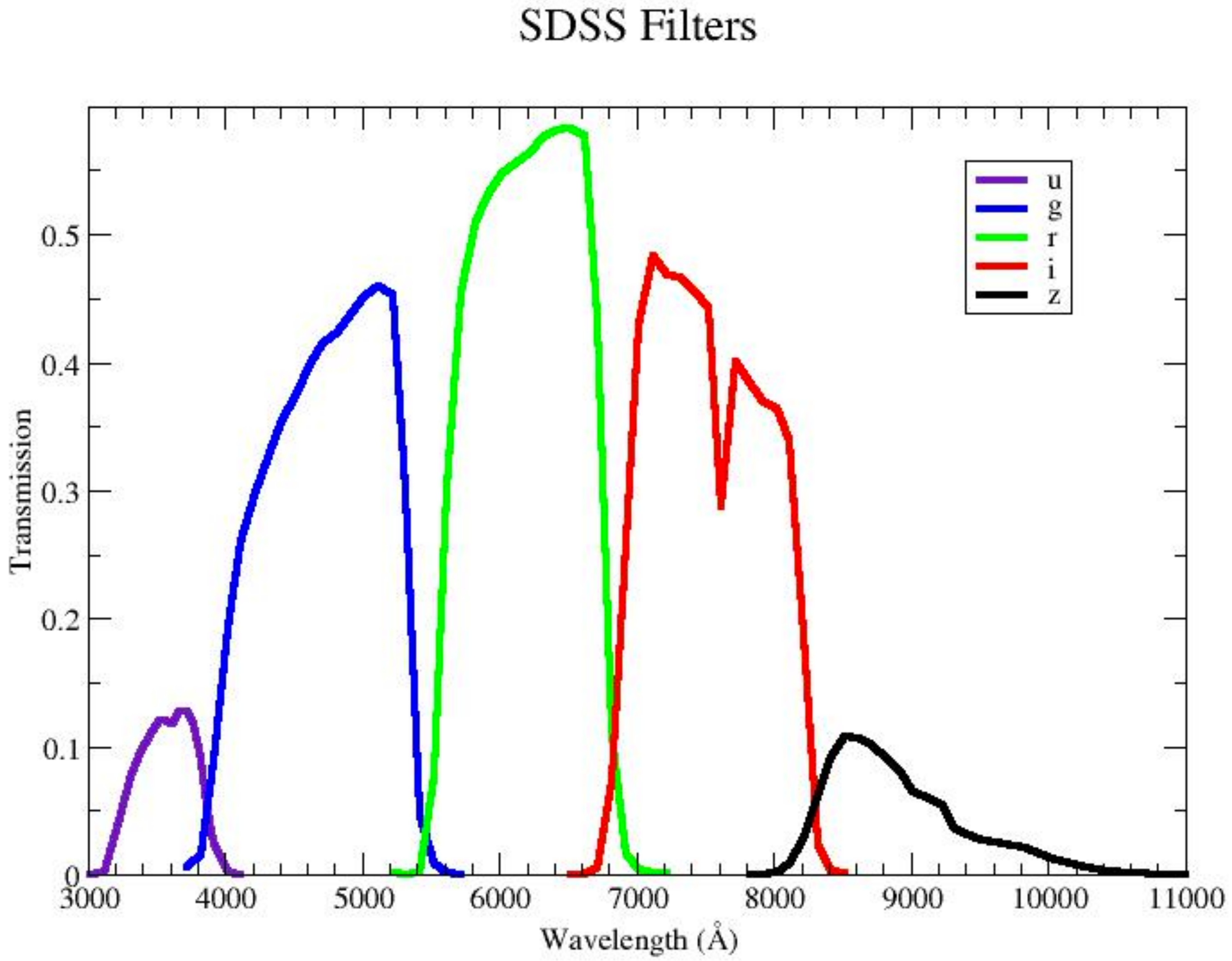


UV/Optical/IR Photometry

- *Aperture Photometry* (Stellar photometry)
  - Aperture Photometry
  - PSF Photometry

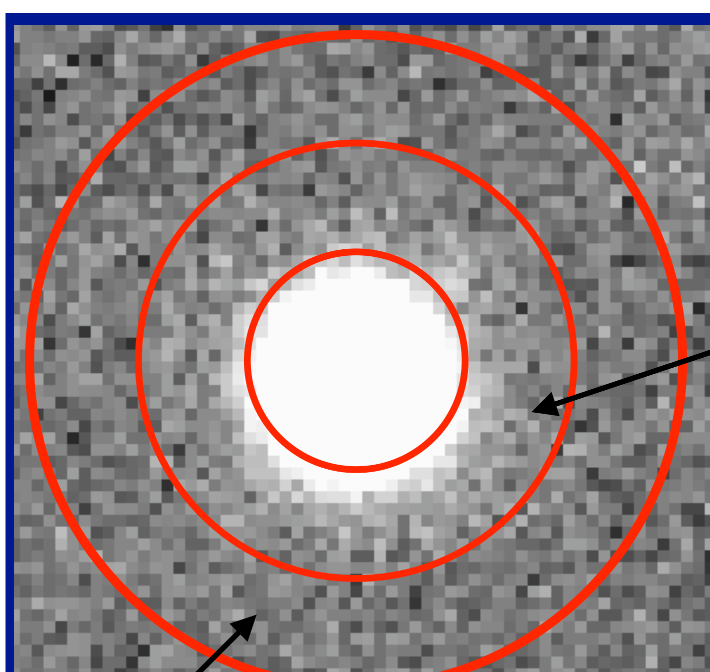
- *Surface Photometry* (Extended Source Photometry)

Aperture Photometry

- *Aperture photometry* measuring the flux within pre-defined (typically circular) aperture.
- Can calibrate as long as you use the same aperture for your standard star.
- Can compute total flux if you know curve of growth.

no. of pixel in aperture

signal



$$S = \Sigma[\mathrm{obj}_{ij} + \mathrm{sky}_{ij}] - N_{pix}B$$

sum over aperture

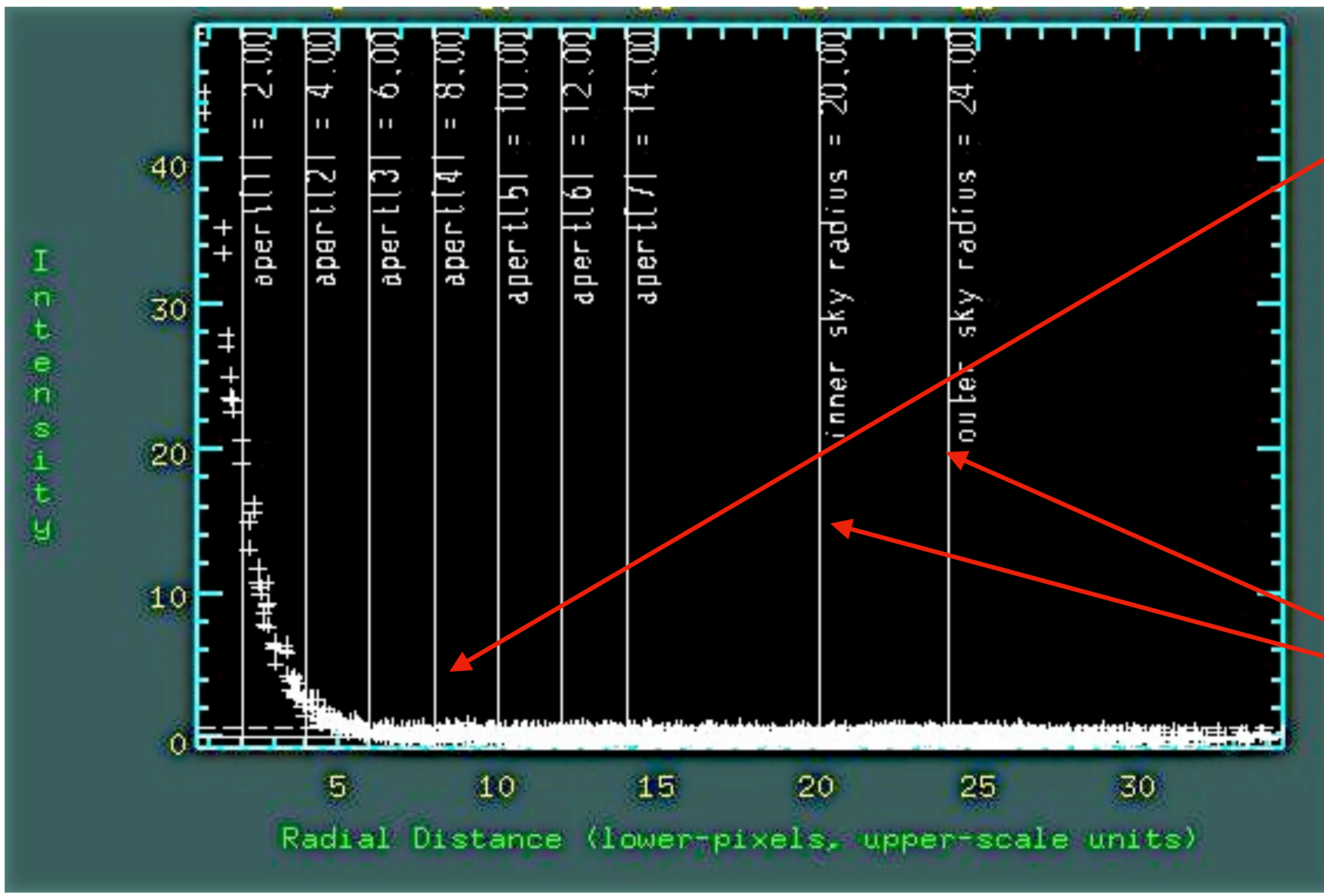
sky background per pixel

estimate sky in local annulus

Aperture Photometry

Curve of Growth

First, it is VERY hard to measure the *total* light as some light is scattered to very large radius.



Perhaps you have most of the light within this radius

Inner/outer sky radii

Aperture Photometry

Advantages:

- *Aperture photometry* measuring the flux within pre-defined (typically circular) aperture.
- Can calibrate as long as you use the same aperture for your standard star.
- Can compute total flux if you know curve of growth.

Aperture Photometry

Disadvantages:

- The simple aperture photometry has an assumption of linearly-varying background in the aperture's vicinity.
- Aperture Size - bigger aperture = more fluxes from target but also more noise from sky & varying background can represent a problem.
- Crowding - neighbours, overlapping source / sky apertures

Easy, fast, works well except for the case of overlapping sources

Aperture Photometry

Crowded-field/PSF Photometry

Aperture Photometry

Crowded-field/PSF Photometry

Point Spread Functions (PSFs)

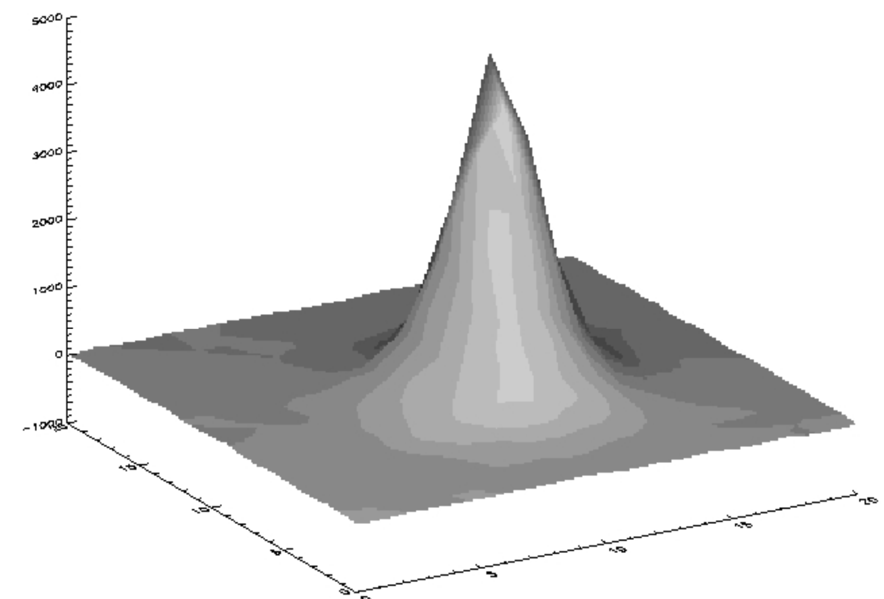
Assume we have a ‘point’ source, or a source that is far smaller than the maximum resolution (a pixel). When we take an image of it, it will ‘spread’ over an area. To quantify that spread, we can define a ‘function’.

Point Spread Functions (PSF) describe the two-dimensional distribution of light in the telescope focal plane for astronomical point sources.

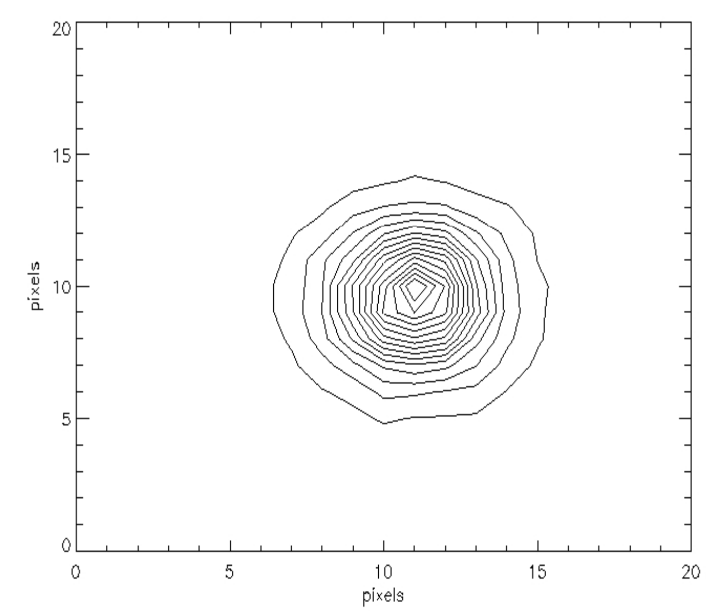
Aperture Photometry

Crowded-field/PSF Photometry

What do PSFs look like?



- Surface plot of bright star in sky subtracted
- Axi-symmetric, centrally peaked
- Basically 2-D Gaussian



Aperture Photometry

Crowded-field/PSF Photometry

Typical parameterisation of PSF —

Gaussian —

$$I(r) = e^{-r^2/2\sigma^2}$$

$$F(r) = 1 - e^{-r^2/2\sigma^2}$$

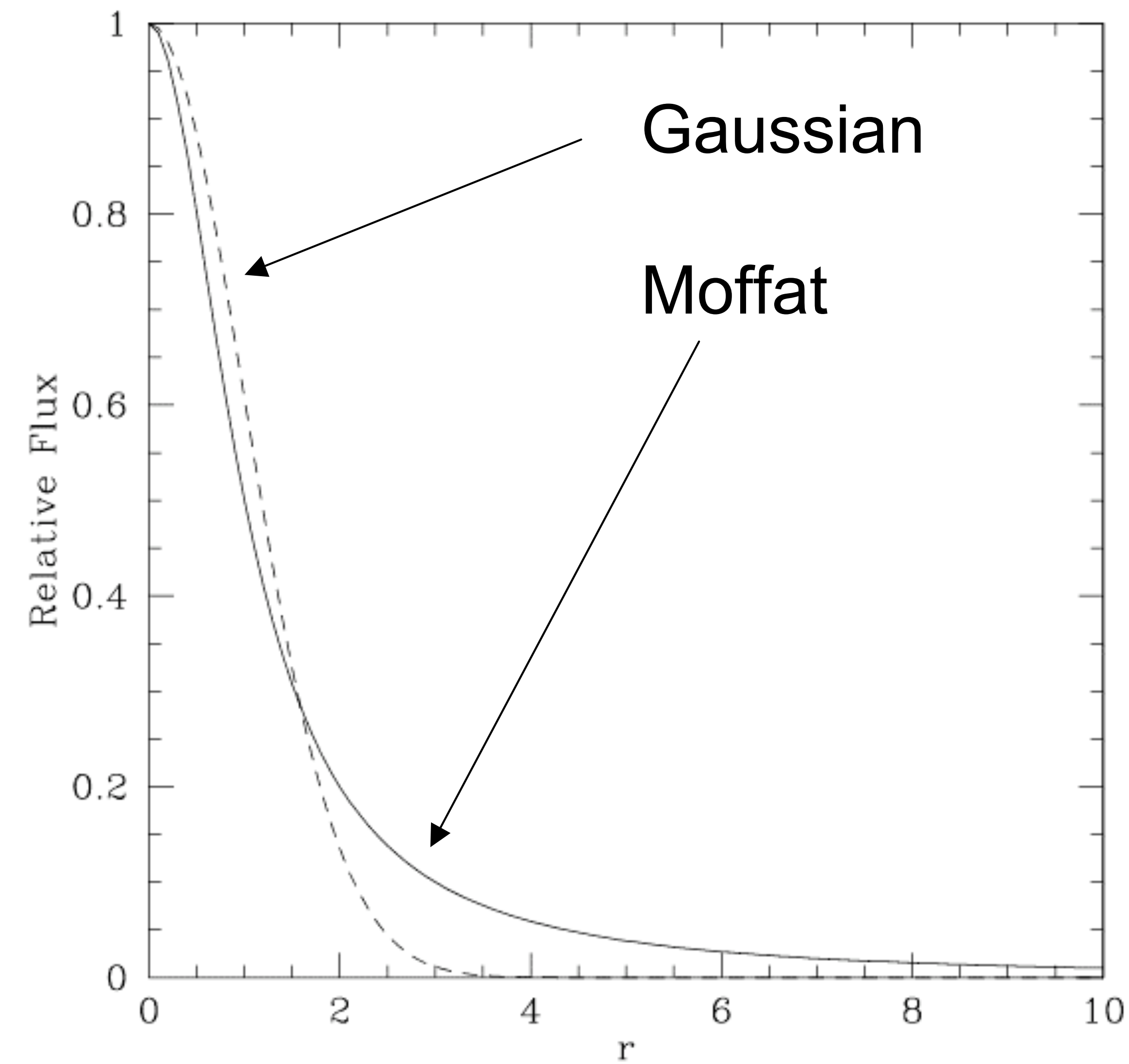
$$FWHM = 2\sigma\sqrt{2\ln 2}$$

Moffat —

$$I(r) = \left(1 + \left(r/\alpha\right)^2\right)^{-\beta}$$

$$F(r) = 1 - \left(1 + \left(r/\alpha\right)^2\right)^{1-\beta}$$

$$FWHM = 2\sigma\sqrt{2^{1/\beta} - 1}$$



Aperture Photometry

Crowded-field/PSF Photometry

Steps

- Create a model for the Point Spread Function of stars. Use large number of stars.
- Iteratively subtracted the model from the data
- Refined the model to minimise the residuals.

Aperture Photometry

Crowded-field/PSF Photometry

Advantages —

Works in crowded fields

Regions with highest S/N have most weight in determining fit

Background is included as one additional parameter (constant in the fit)

Potential problems —

The PSF is not well described by the parametric profiles.

The PSF varies across the detector.

Differential Photometry

- Compare relative magnitudes between object of interest and a "comparison" star nearby
- For single channel systems (e.g. photomultiplier-based photometers), need to flip back & forth between object & comparison star
- Single channel devices use aperture photometry
- Two channel devices can measure two stars simultaneously

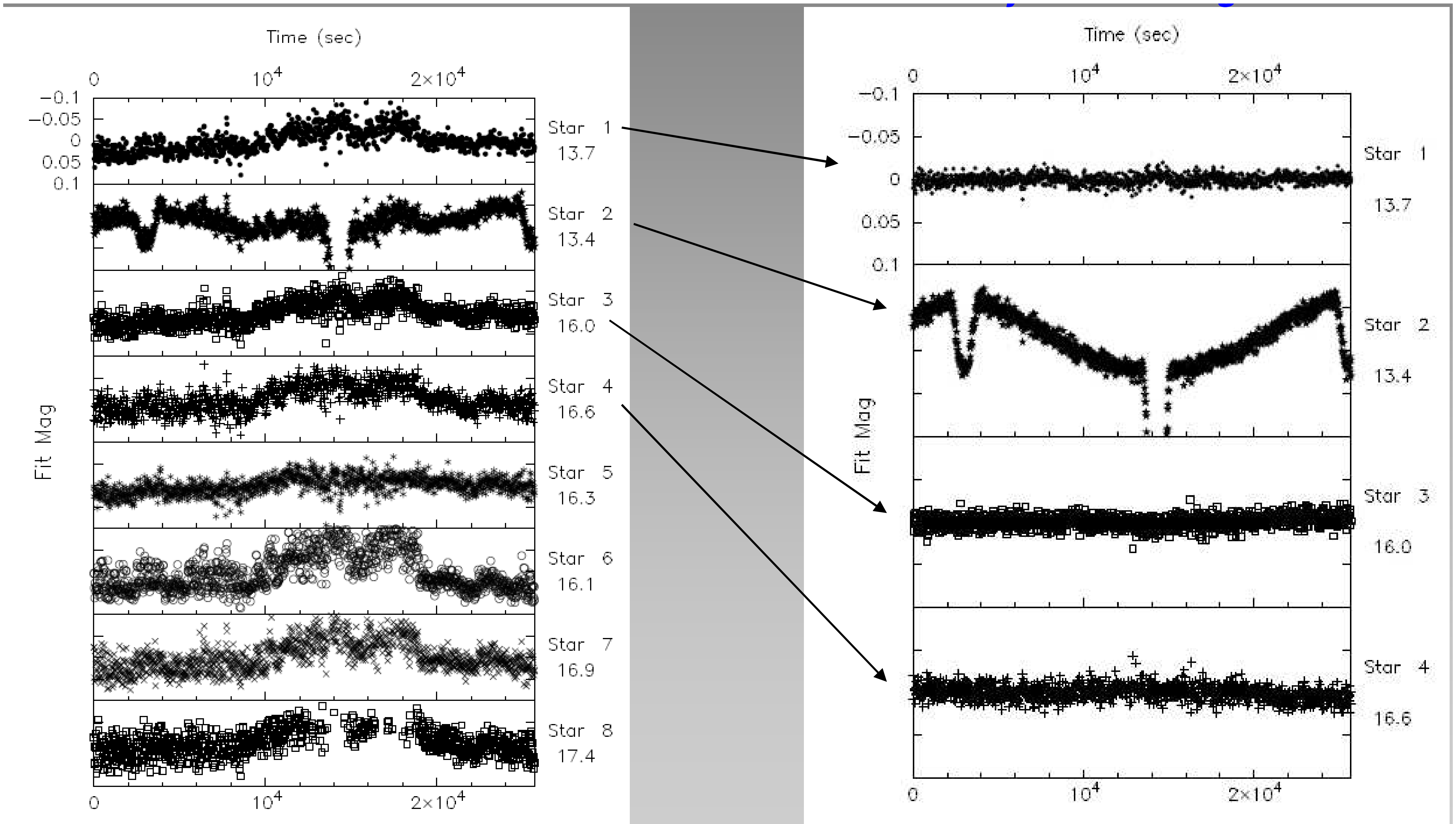
Sometime possible to observe in non-photometric conditions e.g. thin uniform cirrus cloud cover

- 2D imaging devices (e.g. CCDs) can measure many stars simultaneously
  - Able use several stars as "comparisons"
  - Statistically better (average brightness over many stars)
  - Can use profile fitting to PSFs as well as aperture photometry

On SALT can only do differential photometry, due to varying effective collecting area of the telescope

Differential Photometry

Uncorrected light-curves *Differentially corrected light-curves*



Time Resolved Photometry

- Important for any time varying sources

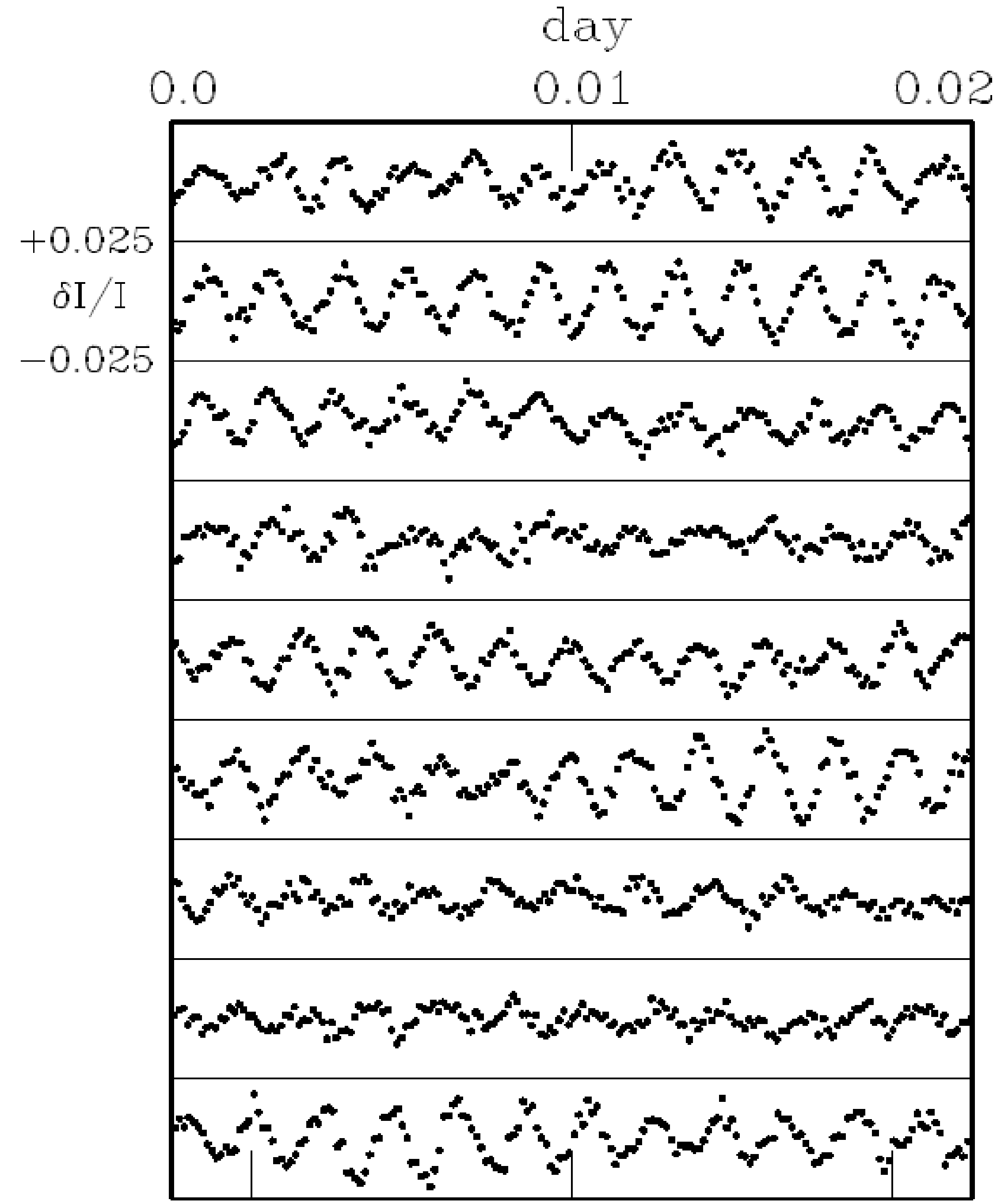
- Long observing spans (hours, all-night) sometimes important for detecting multi- periodic light variations
  - — From stellar pulsations
  - — Spin, orbital & beat period variations

- Analysis of light variations usually done by Fourier analysis, or similar techniques

  — e.g. attempt to match data with a series of sinusoidal variations

  — Varying amplitude, frequency & phase

- Produce a power spectrum (∝ amplitude^2)
  — Shows the likely periodic frequencies that, combined together, can explain the observed light curves



Surface Photometry

Surface photometry is a technique to measure the surface brightness distribution of extended objects (galaxies, HII regions etc.).

Surface photometry: distribution of light (mass), global structure of galaxies, geometrical characteristics of galaxies, spatial orientation, stellar populations, characteristics of dust…

Surface photometry and spectroscopic observations – two major observational methods of extragalactic astronomy.

Surface Photometry

Surface Brightness - radiative flux per unit solid angle of the image

$$I \propto f / \Delta\Omega$$

To a first approximation, the Surface Brightness of an extended object is independent of its distance from us since f and $\Delta\Omega$ are proportional to $1/r^2$ (flat, static Universe)

Optical astronomers measure Surface Brightness in magnitude per square arc second [$^m/arcsec^2$ or $^m/\square''$]:

$$\mu = -2.5 \log I + constant$$

Surface Photometry

The Surface Brightness in magnitude units is related to the surface brightness in physical units of solar luminosity per square parsec by

$$I\ (L_{\odot}/pc^2) = (206265)^2 \times 10^{0.4(M_{\odot} - \mu - 5)} = 4.255 \times 10^8 \times 10^{0.4(M_{\odot} - \mu)}$$

where $M_{\odot}$ is the absolute magnitude of the Sun

In the B passband $M_{\odot, B} = +5.48 \Rightarrow$

$$\mu\ (B) = 27.05 - 2.5 \log I(B)$$

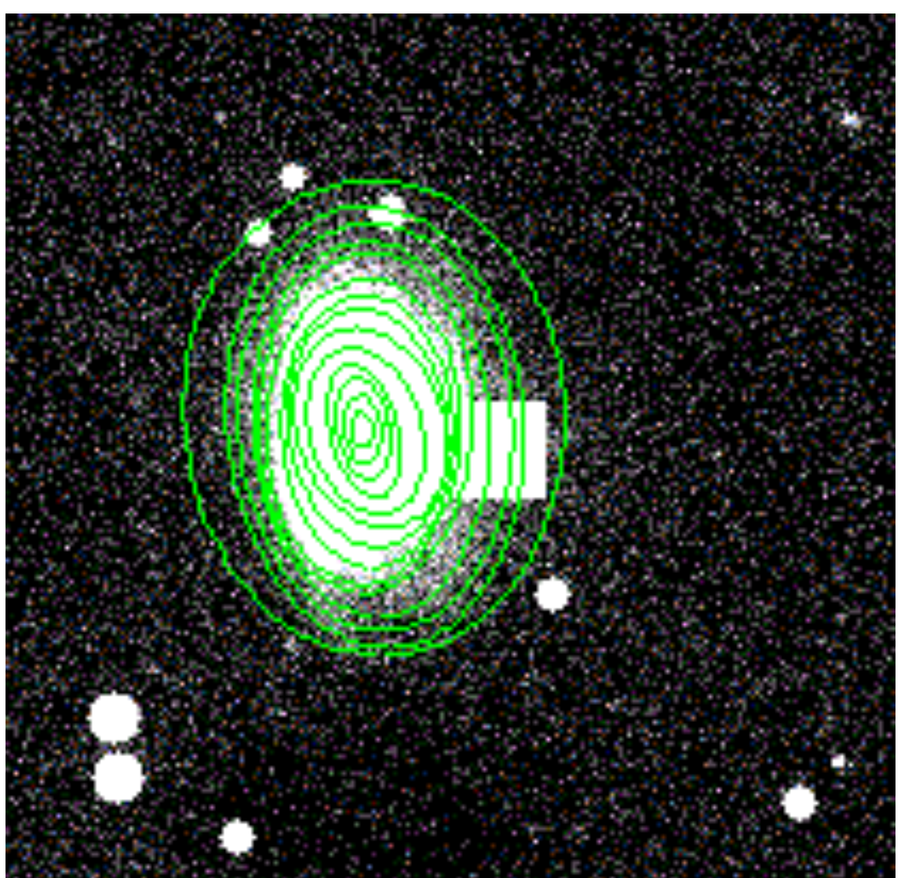
$$\mu\ (B) \sim 27^m/\square'' \text{ corresponds to } I \sim 1\ (L_{\odot,B}/pc^2)$$

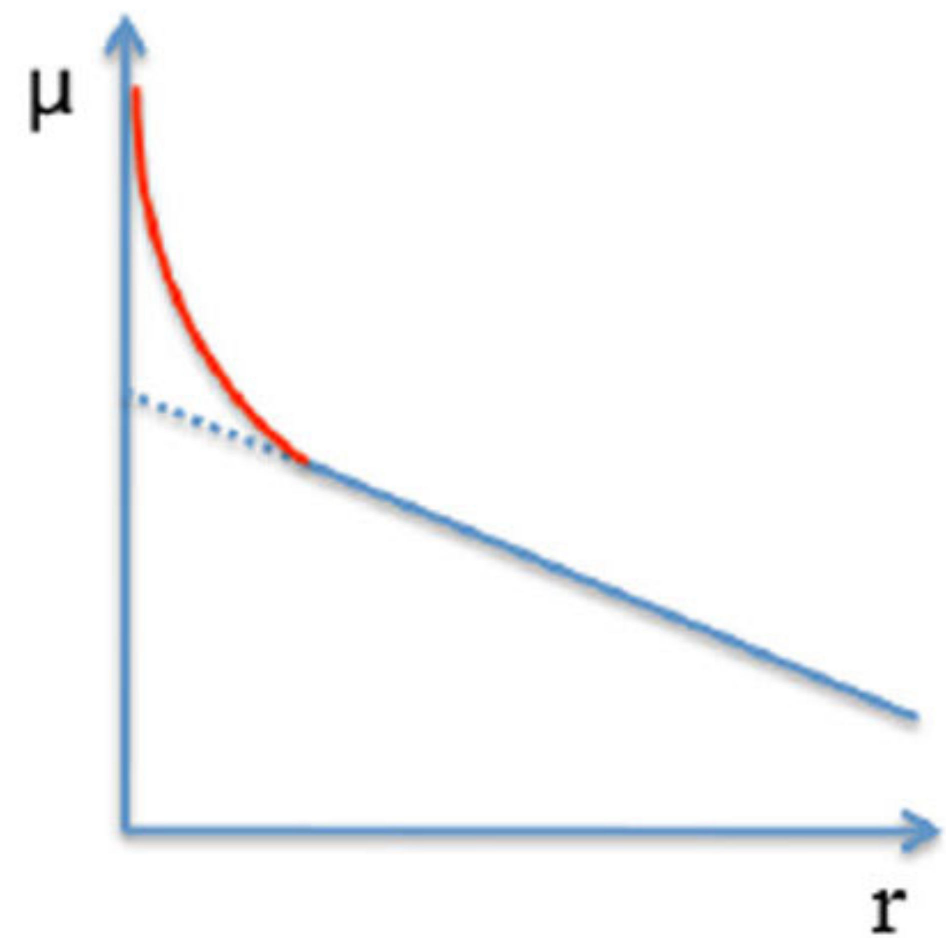
Surface Photometry of Galaxies

Surface brightness profiles are produced by azimuthally averaging around the galaxy along isophotes - lines of constant brightness. These are projected *SB* profiles.

Seeing effects on SB profiles - unresolved points are spread out due to effects of our atmosphere – these effects are quantified by the Point Spread Function (PSF)

- makes central part of profile flatter
- makes isophote rounder

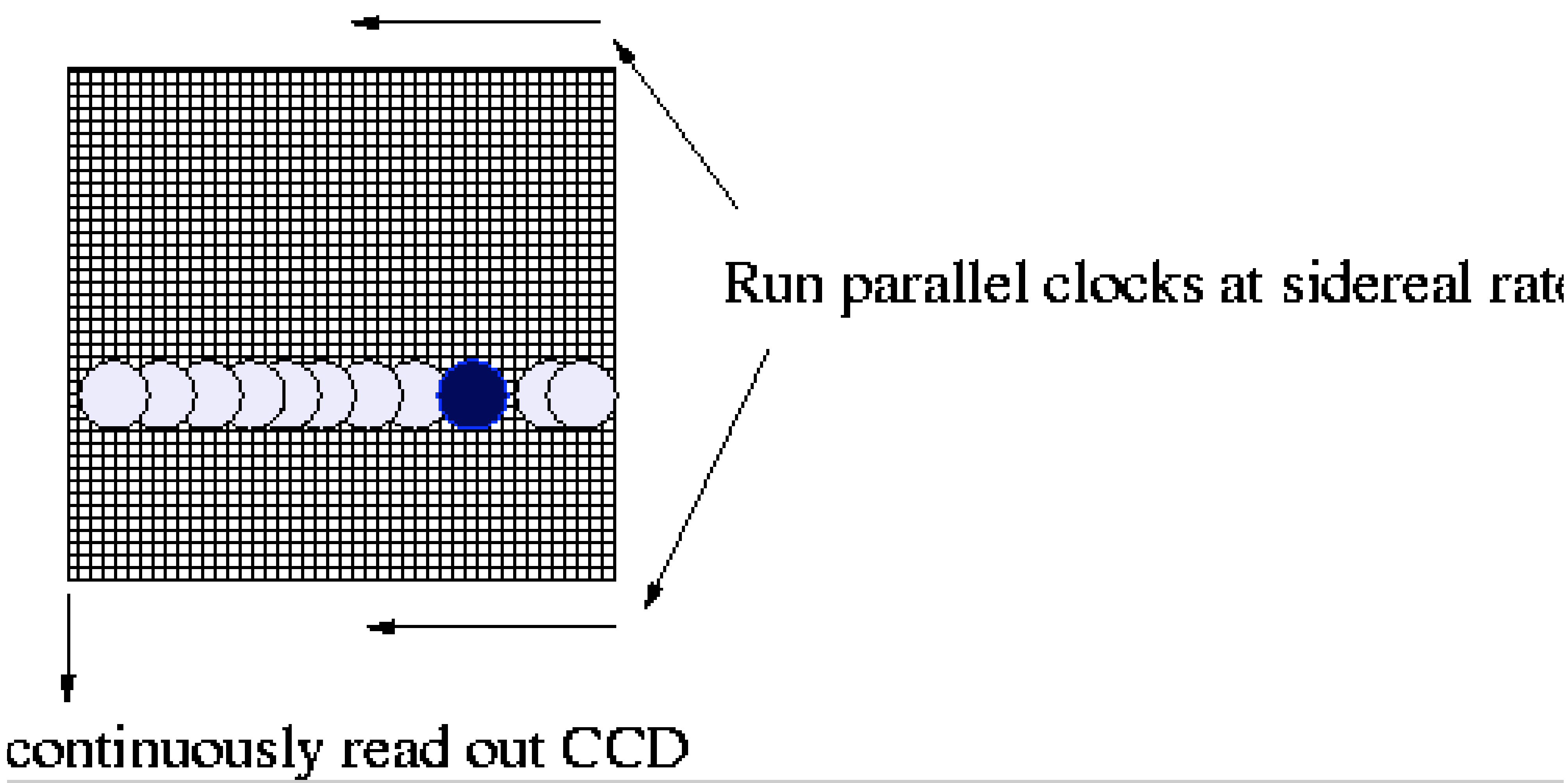




Drift Scanning: A Novel Photometry Method

Instead of letting the telescope track an object across the sky, let the object trail across the CCD detector

- i.e. turn off the telescope drive, or drive it at a non-sidereal rate
- Clock the CCD charge across the chip at the same rate the object moves
- End up with a long strip image of the sky with a “height” = the CCD width and a length set by how long you let the drift run (or by how big your disk storage is).



Drift Scanning: A Novel Photometry Method

The sky goes by at 15 arcseconds/second at the celestial equator and slower than this by a factor of 1/cos(δ) as you move to the poles

- With SALT, at the equator, with 4096 pixels x 0.13”/pixel, you get a total integration time per object of about 35 seconds.

So, what’s the point?

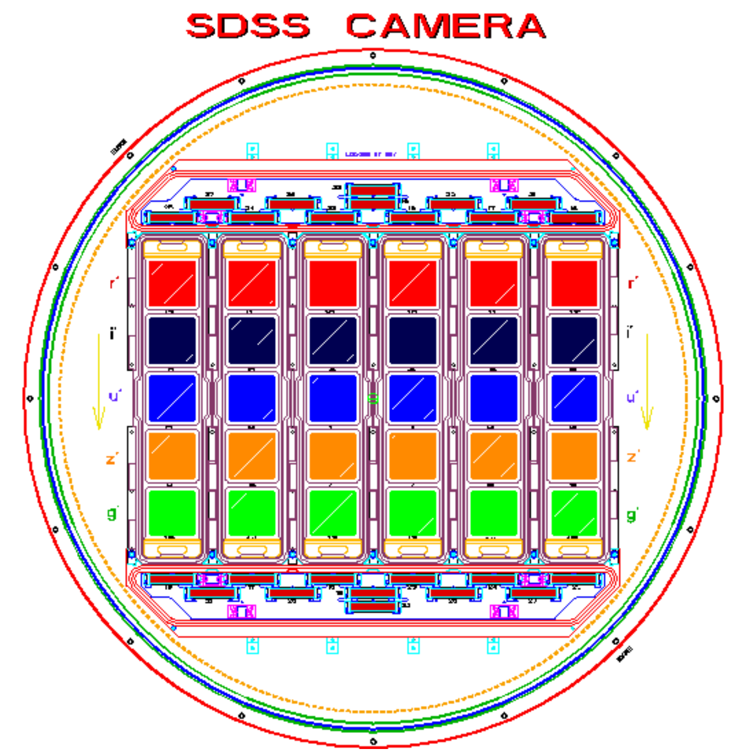
- Survey large strips of the sky – *Good for large area surveys*
- Superb flat-fielding (measure objects on many pixels and average out QE variations)
- Very efficient (don’t have CCD readout, telescope setting)

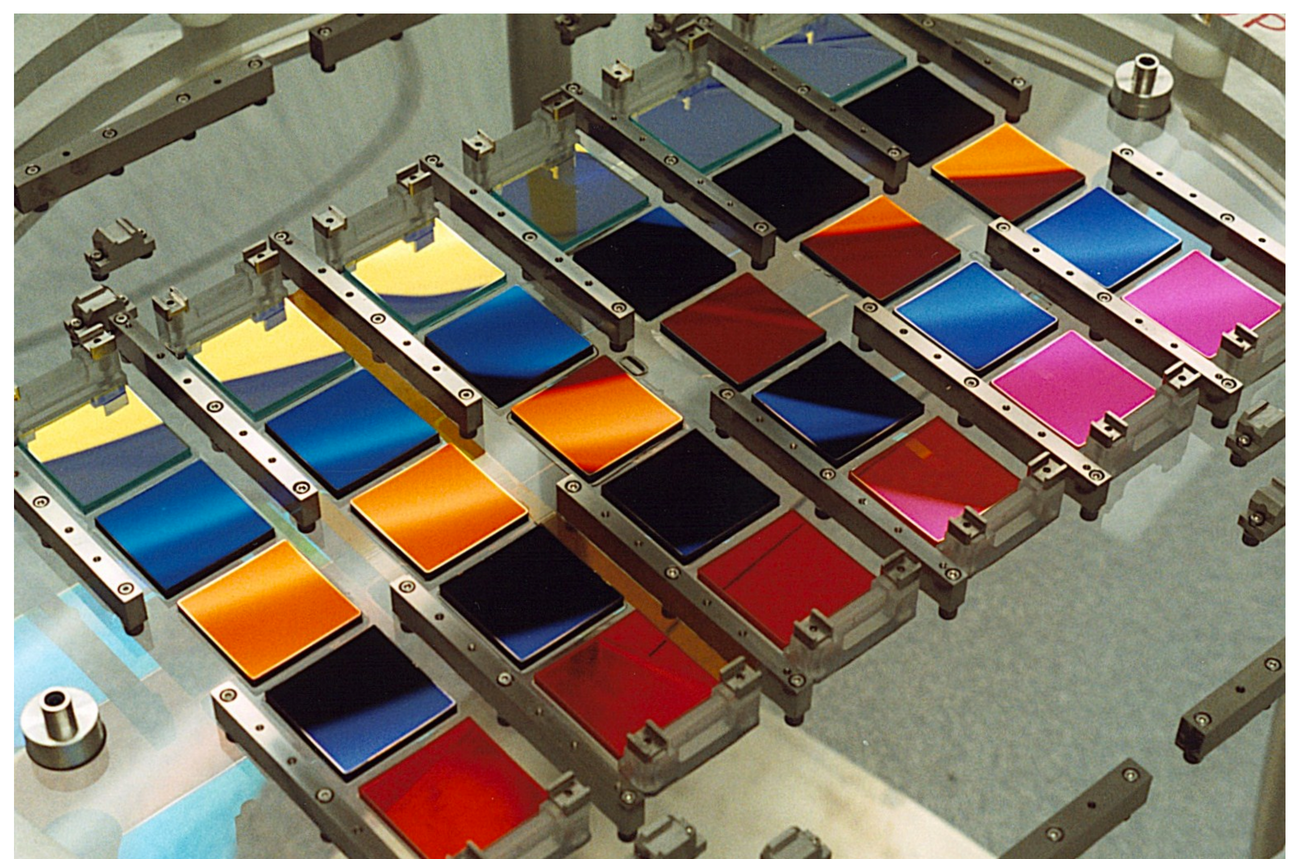
Problem —

- Only at the equator do objects move strictly in straight lines
- As you move toward the poles, the motion of stars is in an arc
    - So stars begin to “creep” in the direction perpendicular to star motion
    - Causes blurring, decreased S/N
    - Can’t drift-scan at high declinations

Drift Scanning example: SDSS

SDSS — Sloan Digital Sky Survey





Atmospheric Extinction

Atmospheric extinction is the reduction in brightness of stellar objects as their photons pass through our atmosphere.

As stellar light makes its way through the Earth's atmosphere, some photons collide with atoms, molecules, water droplets, grains of dust, and other objects. These photons may be absorbed by the objects (in which case they cease to exist), or they may be scattered into a different direction.

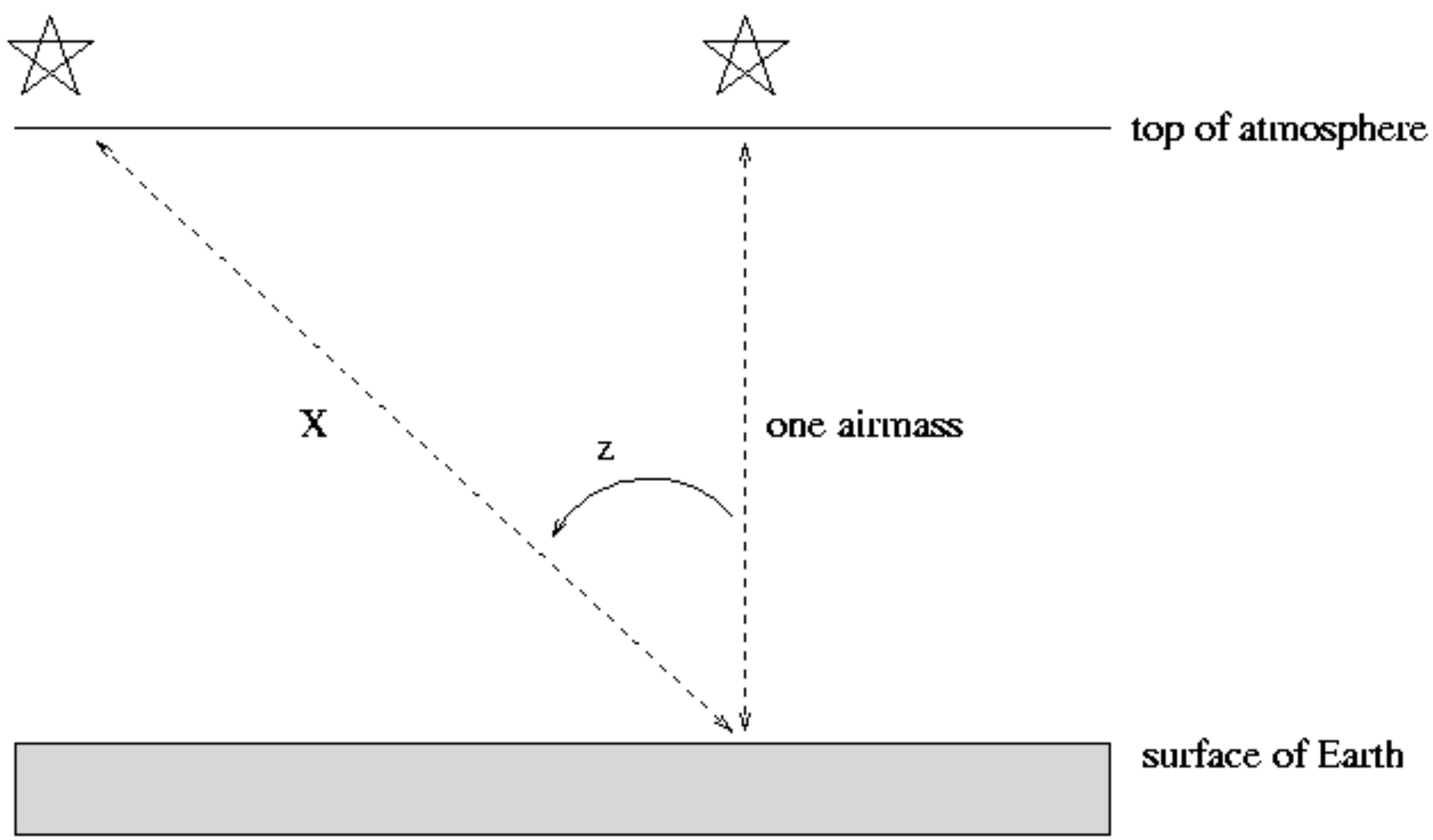
The effects of extinction depend on transparency, elevation of the observer, and the zenith angle, the angle from the zenith to one’s line of sight.

Atmospheric Extinction

The amount of extinction depends on how much air stellar light must traverse.

Astronomers have devised the term **airmass** method to describe this quantity:

one airmass is the amount of air directly above an observer. So, if you are looking at a star at the zenith, you are looking through one airmass.

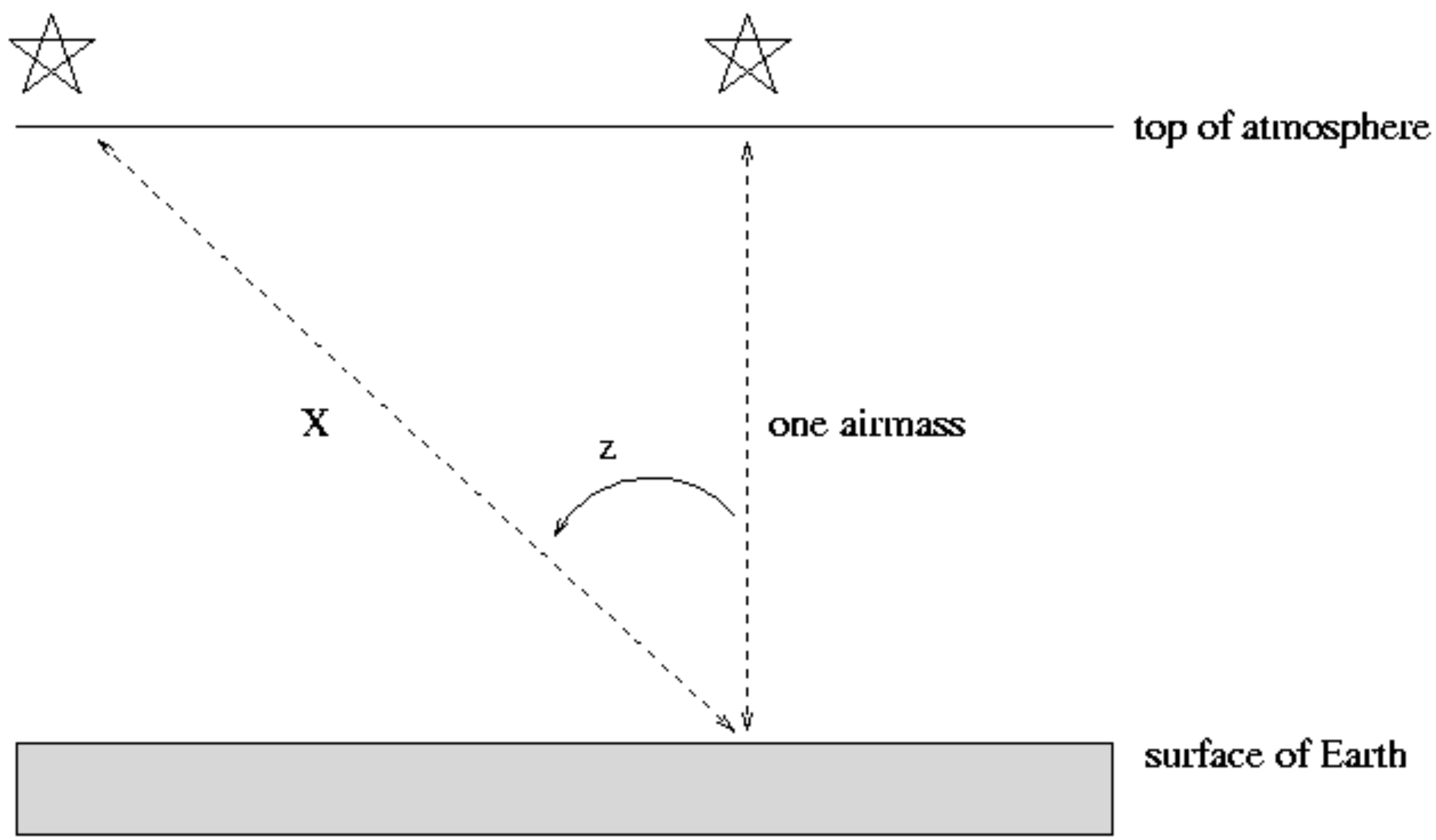


Atmospheric Extinction

The target is some angular distance away from the zenith, indicated by the **zenith angle z** in the diagram.

Its light travels a longer distance through the Earth's atmosphere before it can reach you.

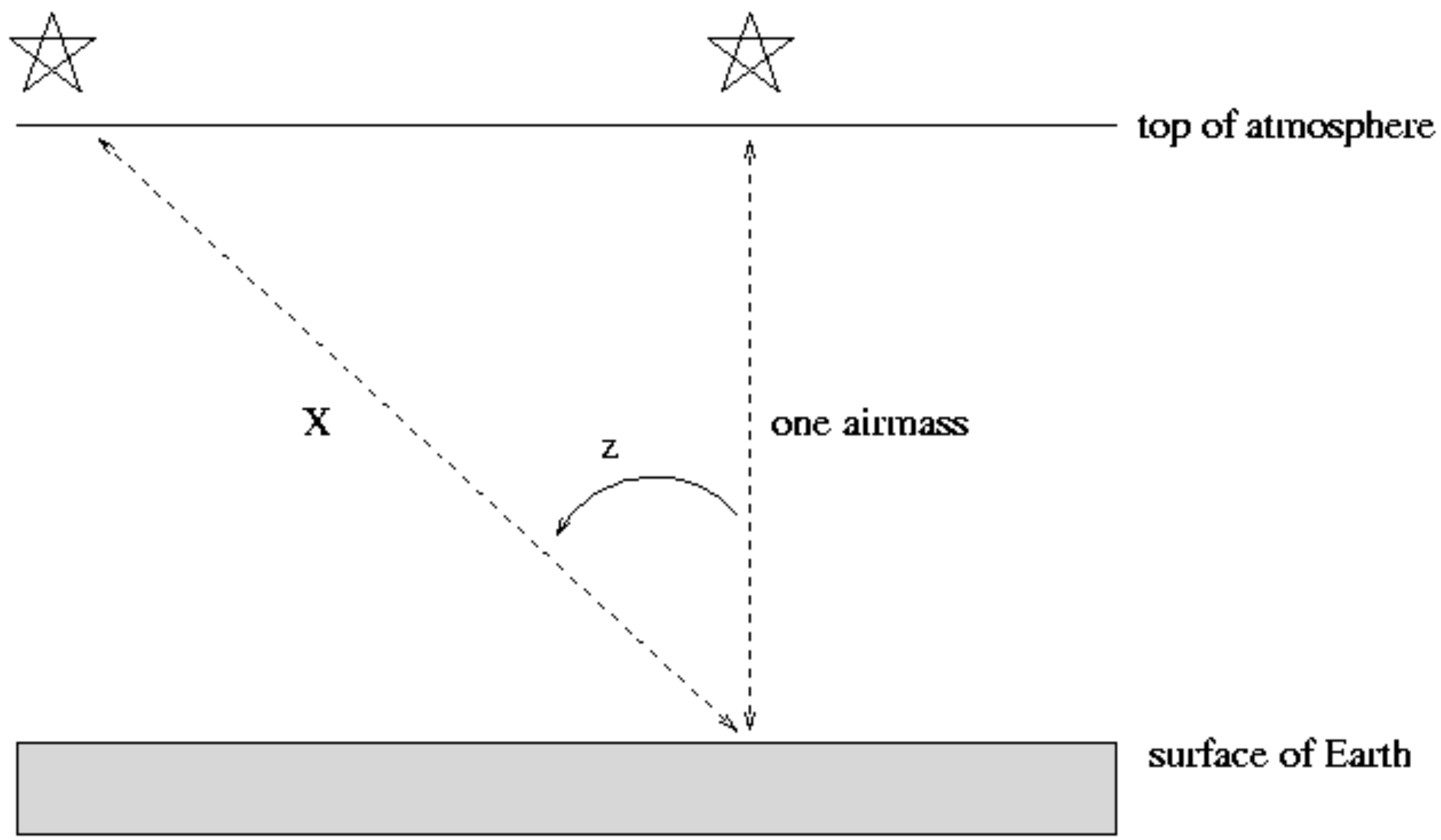
To a reasonable approximation, one can consider the Earth and its atmosphere to be flat, parallel slabs.



Atmospheric Extinction

The distance light travels is —

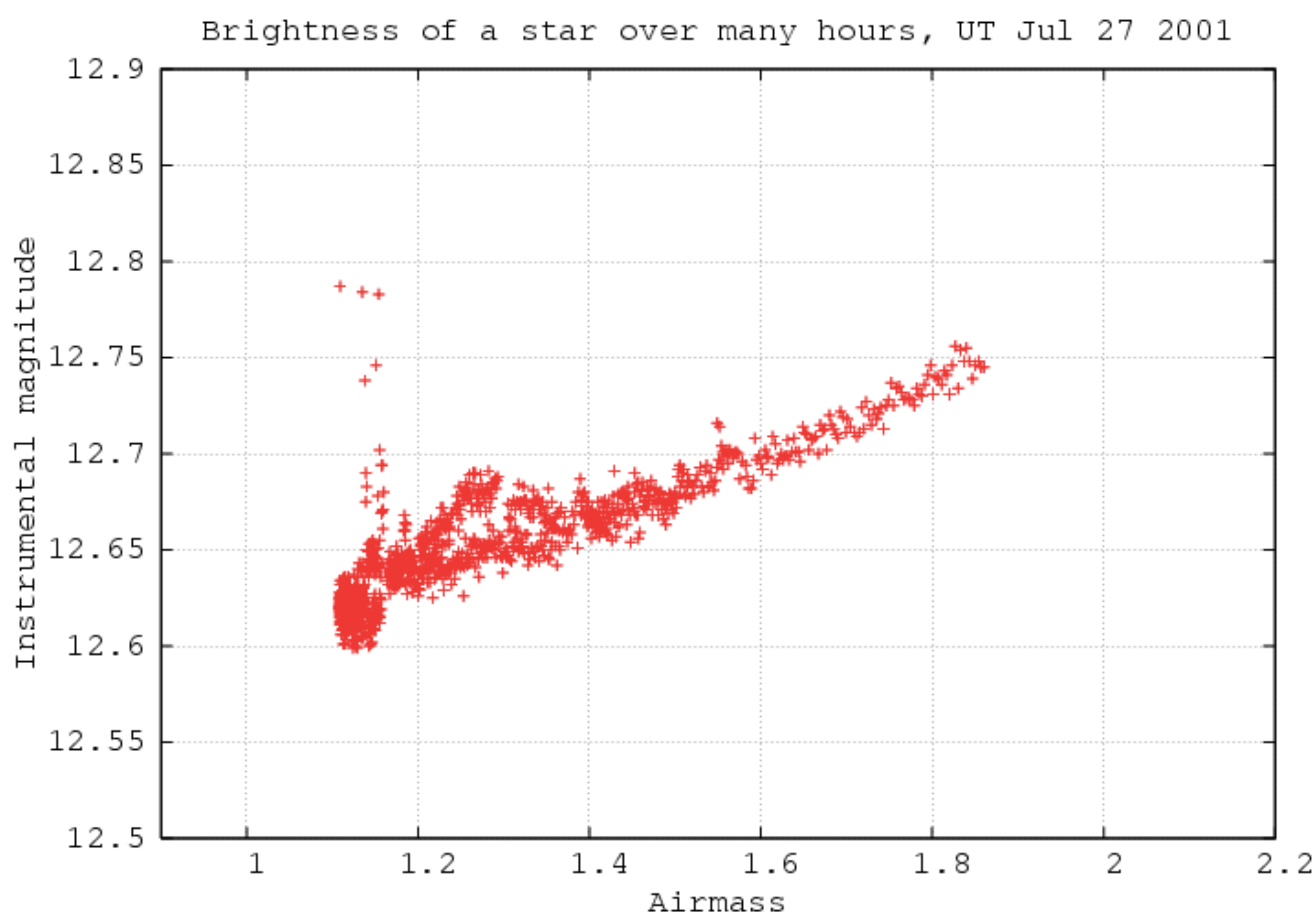
```
                  one airmass
airmass  X  =  -----------  =   (one airmass) * sec(z)
                    cos(z)
```



Atmospheric Extinction

We measure stellar brightness in magnitudes and hence the relationship becomes conveniently linear:

$$m(X) = m_0 + k*X$$



Atmospheric Extinction

We measure stellar brightness in magnitudes and hence the relationship becomes conveniently linear:

$$m(X) = m_0 + k*X$$

where m_0 is the exoatmospheric magnitude, k is constant which depends upon properties of the local atmosphere and the wavelength of light.

We call the coefficient **k** the "first order extinction coefficient." If one observes through the standard Johnson-Cousins **UBVRI filters**, one finds typical values

passband	k
U	0.6
B	0.4
V	0.2
R	0.1
I	0.08

The better the observing site, and the clearer the night, the smaller the extinction coefficient.

Atmospheric Extinction

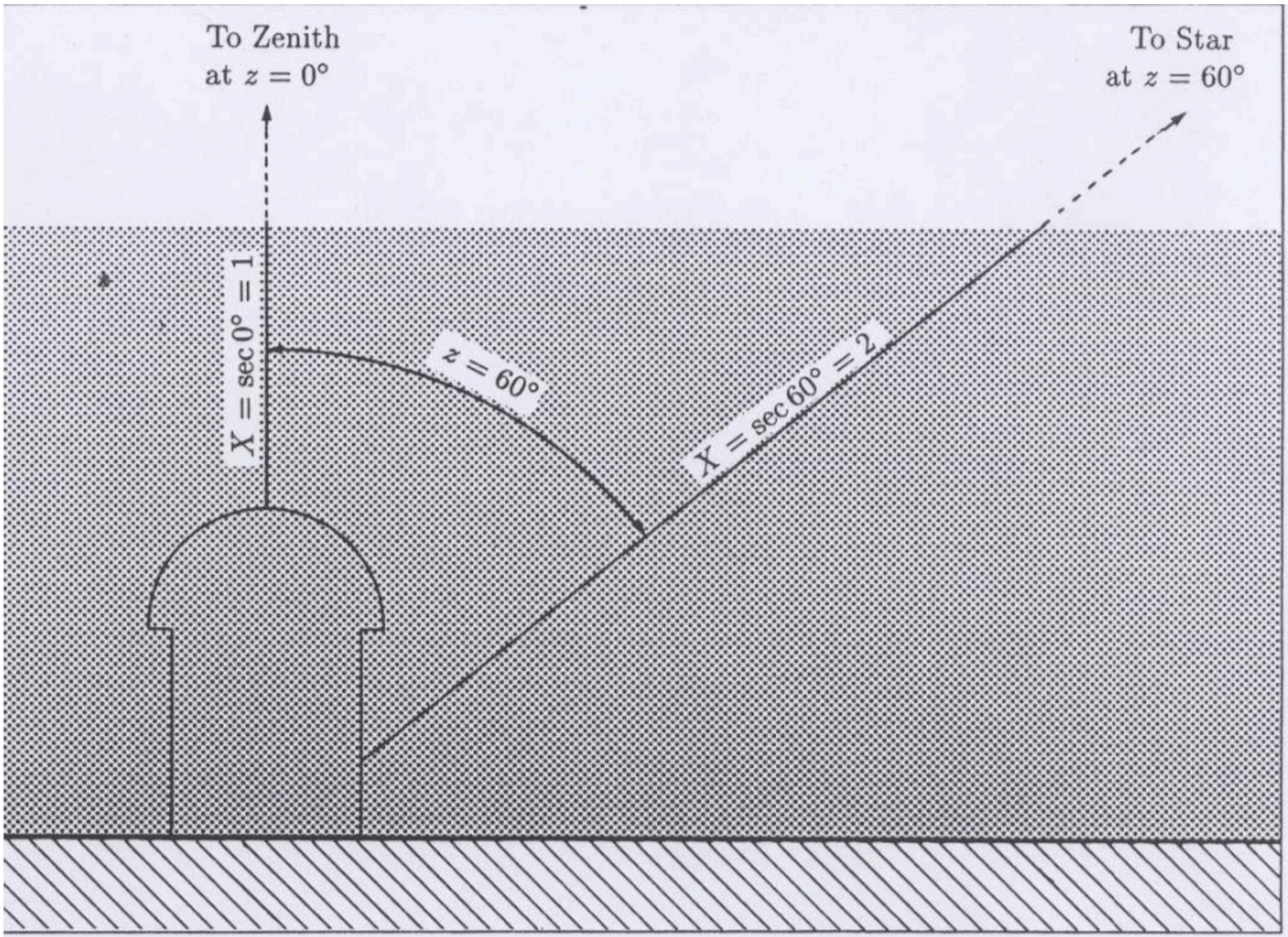
Airmass (X) :
Effective path length of air through which star light must pass to reach observer.

X = sec z where z = zenith angle

$$\sec z = (\sin\phi \sin\delta + \cos\phi \cos\delta \cos H)^{-1}$$

where ϕ = latitude of observing place δ = Declination of the star
H = Hour angle of star

Atmospheric Extinction

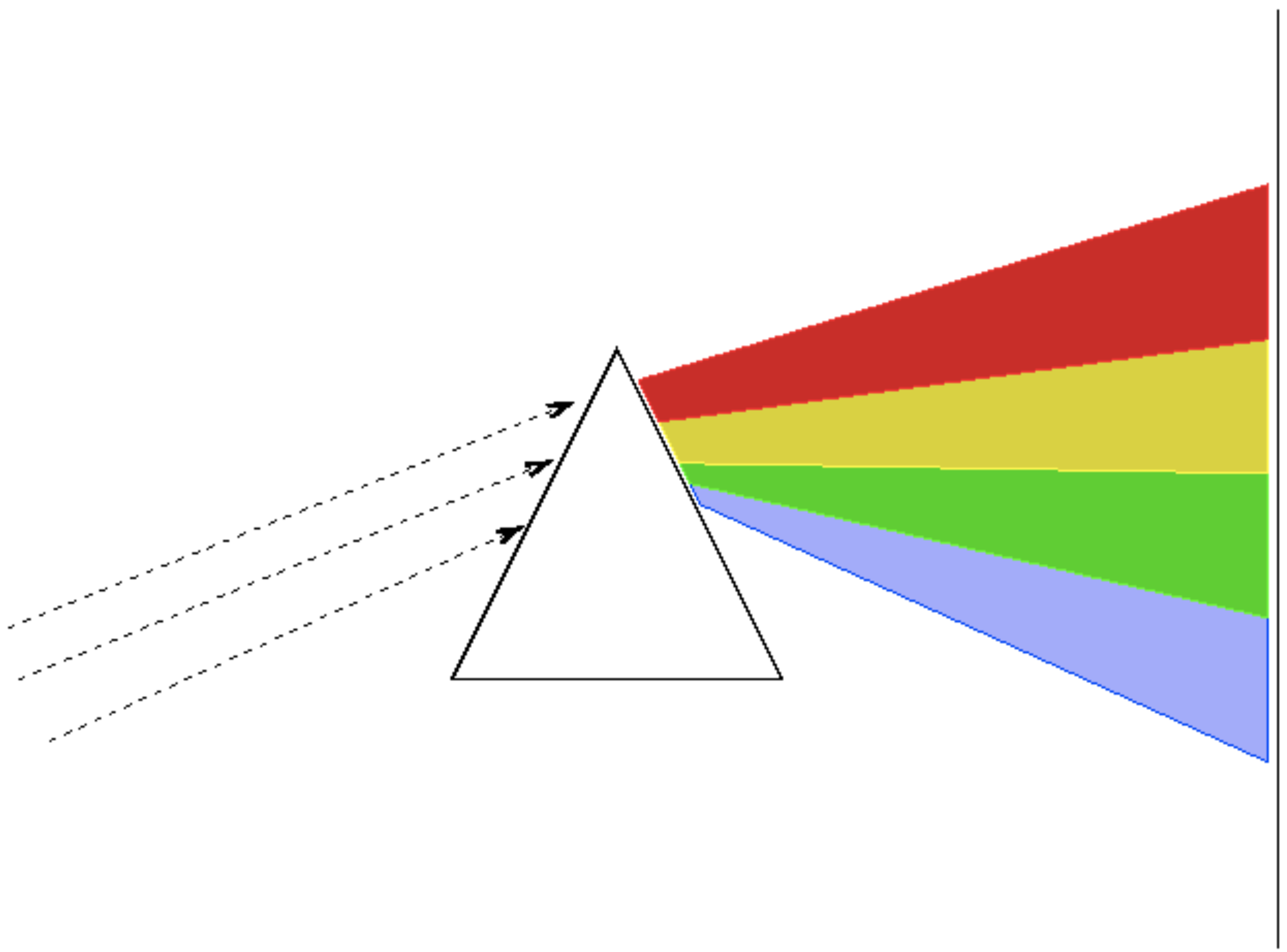


Spectrographs

A spectrograph is an instrument that disperses light into a frequency/wavelength spectrum, which is generally recorded with the use of a camera that focuses the dispersed light on a detector.

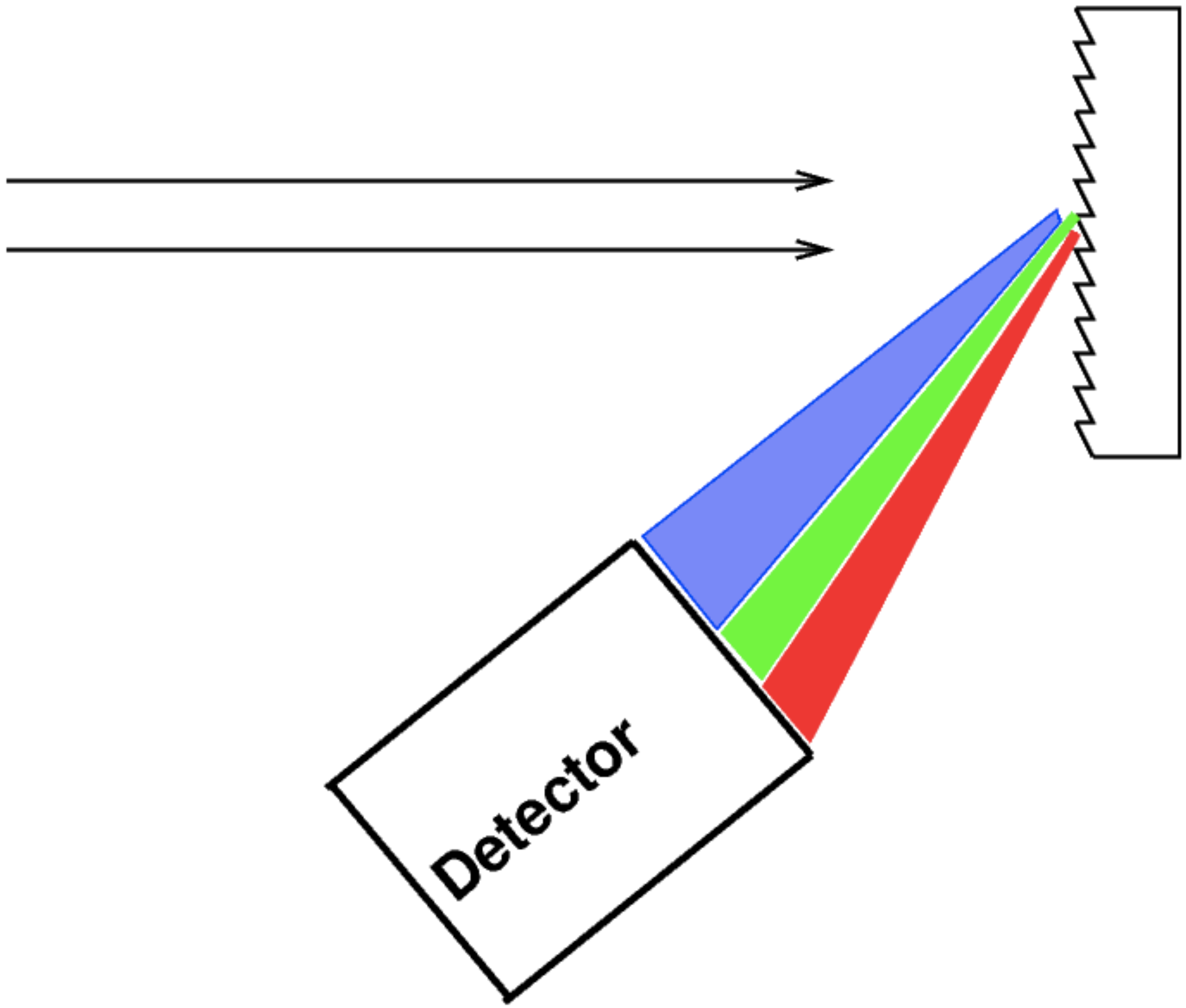
Spectrographs

A spectrograph is an instrument that disperses light using prism into a frequency/wavelength spectrum, which is generally recorded with the use of a camera that focuses the dispersed light on a detector.



Spectrographs

A spectrograph is an instrument that disperses light by bouncing it off (or pass it through) a diffraction grating into a frequency/wavelength spectrum, which is generally recorded with the use of a camera that focuses the dispersed light on a detector.



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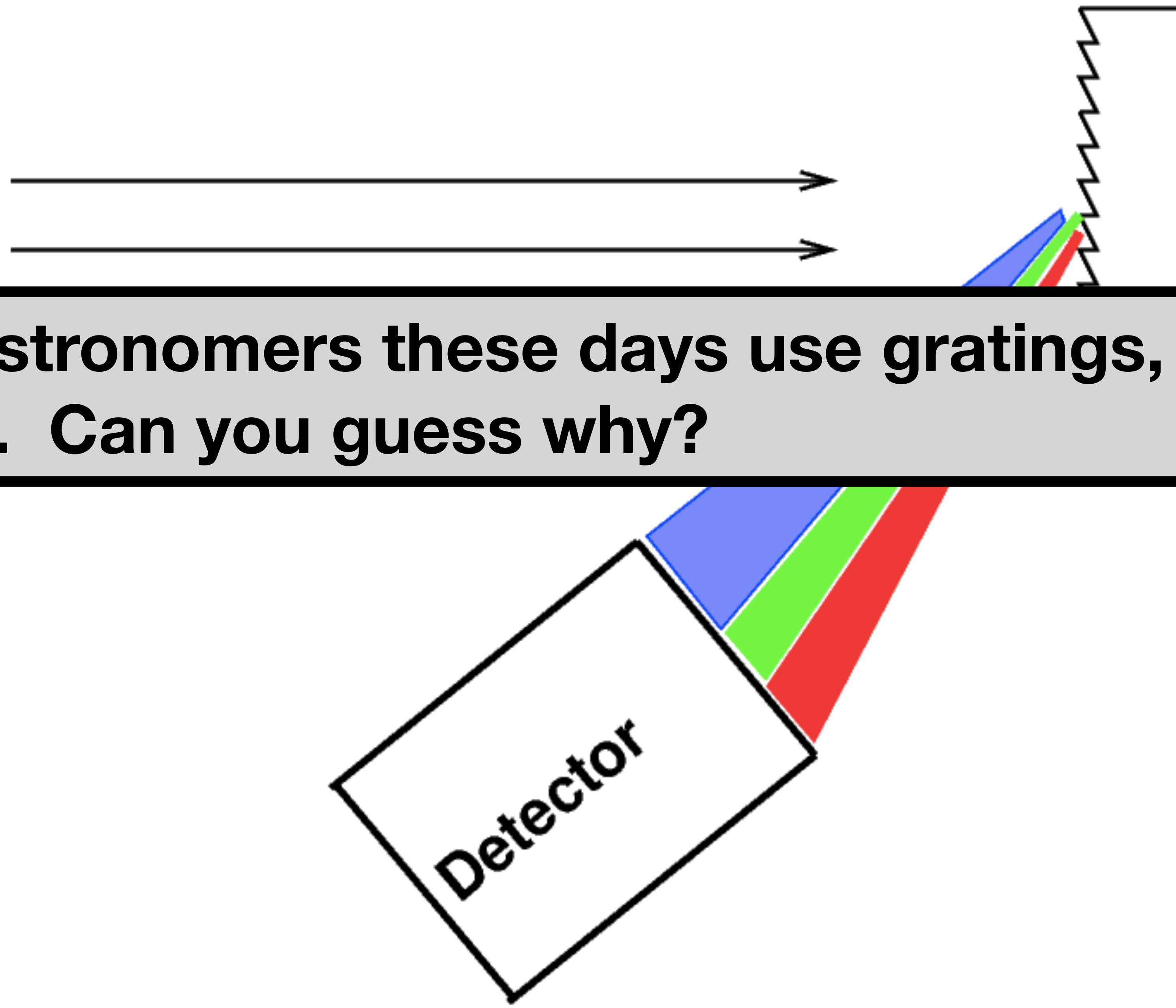


Most astronomers these days use gratings, not prisms. Can you guess why?

Spectrographs

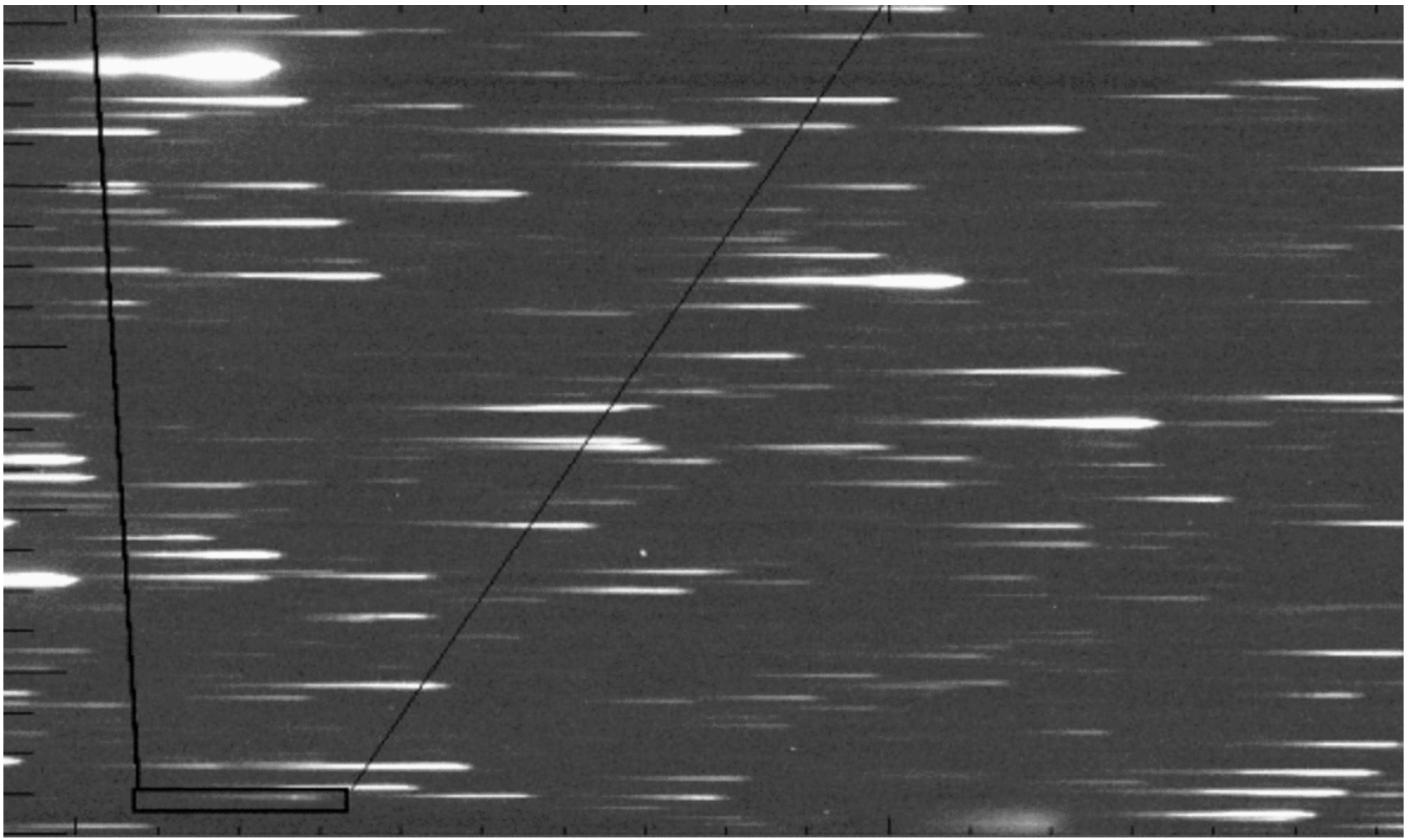
A spectrograph is an instrument that disperses light by bouncing it off (or pass it through) a diffraction grating into a frequency/wavelength spectrum, which is generally recorded with the use of a camera that focuses the dispersed light on a detector.

Most astronomers these days use gratings, not prisms. Can you guess why?

Because light must pass through a prism, some of the light rays will be absorbed or scattered -- in other words, lost. Light needs only bounce off the surface of a grating, so that a larger fraction of the precious light reaches the detector.

Spectrographs

If you just attach a grating (or prism) to your telescope, so that light from all over the field of view strikes the grating (or prism), you will see a somewhat confusing combination of image and spectrum together.



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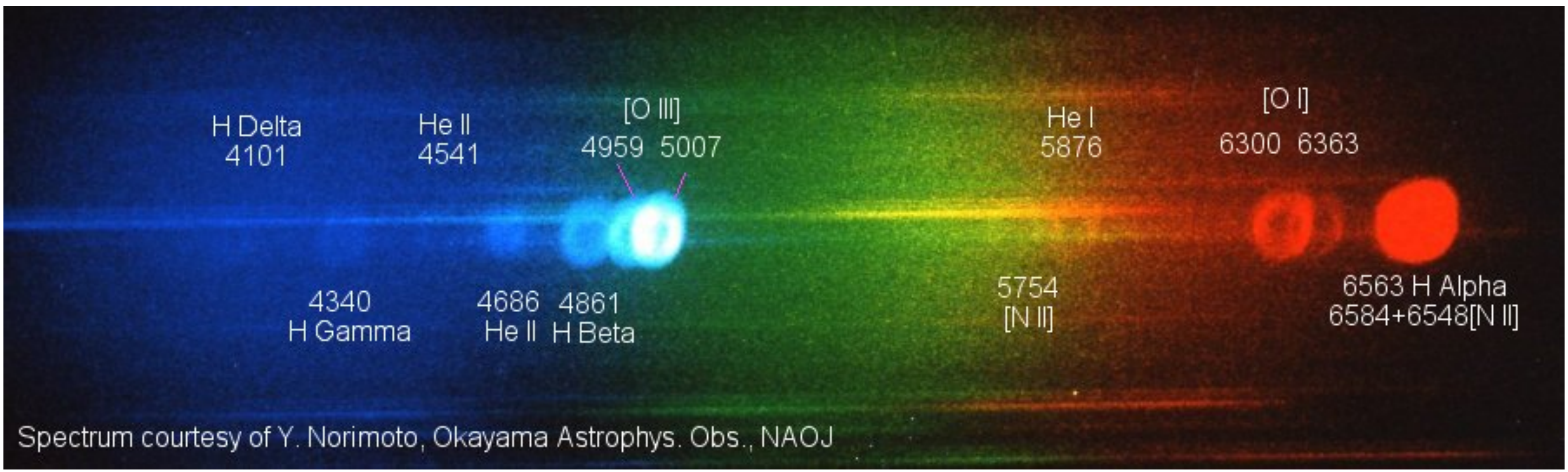
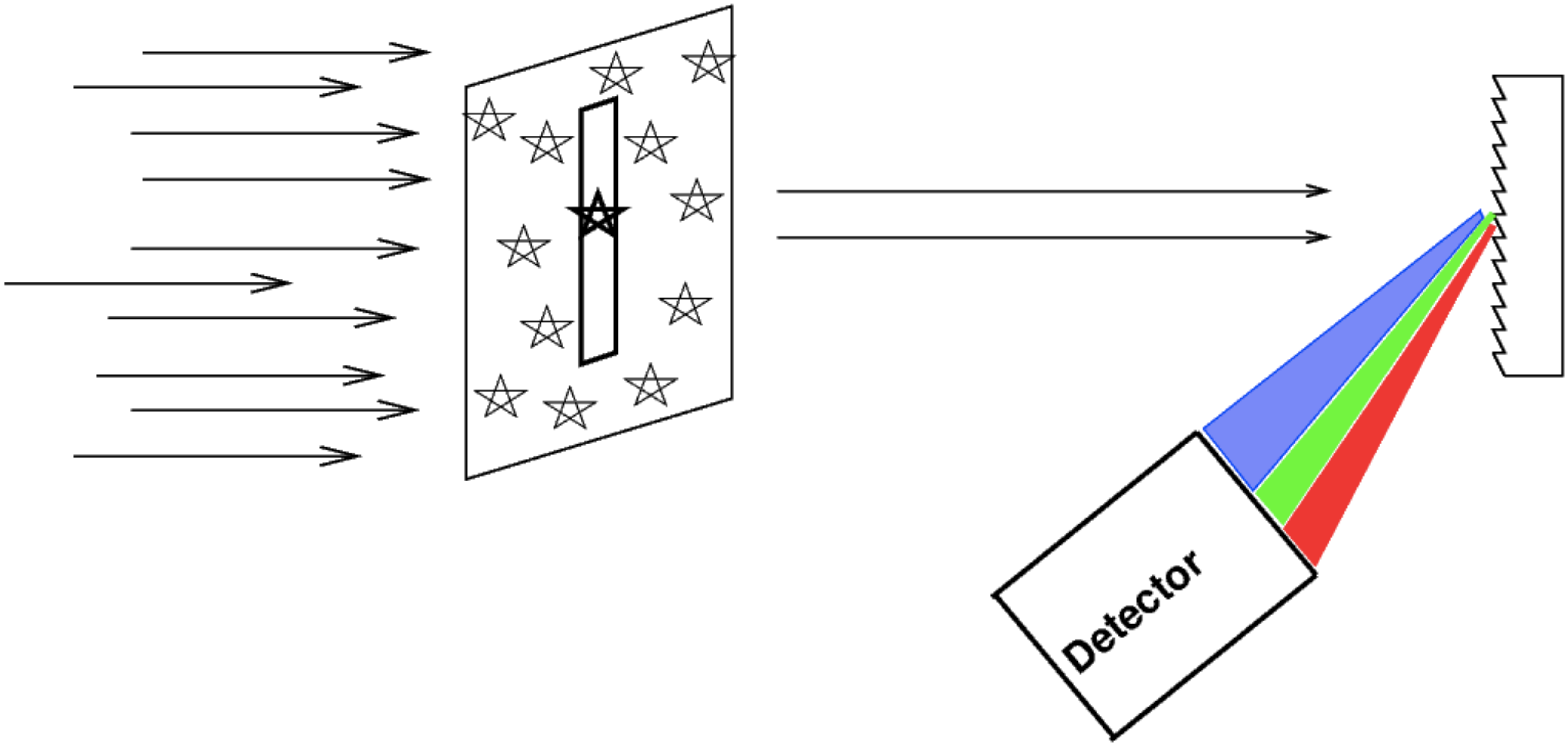


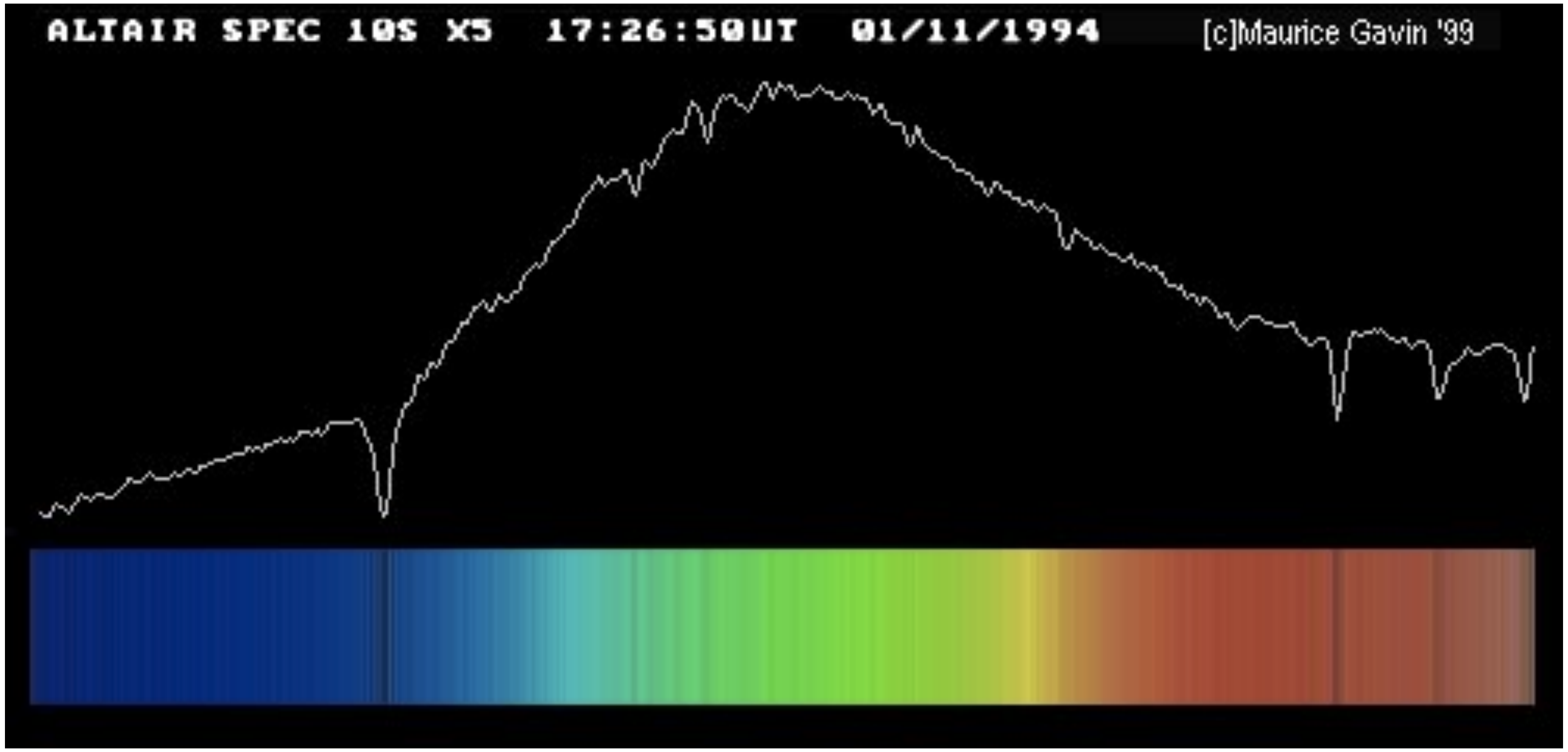
Spectrographs

Astronomers often place a slit over the focal plane of the telescope, centred on the object of interest.



Spectrographs

Only light which passes through this slit will strike the grating (or prism), giving the spectrum a characteristic shape: vertical lines on a long, horizontal canvas.



Spectrographs

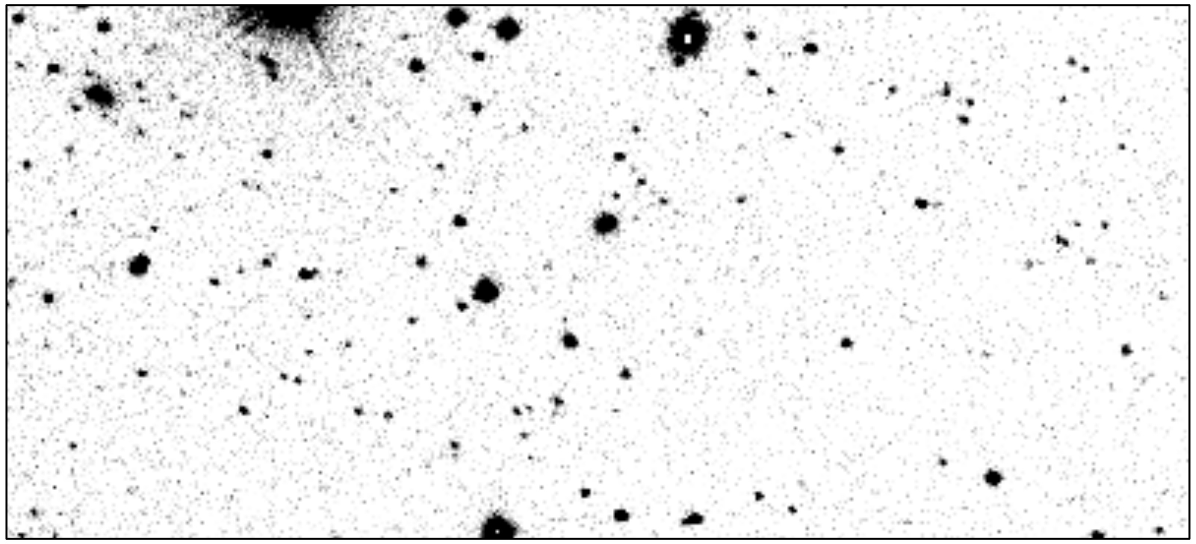
Types of Spectrographs

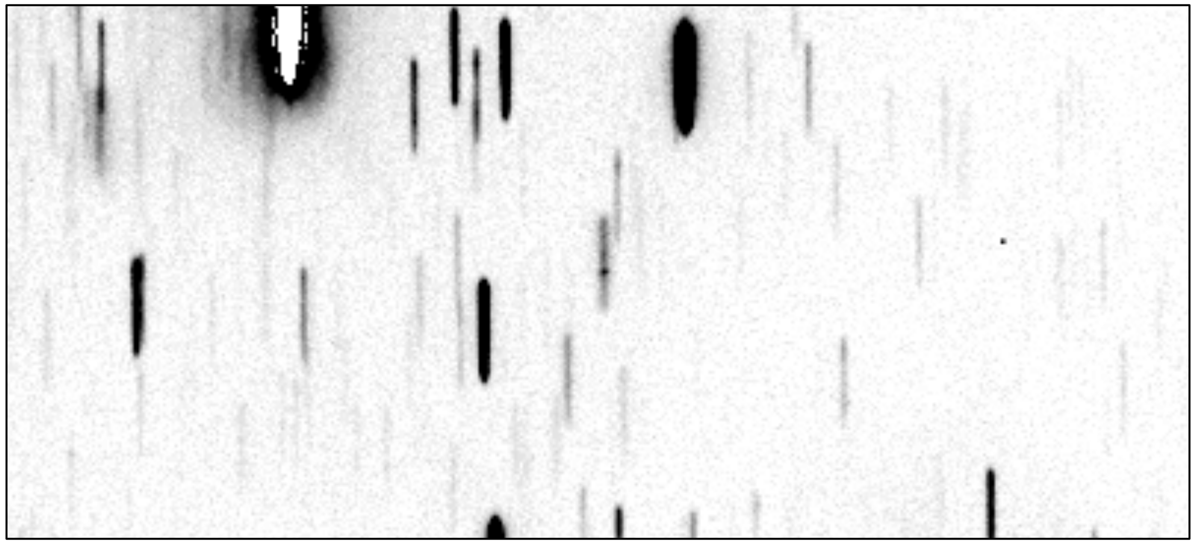
- Objective Prism
- (Long) Slit Spectrograph
- Multi-Object Spectrograph (MOS)
- Integral Field (IF) Spectrograph

Spectrographs

Types of Spectrographs

- Prism installed at the top of the telescope
- Simplest. Light is already parallel, so no extra lenses.
- Each point source produces a spectrum
- No white light reference spot
- Usually low resolution, good for wide-field surveys and meteors



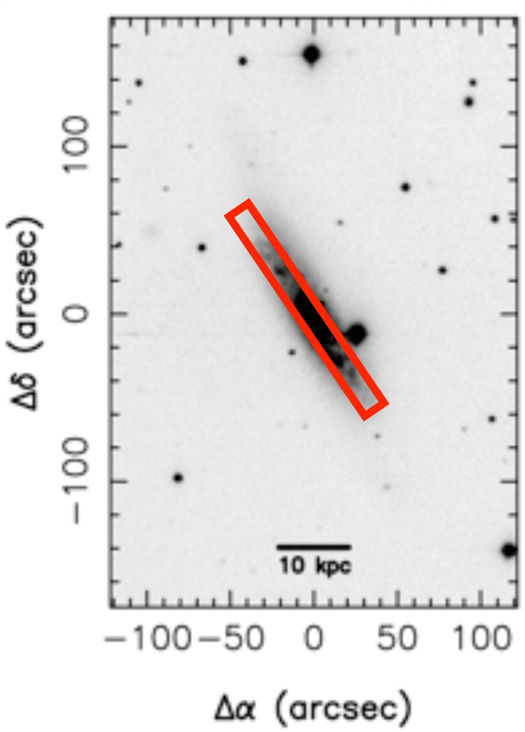


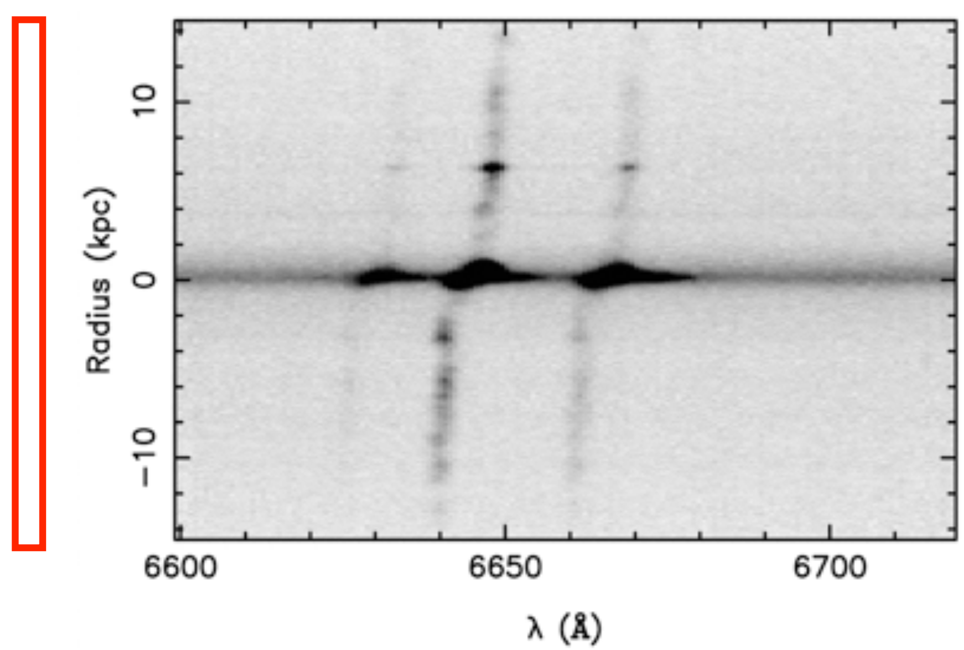
Spectrographs

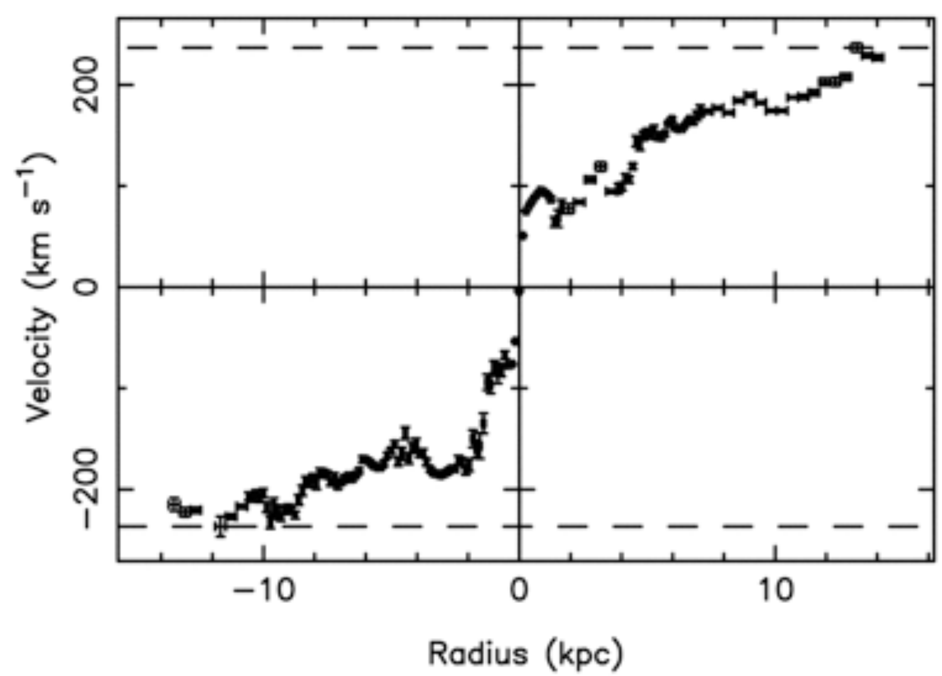
Types of Spectrographs

(Long) Slit Spectrograph

Work horse of astronomical spectroscopy





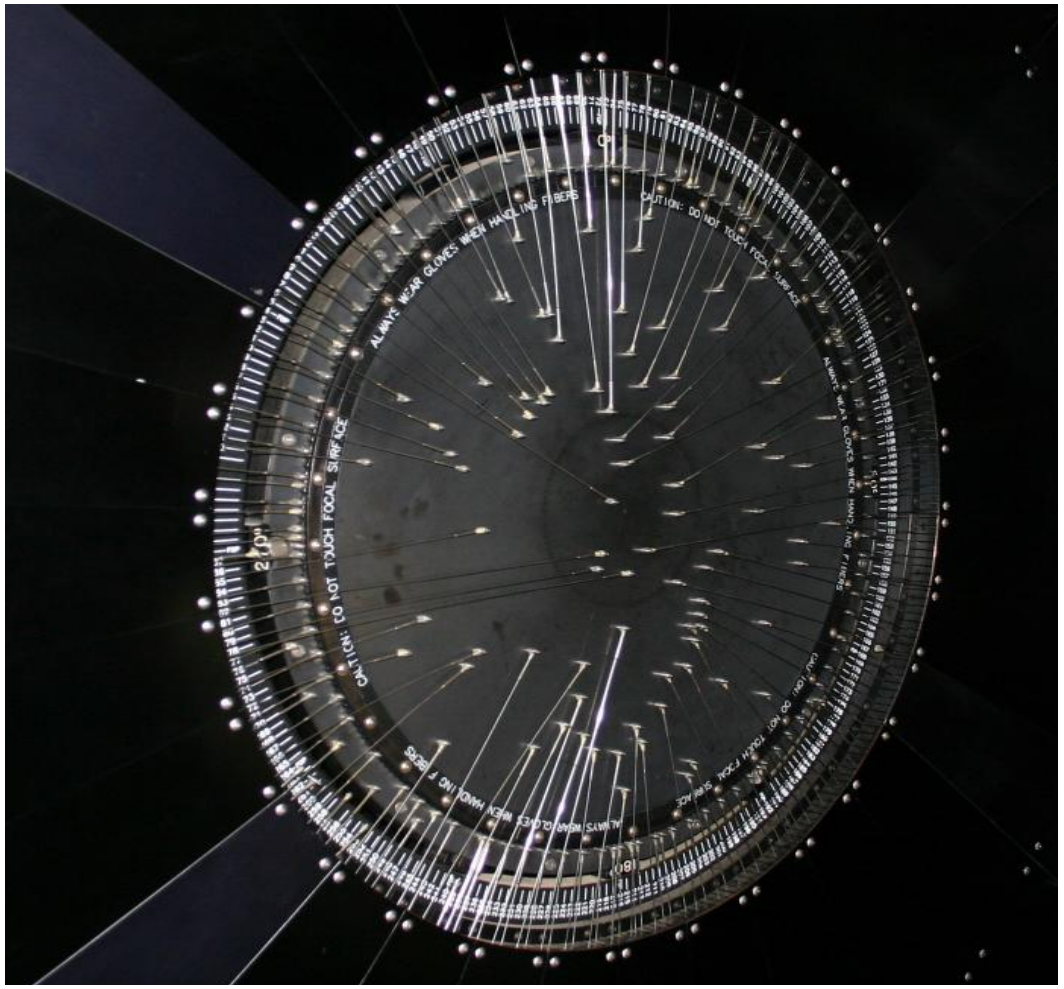


Spectrographs

Types of Spectrographs

Multi-object Spectrograph

- Observing one object at a time is <u>inefficient</u>
- When many stars are available in a field (e.g. a star cluster) use multi-object spectroscopy
- Put an optical fiber at locations of objects to take spectra.
- Feed the optical fibers into a spectrograph.

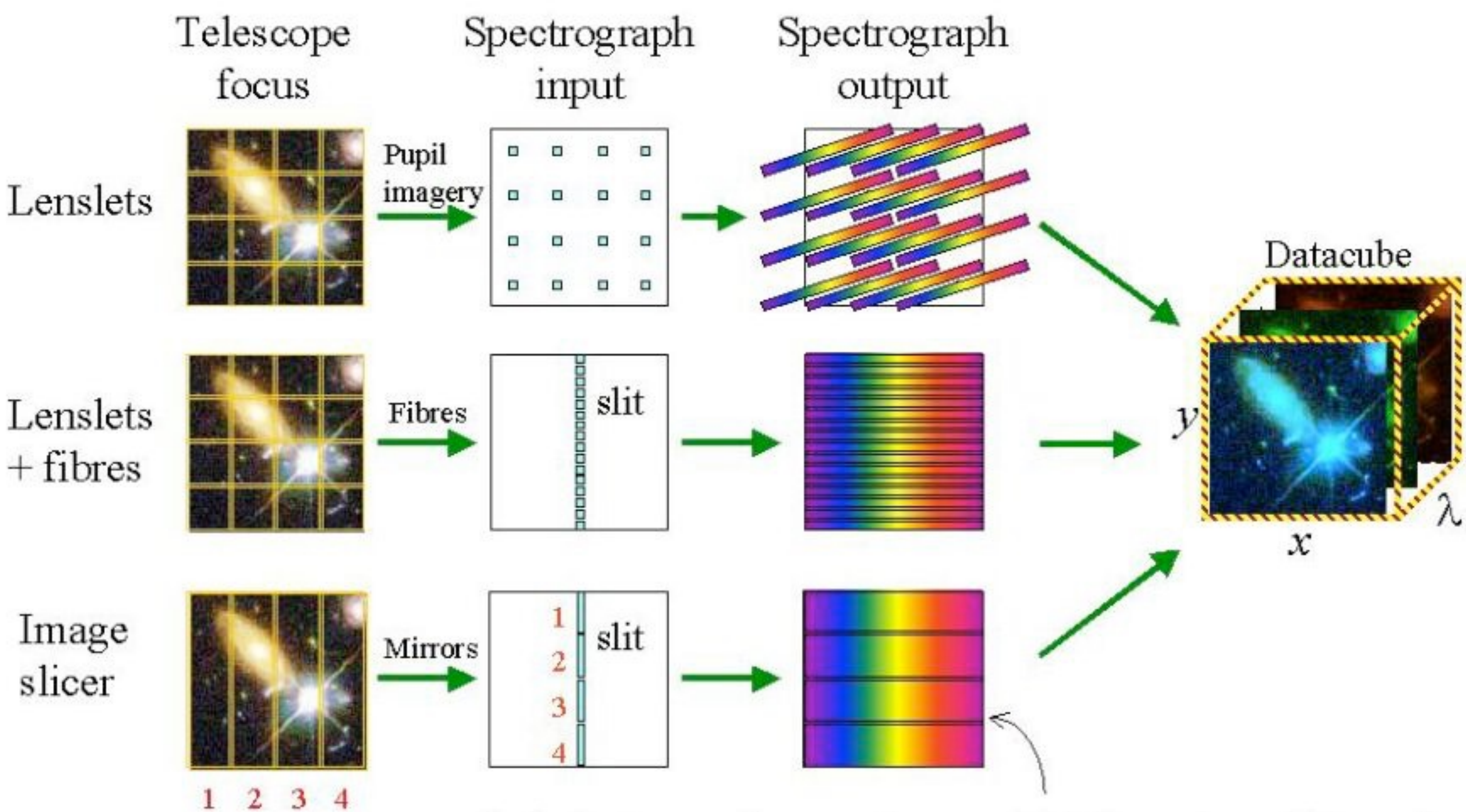


Spectrographs

Types of Spectrographs

Integral Field Spectrograph (IFS/IFU)

Used to obtained 2D spectra of a small field of view.



Spectrographs

Types of Spectrographs

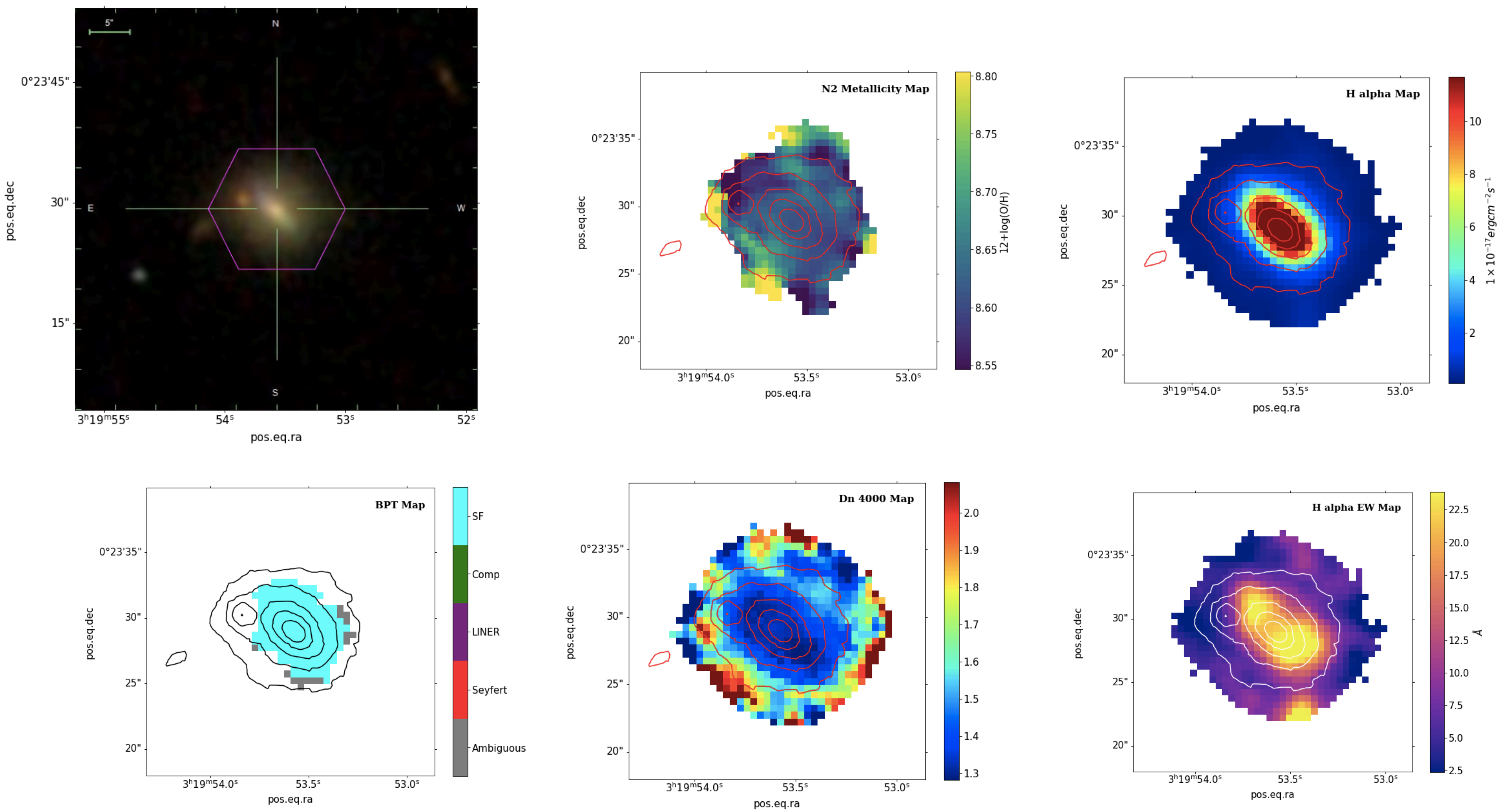
Integral Field Spectrograph (IFS/IFU)

Used to obtained 2D spectra of a small field of view.

- MUSE — Multi Unit Spectroscopic Explorer
- MaNGA — Mapping Nearby Galaxies at APO
- SINFONI — Spectrograph for INtegral Field Observations in the Near Infrared
- VIMOS — Visible Multi-Object Spectrograph
- FLAMES — Fibre Large Array Multi Element Spectrograph
- KMOS — K-band Multi Object Spectrograph
- SAURON — Spectrographic Areal Unit for Research on Optical Nebulae
- CALIFA — Calar Alto Legacy Integral Field Area survey
- SAMI — Overview of the SAMI Survey
- INTEGRAL — A Simple and Friendly Integral Field Unit Available at the WHT

Spectrographs

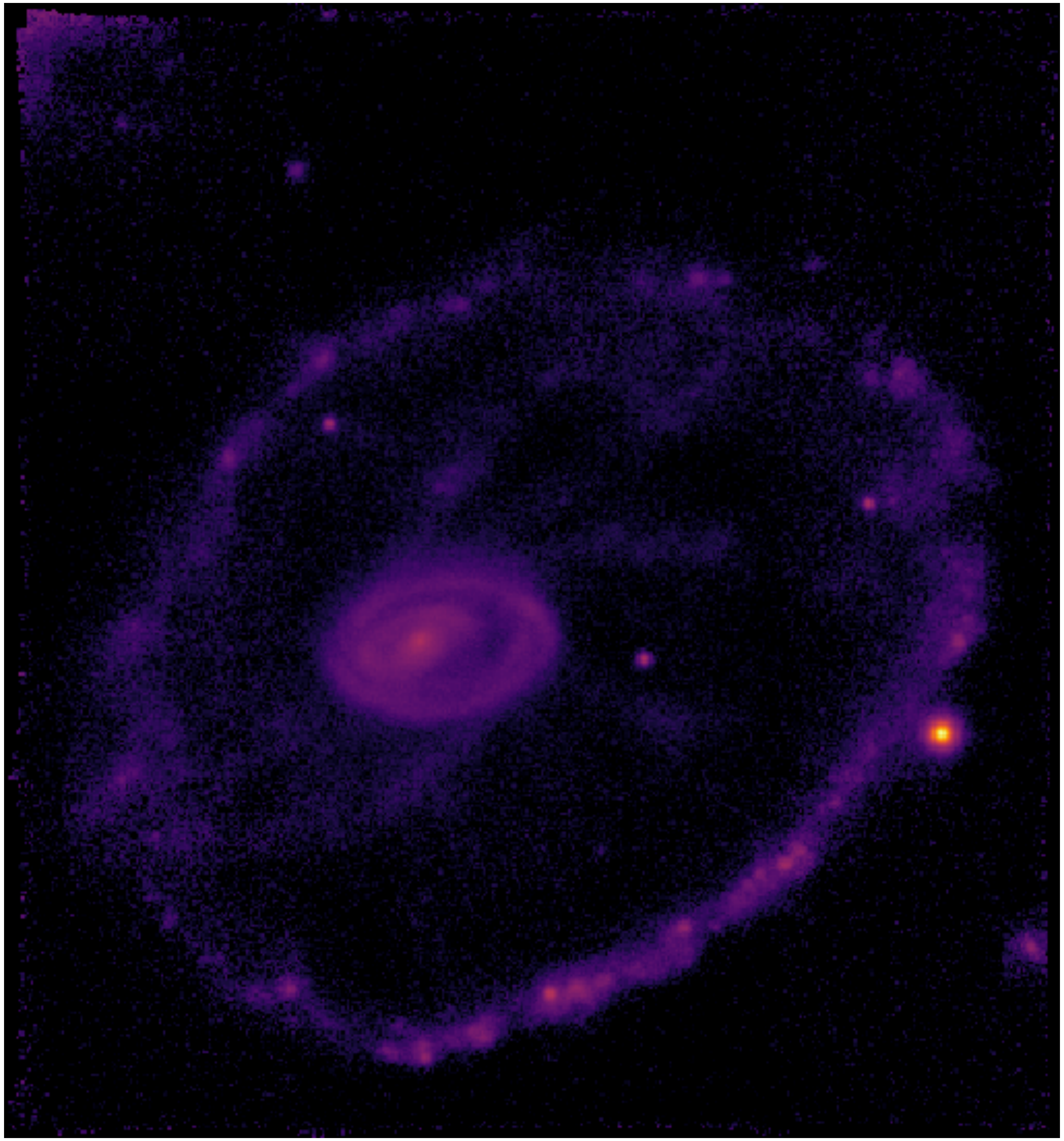
MaNGA — Mapping Nearby Galaxies at APO



Credit — Avinash C K (M Sc Thesis)

Spectrographs

MUSE — Multi Unit Spectroscopic Explorer

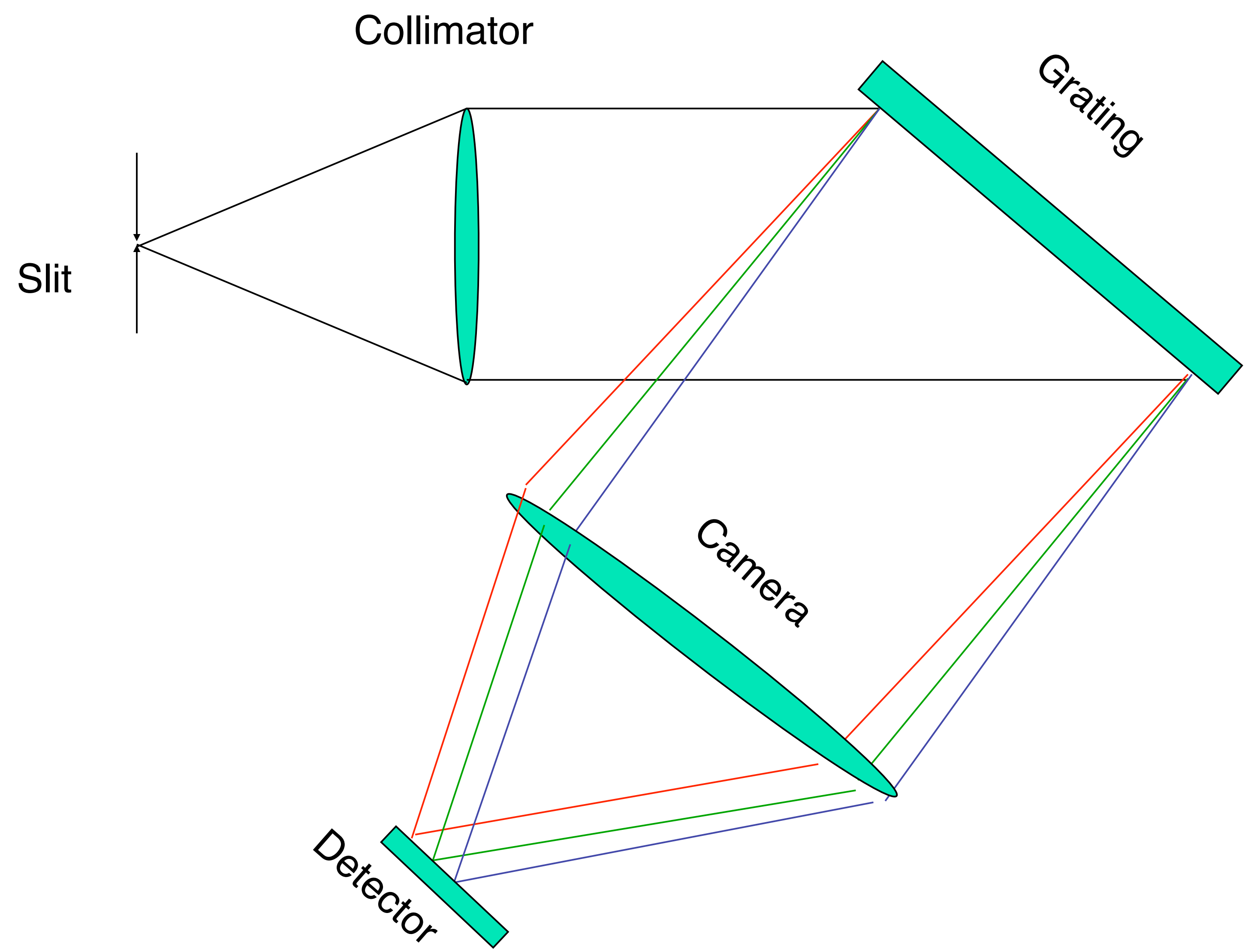


Spectrographs

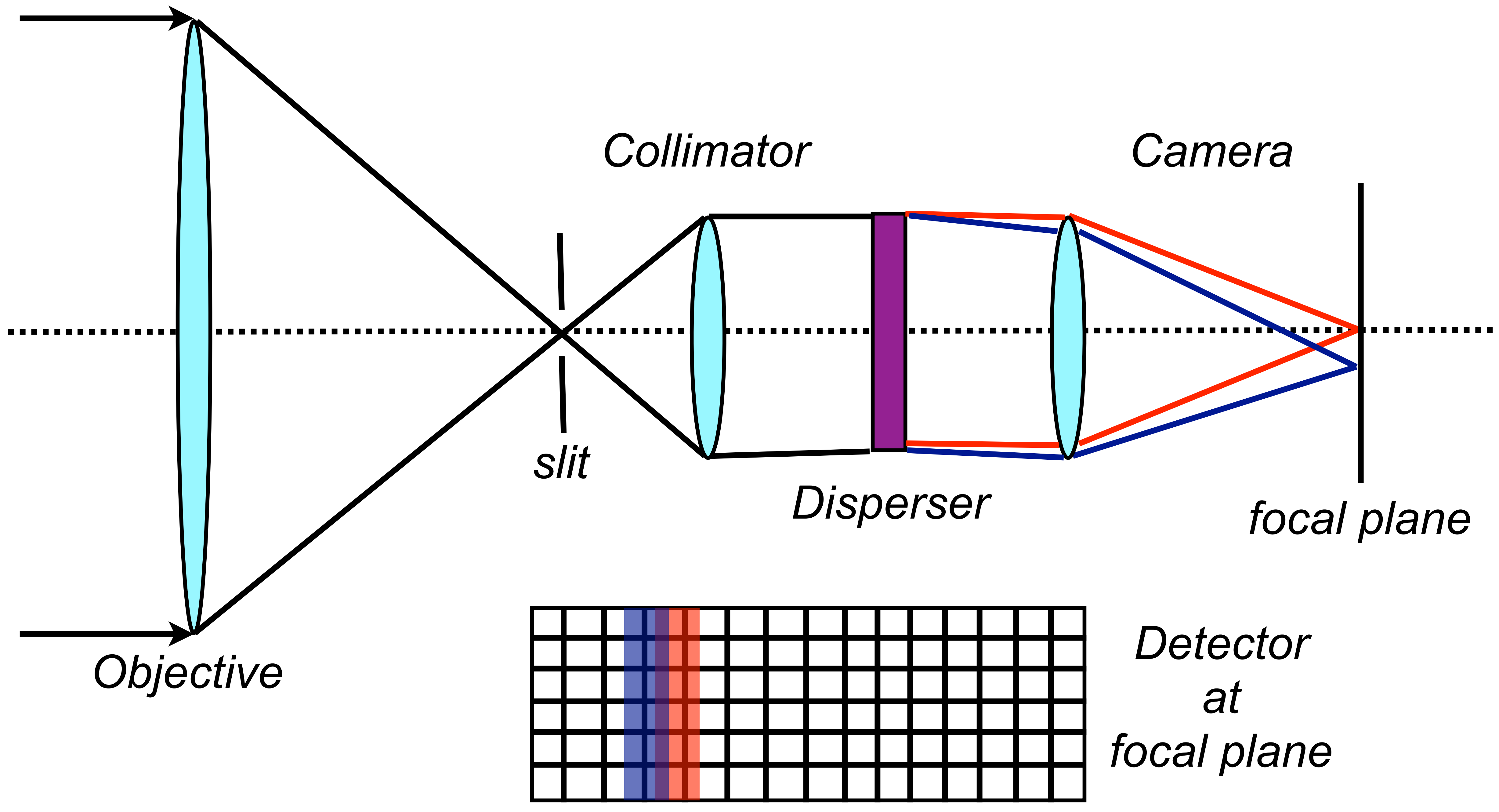
A Spectrograph is a camera coupled with a dispersing element.

Images of the source at different wavelengths fall on different places in the detector.

The amount of light emitted at each wavelength can be measured: the spectrum



Spectrographs



Spectrographs

- Slit spectroscopy: entrance aperture of the spectrometer is a narrow slit.
- Entrance slit must be
  – wide enough to allow light from the source through to spectrograph,
  – narrow enough to preserve a desired spectral resolution.
- Typical slit width ~1 arcsec, while seeing discs are usually >1 arcsec, so lose some light from source.
- Need to design spectrograph optics to give required spectral resolution for a given slit width.
  – Cannot use a slit spectrograph for spectrophotometry because light losses vary with seeing, unless you open the slit wide.

Spectrographs

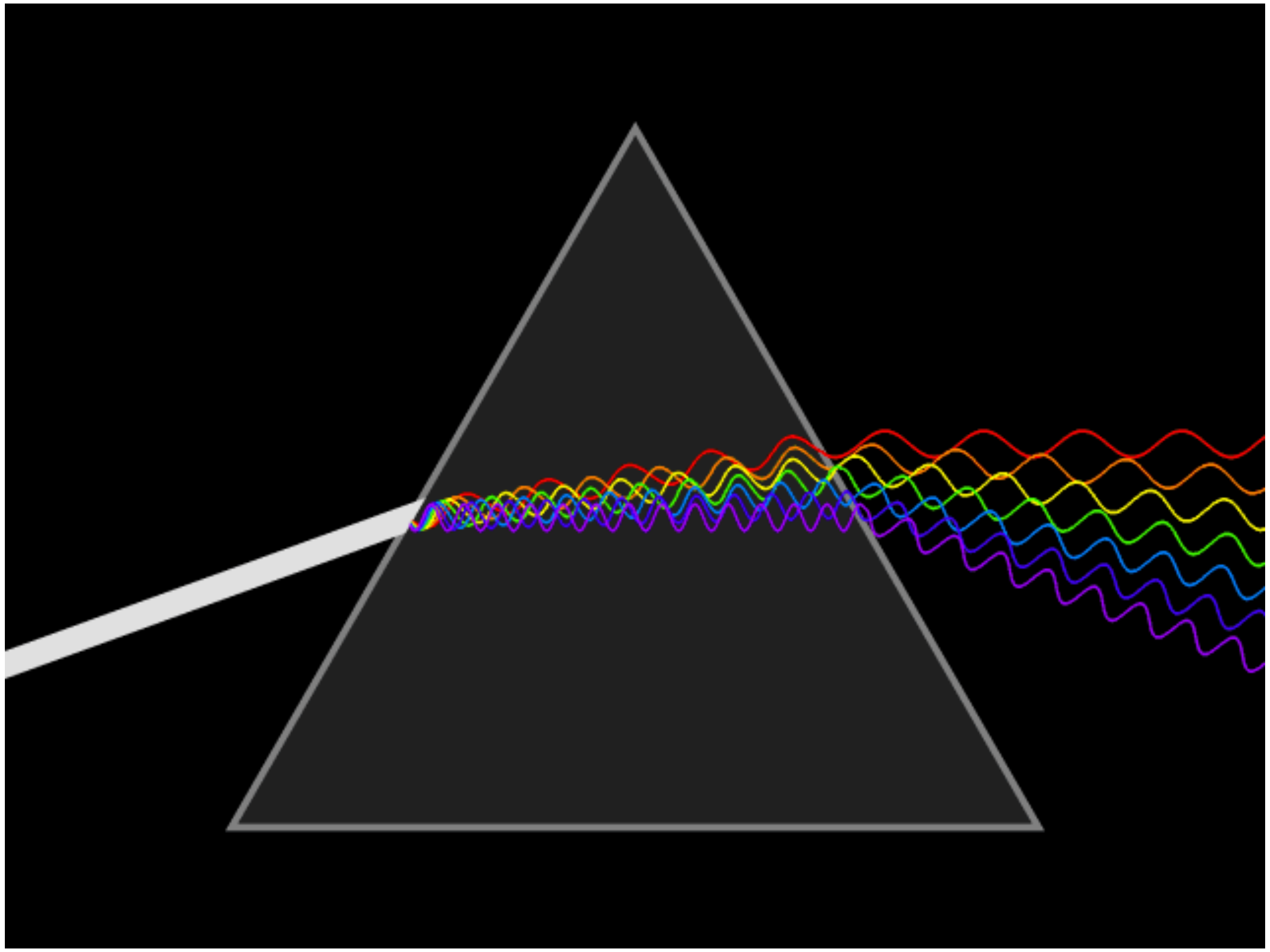
Dispersers

- Prism - Typically low resolution
- Grating - Low to very high resolution
- Grism - (prism+grating) Low to moderate resolution
- (Fabry-Perot, Michelson Interferometer)
- (Heterodyne)

Spectrographs

Dispersers — The humble prism

- First dispersing element invented/discovered
- Uses the fact that refraction is dependent on light wavelength (any refractive element is chromatic)
- Longer wavelength, redder light is deviated less than bluer, shorter wavelength light.
- In general prisms have low dispersion



Spectrographs

DISPERSION:

The angular (or spatial, after focusing by a camera on a focus plane / detector) separation between two wavelengths after passing through a dispersing element:

$$\frac{\delta\lambda}{\delta\theta} \quad or \quad \frac{\delta\lambda}{\delta x} = \frac{\delta\lambda}{\delta\theta}\frac{1}{f_{cam}}$$

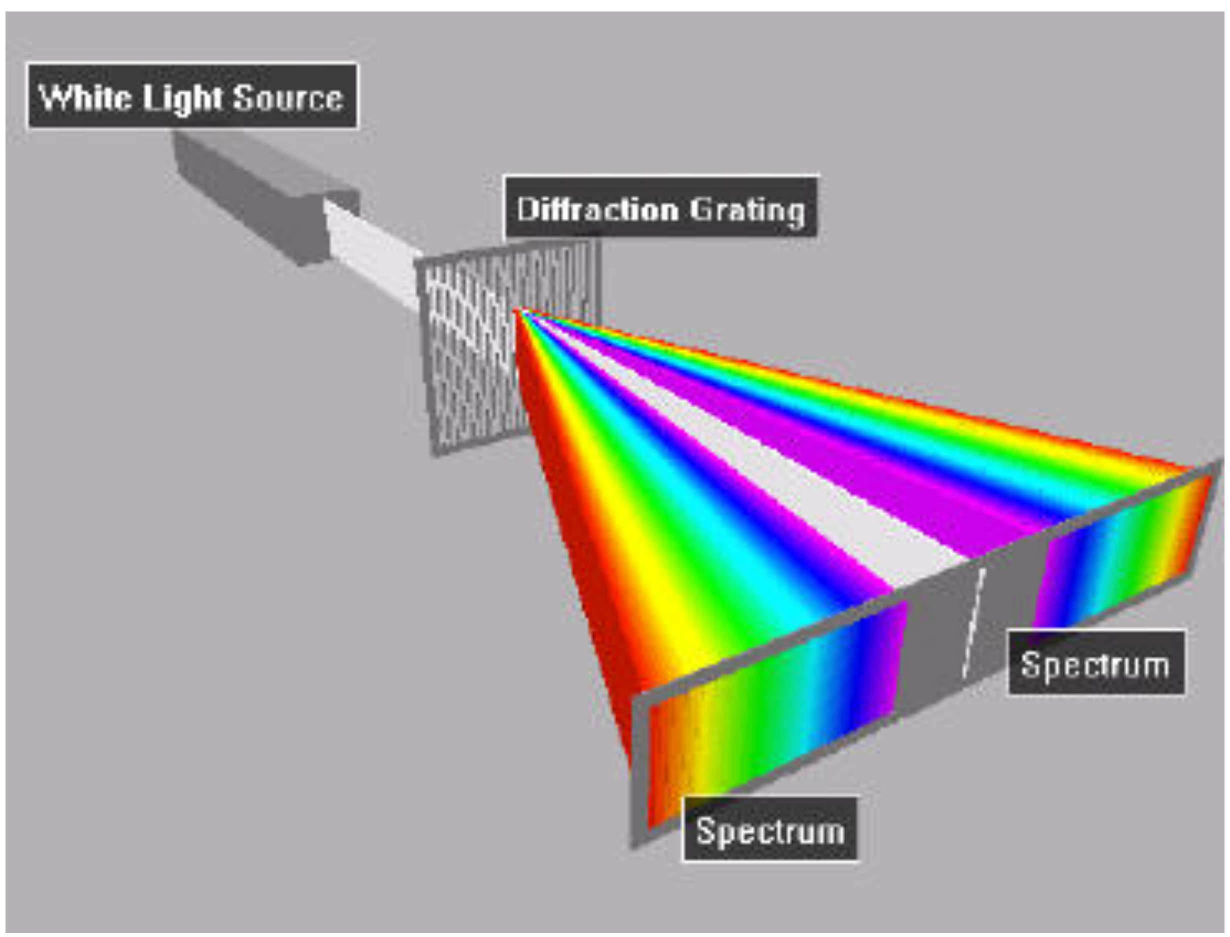
where f_{cam} is the camera focal length.

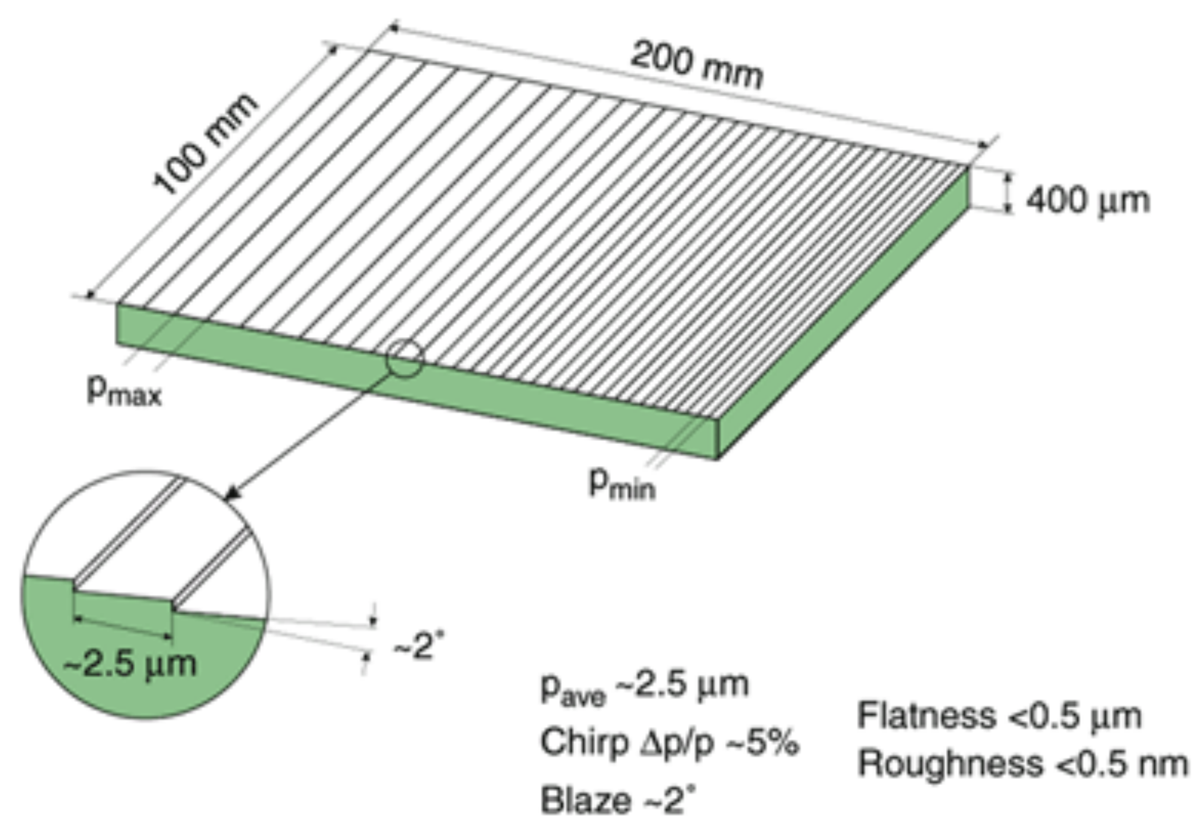
Do <u>not</u> confuse it with <u>resolution!</u>

Spectrographs

Dispersers — Diffraction Gratings

- Multi-slit diffraction
- reflection gratings and transmission gratings
- most astronomical gratings are reflection gratings



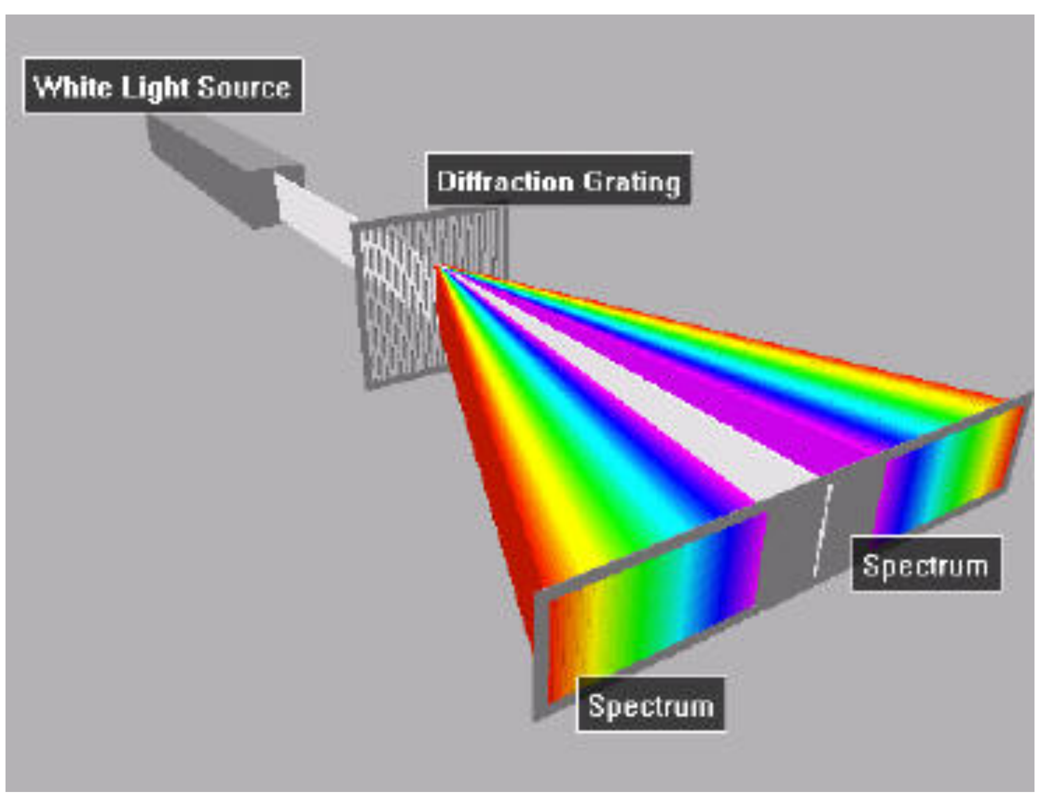


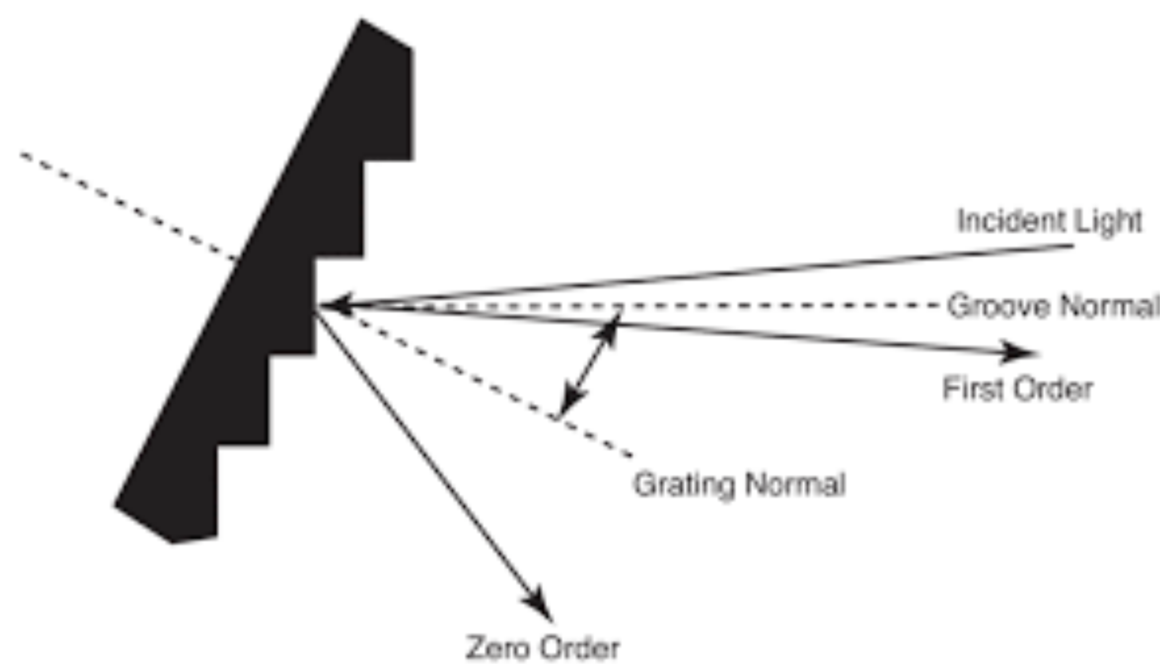
Spectrographs

Dispersers — Diffraction Gratings

There are two types of diffraction grating in use:

- a *transmission grating*, where a large number of fine, equidistant, parallel lines are ruled onto a transparent glass plate so that light can pass *between* the lines, but not through them.
- a *reflection grating*, where the lines are ruled onto a reflective piece of glass so that only the light between the lines is reflected.

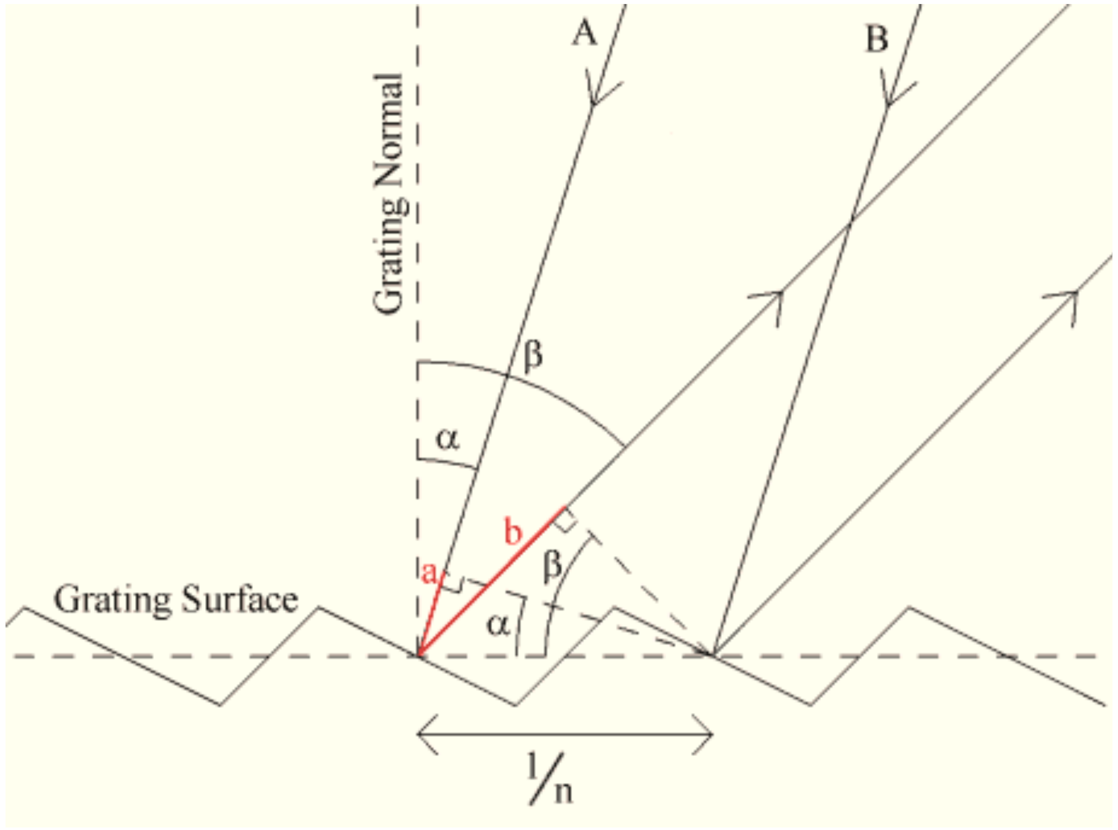




Spectrographs

Dispersers — Reflection Gratings

Light reflecting from grooves A and B will interfere constructively if the difference in path length is an integer number of wavelengths.



- The path difference is $d \sin\alpha + d \sin\beta$ (where d is the distance between facets on the grating), so

$$d\,(\sin\alpha + \sin\beta) = n\lambda$$ → the grating equation

- n is the "spectral order" and quantifies how many wavelengths of path difference are introduced between successive facets or grooves on the grating)

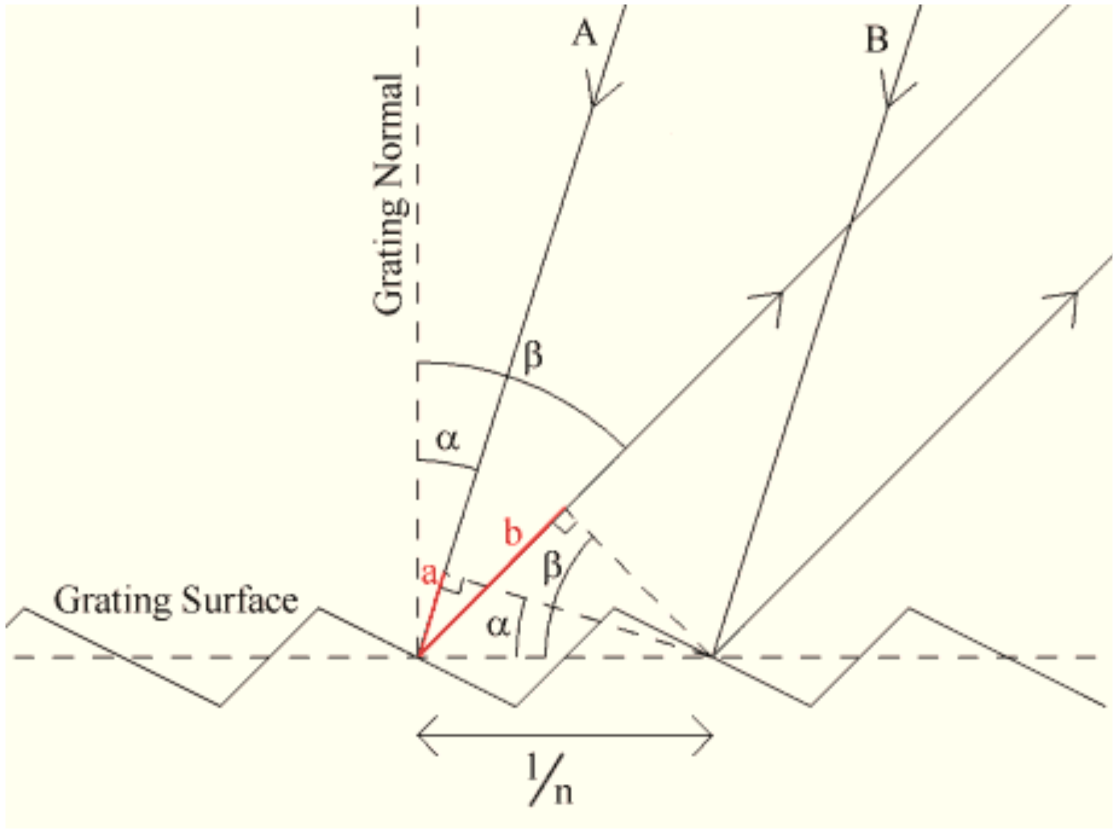
Spectrographs

The Grating Equation

$$\boxed{d\,(\sin\alpha + \sin\beta) = n\lambda}$$

- The groove spacing d is a feature of the grating
- The angle of incidence, α, is the same for all wavelengths
- The angle of diffraction, β, must then be a function of wavelength

$$\sin\beta = n\lambda/d - \sin\alpha$$



Spectrographs

Dispersers — Grism

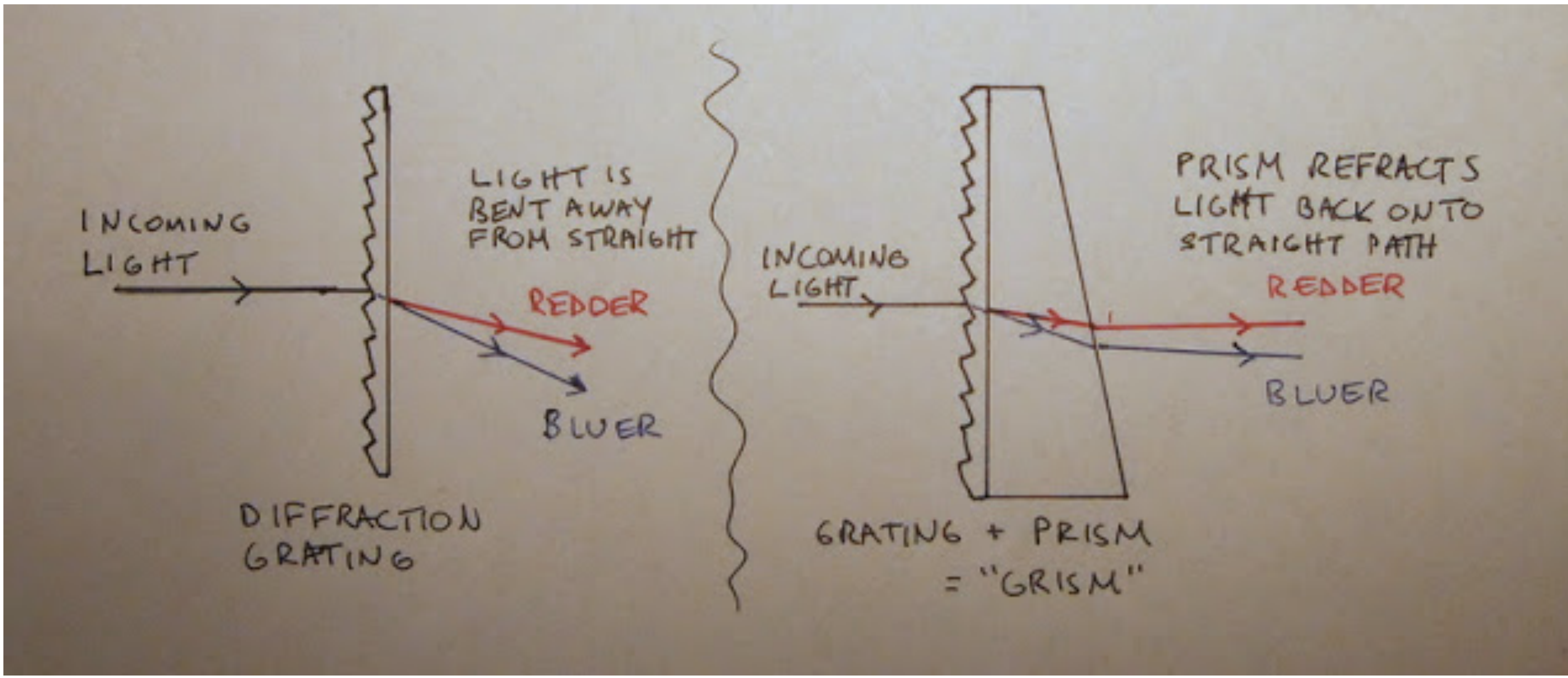
- A **grism** (also called a **grating prism**) is a combination of a prism and grating arranged so that light at a chosen central wavelength passes straight through.

- The advantage of this arrangement is that one and the same camera can be used both for imaging (without the grism) and spectroscopy (with the grism) without having to be moved.

- Grisms are inserted into a camera beam that is already collimated. They then create a dispersed spectrum centered on the object's location in the camera's field of view.

Spectrographs

Dispersers — Grism



Spectrographs

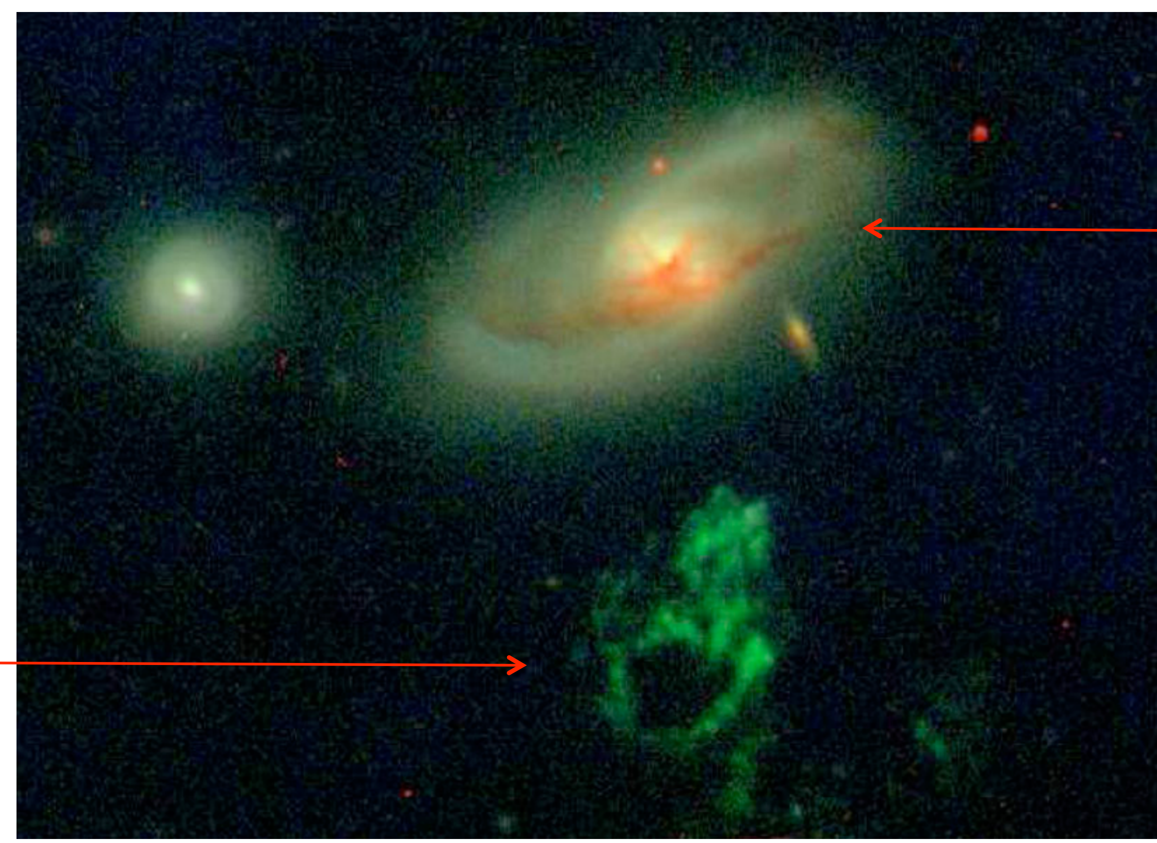
Application to Astronomical Objects

- The absorption lines in stellar spectra can be used to determine the chemical composition of the star. Of particular importance are the absorption lines of hydrogen.
- In conjunction with atomic physics and models of stellar evolution, stellar spectroscopy is used to determine properties of stars such as, their *distance*, *age*, *luminosity* and *rate of mass loss*.
- The Doppler shift studies can uncover the presence of hidden companions such as black holes and exoplanets.
- Planets and asteroids are visible by reflecting the sunshine.
- The reflected light contains absorption bands due to mafic silicates in the rocks present for rocky bodies (800-1,100nm), or due to the elements and molecules present in the atmospheres of the Gas giants (890nm, CH_4).
- The spectra of comets consist of a reflected solar spectrum from the dusty clouds surrounding the comet, as well as emission lines from gaseous atoms and molecules excited by sunlight fluorescence and/or chemical reactions.

HANNY and the Mystery of the Voorwerp

The story of Hanny and mystery of Voorwerp

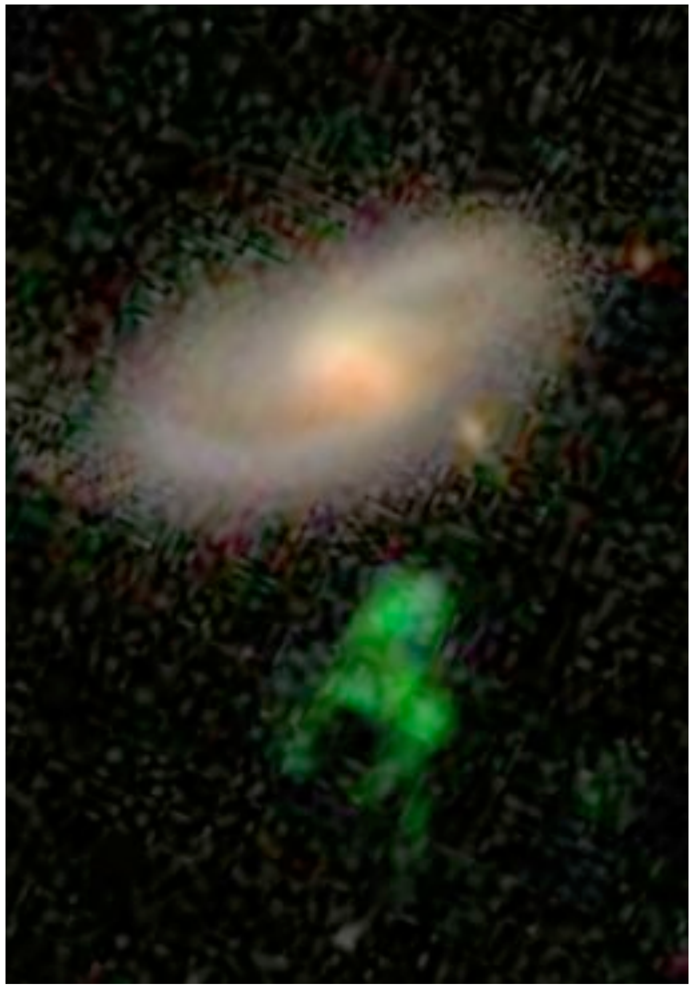
While classifying galaxies online, Hanny van Arkel saw a strange green blob next to a spiral galaxy. “It looked like a dancing frog”, She says.

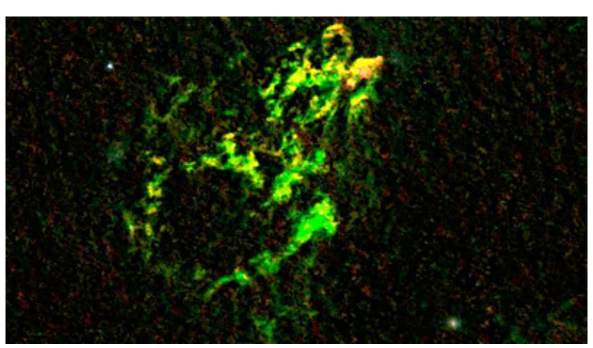


IC 2497

Vooerwerp

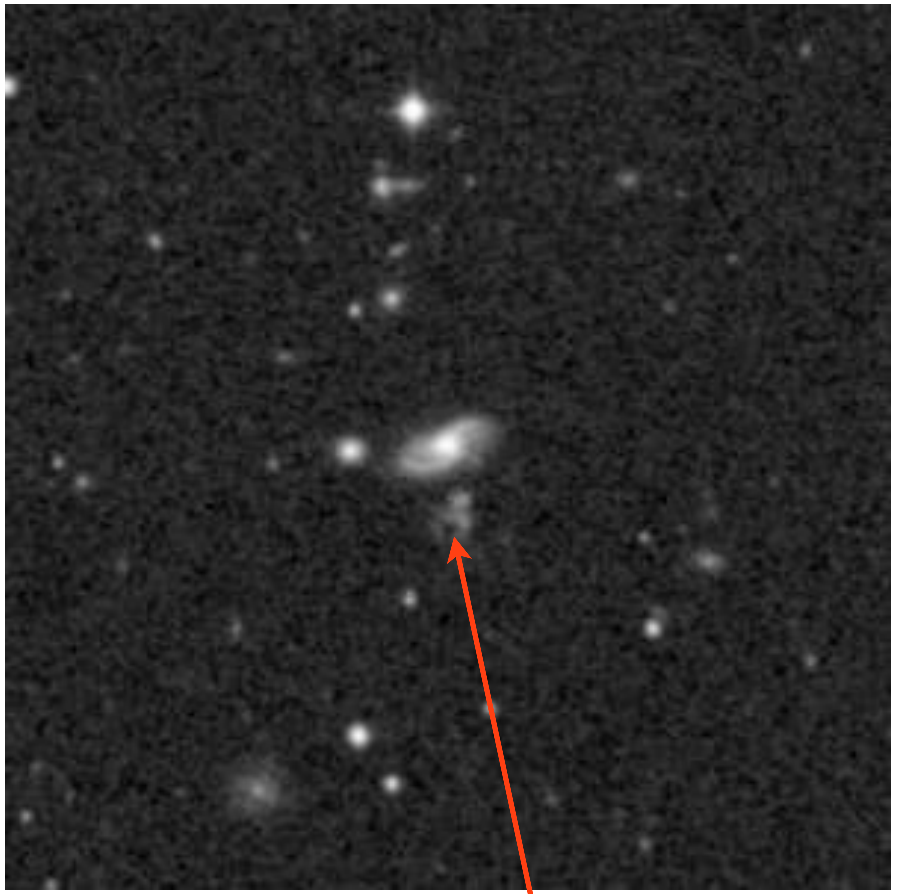
The story of Hanny and mystery of Voorwerp





- Is it real?
- Is there anything else like it?
- Is it local?
- Did a Supernova create the loop?
- Does it contain stars?
- Is it just an unusual nebula?
- Is it a weird galaxy?
- Is it at the edge of the universe?

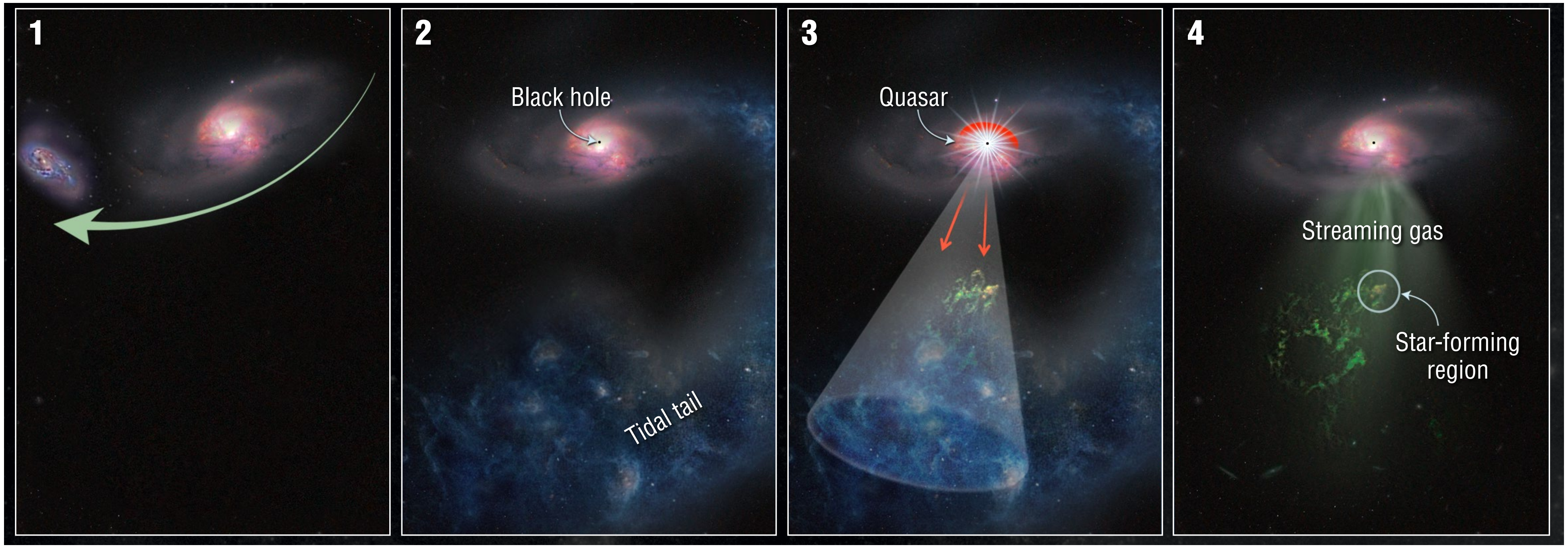
The story of Hanny and mystery of Voorwerp



- It is real - although no one ever noticed it
- Tiny spot among thousands on images taken by Palomer Telescope
- The Vooerwerp was first images in 1953 as a part of an all sky survey - DSS - Digital Sky Survey

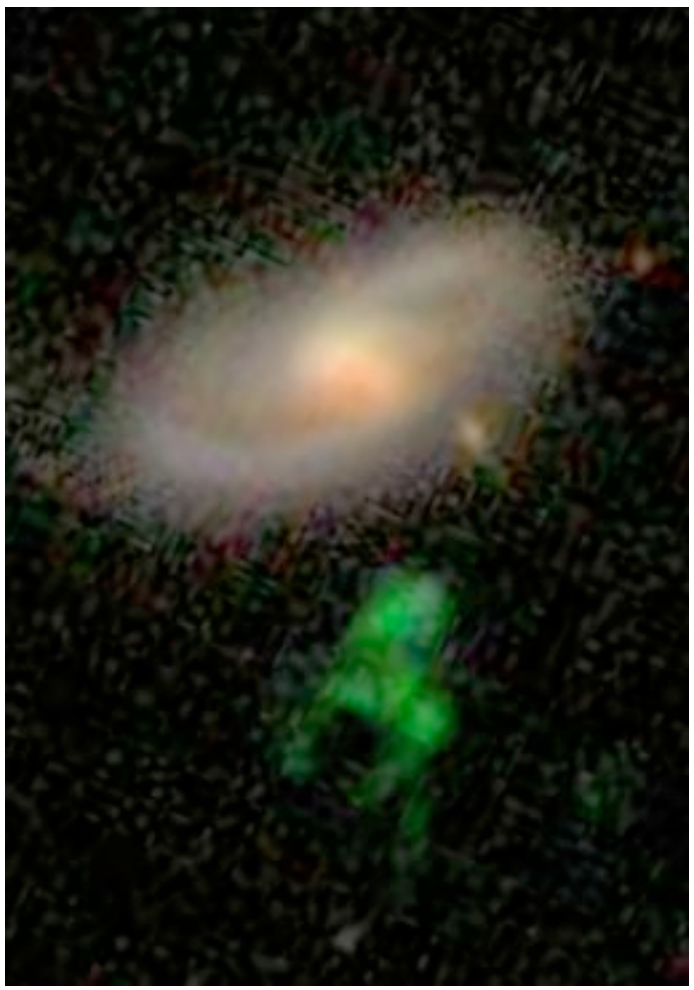
It is real but no knows what it is until recently

The story of Hanny and mystery of Voorwerp



1. Spiral galaxy IC 2497 gravitationally interacts with a passing galaxy.
2. A large tidal tail of gas is pulled from the spiral galaxy.
3. Engorged with gas, a black hole at the centre of IC 2497 “turns on” as a quasar and emits a powerful cone of light, which ionises a portion of the tidal tail, creating Hanny’s Voorwerp.
4. Gas streaming from the galaxy’s centre impacts the tidal tail and triggers star formation.

The story of Hanny and mystery of Voorwerp



Hanny's Voorwerp

This discovery was made because of the participation of people in astronomy research project that has huge amount of data

Astronomy in the Era of Information Abundance

Data and Data Archives in Astronomy

The Age of Mega Surveys

- Large number of surveys
  - multi-TB in size, ~1000 million objects or more
  - individual archives are planned, or under way
- Multi-wavelength view of sky
  - more than 13 wavelength coverage in 5 years
- Impressive early discoveries
  - finding exotic objects by unusual color

    L,T drwaf, high-z quasars, Hanny's voorwerp
  - finding objects by time variability

    gravitational microlencing

MACHO
2MASS
DENIS
SDSS
GOODS
PRIME
DPOSS
GSC-II
COBE
MAP
NVSS
FIRST
GALEX
ROSAT
OGLE
LSST...

Data and Data Archives in Astronomy

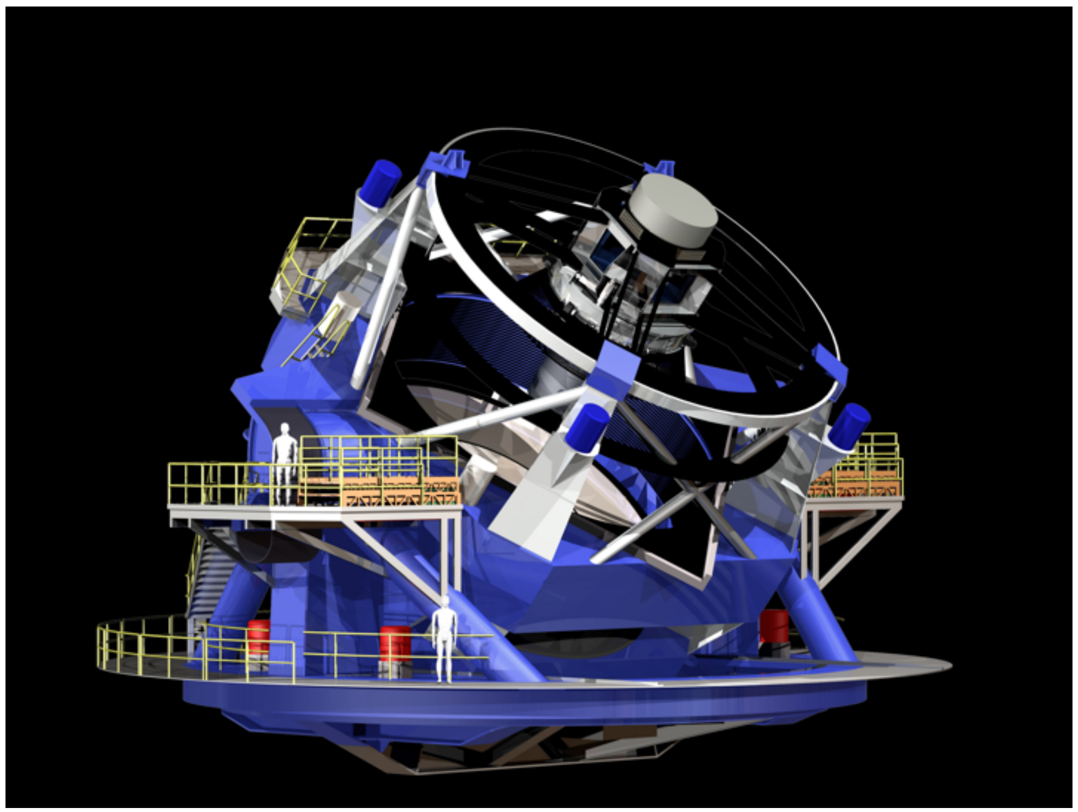
The Age of Mega Surveys

- Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Surveys
- Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey
- The SKA Mid-frequency All-sky Continuum Survey
- The NRAO VLA Sky Survey

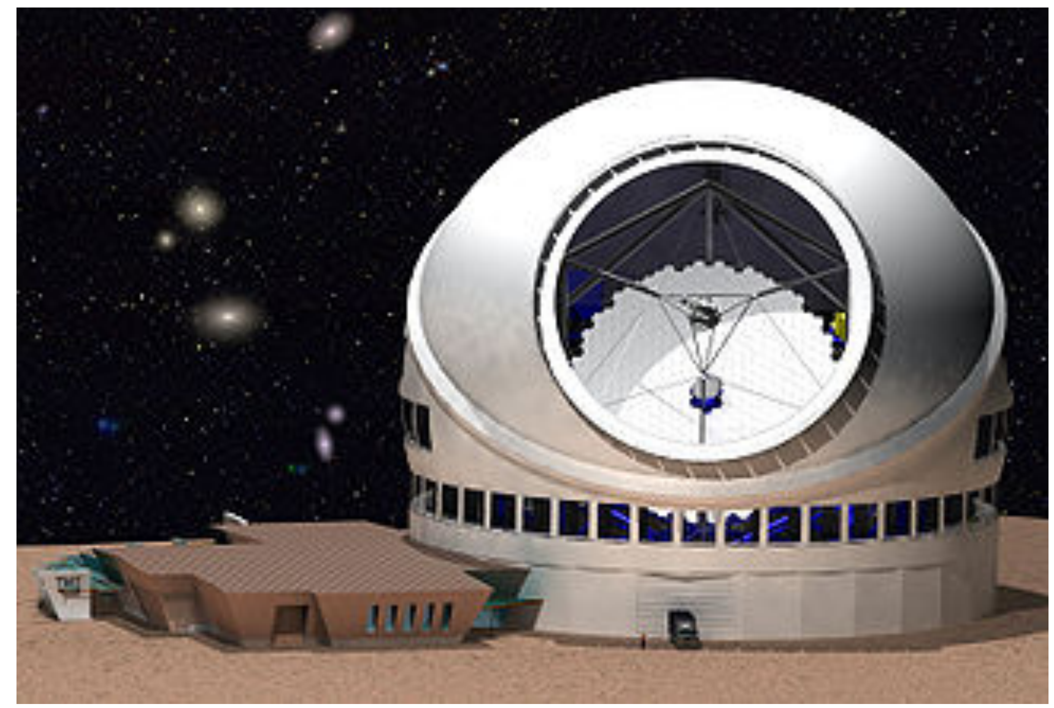
MACHO
2MASS
DENIS
SDSS
GOODS
PRIME
DPOSS
GSC-II
COBE
MAP
NVSS
FIRST
GALEX
ROSAT
OGLE
LSST...

Why there is huge amount of data?The Era of Large Telescopes

Why there is huge amount of data?The Era of Large Telescopes

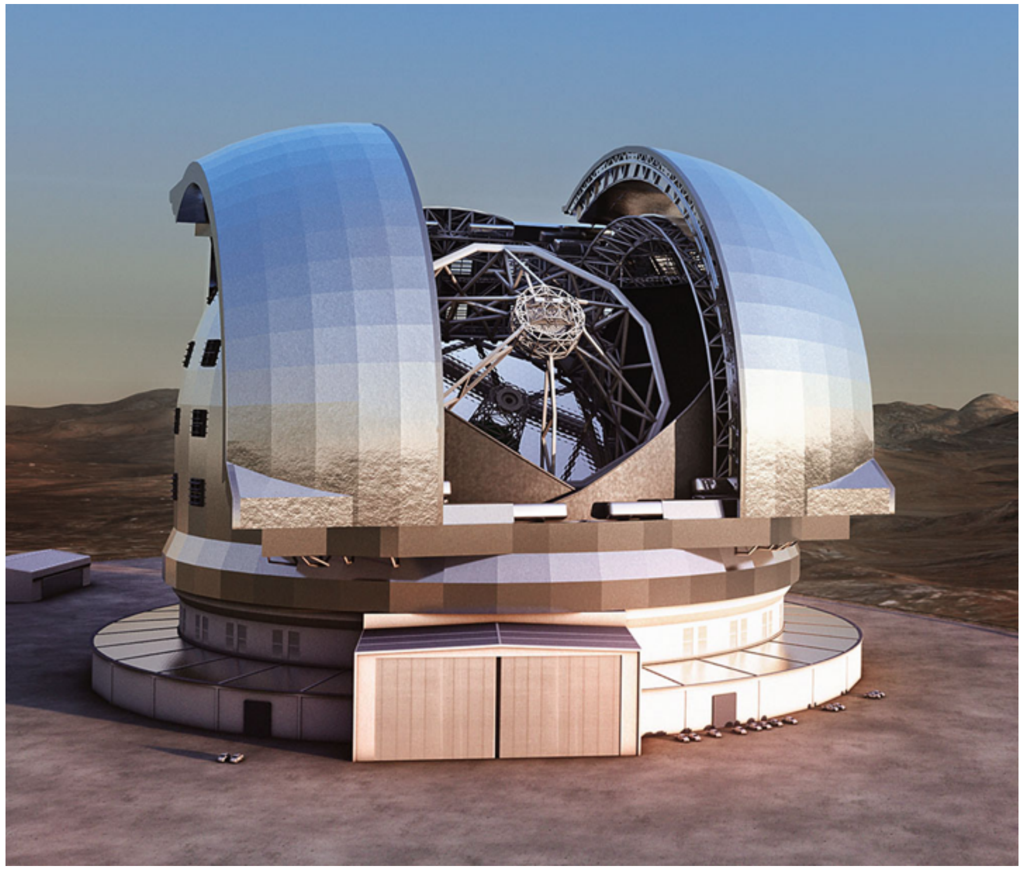


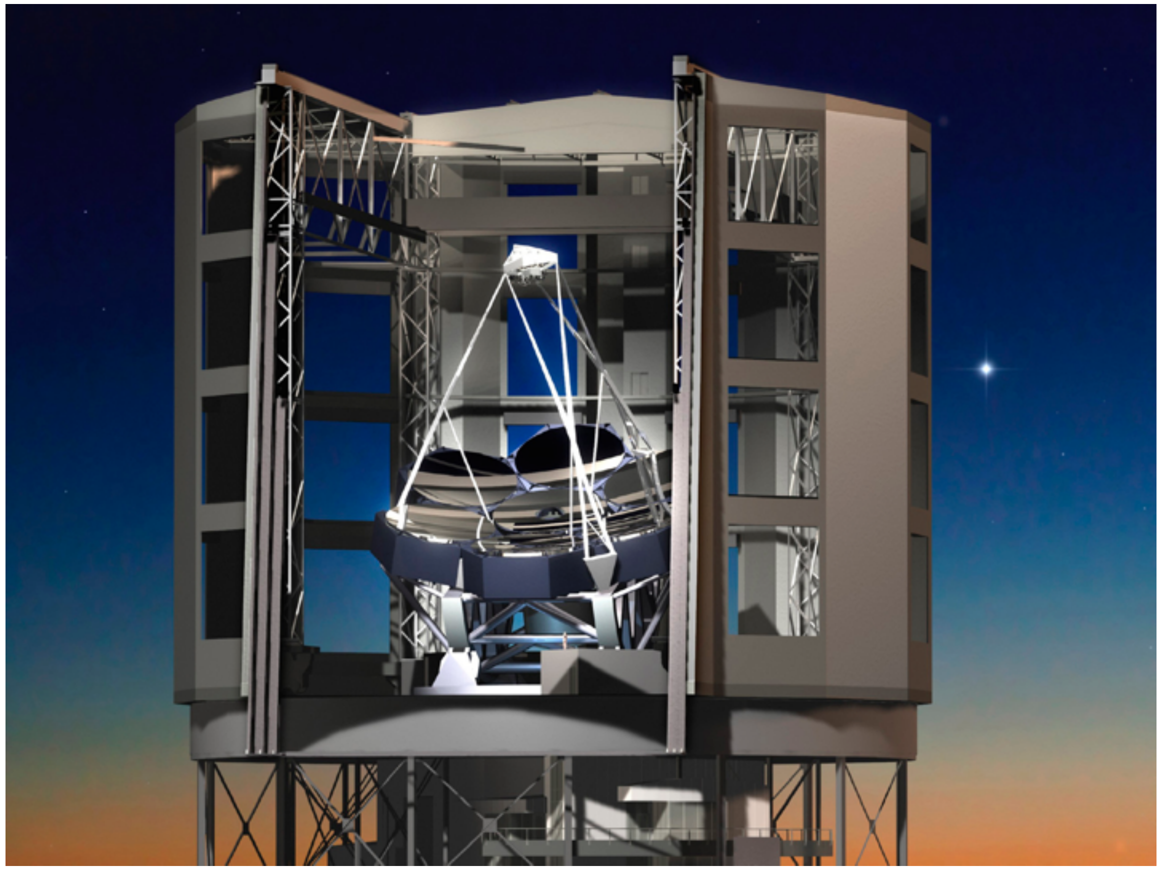
Large Synaptic Survey Telescope



Thirty Meter Telescope

Why there is huge amount of data?The Era of Large Telescopes





Extremely Large Telescope **Giant Magellan Telescope**

Why there is huge amount of data?The Era of Large Telescopes

The Data Flood

Terabytes of data are now available, Petabytes will soon be available

Next generation telescopes will produce the data volumes of SDSS every day!

This Data Flood can be use to learn, communicate & teach astronomy

Why there is huge amount of data?The Era of Large Telescopes

The Data Flood

Himalayan Chandra Telescope (HCT) ~01TB/Year

Large Synoptic Survey Telescope (LSST) ~30 TB/night

Square Kilometer Array (SKA) ~10^6 TB/second (raw data)

SDSS every day?

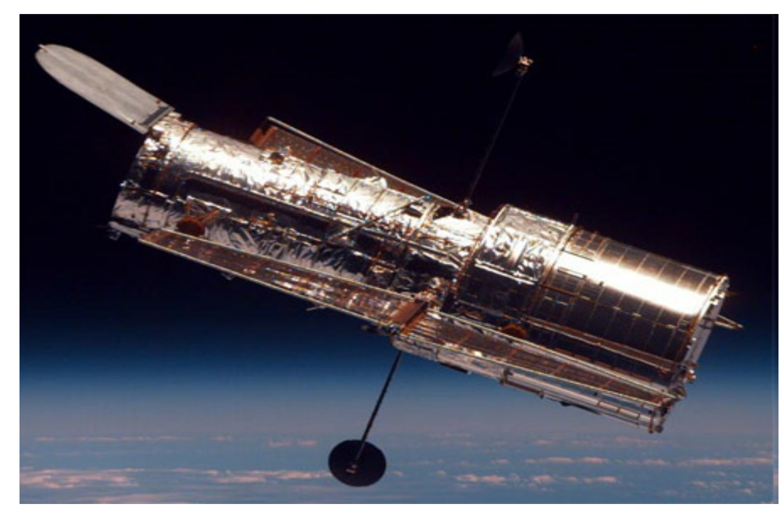
This Data Flood can be use to learn, communicate & teach astronomy

Virtual Observatory

What is a Virtual Observatory?

First, a real Observatory -

- Telescope (Optical, Infrared, Ultra-Violet, Radio, X-ray)
- Detectors, instruments (cameras, photometers, spectrograph)
- Site (ground & space)
- Computers (telescope control, instrument control, data acquisition, data processing, data storage & data archive)
- Astronomers, engineers, technicians, support staff...........



What is a Virtual Observatory?

Virtual Observatory -

- Telescope → digital data accessible over internet
- Detectors, instruments → computer programmes
- Site → user’s desktop
- Computers (telescope control, instrument control, data acquisition, data processing, data storage & data archive)
- Astronomers, engineers, technicians, support staff...........

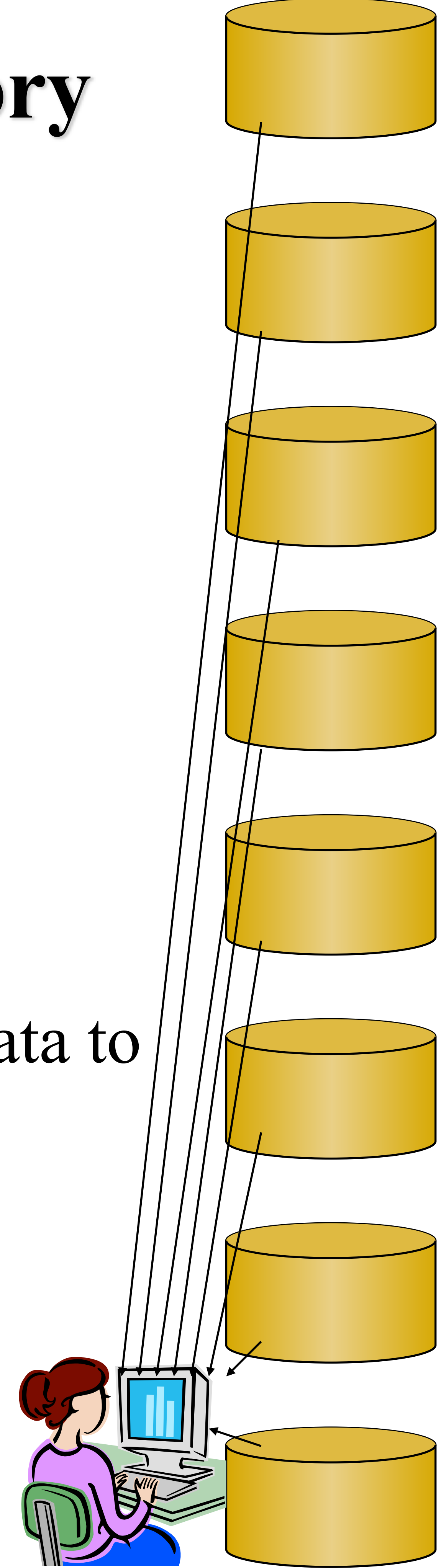
What’s a Virtual Observatory?

A Virtual Observatory (VO) provides a scientific research environment with a collection of interoperable data archives, software tools and applications which utilize the power of Internet or WWW to conduct astronomical research projects.

Wikipedia

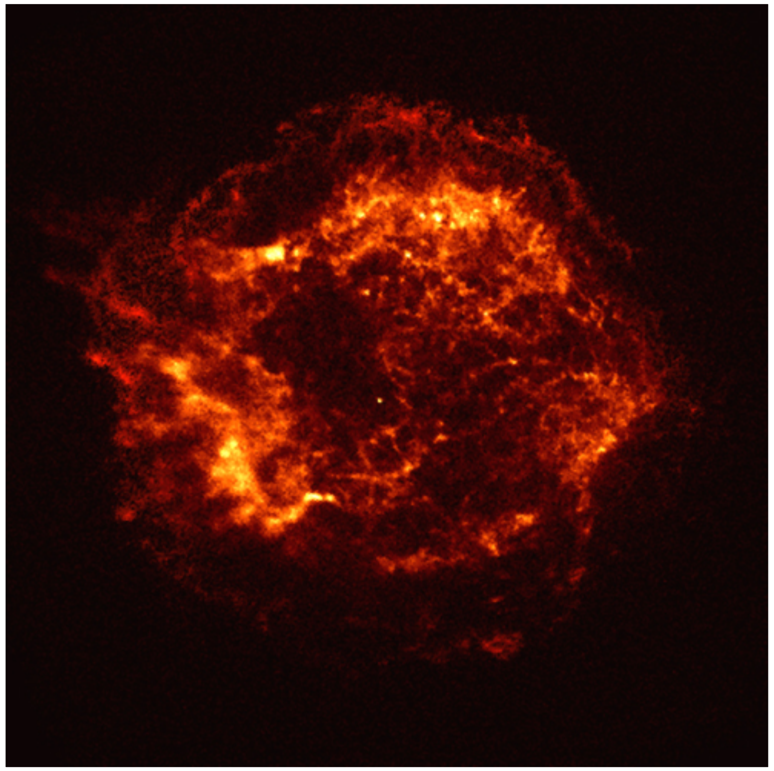
The Virtual Observatory

- Premise: most data is (or could be) **online**
- The Internet is the world's best telescope:
  - It has data on every part of the sky
  - In every measured spectral band; Optical, X-ray, Radio……..
  - As deep as the best instruments
  - It is up when you are up
  - The "seeing" is always great
  - It's a smart telescope; links objects and data to literature

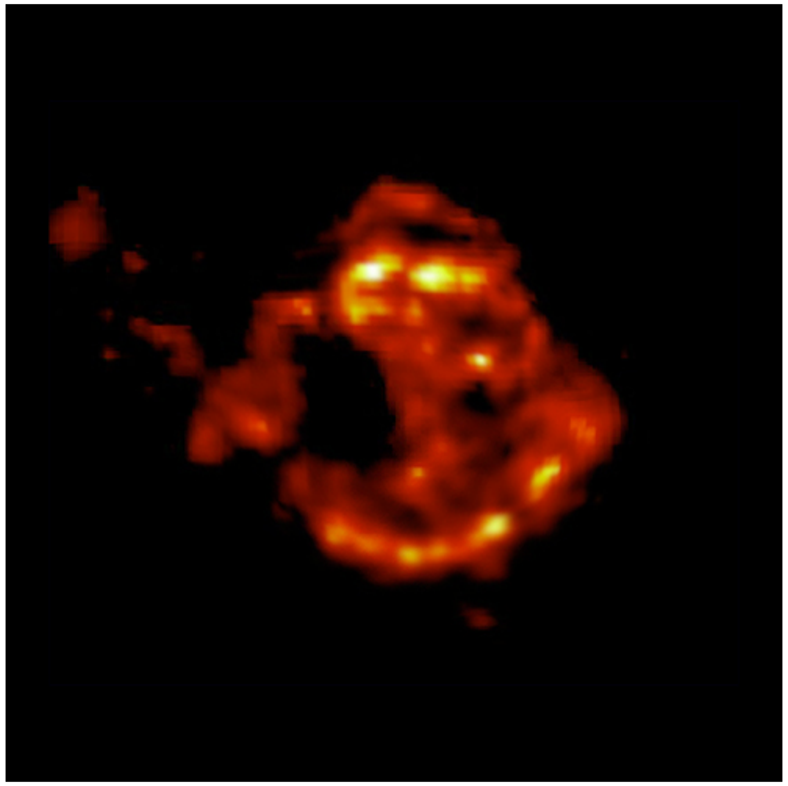


Data integration

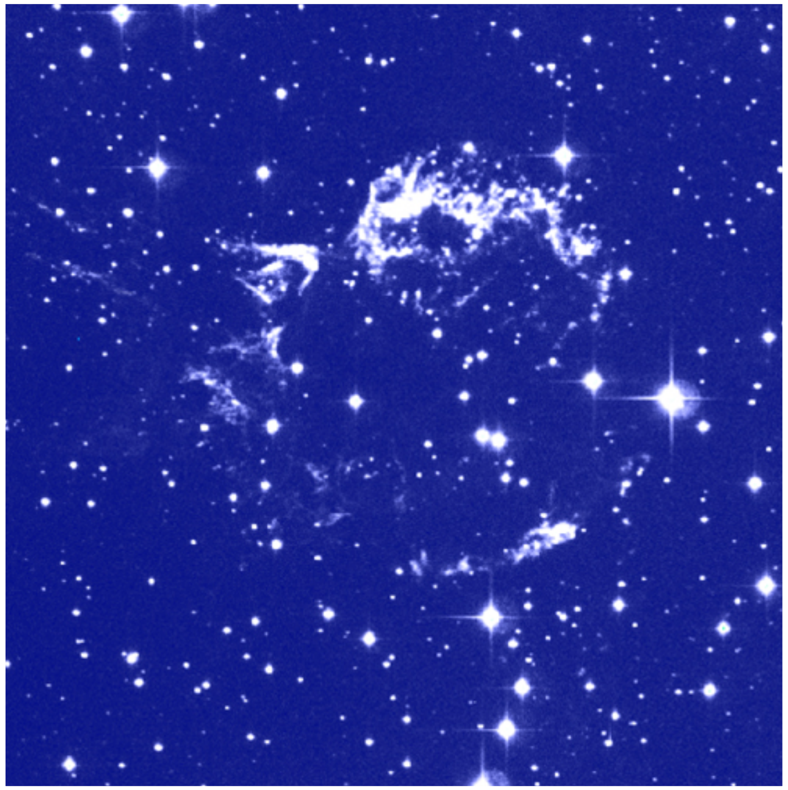
Multi-wavelength view of
Cas A
Supernova remnant



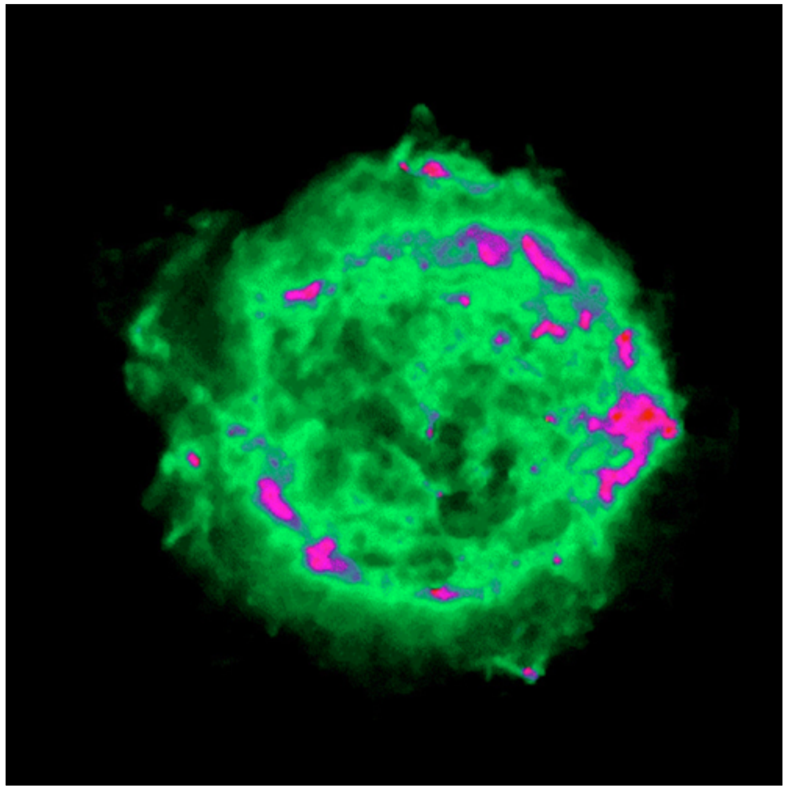
Shocks seen in the X-ray



Dust seen in the IR

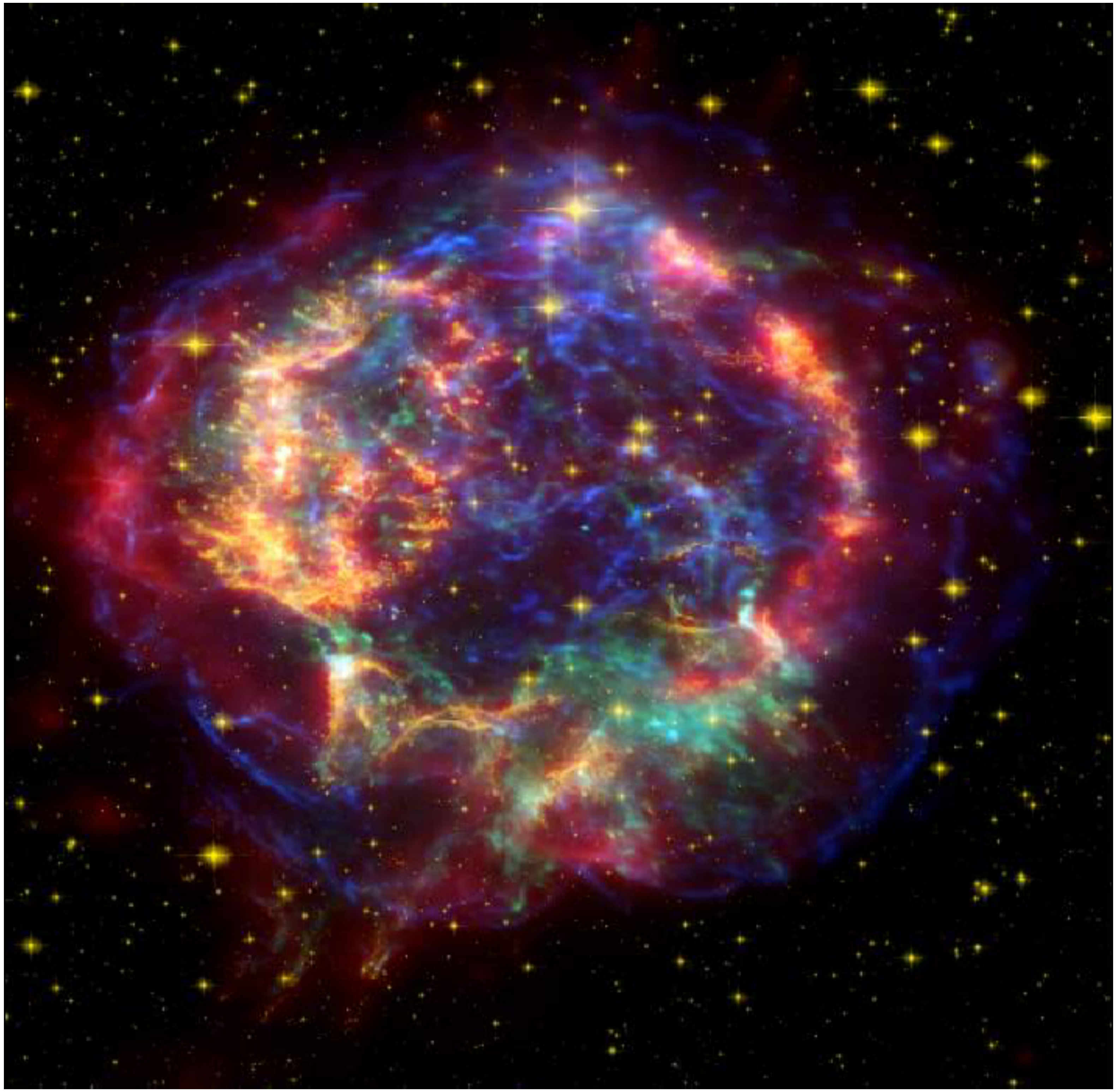


Heavy elements seen in the optical



Relativistic electron seen in the radio

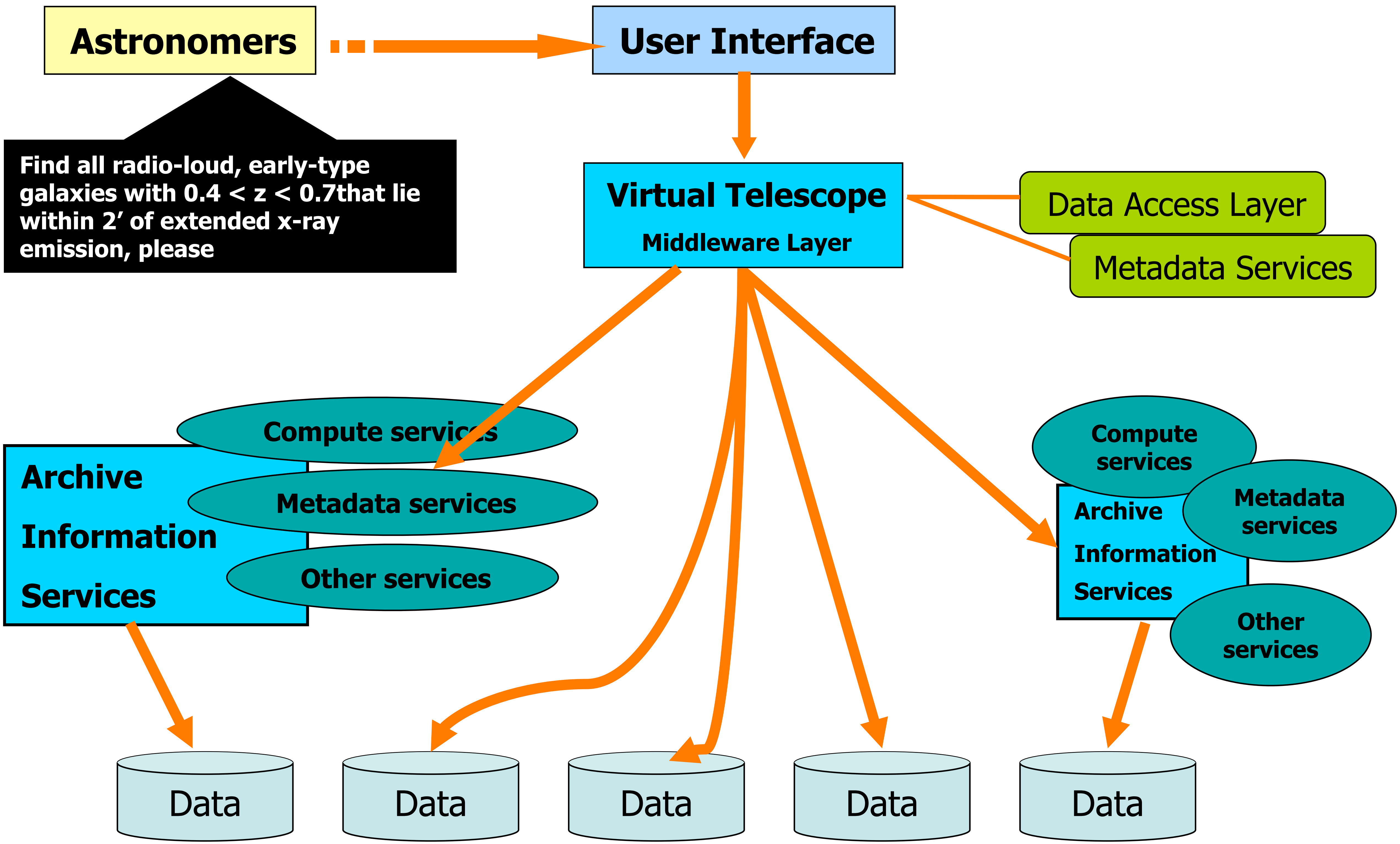
Data integration



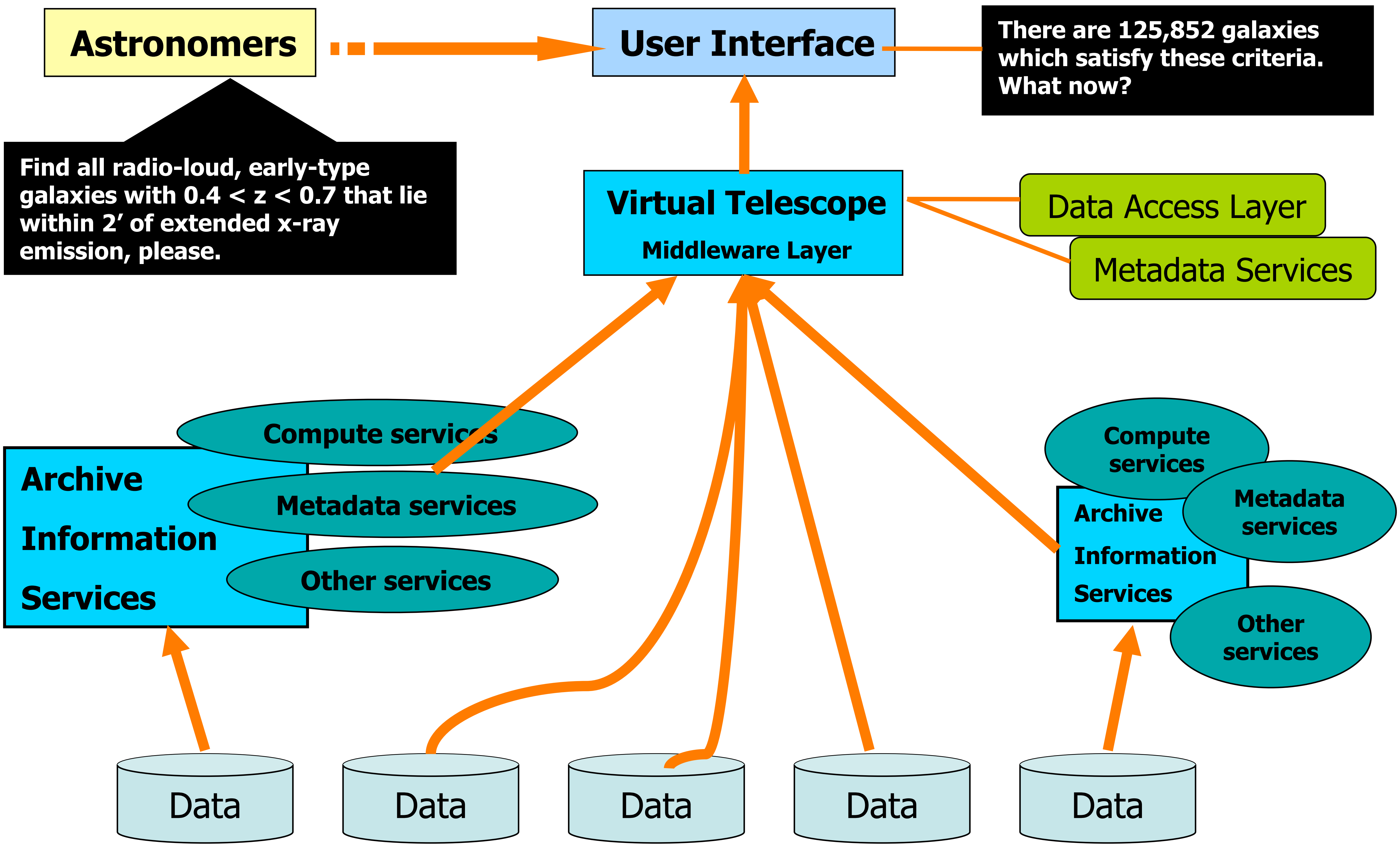
Why not just use Google?

- Very little astronomical data is text-based
- Text-based searches are unstructured
- Need to get inside data archives and databases to find the actual measurements and their uncertainties
- Google just leads you to web sites; the VO finds data and delivers it

The Virtual Observatory concept



The Virtual Observatory concept



Virtual Observatory Concept

WWW -
all the documents in the world inside your PC

VO -
all the database in the world inside your PC
A set of services & tools

Galaxy Zoo, Zoo-universe, World wide telescope (WWT), Google Sky-Earth-Moon-Mars

Some real life examples

- World's largest taxi company owns no taxis (Uber)
- Largest accommodation provider owns no real estate (Airbnb)
- Largest phone companies own no telco infra (Skype, Whatsapp)
- World's most valuable retailer has no inventory (Alibaba)
- Most popular media owner creates no content (Facebook)
- World's largest movie house own no cinemas (Netflix)
- Largest software vendors don't write the apps (Apple, Google)

VO data services

VO data services are Web-based

NED - NASA/IPAC Extragalactic Database http://nedwww.ipac.caltech.edu/

SIMBAD - Simbad astronomical database http://simbad.u-strasbg.fr/simbad/

VizieR - Service for Astronomical Catalogues http://vizier.u-strasbg.fr/cgi-bin/VizieR

MAST - Multimission Archive at STScI (for HST data) http://archive.stsci.edu/

ADS - Astrophysics Data System (Digital Library portal) http://
www.adsabs.harvard.edu/

SDSS, 2MASS, ESO data archive, 2dFGRS, Chandra data archive ……….

SALT-VODAS, MeerKat………

VO Tools And Services

- Web-based applications
- Stand-alone applications
- Smart Phone apps
- Scripting and programming environments –

  IDL, java, Python and IRAF

VO Tools And Services

- **Plotting** – provide variety of display options

includes some analysis facilities – statistics, filtering, corssmatching

VOPlot http://vo.iucaa.ernet.in/~voi/voplot.htm (VO-India)

TOPCAT http://www.star.bris.ac.uk/~mbt/topcat/ (Astrogrid)

- **Visualization** – image display, catalogue overlay …….

Aladin http://aladin.u-strasbg.fr/aladin.gml (CDS)

Mirage http://cm.bell-labs.com/who/tkh/mirage/index.html

VO Tools And Services

- **Data discovery** – locate (find), compare & retrieve data from variety of VO-accessible data archive… one-stop shopping

Datascope http://heasarc.gsfc.nasa.gov/cgi-bin/vo/datascope/init.pl (NVO)

SkyView http://skys.gsfc.nasa.gov/

- **Analysis Tools** – provide sophisticated analysis capabilities for making queries, cross-correlating catalogues, spectrum analysis……

Open SkyQuery http://openskyquery.net/Sky/skysite/browse/Browse.aspx

VOSpace http://esavo.esa.int/vospecapp

VOSed http://sdc.laeff.inta.es/vosed/jsp/form_search.jsp

SPLAT http://star-www.dur.ac.uk/~pdraper/splat/splat-vo/

MySpace

TOPCAT

EURO-3D

PLASTIC

Helioscope

ASTRO RUNTIME

Web Service

Yafit

VizieR

VOSpec

VOEventNet

WORKFLOW

SIA

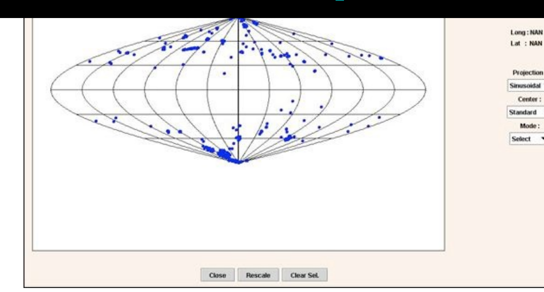
Simbad

Specview

representative and by no means complete!

Aladin

Astrogrid Workbench



VOPlot

VOTABLE

VisIVO

Open SkyQuery

SPLAT

ADS

Astroscope

STILTS

Registry

DATASCOPE

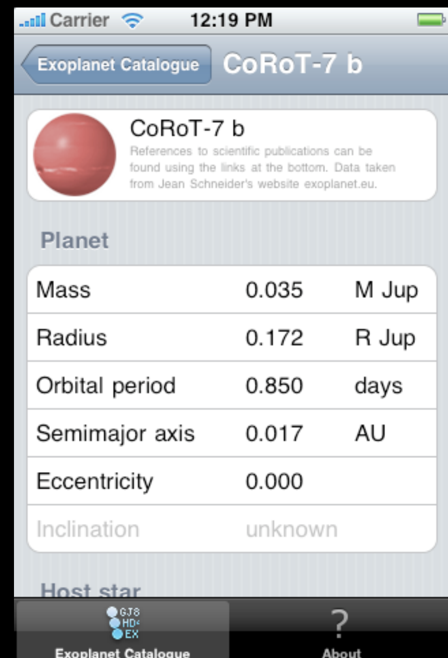
SSA

VOSED

VO apps for smart phones

VO apps for smart phones

SkySafari 3



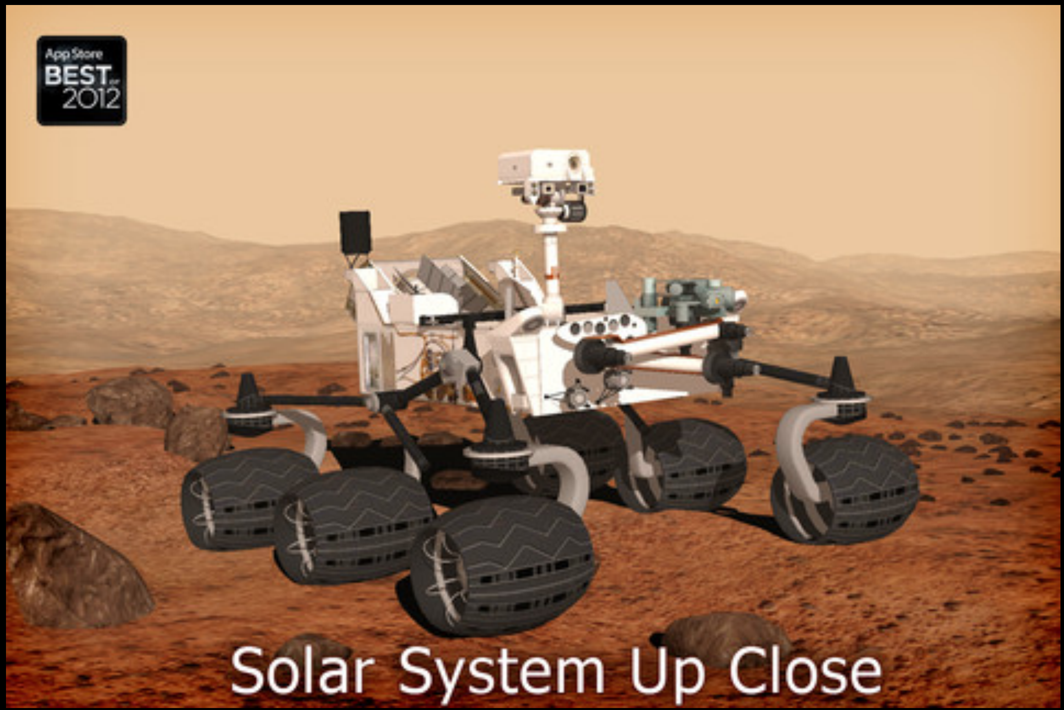
Exoplanet

Sky View

Star Walk

HubbleZoom

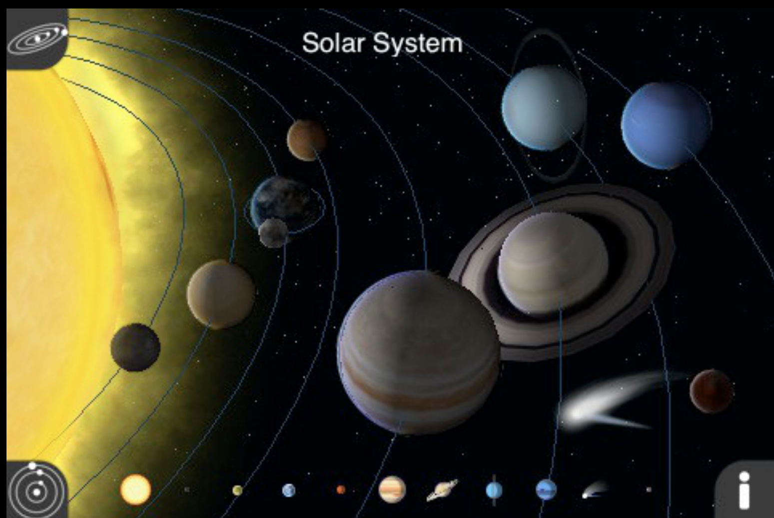
Galaxy Zoo



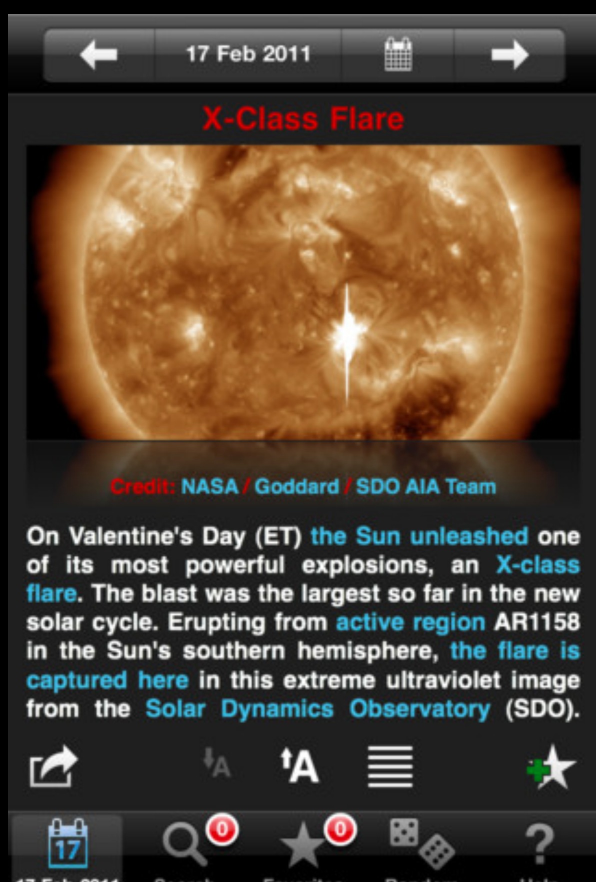
Solar Walk

VO apps for smart phones

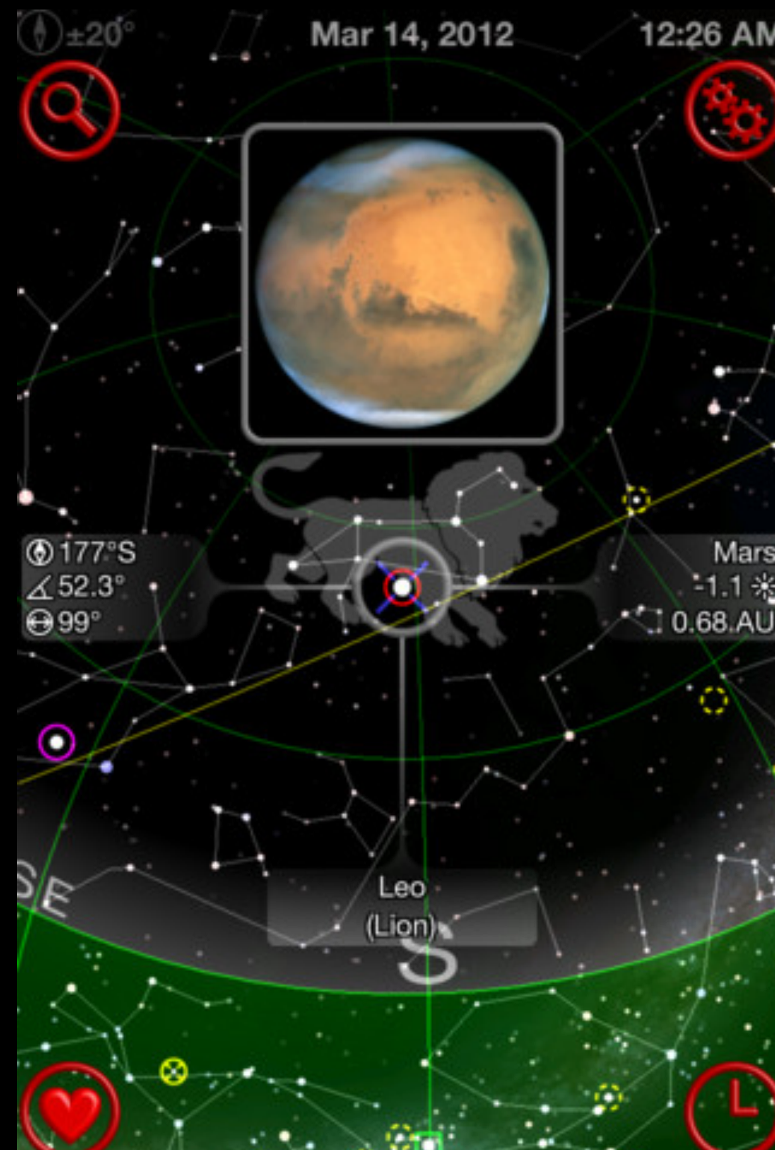
Android market ~350 astronomy apps



Solar System



APOD viewer



GoSky watch

Google Sky Map

Citizen Science Projects

Space

Sort by Category

How do galaxies form?

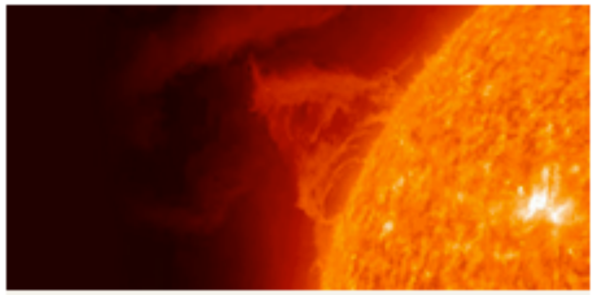
NASA's Hubble Space Telescope archive provides hundreds of thousands of galaxy images.

GALAXY ZOO

Explore the surface of the Moon

We hope to study the lunar surface in unprecedented detail.

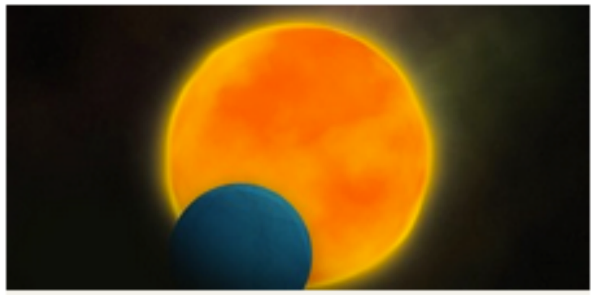
MOON ZOO



Study explosions on the Sun

Explore interactive diagrams to learn out about the Sun and the spacecraft monitoring it.

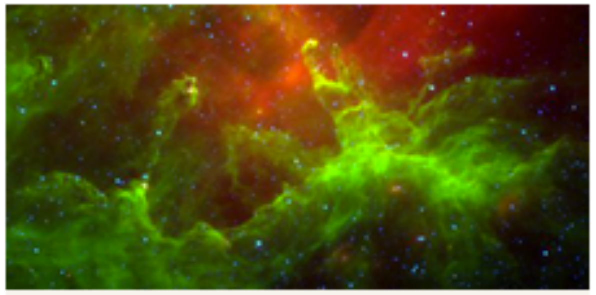
SOLAR STORMWATCH



Find planets around stars

Lightcurve changes from the Kepler spacecraft can indicate transiting planets.

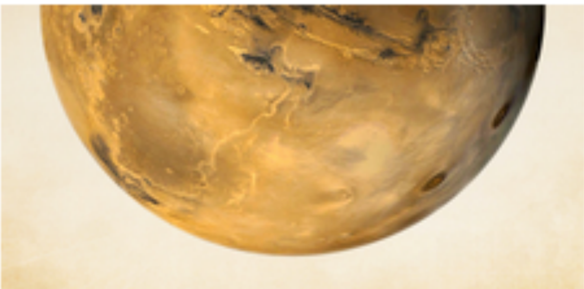
planethunters.org



How do stars form?

We're asking you to help us find and draw circles on infrared image data from the Spitzer Space Telescope.

THE MILKY WAY PROJECT



Explore the Red Planet

Planetary scientists need your help to discover what the weather is like on Mars.

PLANET FOUR

Climate

Model Earth's climate using wartime ship logs

Help scientists recover worldwide weather observations made by Royal Navy ships.

oldWeather

Classify over 30 years of tropical cyclone data.

Scientists at NOAA's National Climatic Data Center need your help.

CycloneCenter

Humanities

Study the lives of ancient Greeks

The data gathered by Ancient Lives helps scholars study the Oxyrhynchus collection.

ANCIENT LIVES

Nature

Hear Whales communicate

You can help marine researchers understand what whales are saying

WHALE FM

Help explore the ocean floor

The HabCam team and the Woods Hole Oceanographic Institution need your help!

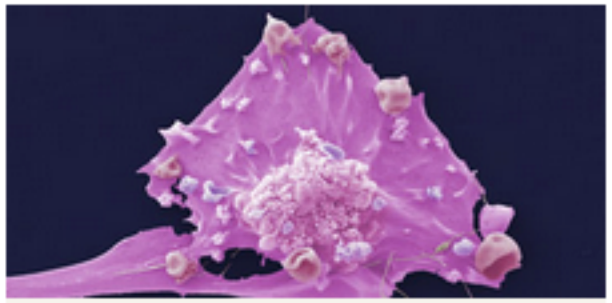
SEAFLOOR EXPLORER

You're hot on the trail of bats!

Help scientists characterise bat calls recorded by citizen scientists.

BAT DETECTIVE

Biology



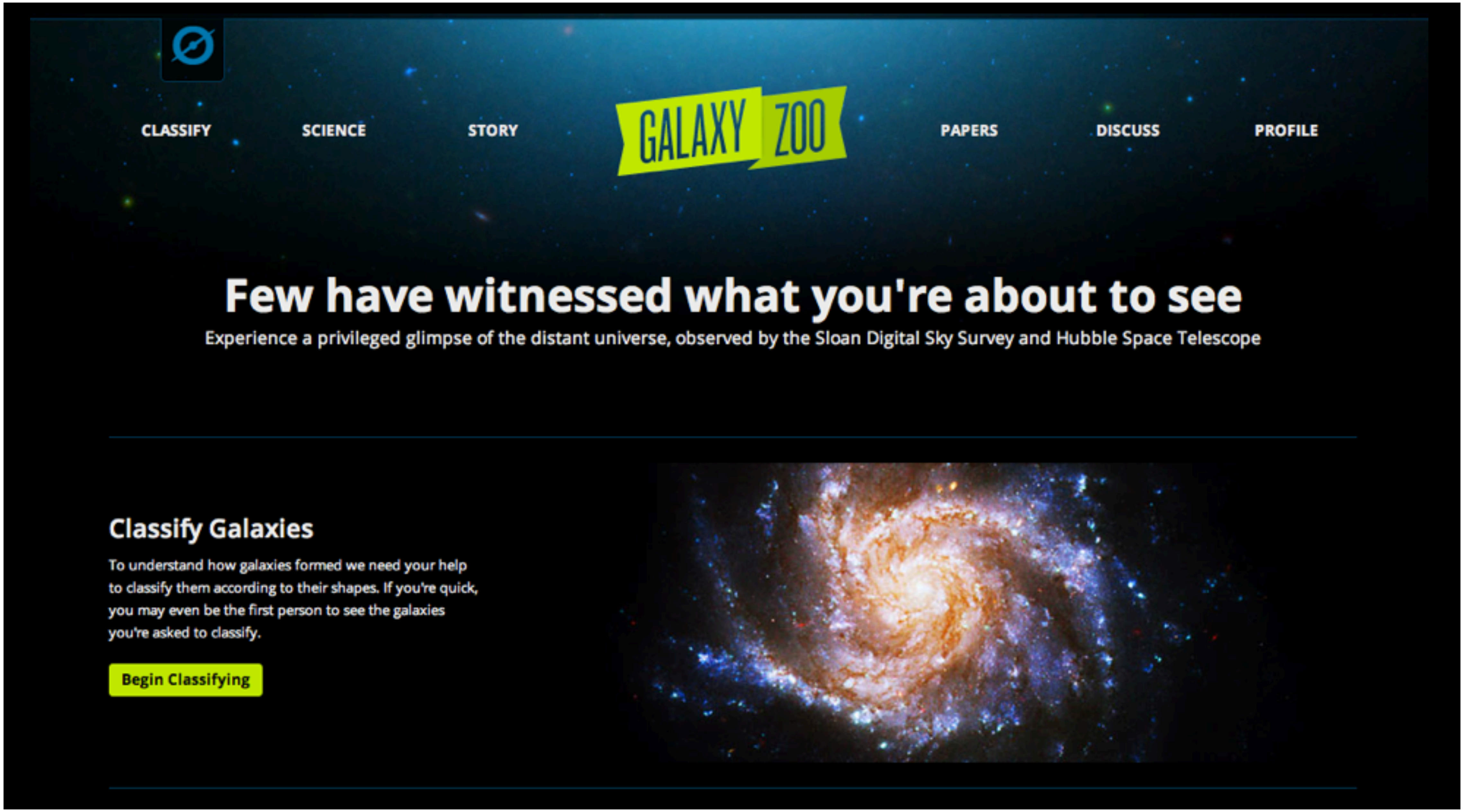
Analyse real life cancer data.

You can help scientists from the world's largest cancer research institution find cures for cancer.

Cell Slider

Citizen Science project

Galaxy Zoo Legacy - Zoo Universe



Pune Knowledge Cluster
Citizen Science Project

Citizen Science

Astronomy

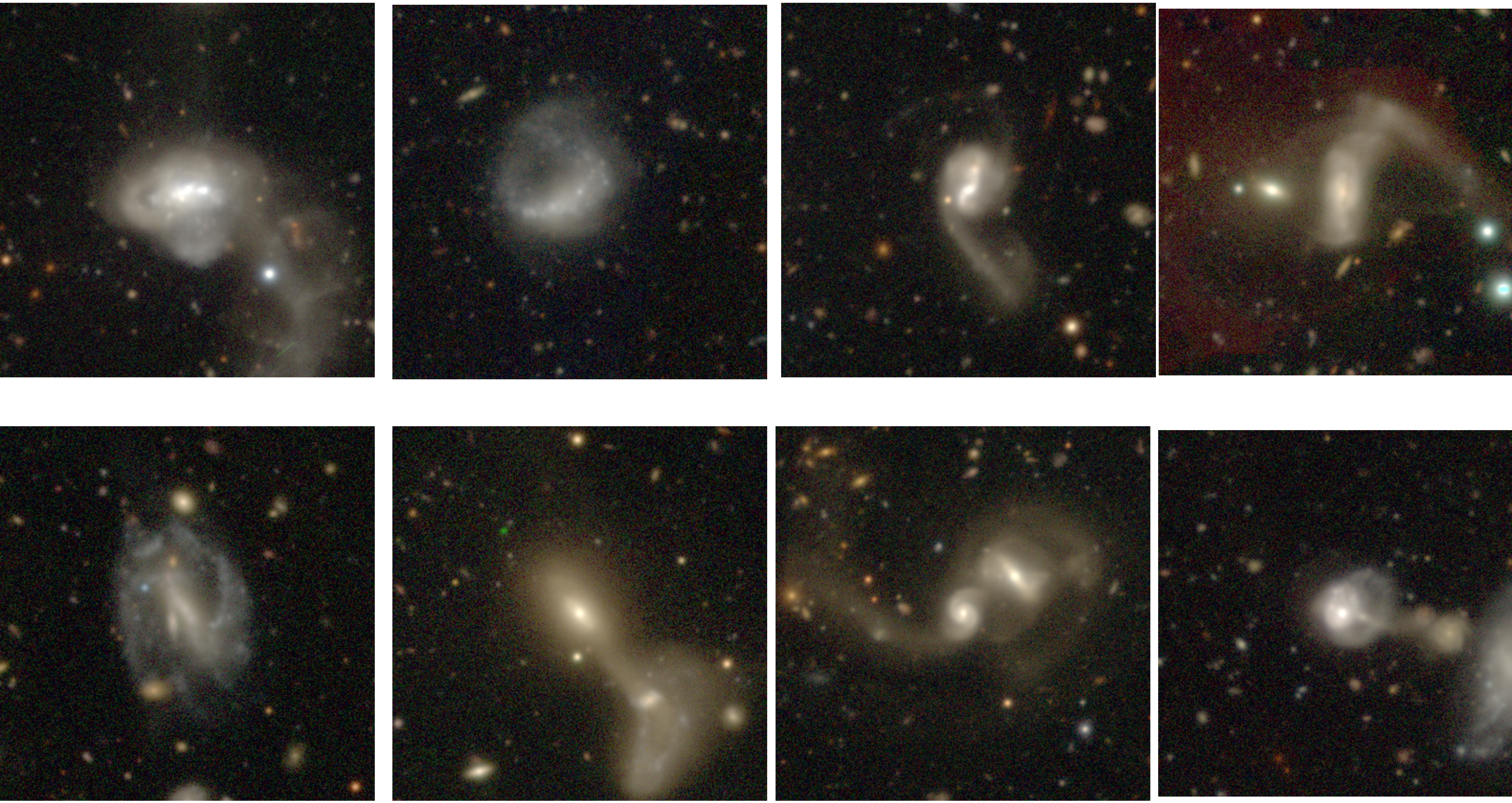
One Million Galaxies

The program helps connect citizens to the frontiers of current scientific projects. In order to save computational resources, this platform can be used by scientists to get first- hand data analytics leveraging on enthusiastic smart citizens.

Participate

http://csa.pkc.org.in/

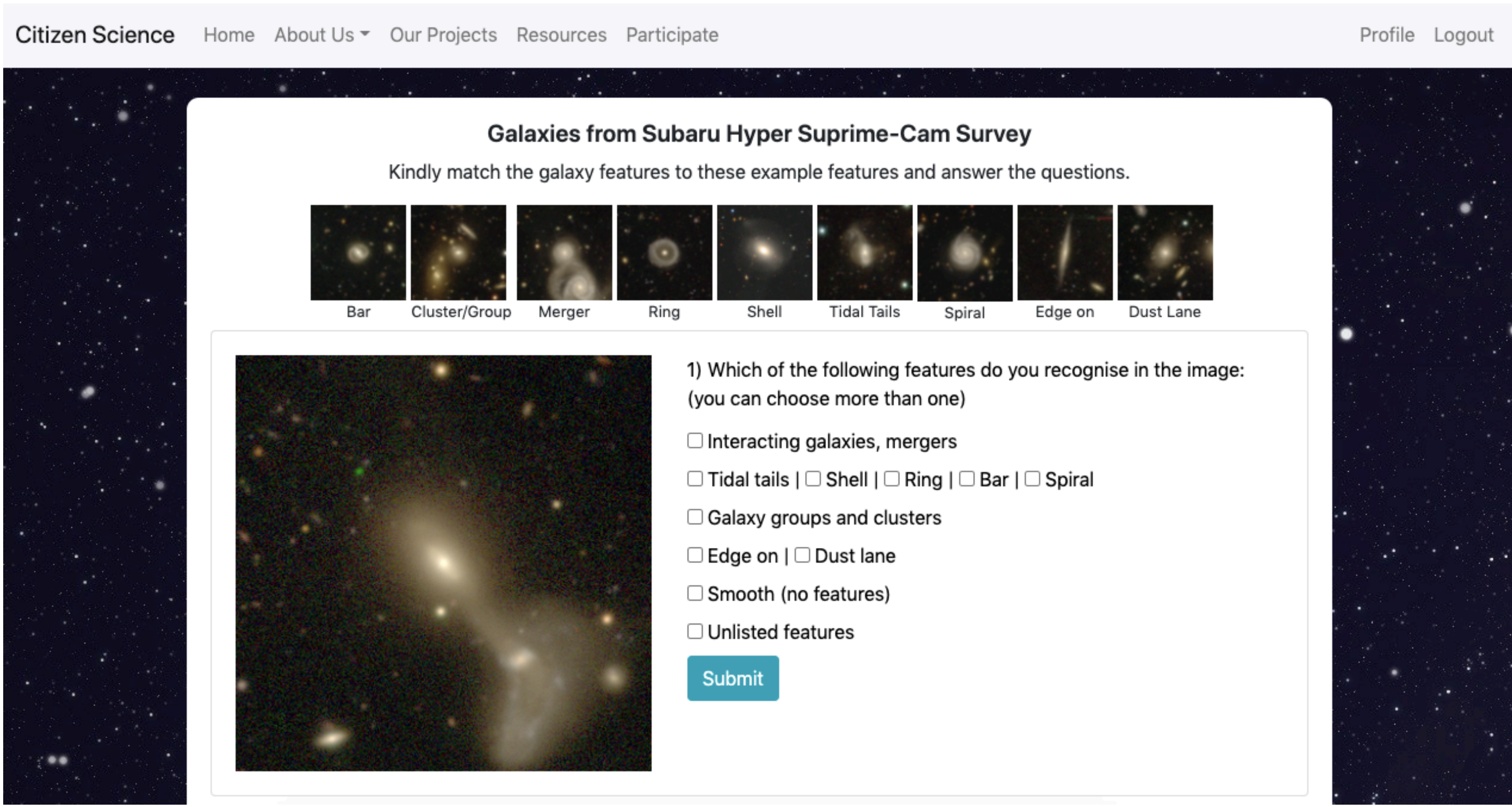
PKC Citizen Science Project



(Image credit: Subaru HSC survey)

PKC Citizen Science Project

Youtube channel for training sessions — https://bit.ly/3kPalur



Virtual Observatory for Fun

World Wide Telescope (WWT)

World Wide Telescope

World Wide Telescope

- Knited together terabytes of online data (data from various telescopes and surveys) into a seamless, zoomable experience
- Lets users create their own guided tours of the deep sky (Smallest user is 6 years old)
- Translate WWT desktop in any language

WWT Tour - The Hopeless Hunter

Credits - Troshini Naidoo, Veronique Kazie-Ravet, Francois Taljaarad, Temba Matomela
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The Hopeless Hunter

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Summary

- VO relies on data collected and archived from real observatories.
- All astronomical databases one click away.
- All major data centers provide or planning VO-compatible interface to their data.
- VO enables research that cannot be done with one telescope or instrument.
- VO provides a computational framework that supports research questions that are now difficult, if not impossible, to carry out.
- The final goal is **Science**.

Thank You!

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