Variable Star Search Using ROTSE3 Data

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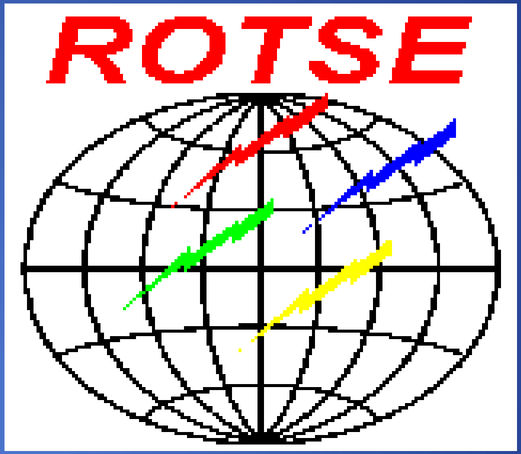


Outline

- Celestial Coordinates
- CCDs
- HR Diagram
- ROTSE
- ROTSE3
- Variable Stars
- Binary Stars
- Eclipsing Binary Stars
- Contact Binary Stars
- Light Curves
- Conclusion
- References

V838 Monocerotis and light echo

CCD History

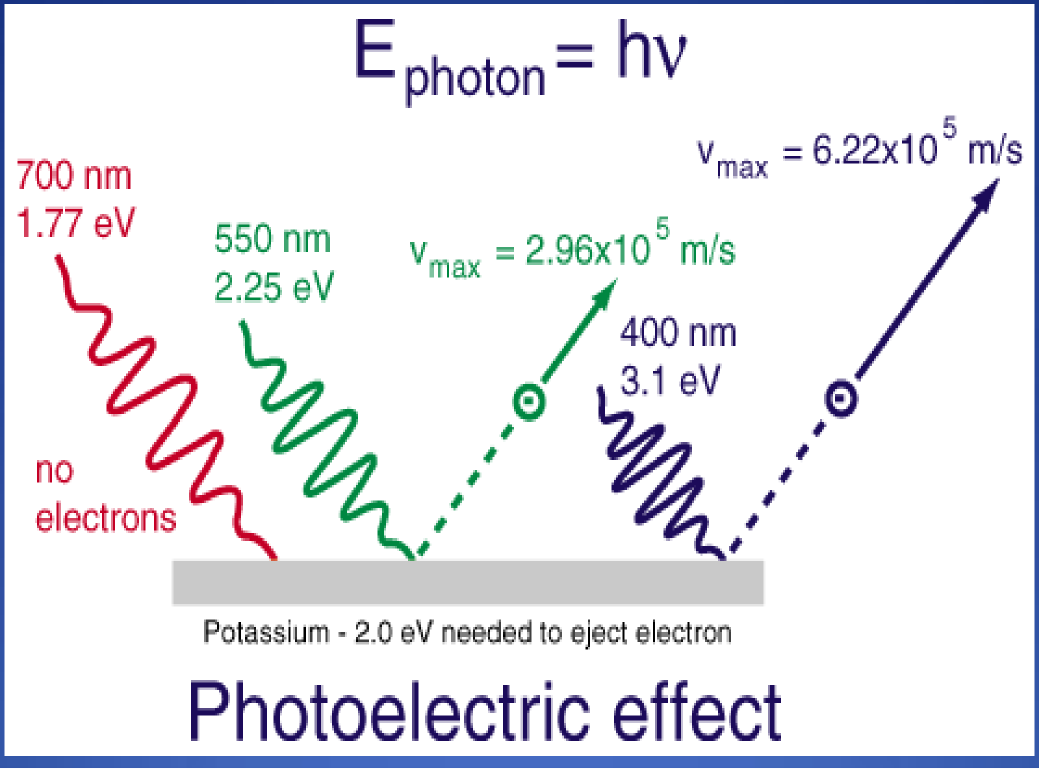
- Invented by William S. Boyle & George E. Smith at AT&T Bell Labs, 1969 -- awarded 2009 Nobel Prize for Physics
- Working version produced within a year
- Light sensitive properties were quickly exploited for imaging applications -- major revolution in Astronomy
- Improved the light gathering power of telescopes by almost two orders of magnitude
- CCDs are present in every instrument which uses electronic imaging -- TV, video systems, digital cameras, optical scanners

The Tadpole Galaxy (UGC 10214; Arp 188). The "narrow filament", which appears to be tidal feature caused by a gravitational interaction, can be seen extending across this image.

CCD & Film Comparison

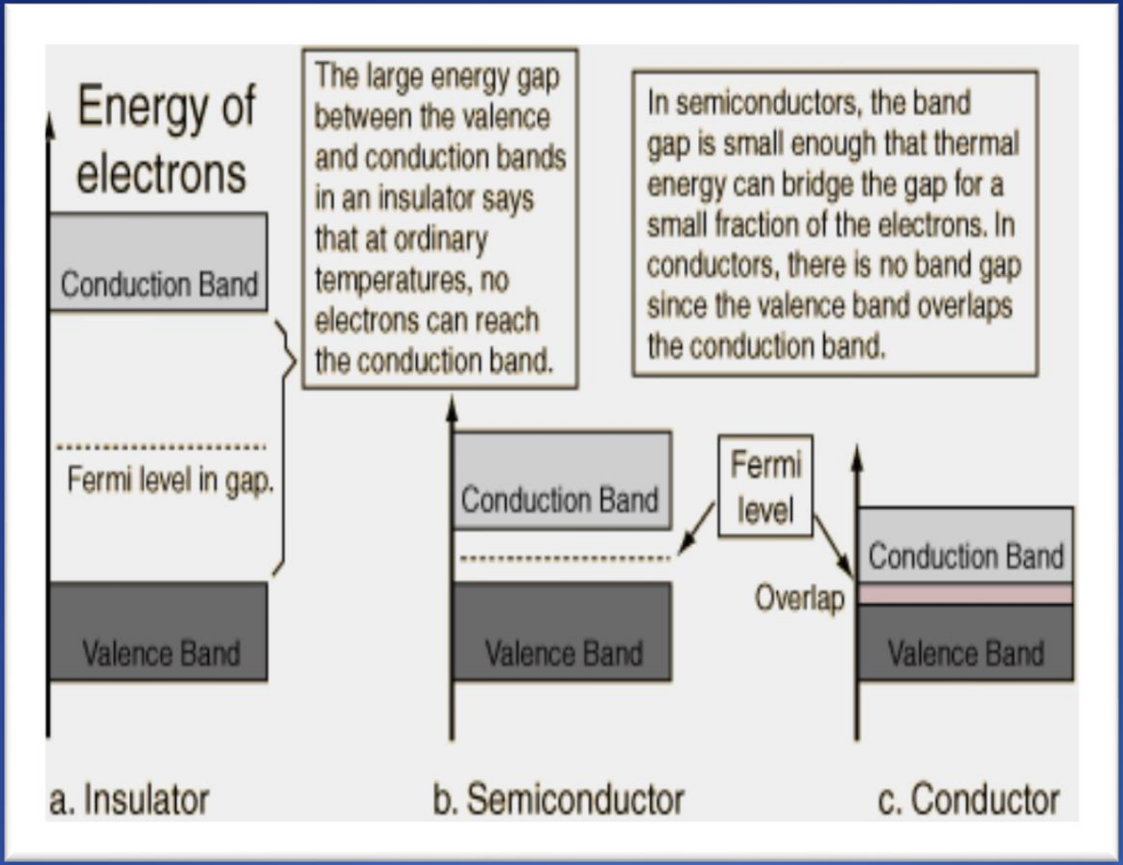
	FILM	CCD
Type of reaction	Chemical, physical	Physical
Quantum Efficiency	<10%	>80%
Resolution	10 to 25 micron	6 to 24 micron
Pixel matrix size	1200x1800 (24x36 format)	512x512 to 8192x8192
Spectral response	350 to 650 nm can be extended from 250 to 950 nm	400 to 900 nm can be extended from 300 to 1100 nm
Time from the end of the exposure to image	>30 minutes	< 10 seconds (for larger format CCD)
Dynamic range	<16 bits	>=16 bits (65536 gray levels)
Equipment cost	Low	High
Auto guiding when exposing	Not possible	Yes
Direct image processing	Only after scanning the image	Yes
Remotely image acquisition	Not possible	Yes
Automatic image capturing (no need for operator)	Not possible	Yes
Need for cooling system	No	Yes
Special chemical and physical processes and procedures for sensitivity increment	Yes	No need
Special environment for developing	Yes	No
Interferometric telescope connection capability	Not possible	Yes
Automatic correction on adaptive and active optics capability	Not possible	Yes
Automatic protection against saturation	Not possible	Yes
Antiblooming capability	Not possible	Yes
Reciprocity effect failure	Yes	No
Loss of sensitivity if not cooled	Yes but low	Yes but high
Binning capability	Only after scanning the image	Yes
Resolution increasing	Not possible	Yes

Photoelectric Effect



- $K = hf - W$ (W = work function -- minimum energy required to remove an electron from the surface of any given metal)
- An image is acquired when incident light in the form of photons falls on the array of pixels.
- The energy associated with each photon is absorbed by the silicon and a reaction takes place that creates an electron-hole charge pair .
- The number of electrons collected at each pixel is linearly dependent on light level and exposure time, nonlinearly dependent on wavelength.

Semiconductors

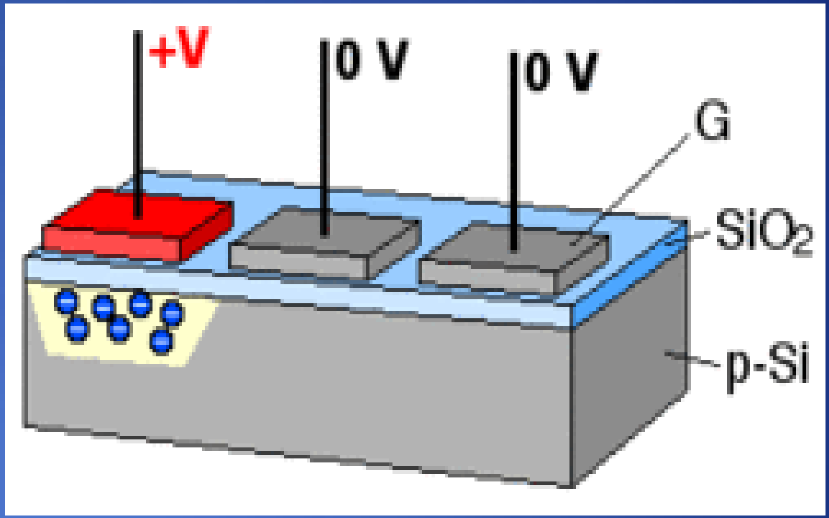


- Intermediate conductivity between insulators & conductors
- Small energy input can promote e- to conduction band
- Silicon band gap = 1.12 eV; λ = 1 μm (NIF)

CCD Basic Principles

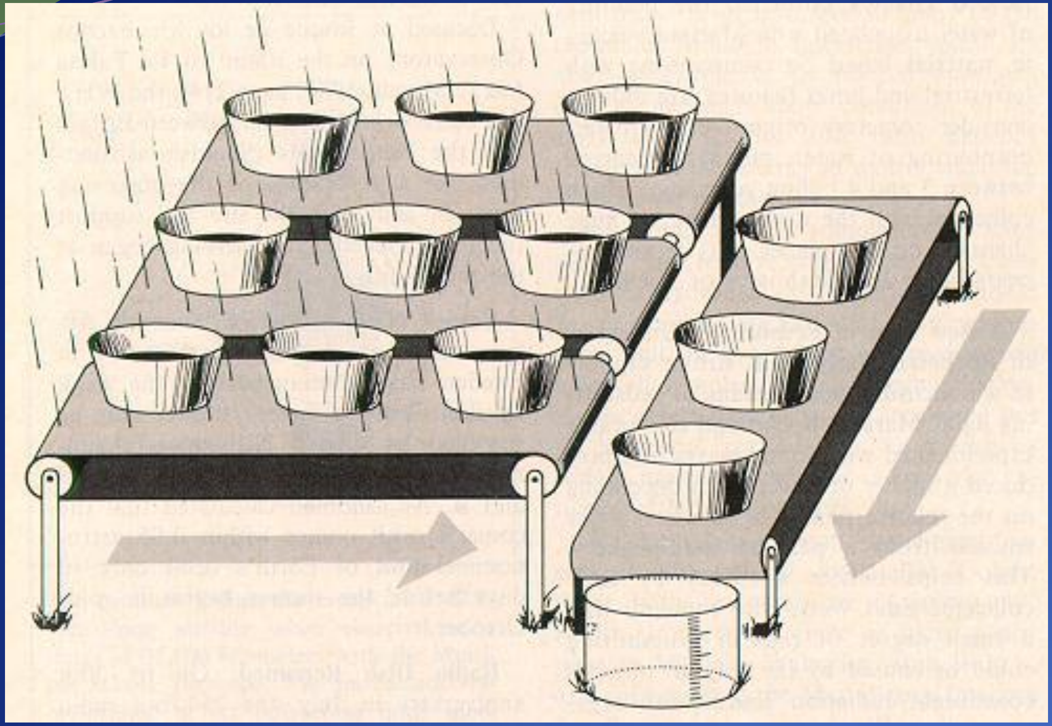
- CCD: charge-couple device
- Array of linked ("coupled") capacitors
- Photons interact in a semiconductor substrate, electrons released
- Applied electric field collects & stores the electrons in pixels
- Pixels are coupled and can transfer their charges to neighboring pixels
- Stored charge is transferred to a output amplifier and read out, stored on a computer as an image file

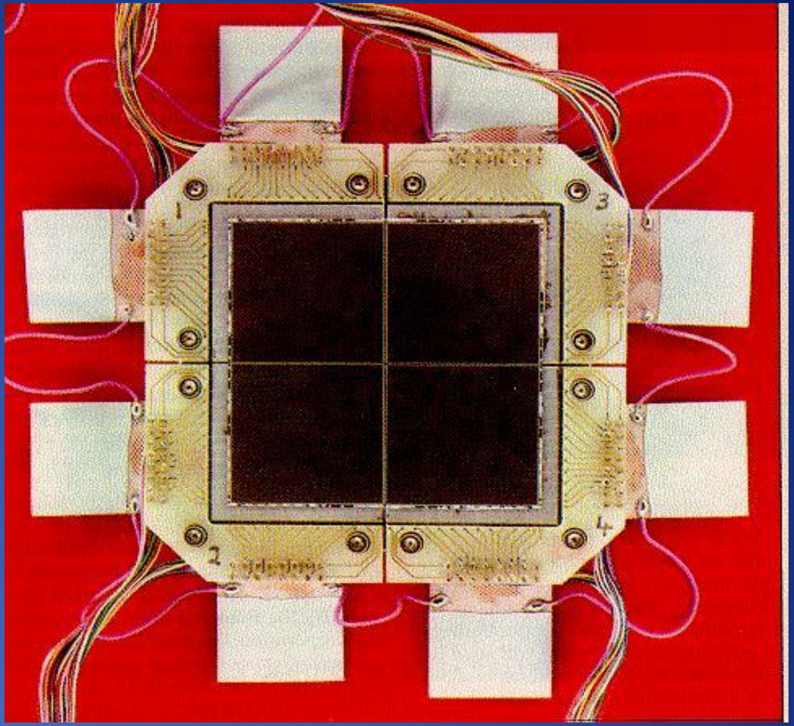
CCD from a 2.1 megapixel Hewlett-Packard digital camera.



The charge packets (electrons, blue) are collected in potential wells (yellow) created by applying positive voltage at the gate electrodes (G). Applying positive voltage to the gate electrode in the correct sequence transfers the charge packets.

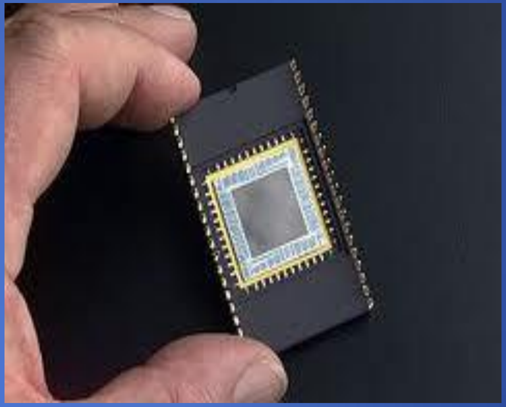
Operation: How Does a CCD Work?



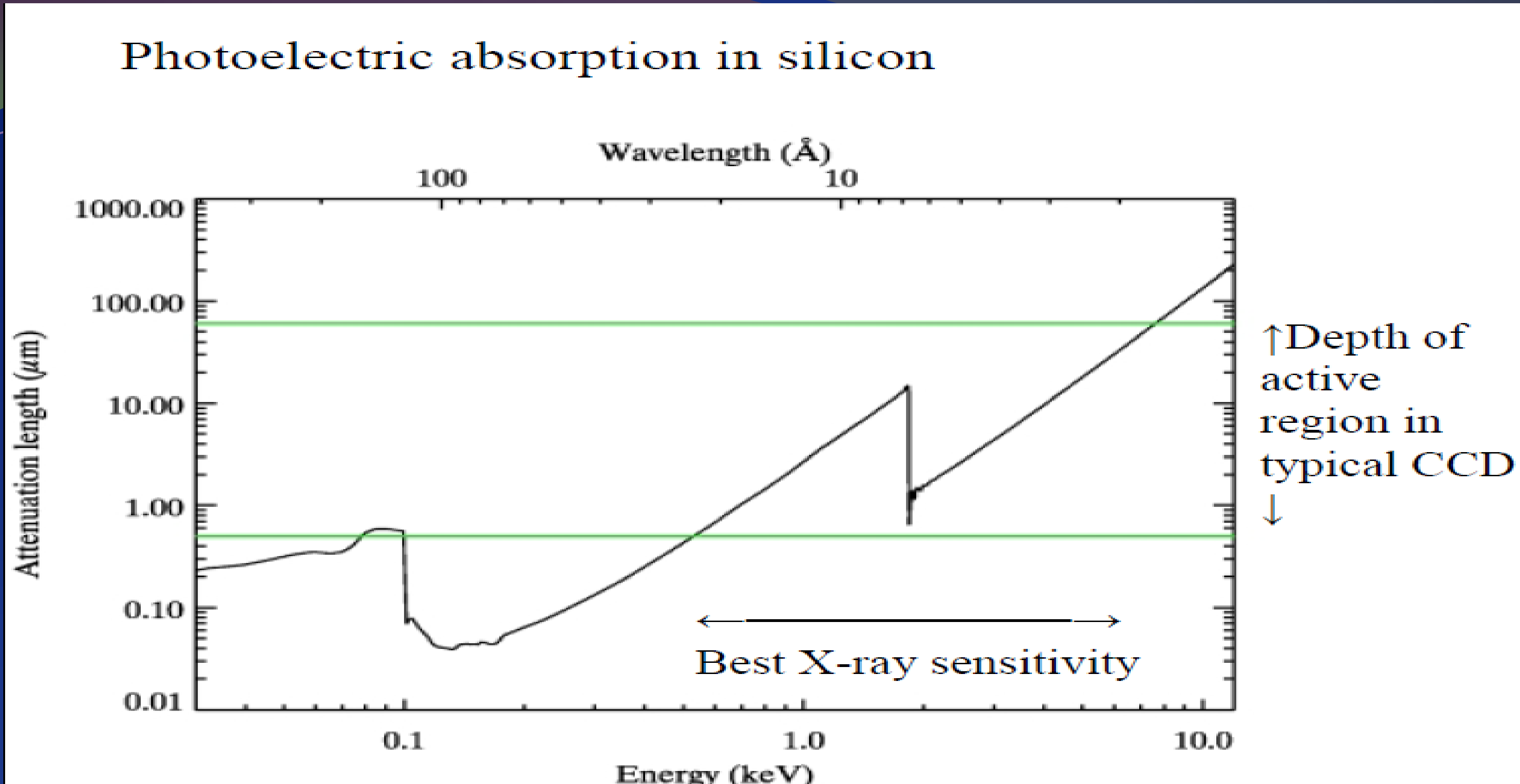


In order to produce an image, a CCD must accomplish 4 functions:

- Generate photoelectrons (rain drops)
- Collect electrons (buckets)
- Transfer the collected charges (conveyor belts)
- Read the charges (weighing stations)



A specially developed CCD used for ultraviolet imaging in a wire bonded package.



Photoelectric interaction of photon with Si atoms generates electron-hole pairs

-- Ne = E / W (on average)

– Ne = number of electrons– E = energy of photon

– W ~ 3.7 eV/e- (temperature dependent)

Incident photons create a charge cloud which can diffuse and/or move under influence of an electric field

Charge collection

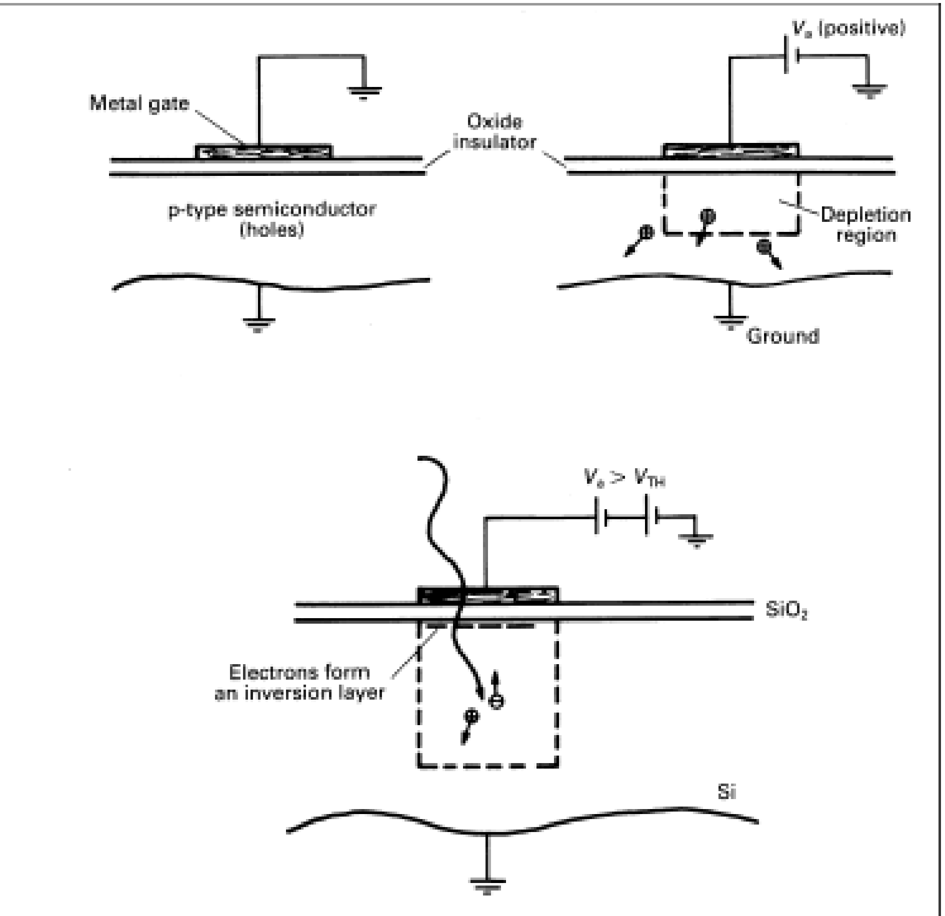


Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.

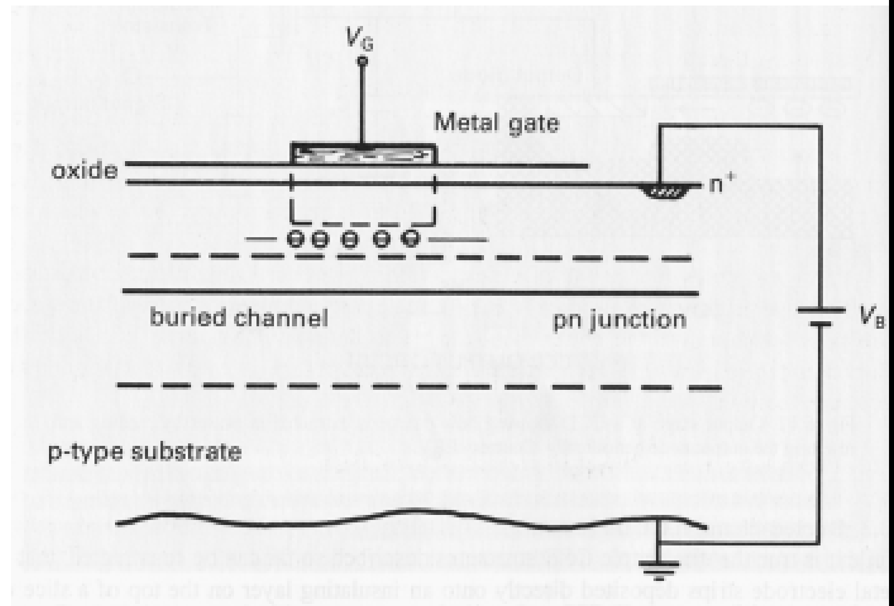


Fig. 6.12. (a) A single storage site in the buried-channel type of CCD. As the gate voltage increases the depleted zones finally meet.

A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD

Buried channel CCD
MOS plus pn junction
Prevents trapping by surface states at the semiconductor-oxide interface

Electrostatic Potential in CCD

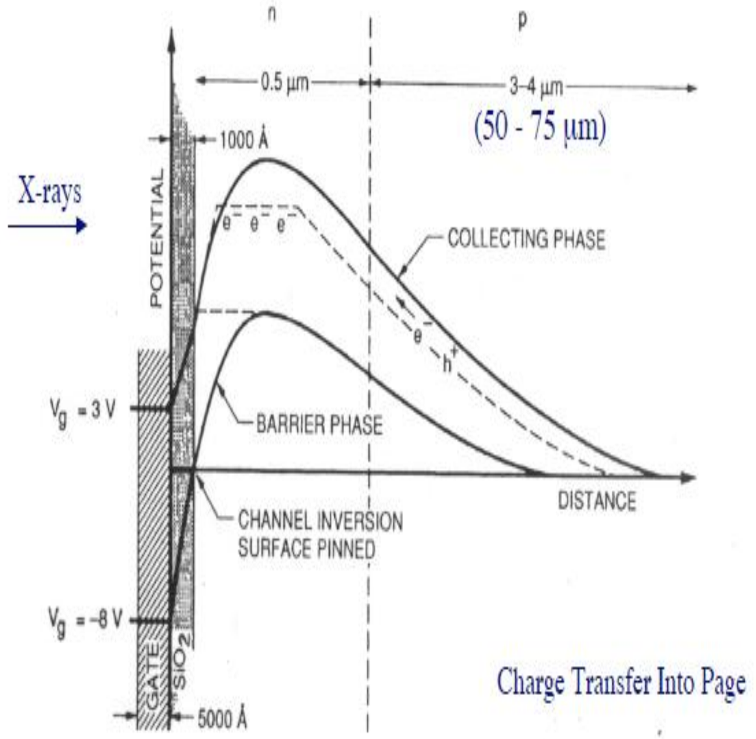
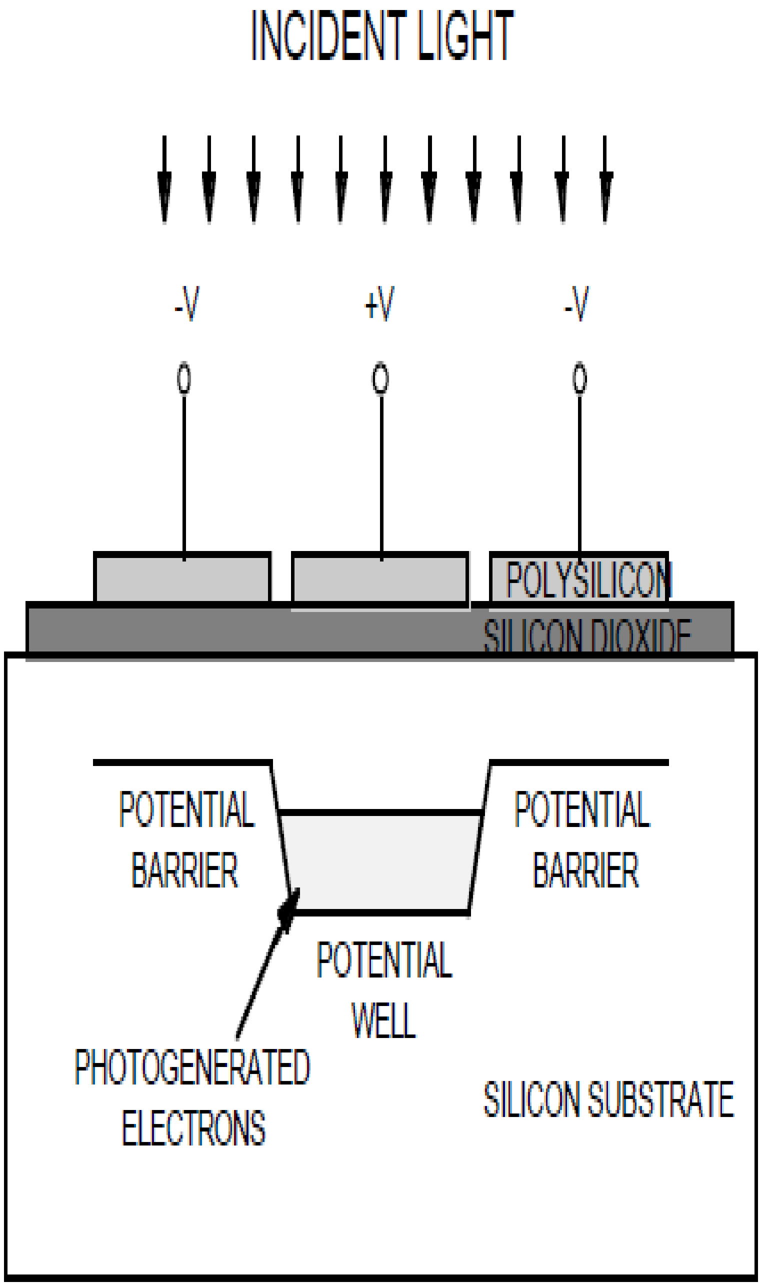
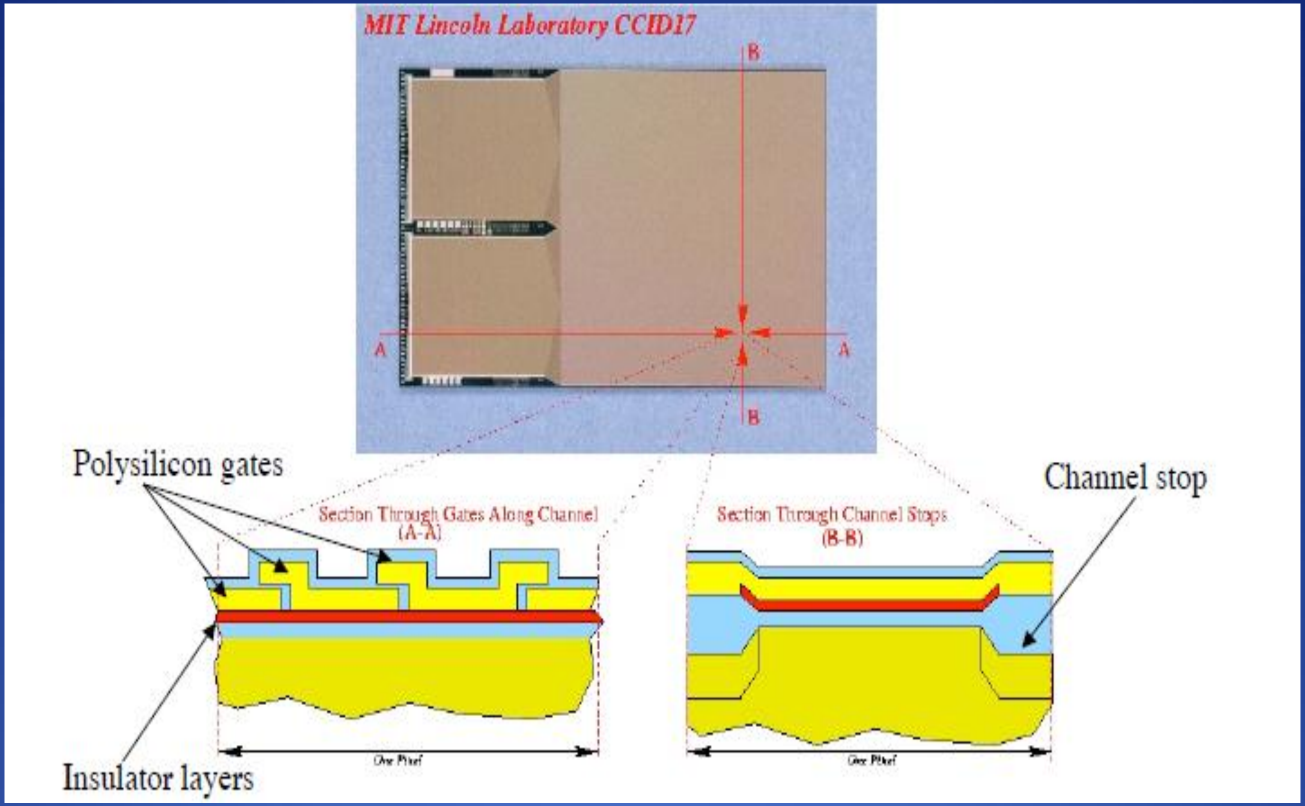


Figure 1.19 Buried-channel potential well.

Janesick, 2001

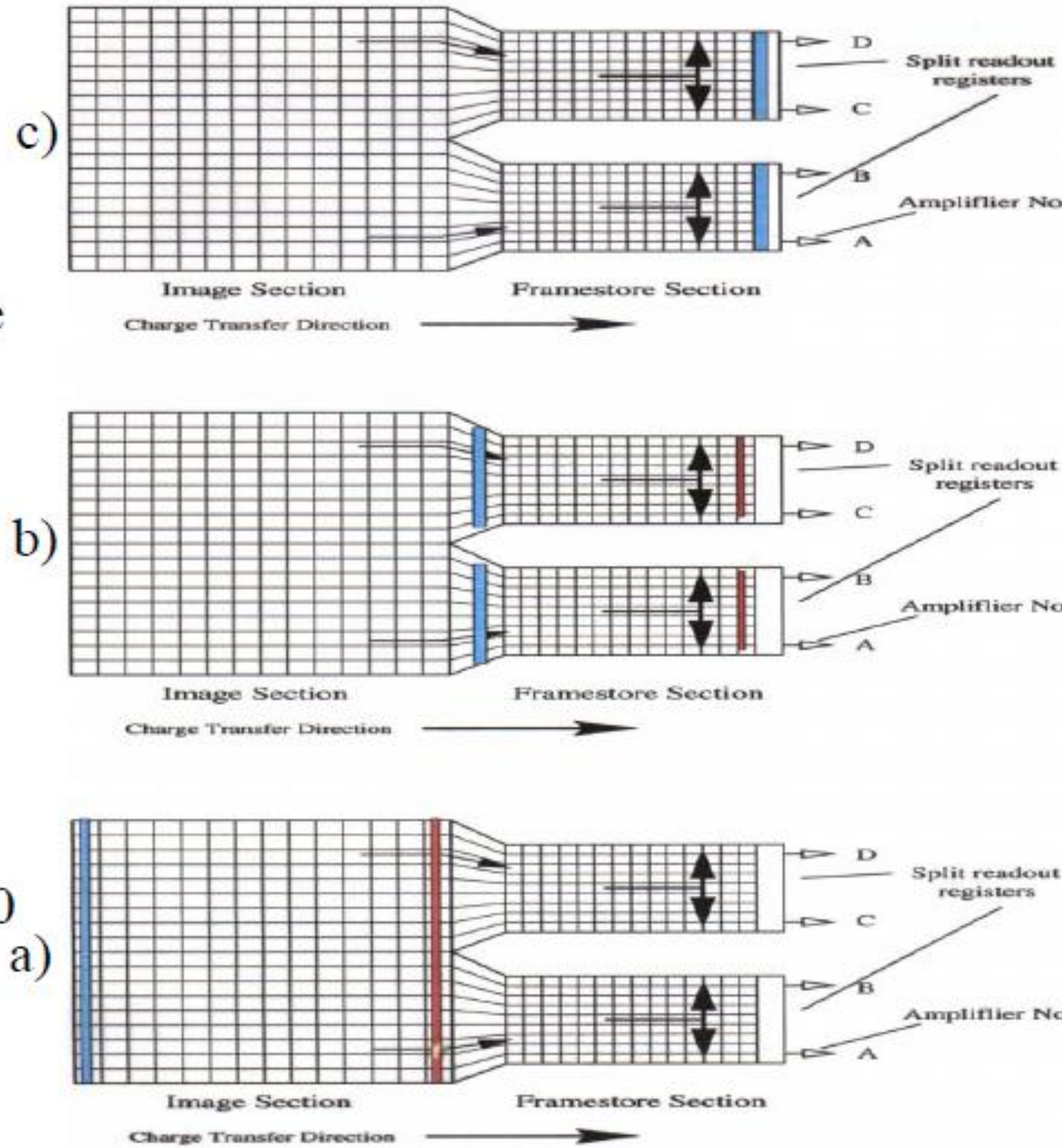


Pixel Structure & Charge Transfer



- As charge is integrated and stored in the pixel architecture, there must be a means of getting the charge to the sense amplifier -- physically separated from the pixels
- As the charge associated with one pixel moves, the charge in all the pixels associated with that row or column moves simultaneously
- Charge packets are eventually shifted to the output sense node -- electrons are converted to voltage (charge-to-voltage amplifier)

- Charge readout
  - Rapid transfer to framestore region; a)→b)
  - Slower line-by-line transfer to serial register; b)→c)
  - Charge in each pixel measured by amplifier (the slower the measurement, the lower the noise)
  - Chandra ACIS: 100 kHz readout produces a 3.2 second frametime



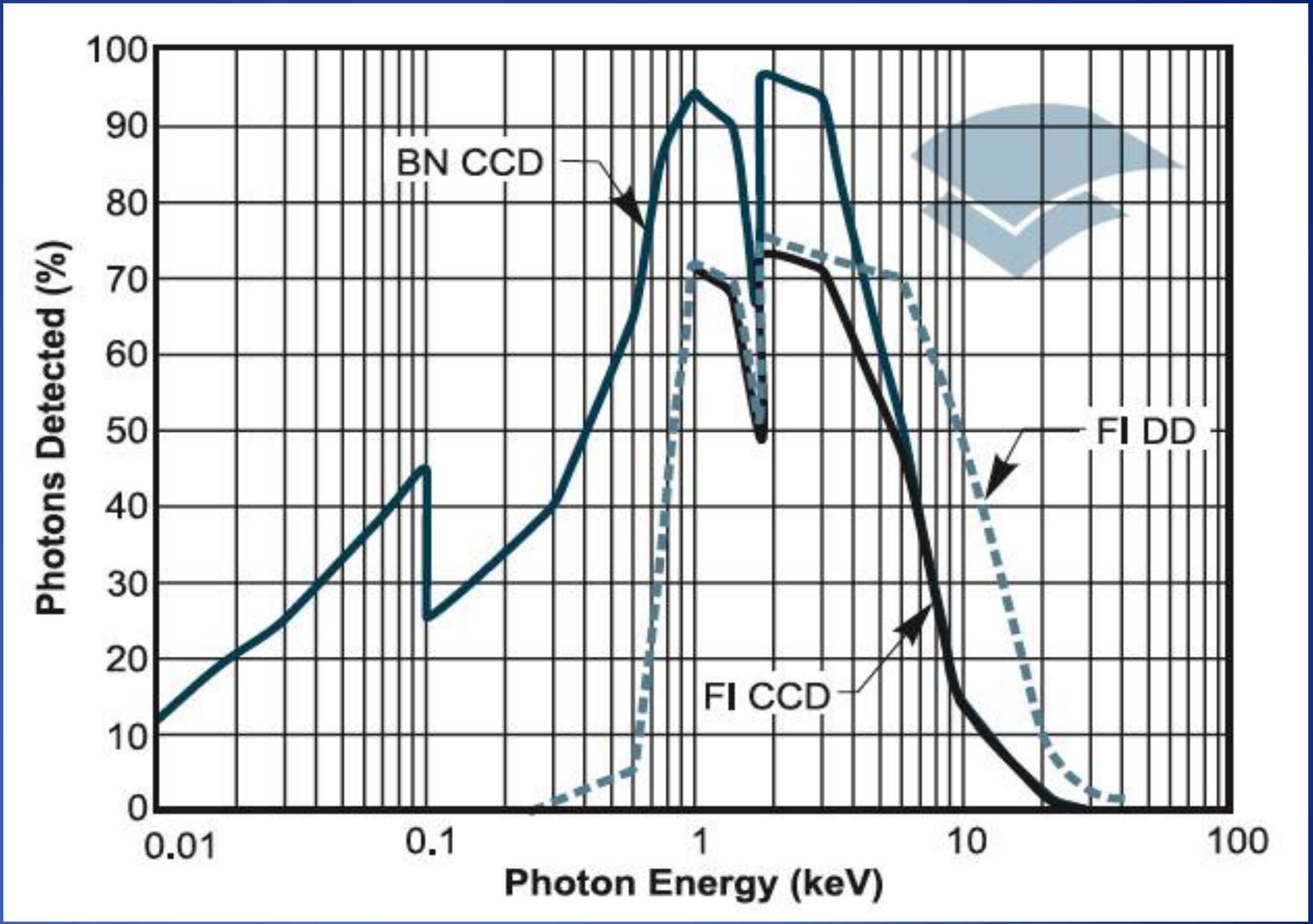
Energy Resolution

Spectral Range

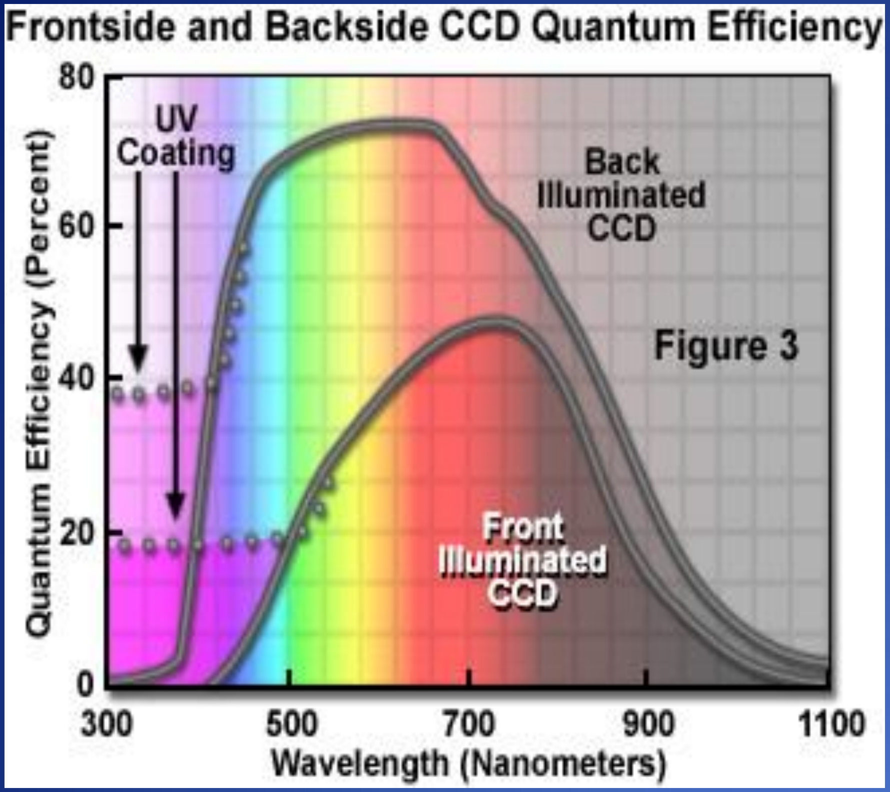
FI: front illuminated

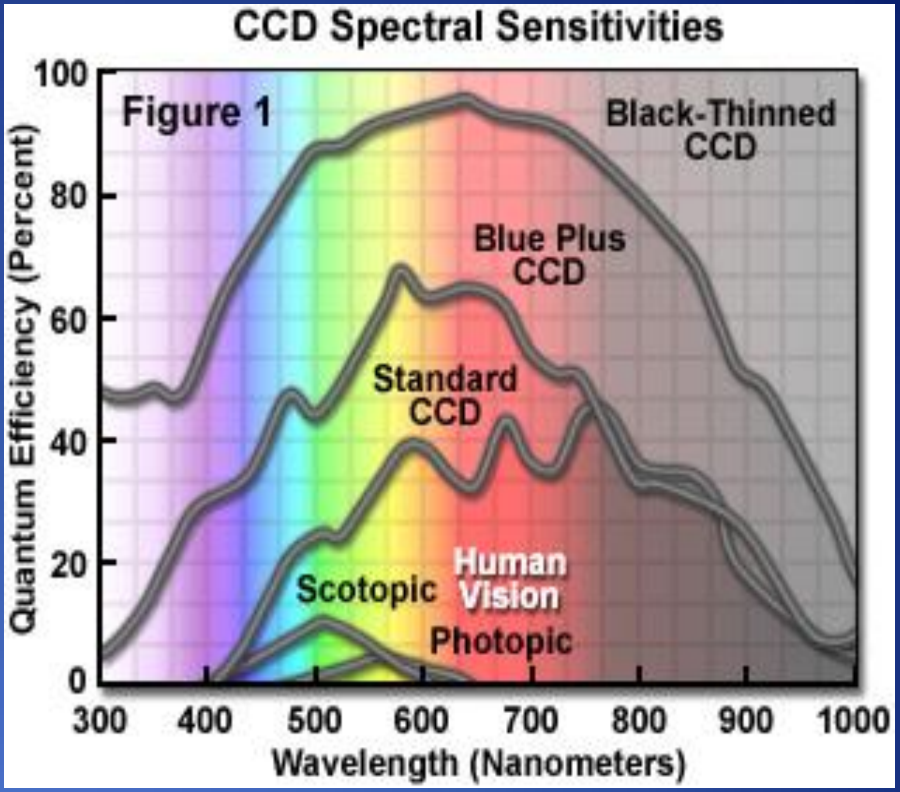
BN: back illuminated, no coating

DD: deep depletion



Quantum Efficiency





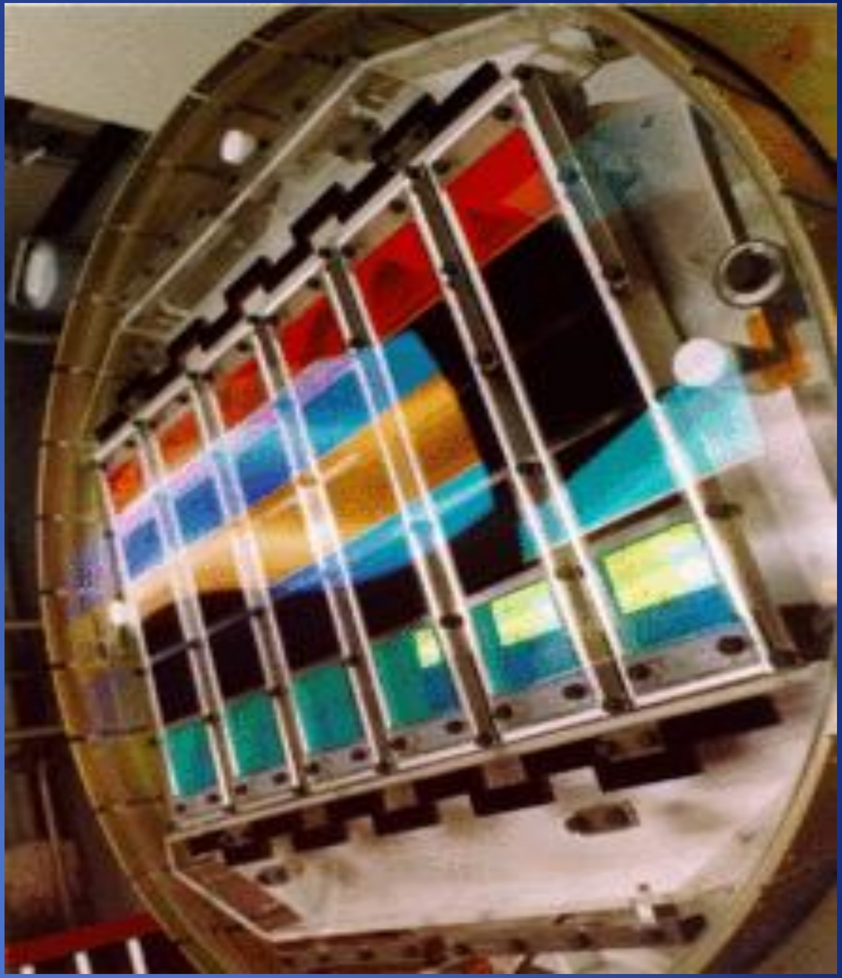
Quantum efficiency (ratio of output electrons to input photons) : >50%; >80% for certain wavelengths

Graphs: quantum efficiency as a function of wavelength for several types of CCDs

Large domain of wavelengths for the spectral response of CCDs

Experimental Applications

- Particle Physics
  - Track detectors (ionization)
  - Vertex detector at International Linear Collider (ILC)
  - In-situ Storage Image Sensor (ISIS)
- Astrophysics
  - Hubble Space Telescope (ACS)
  - Chandra X-ray Observatory
  - XMM-Newton X-ray Observatory
  - Sloan Digital Sky Survey
  - ROTSE



Array of 30 CCDs used on Sloan Digital Sky Survey telescope imaging camera, an example of "drift-scanning."

Summary

Advantages

- Good spatial resolution
- High quantum efficiency
- Large spectral window
- High dynamic range
- High photometric precision
- Good linearity
- Reliable rigidity

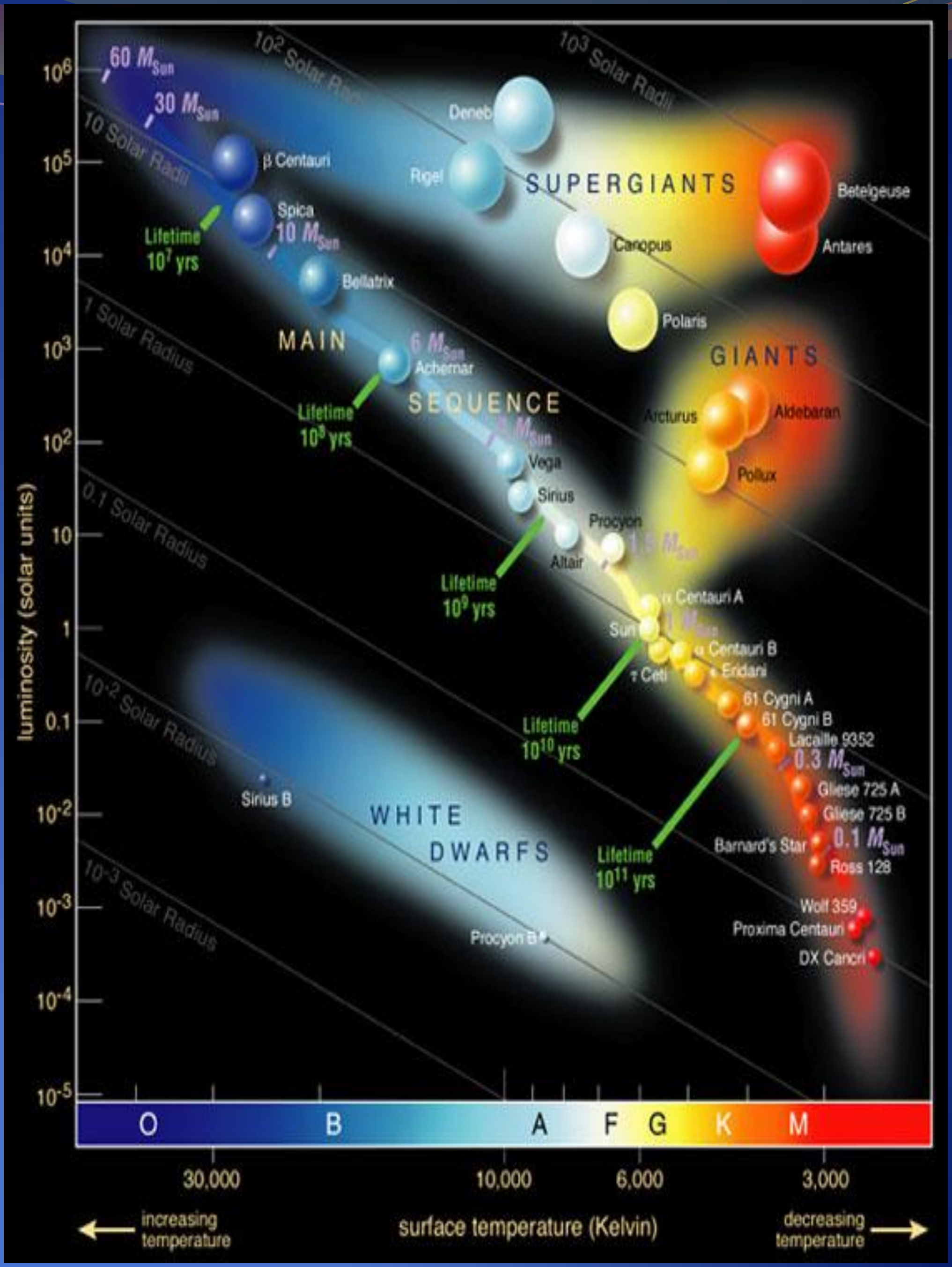
Disadvantages

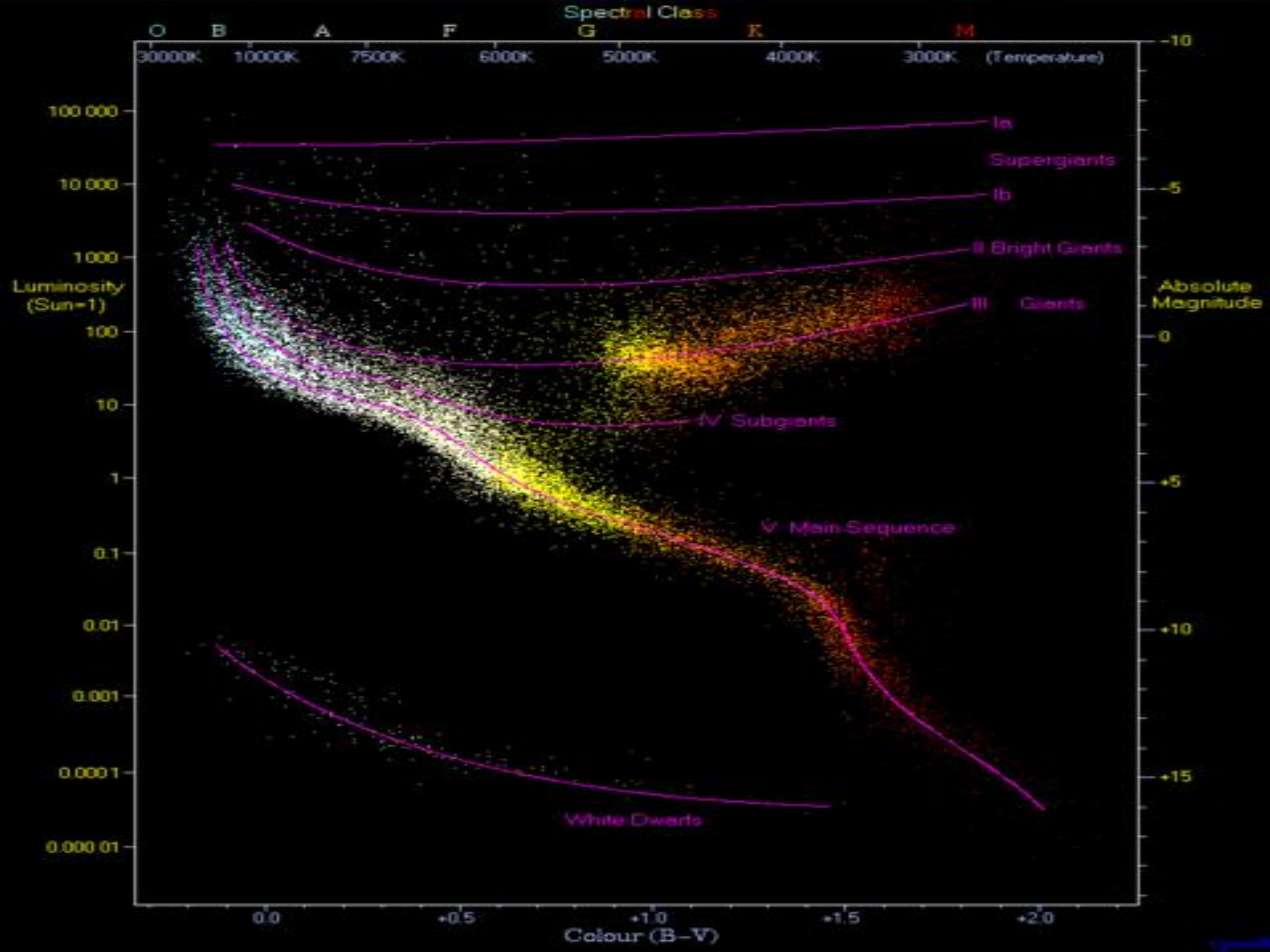
- Limited in size
- Thin depletion area (20-40 μm): small # of electron-hole pairs per ionizing particle
- Thermal noise (dark current) -- requires cooling
- Noise due to cosmic rays
- Blooming
- Slow readout

Vertical smear: If the shifting is not fast enough, errors can result from light that falls on a cell holding charge during the transfer. These errors are referred to as "vertical smear" and cause a strong light source to create a vertical line above and below its exact location.

HR Diagram

- 20th century telescopes determined the apparent brightness of many stars
- Combined with the distances to nearby stars obtained from parallax, absolute magnitude (luminosity) of nearby stars could be inferred from inverse square law
- Ejnar Hertzsprung (1873-1967) & Henry Russell (1877-1957) plotted absolute magnitude against surface temp (1905-1915) to create HR diagram
- Used to define different types of stars & to match theoretical predictions of stellar evolution using computer models with observations of actual stars
- Used to determine distance of stars too far away for trigonometric parallax:
  - Measure apparent magnitude
  - Spectroscopy yields surface temp, hence luminosity (absolute mag)
  - Calculate distance
- Effective to ≈ 300 kly; beyond that stars are too faint to be measured accurately





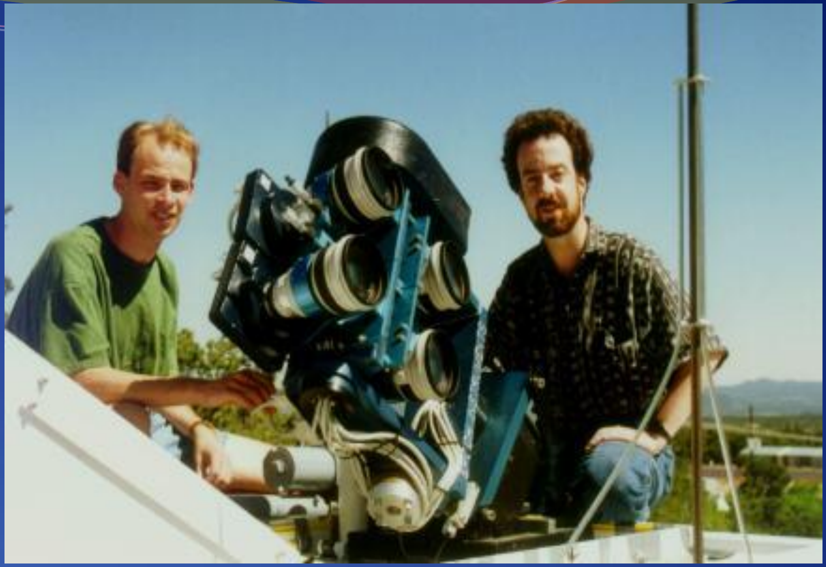
Spectral Class
O
B
A
F
G
K
M
30000K
10000K
7500K
6000K
5000K
4000K
3000K
(Temperature)
Luminosity (Sun=1)
100 000
10 000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.000 01
Absolute Magnitude
-10
-5
0
+5
+10
+15
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
V Main Sequence
White Dwarfs
0.0
+0.5
+1.0
+1.5
+2.0
Colour (B−V)

ROTSE

- ROTSE: Robotic Optical Transient Search Experiment
- Primary goal: Observations in optical light of GRBs
- Observation and detection of optical transients on time scales of seconds to days
- Also used for variable star searches, identification of other transient events (AGNs, supernovae, flare stars, X-ray binaries, SGRs)

ROTSE

- **ROTSE1:**
  - Initiated in 1998
  - Four CCD cameras w/ telephoto lenses
  - FOV: 16°×16°
  - Limiting magnitude: 14-15
  - Observed 1st optical counterpart to GRB in progress on 01/23/99
  - Retired from active operation

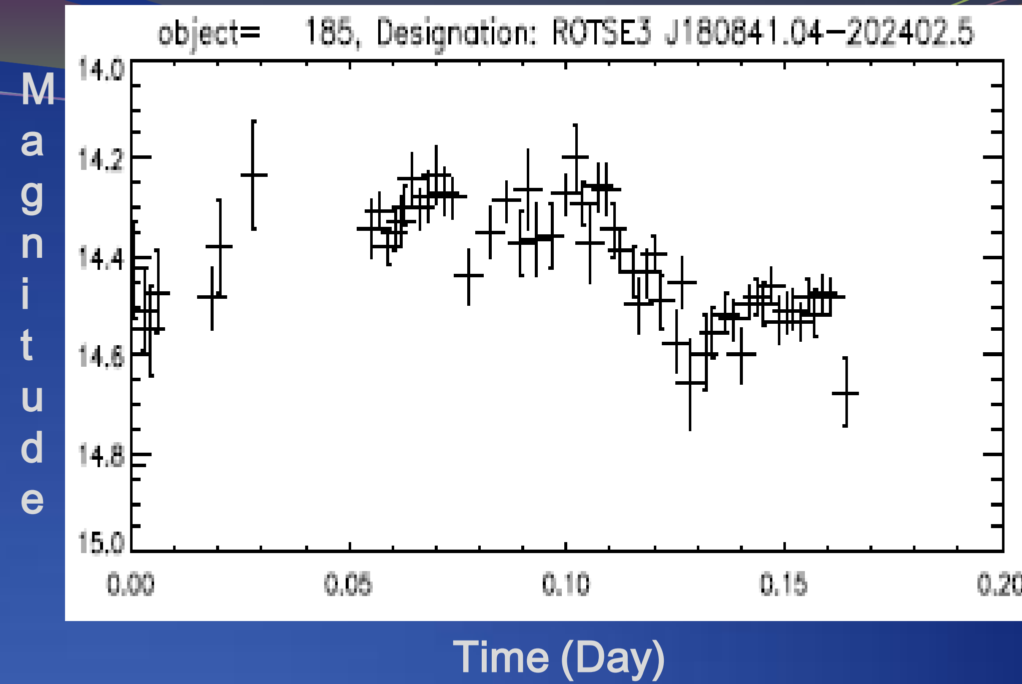


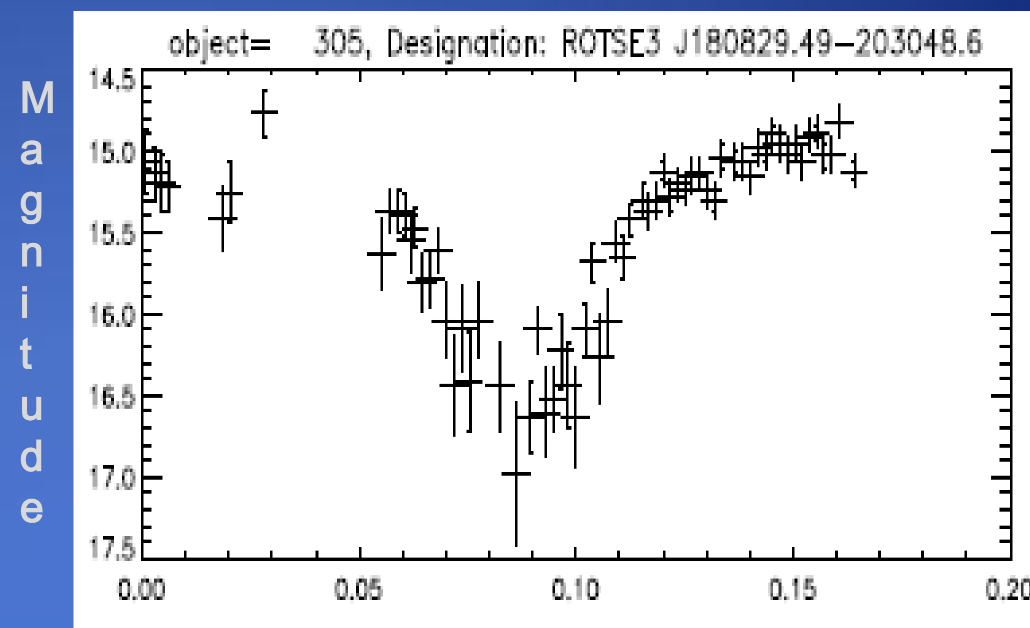
- **ROTSE3:**
  - Initiated in 2003
  - Four 0.45 m robotic reflecting telescopes
  - Managed, fully automated, Linux environment
  - Greater sensitivity than ROTSE1
  - f-ratio: 1.9
  - Limiting magnitude: 19-20
  - FOV: 1.85°×1.85°

ROTSE3

- **DATA:**
  - ROTSE3 file GRB040408
  - 417 observations imaged over 4 hours
  - RA: 272.24º, DEC: -20.40º
  - Field located in Sagittarius (toward galactic center)

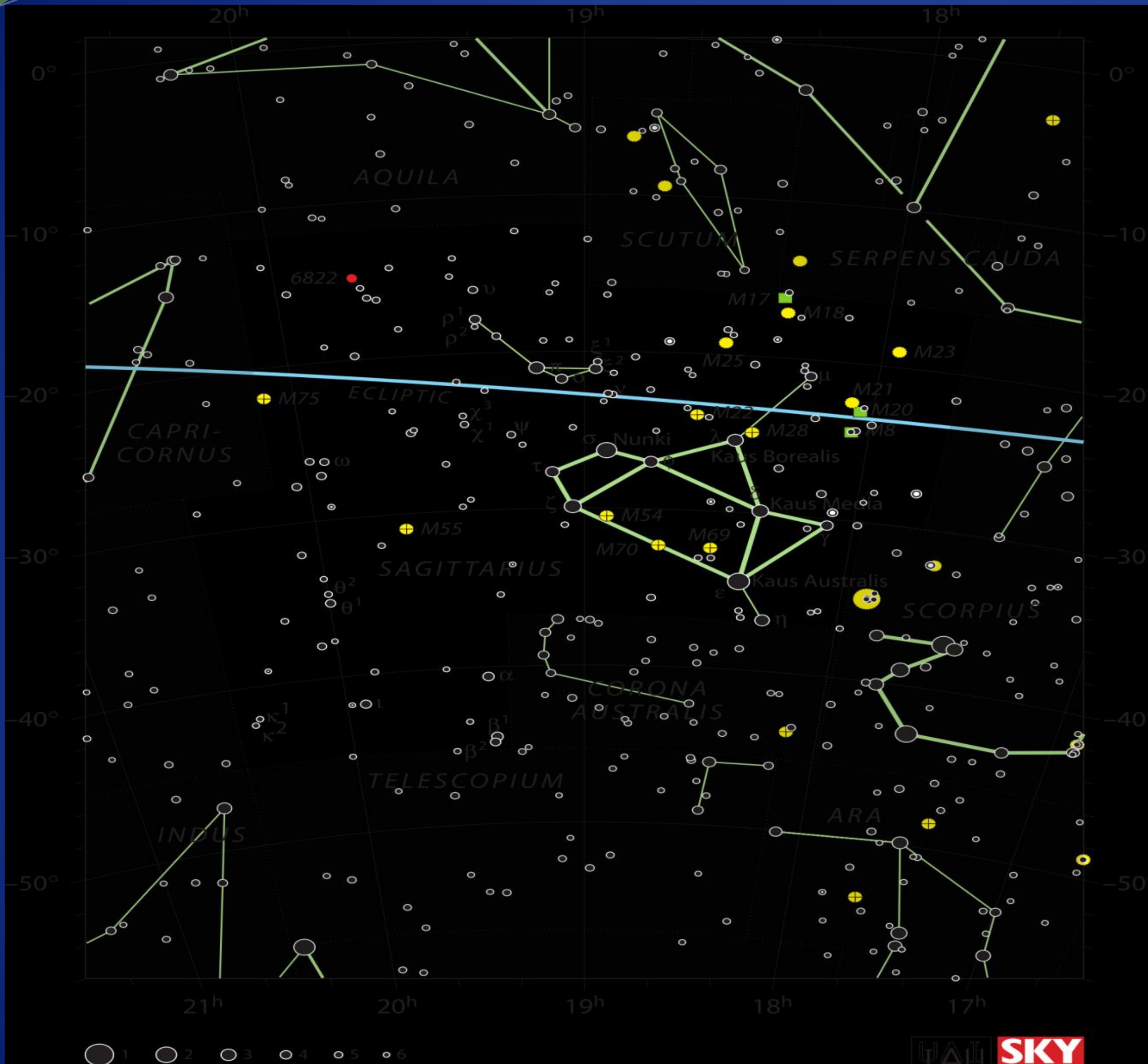
- **ANALYSIS:**
  - University of Michigan ROTSE IDL library, ported to SMU
  - Examine raw images, drop poor ones
  - Process & calibrate raw images
  - Investigate time variation of optical light output for variable star candidates
  - Photometry: Measurement of changes in brightness plotted to generate light curves
  - Determine shape, period, amplitude
  - Identify short period pulsating variable stars (δ Sct), or other variable types (eclipsing binary, contact binary)



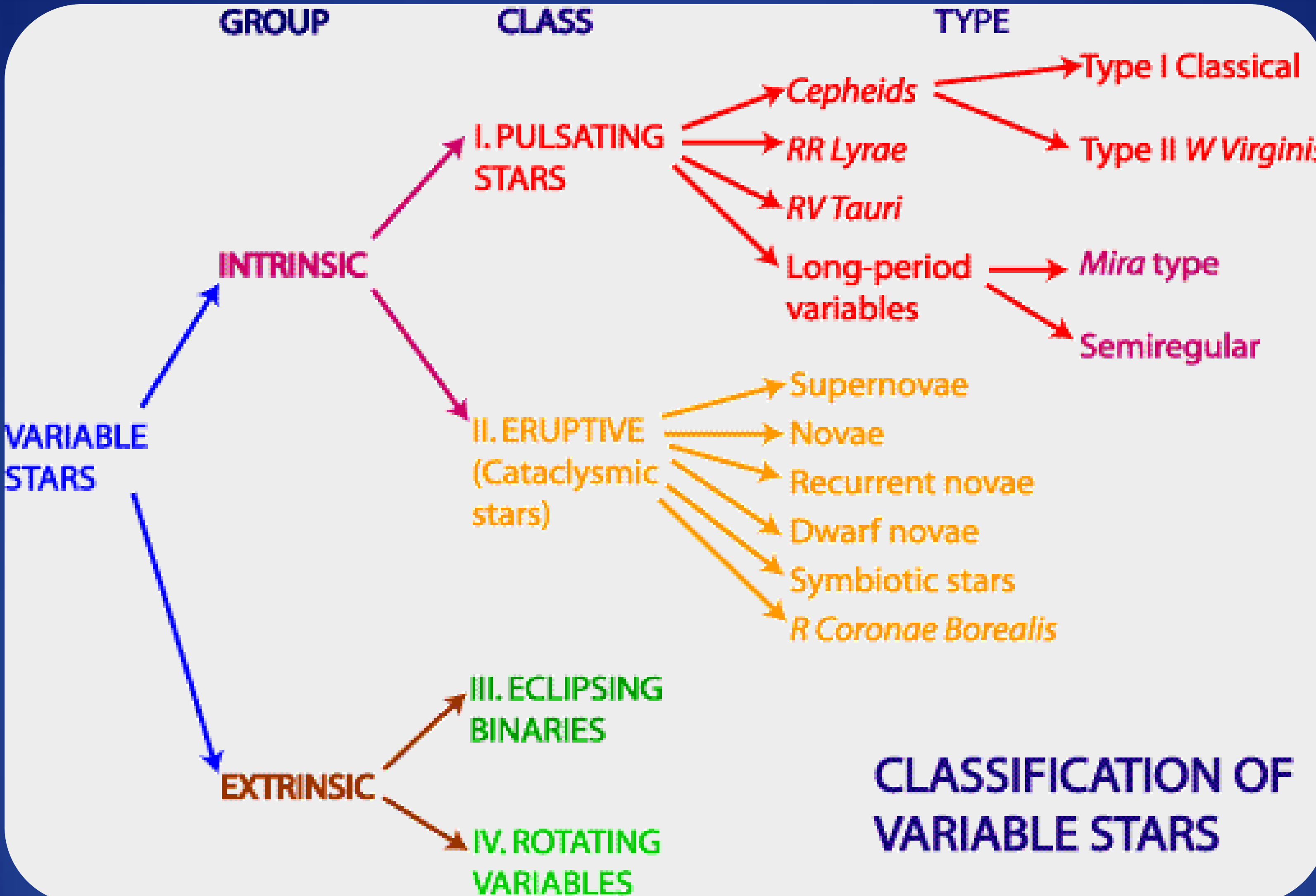


Time (Day)

ROTSE3: Target field in Sagittarius

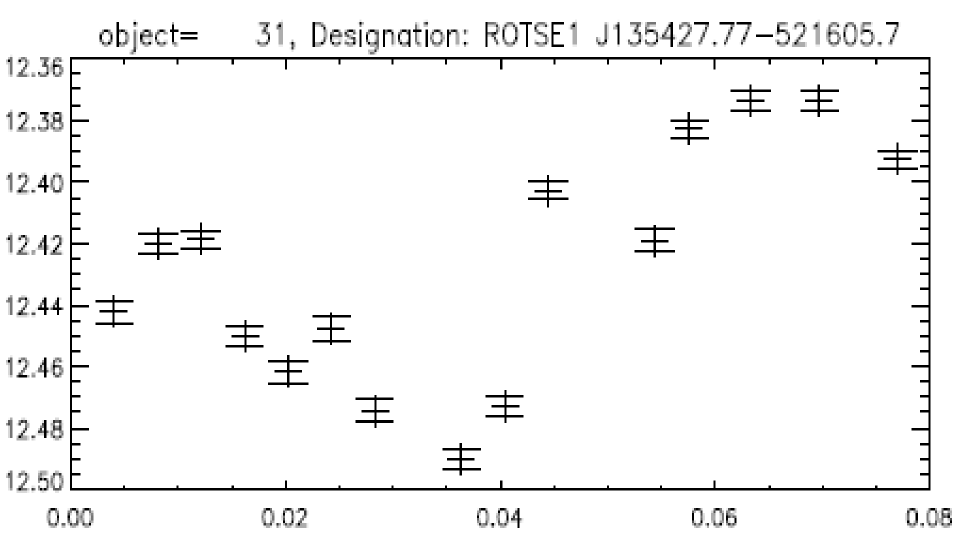


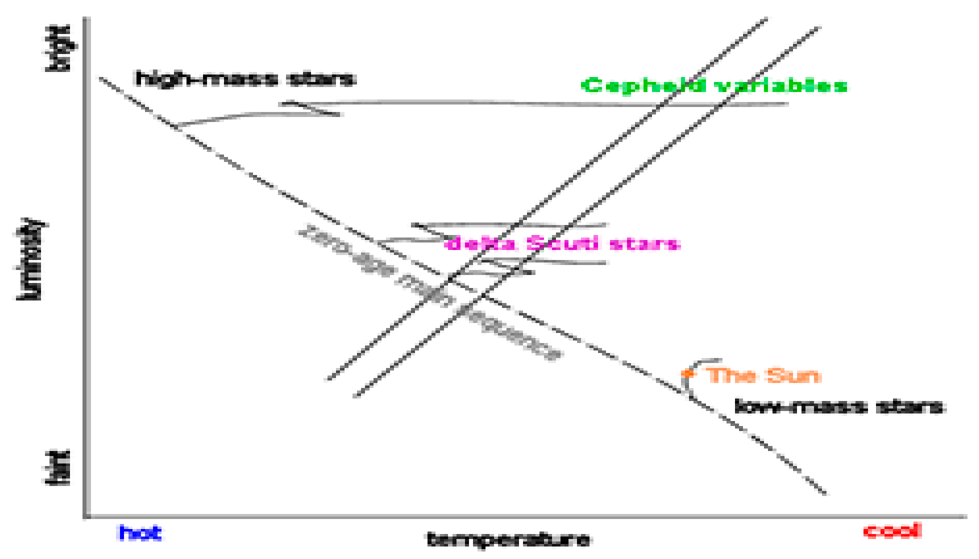
Variable Stars



Pulsating Variable Stars: δ Scuti

- Low amplitude pulsating variables (dwarf Cepheids)
- Some have amplitudes of about one magnitude & regular light curves
  - Radial pulsations
  - One dominant pulsation mode
- Others have complex light curves & multiple periods with smaller light variations
  - Radial & non-radial pulsations
  - May have multiple modes of oscillation
- Reside near instability strip of HR diagram
- Importance:
  - Asteroseismology: Pulsations used to study interior structure
  - Standard candles (higher amplitude)



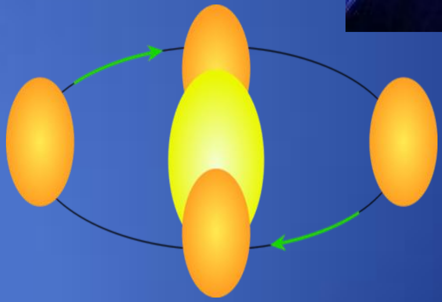


Binary Stars

- Classified into 4 types by the method in which they are observed:
  - Visual: By observation of double stars (may or may not be gravitationally bound; Example: Mizar)
  - Astrometric: By measuring a deviation in a star's position caused by an unseen companion (wobble about a point in space)
  - Photometric: By changes in brightness due to an eclipse
  - Spectroscopic: By periodic changes in spectral lines (Doppler effect – small separation between stars, high orbital velocity)
- Best method available to determine the mass of a distant star:
  - Orbit around their common center of mass
  - Mass of individual stars determined using Kepler’s laws & Newton’s law of universal gravitation
  - Establishes relationship between a star's temperature, radius, & mass
  - Allows for the determination of the mass of non-binaries
- Large proportion of stars exist in binary systems (estimated 1/3 of stars in Milky Way)
  - Binaries important to our understanding of the processes by which stars form
  - Period and mass of the binary components reveal amount of angular momentum in the system
  - Provide important clues about the conditions under which the stars were formed

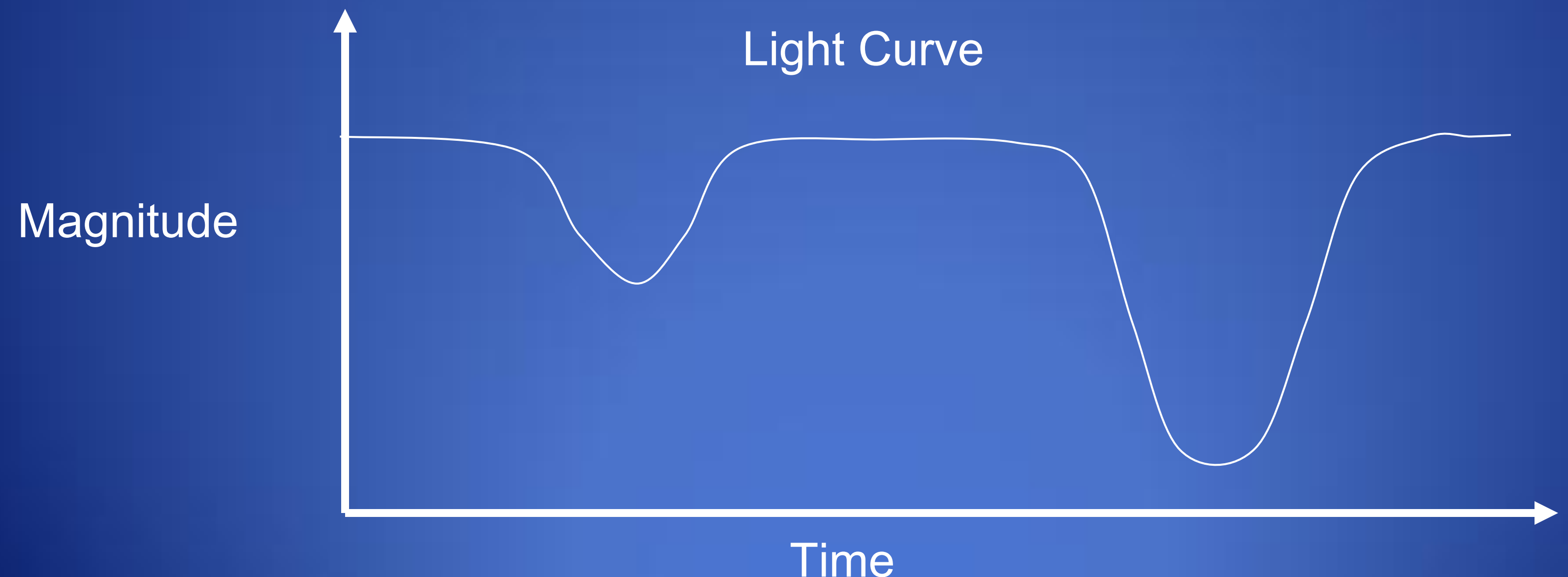
Visual binary: The two visibly distinguishable components of Albireo. The brighter member (γ star of the constellation Cygnus) is a close binary itself.

Hubble image of the Sirius binary system; Sirius B can be seen (lower left)



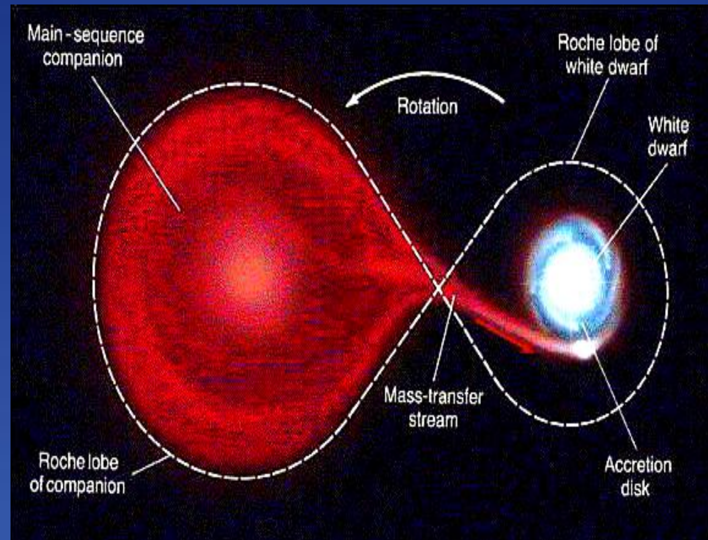
Eclipsing Binary Stars

[Eclipsing Binary Star]



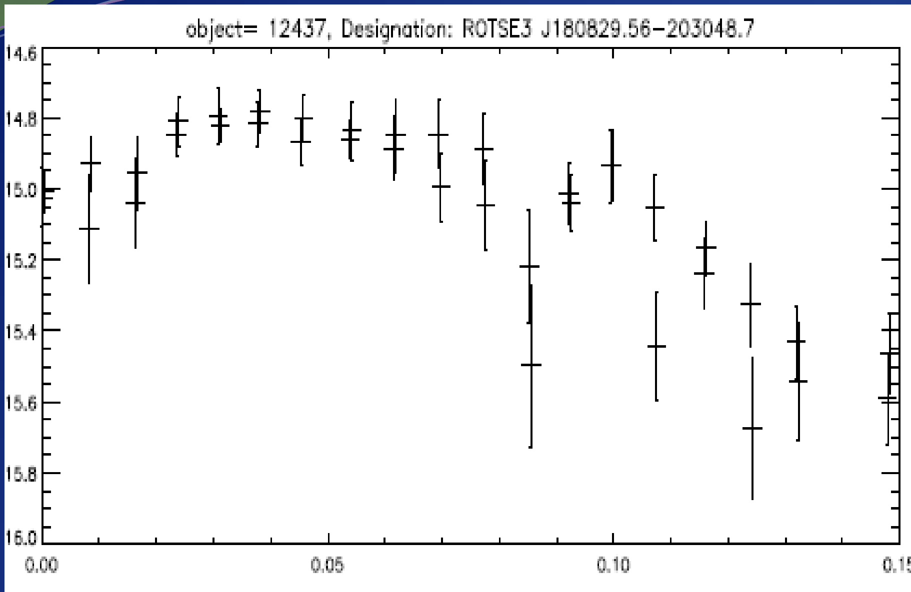
Contact Binary Stars (*W Ursae Majoris variables)*

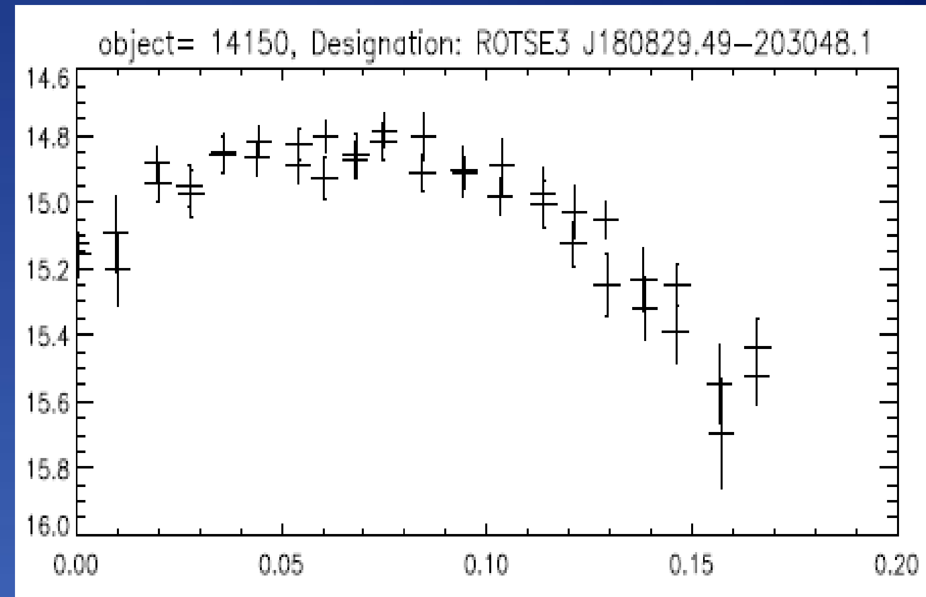
- Almost all known contact binary systems are also eclipsing
- Constitute about 1% of all stars
- Spectral class: F, G, K
- Component stars are so close that they are in physical contact
- Roche lobes: Region of space around a star in a binary system within which orbiting material is gravitationally bound to that star
- Roche lobes are filled for contact binaries; surrounds both stars, shared by both
- Typical lifetime of millions to billions of years
- As friction of the envelope brakes the orbital motion, stars may eventually merge -- Chandrasekhar limit (supernova)

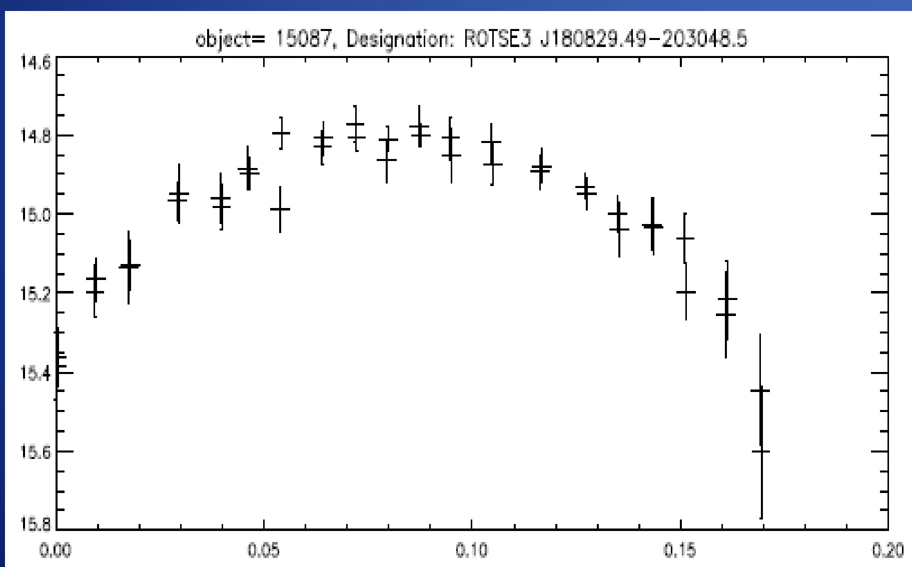


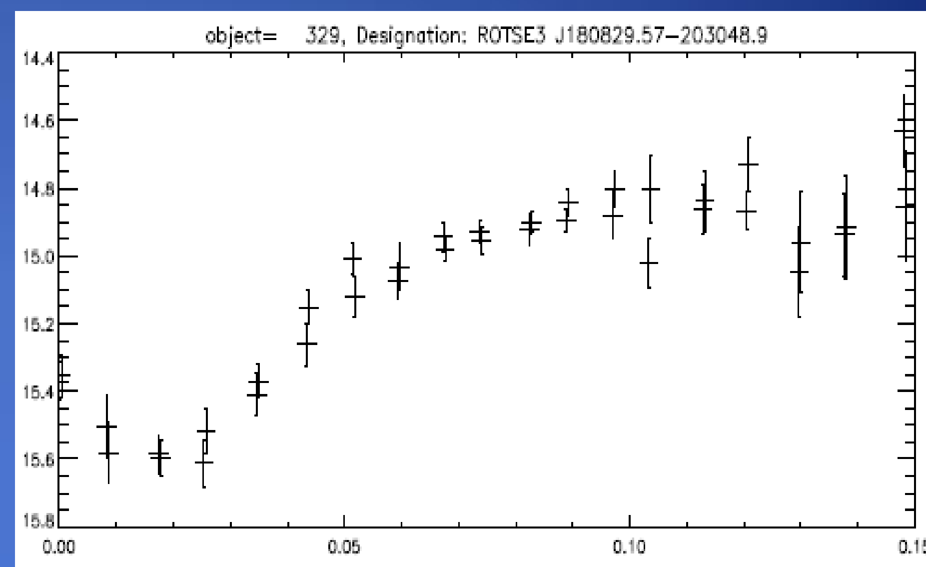
Contact Binary Stars: Algol (β Persei)

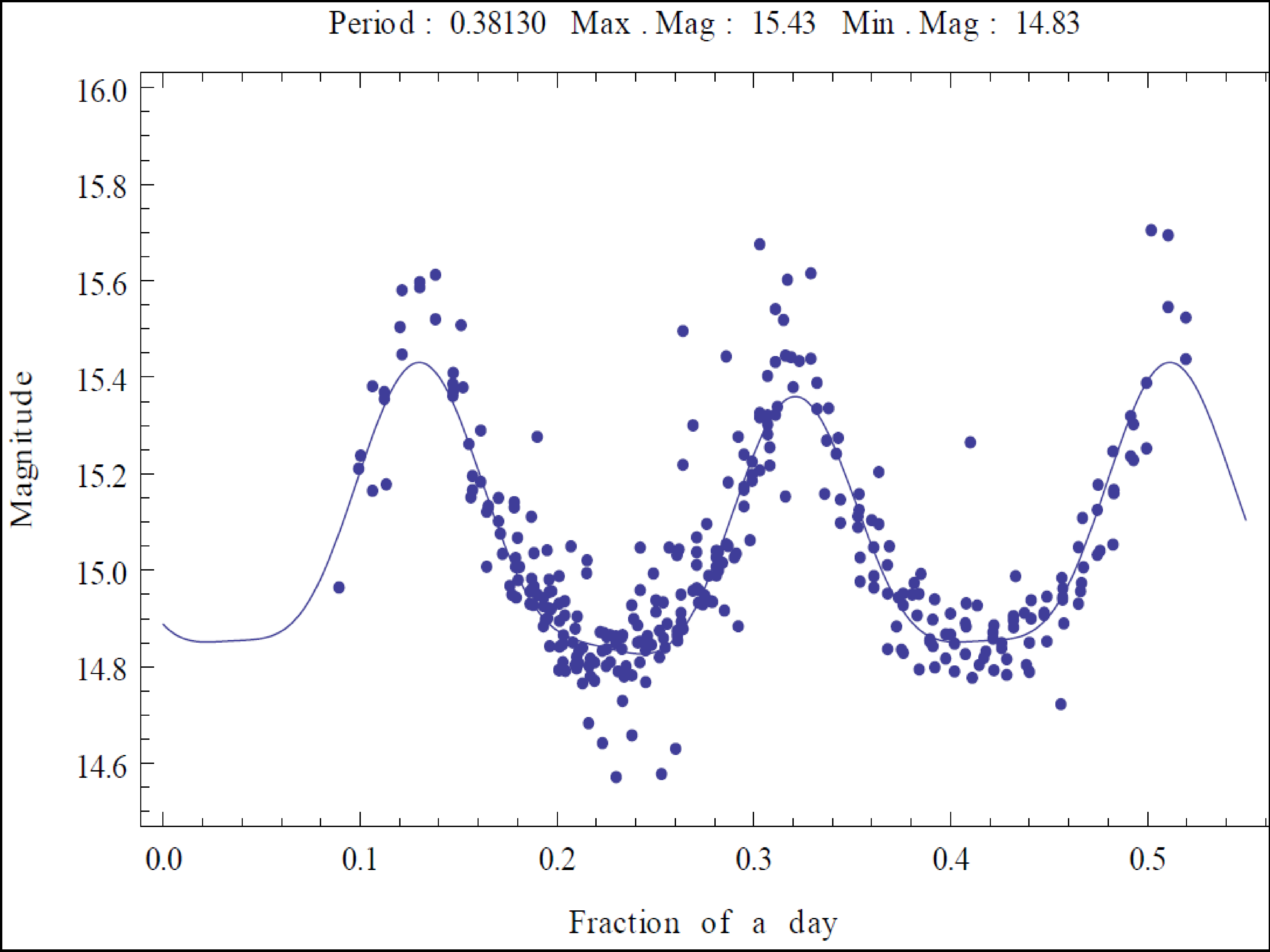
Candidate Contact Binary Star





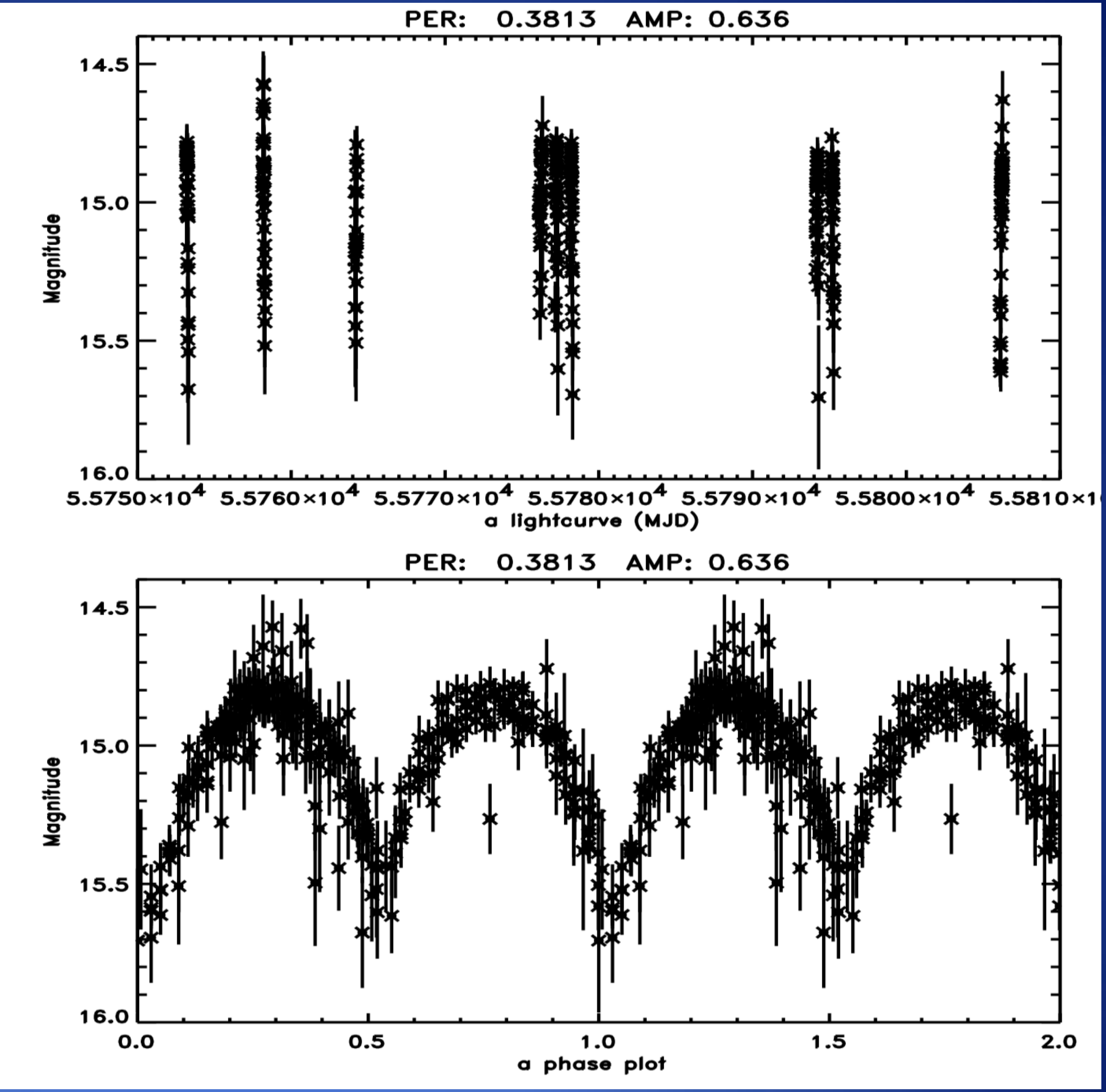




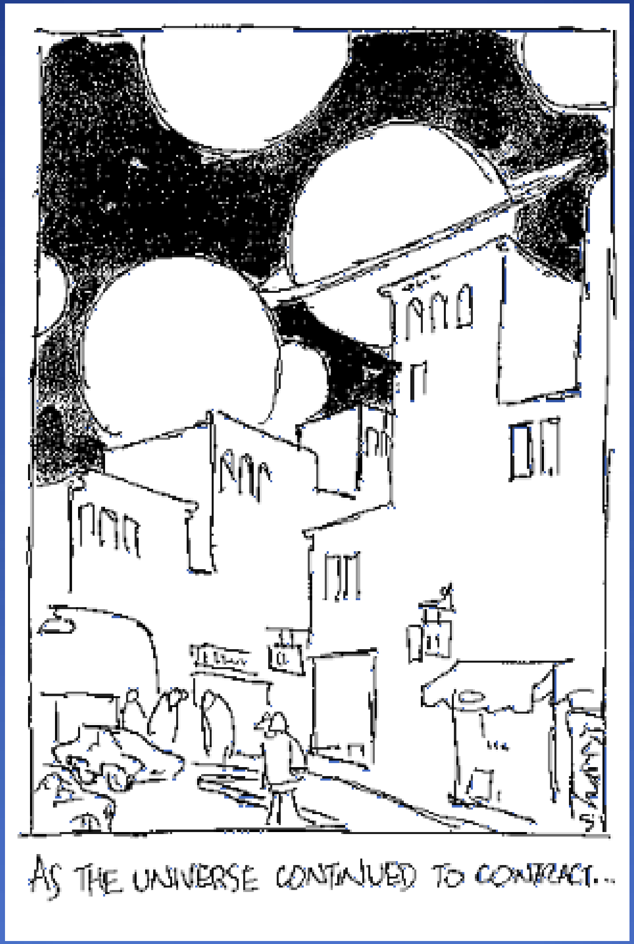

Period : 0.38130 Max . Mag : 15.43 Min . Mag : 14.83
Magnitude
16.0
15.8
15.6
15.4
15.2
15.0
14.8
14.6
0.0
0.1
0.2
0.3
0.4
0.5
Fraction of a day

Conclusion: Discovery

- VSX J180829.4-203047
  - Type: EW
  - Period: 0.3813 d
  - Amplitude: 0.636
  - Discoverers:
    - Farley Ferrante (SMU)
    - Weikang Zheng (Michigan)
    - Govinda Dhungana (SMU)
    - Robert Kehoe (SMU)
- 3 additional discoveries:
  - VSX J154029.8+453200
  - VSX J161803.4+420417
  - VSX J162221.9+412340
- More to come…
- And supernovae too…



Intermission



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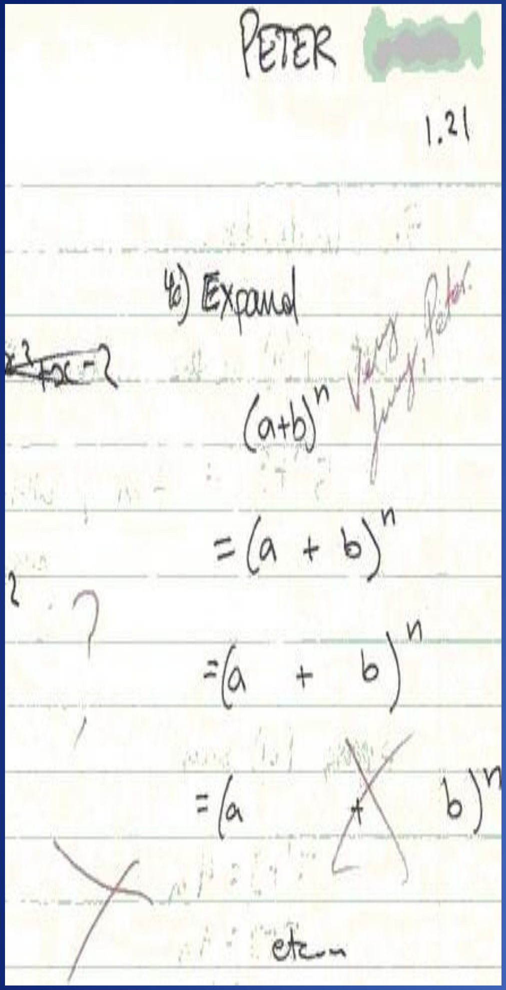
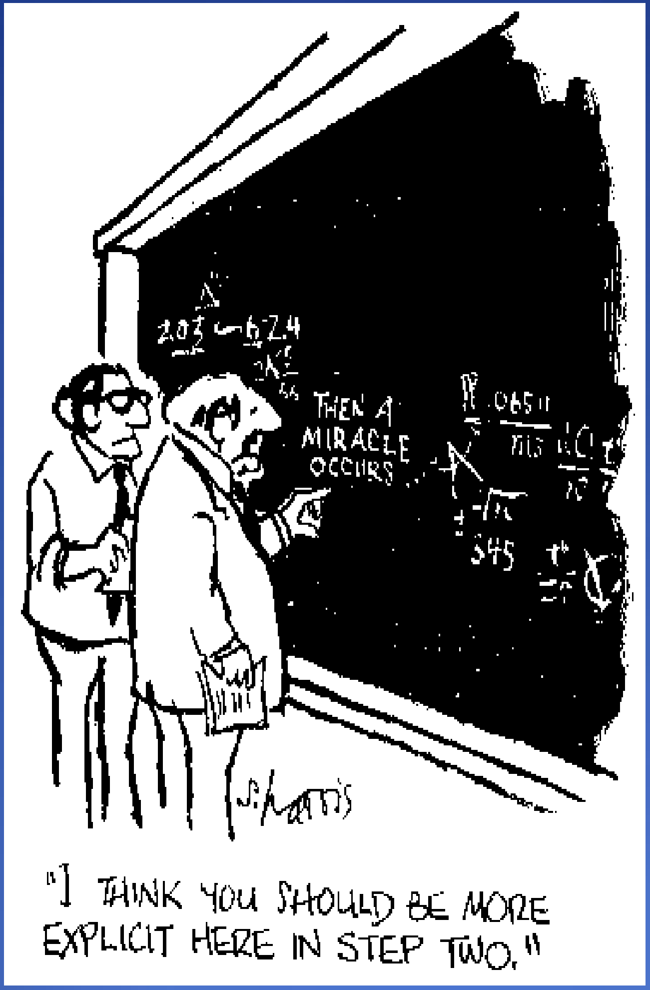
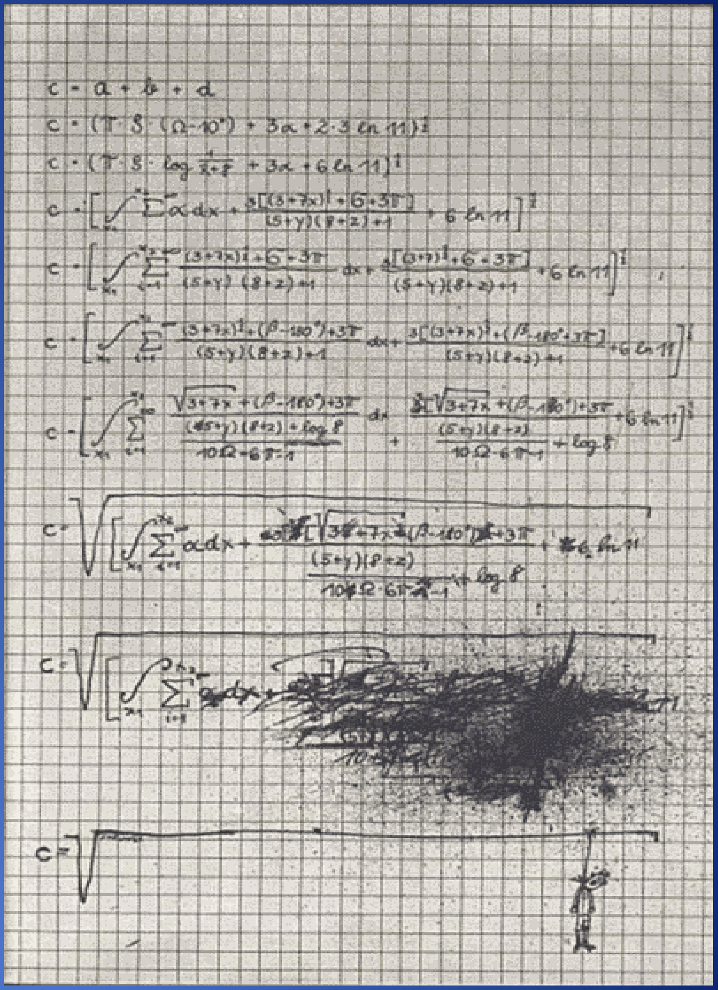
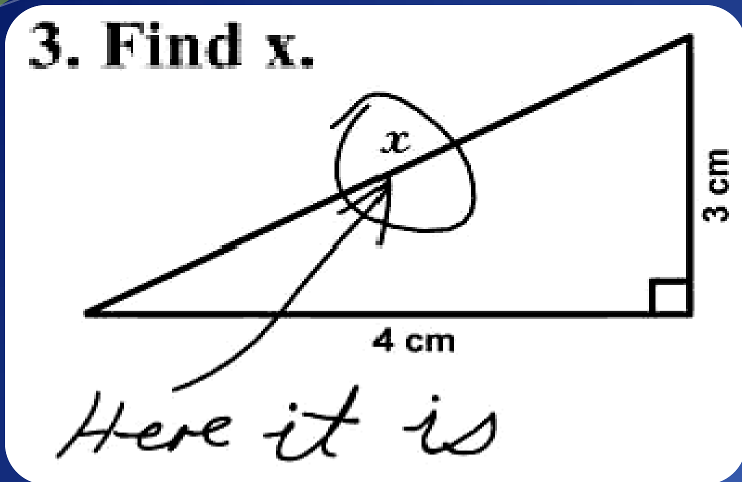
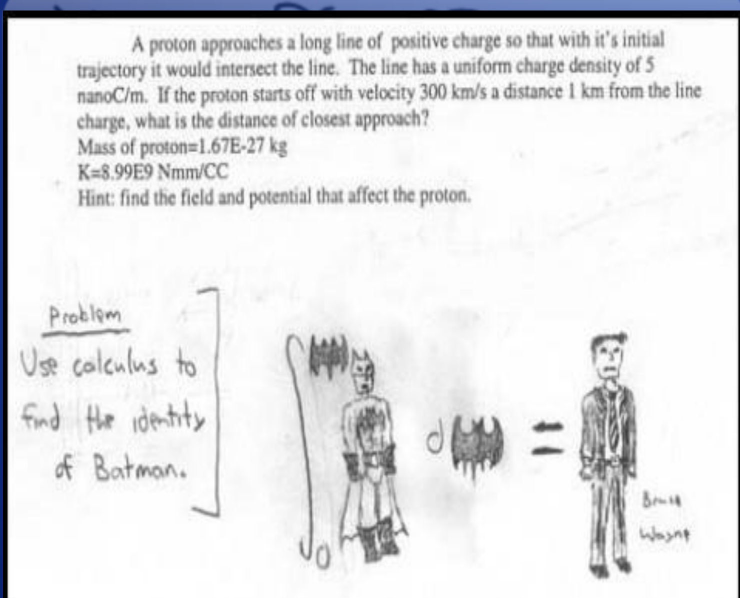


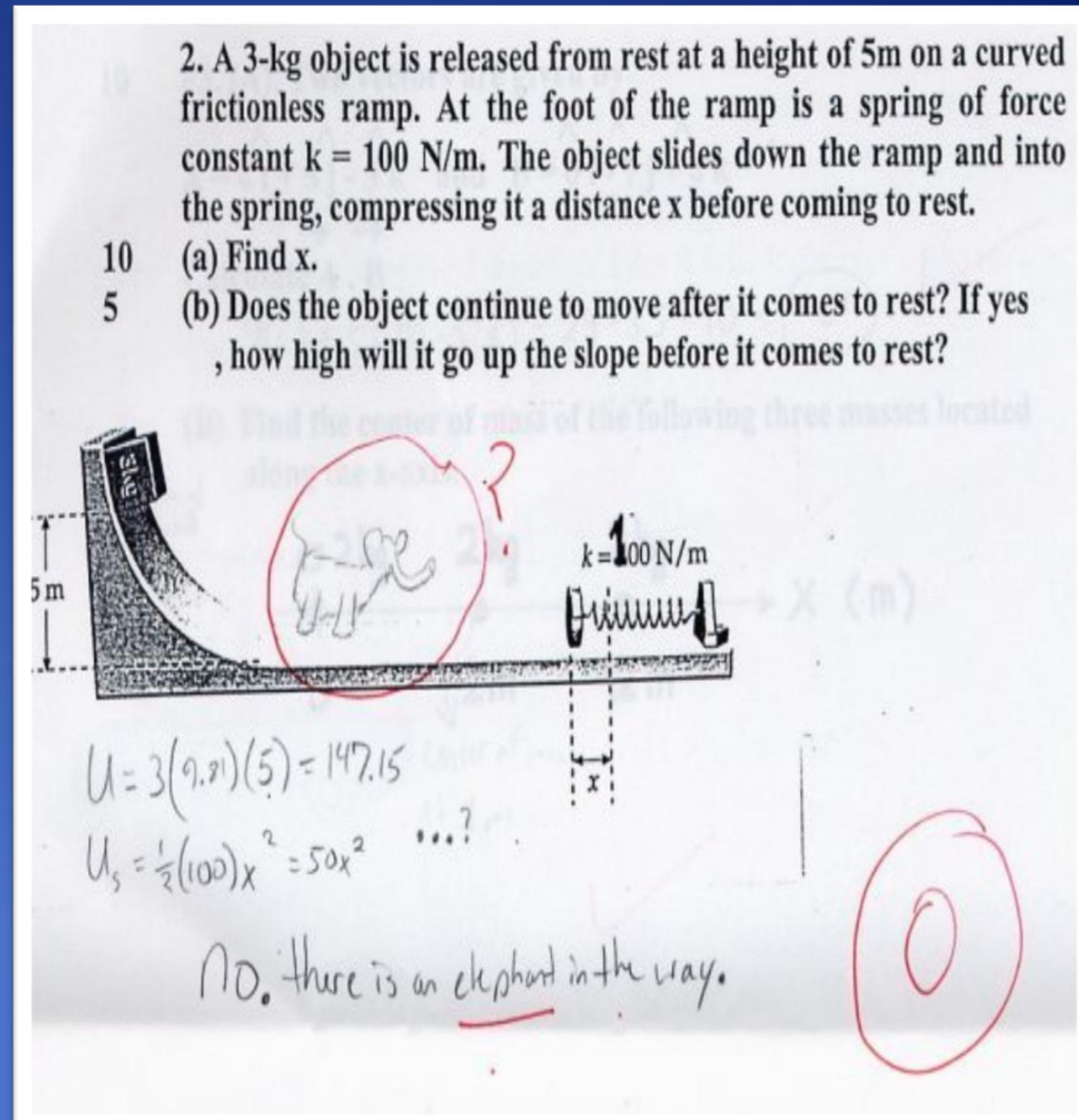




Intermission







Standard Candles: Distance Measurement in Astronomy

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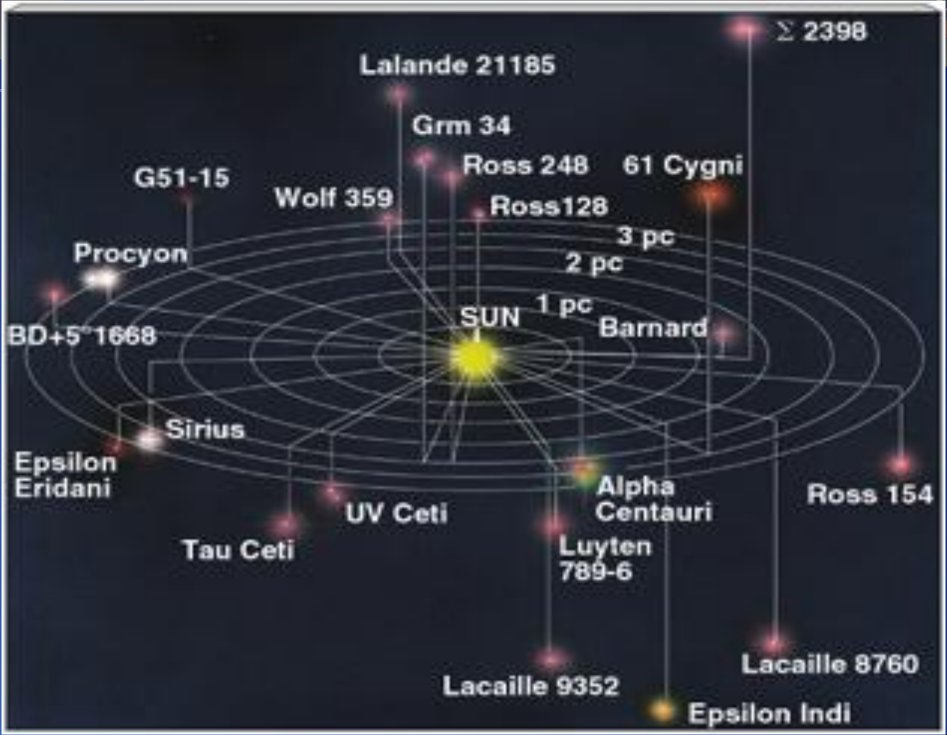
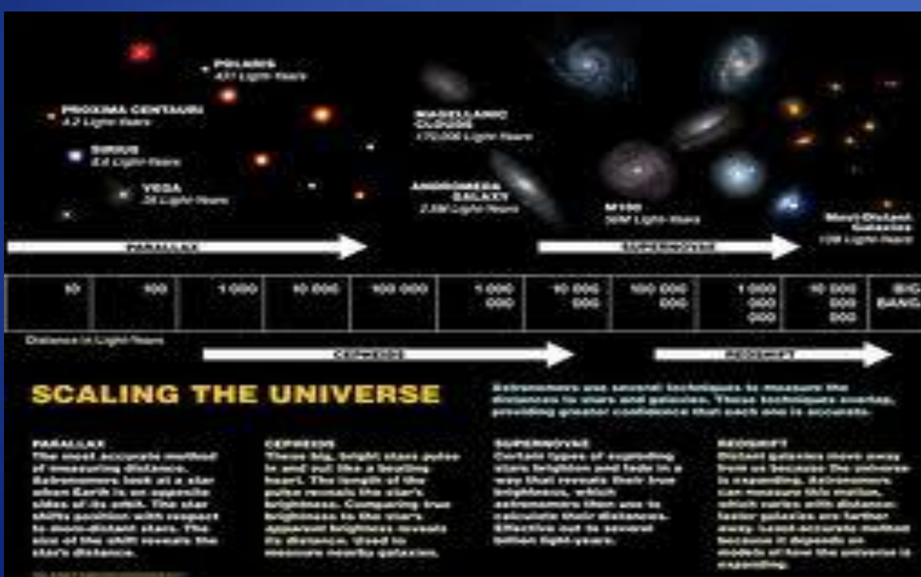
OUTLINE

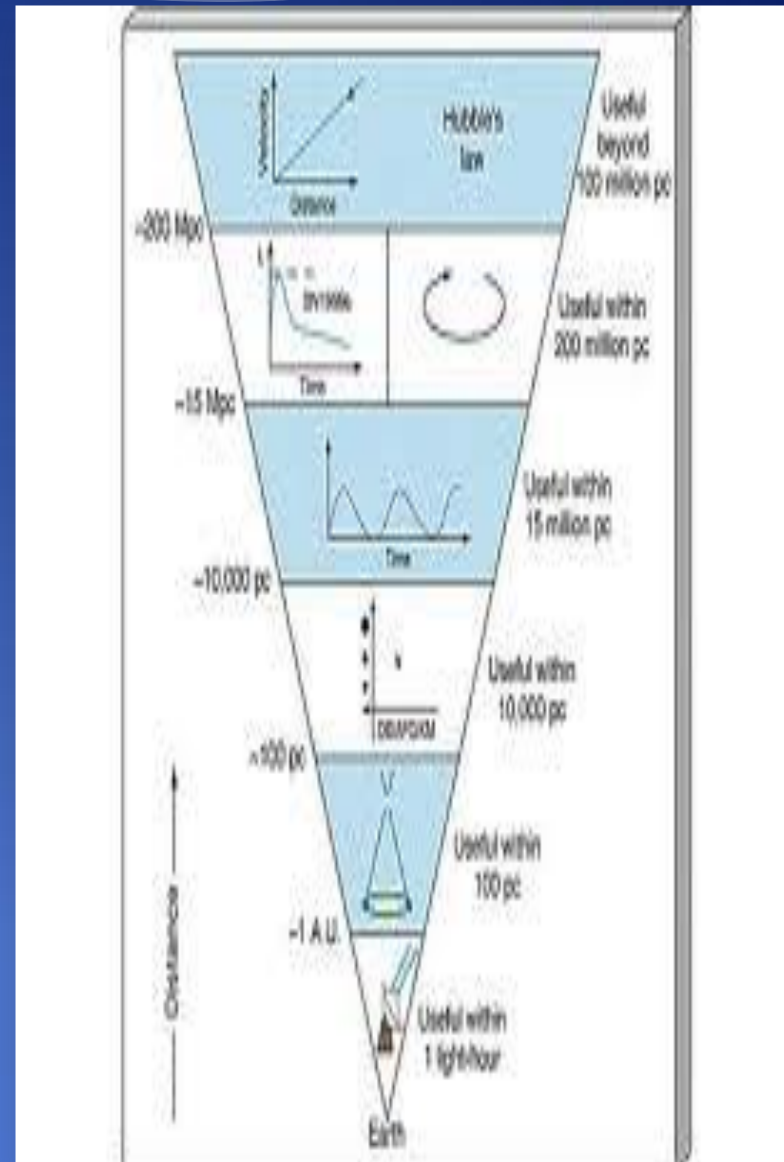
- Cosmic Distance Ladder
- Standard Candles
  - Parallax
  - Cepheid variables
  - Planetary nebula
  - Most luminous supergiants
  - Most luminous globular clusters
  - Most luminous H II regions
  - Supernovae
  - Hubble constant & red shifts



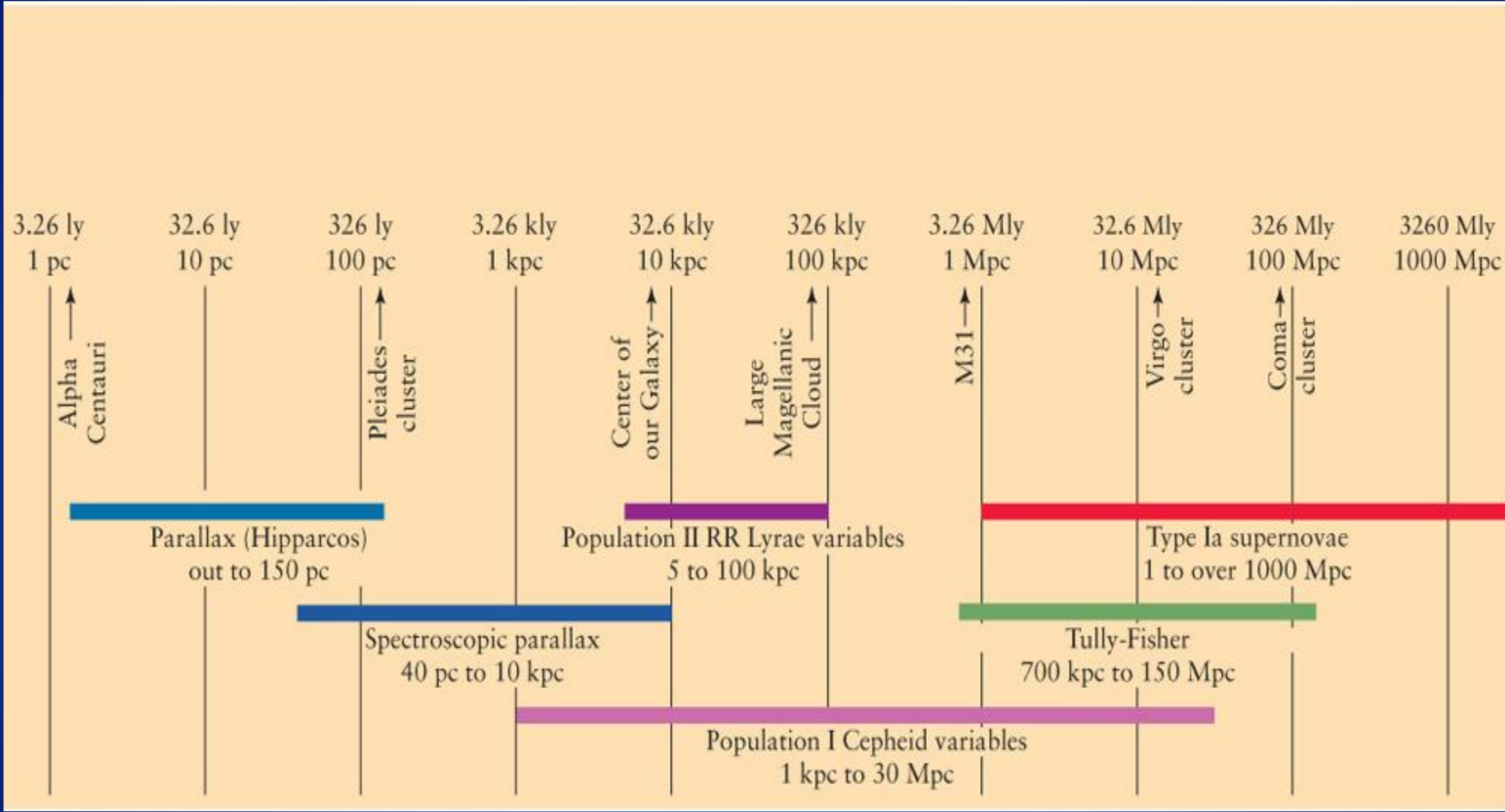
The Cosmic Distance Ladder

- Distances far too vast to be measured directly
- Several methods of indirect measurement
- Clever methods relying on careful observation and basic mathematics
- Cosmic distance ladder: A progression of indirect methods which scale, overlap, & calibrate parameters for large distances in terms of smaller distances
- More methods calibrate these distances until distances that can be measured directly are achieved



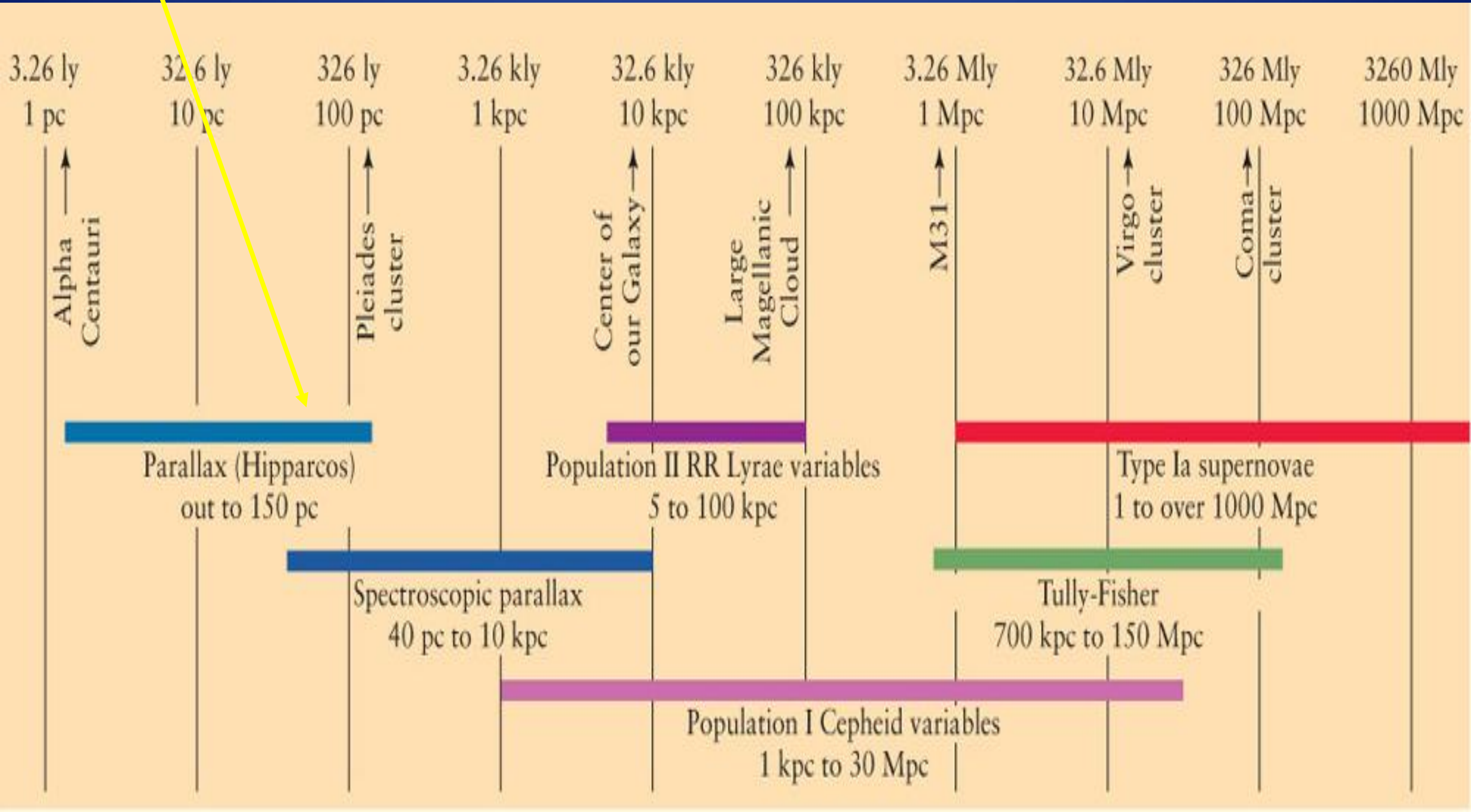


The Cosmic Distance Ladder



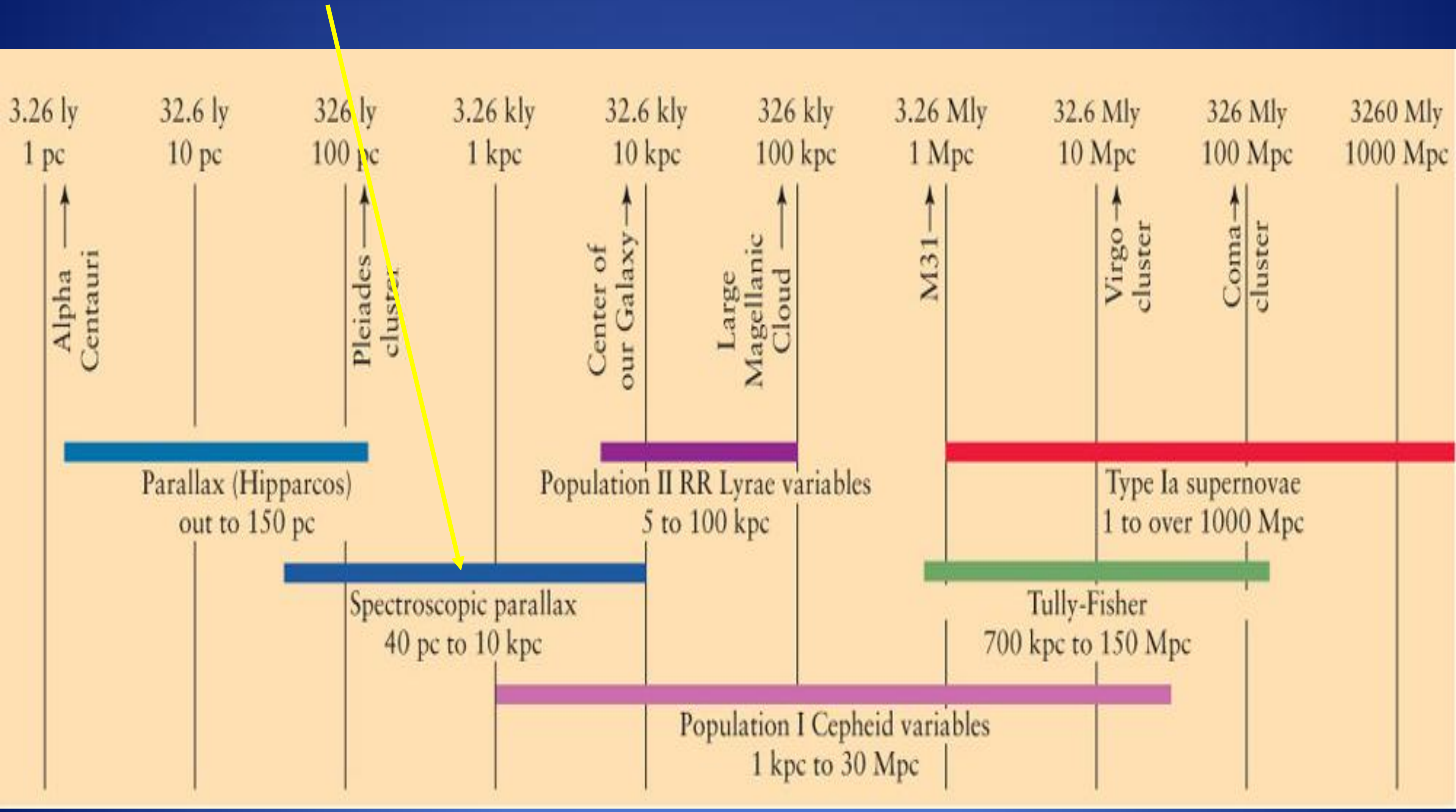
The Cosmic Distance Ladder

Parallax to nearby stars *~500 ly*



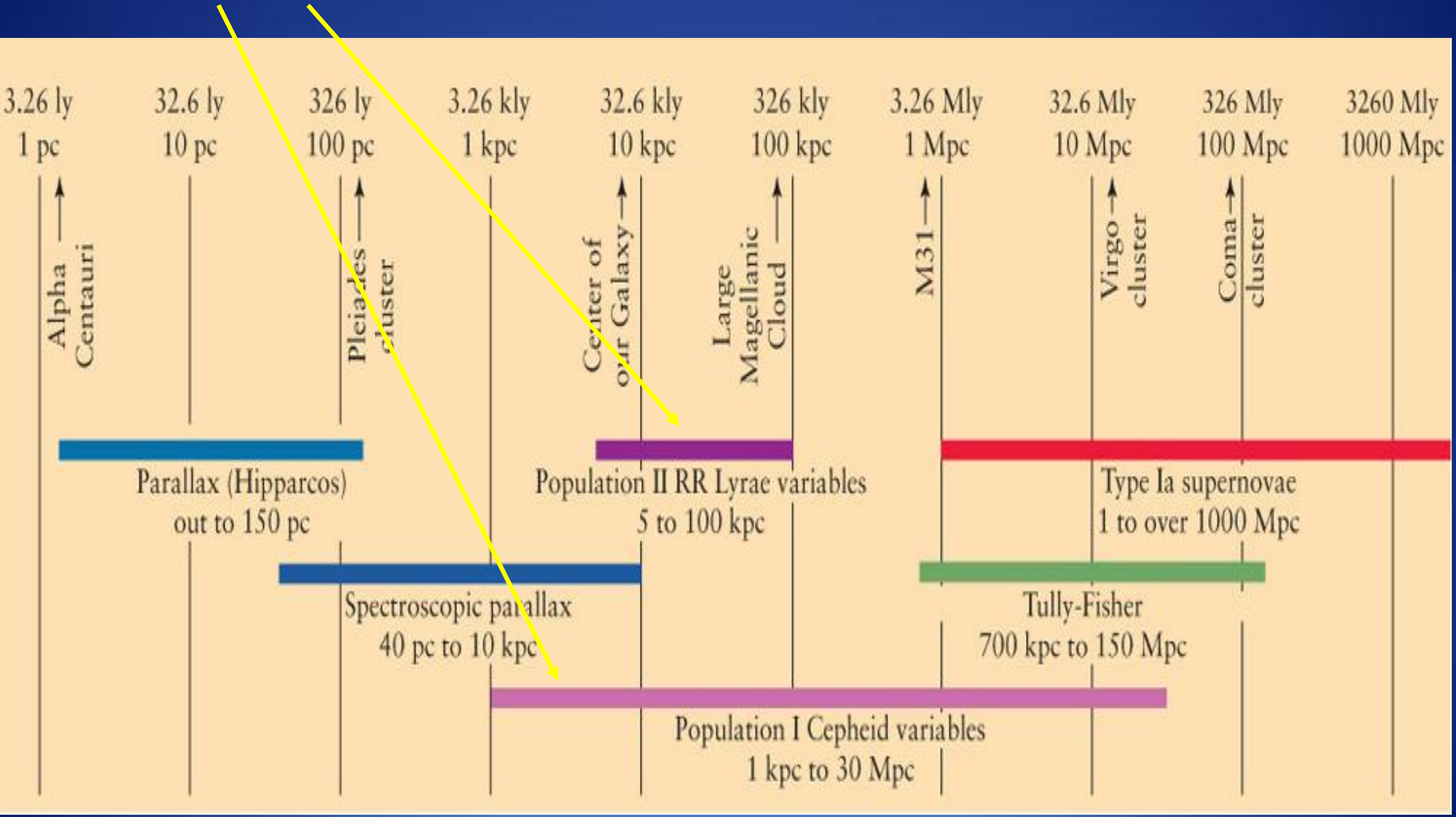
The Cosmic Distance Ladder

Spectroscopic parallax to stars in galaxy *~30,000 ly*



The Cosmic Distance Ladder

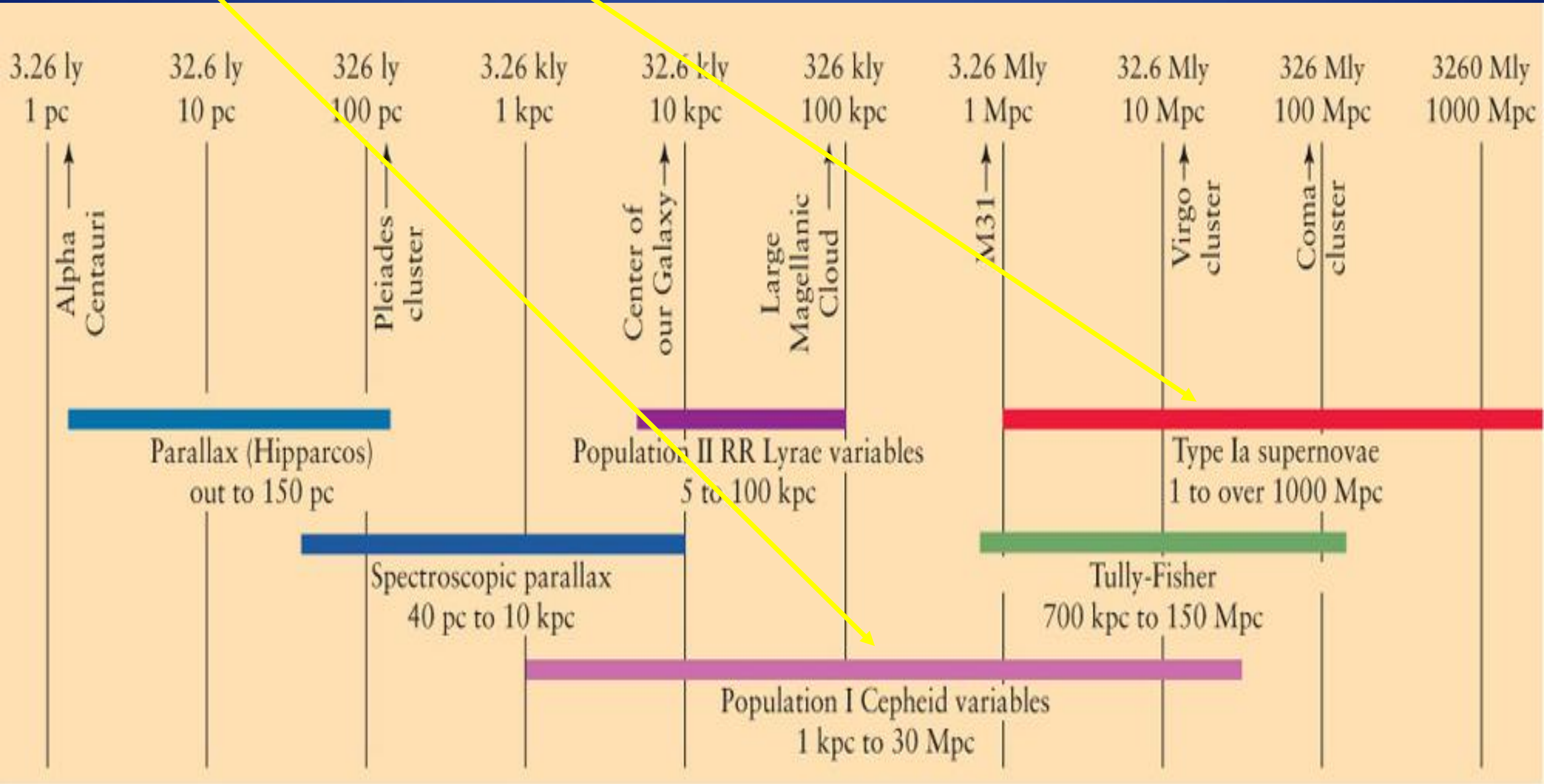
Calibrated variable stars in galaxy *~50,000 ly*



The Cosmic Distance Ladder

Calibrated variable stars, supernovae in 'nearby' galaxies

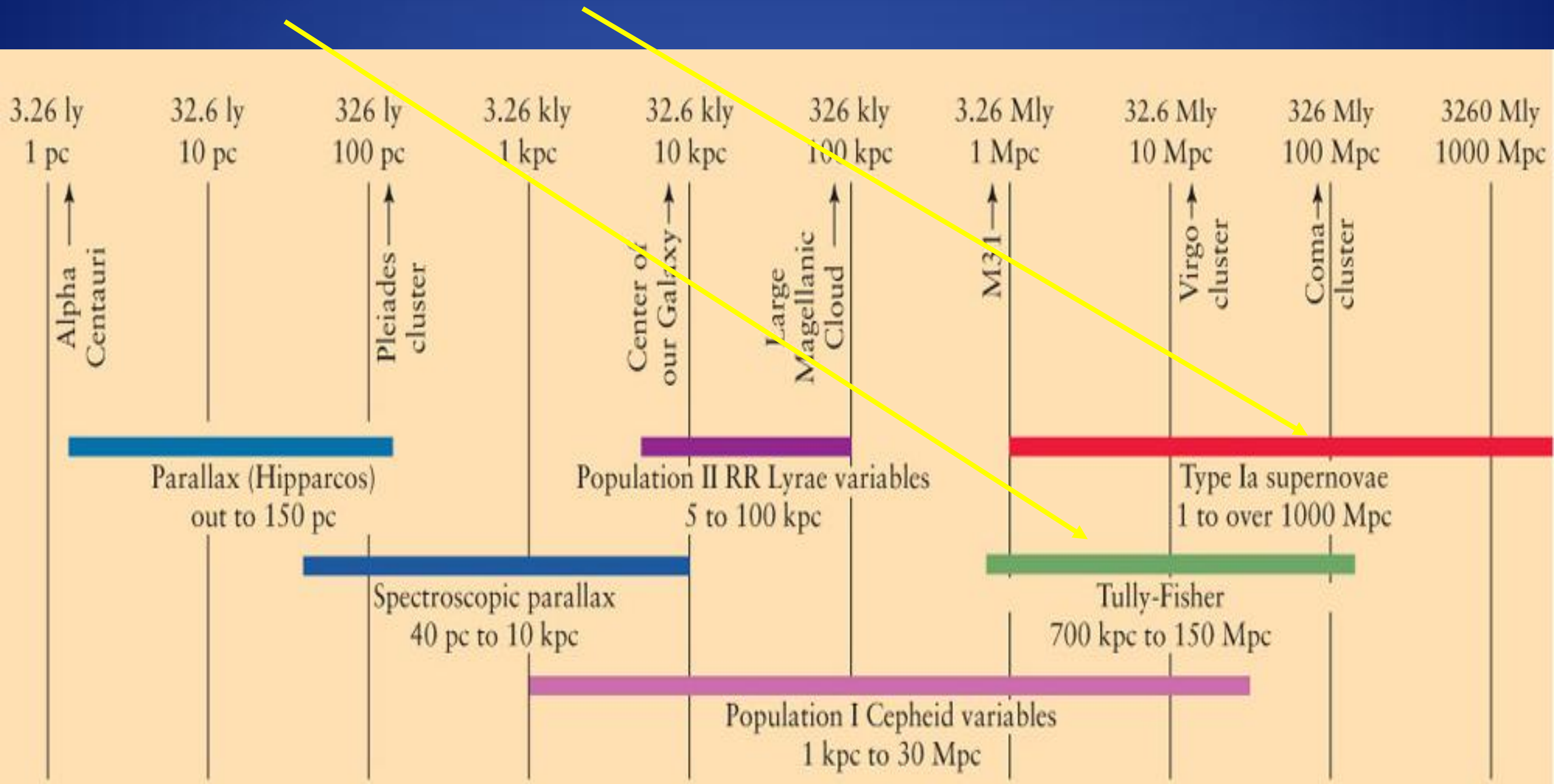
~10 Mly



The Cosmic Distance Ladder

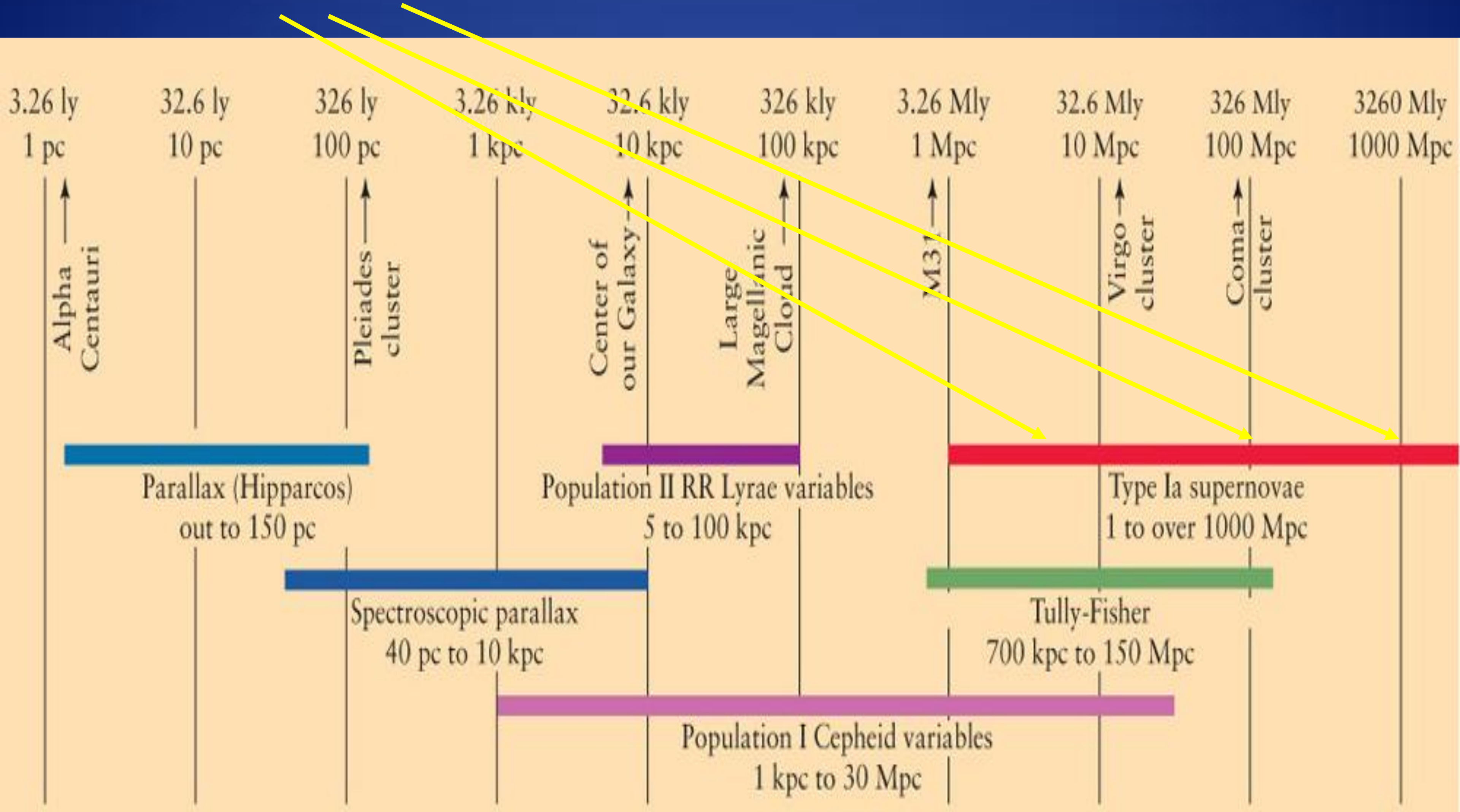
Calibrated variable stars, supernovae, most massive galaxies in 'distant' clusters

~500 Mly to 5 Gly

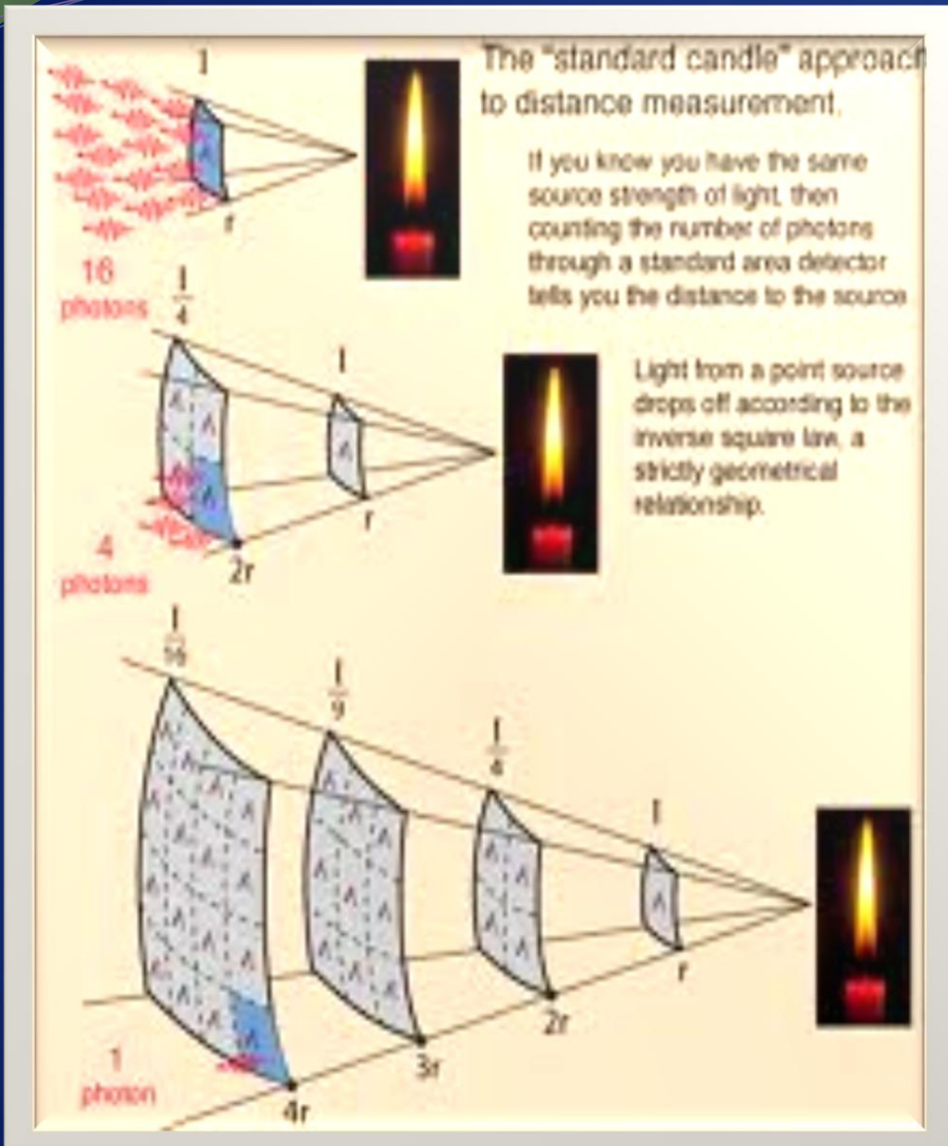


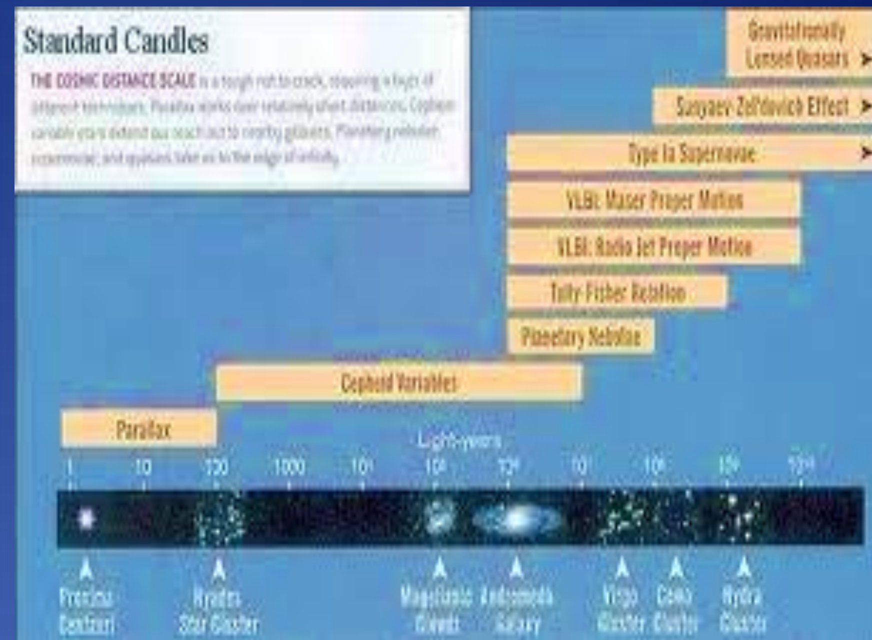
The Cosmic Distance Ladder

Hubble's Law *~10 Gly*

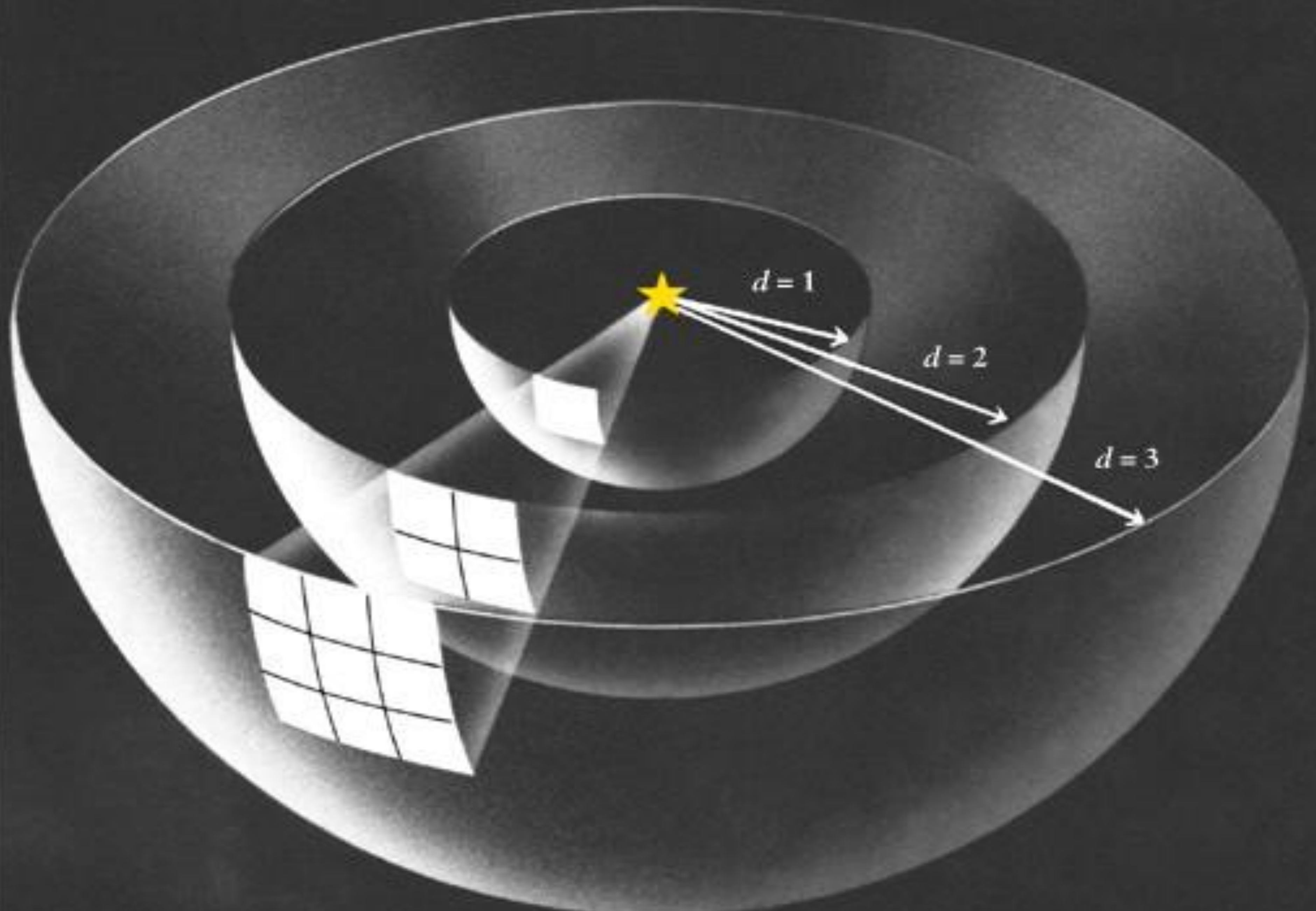


Standard Candles



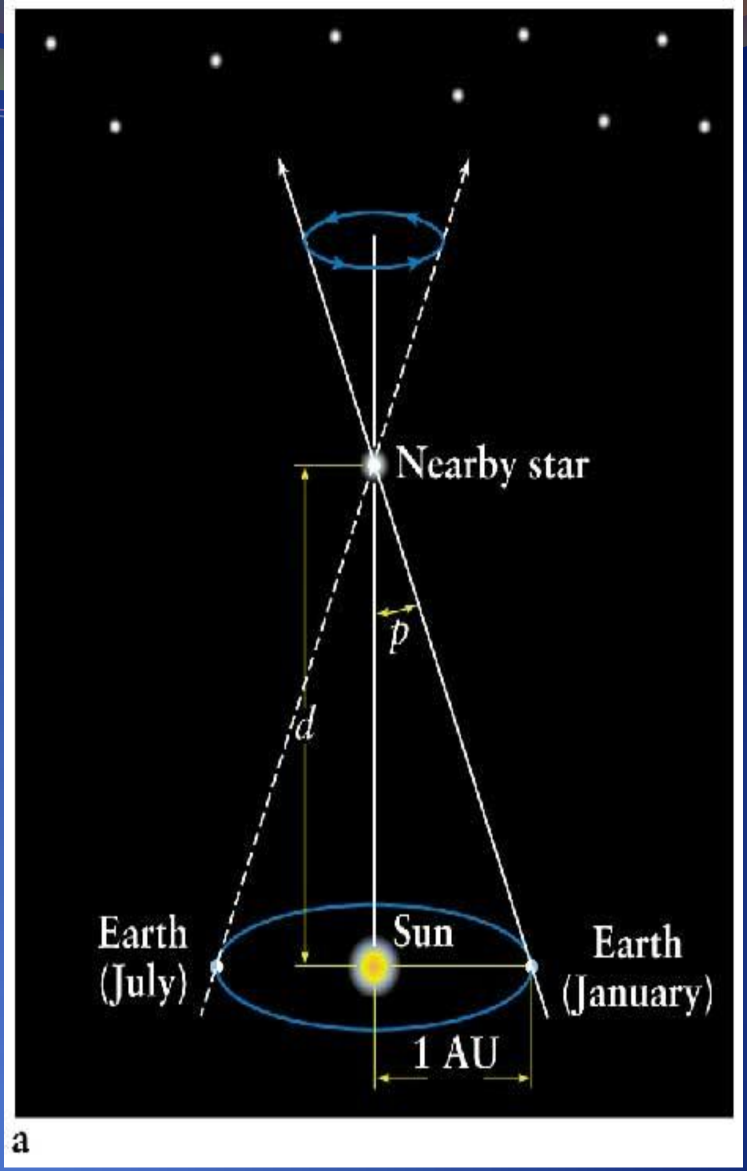


- Magnitude: Historical unit (Hipparchus) of stellar brightness such that 5 magnitudes represents a factor of 100 in intensity
- Apparent magnitude: Number assigned to visual brightness of an object; originally a scale of 1-6
- Absolute magnitude: Magnitude an object would have at 10 pc – convenient distance for comparison
- List of most luminous stars


d = 1
d = 2
d = 3

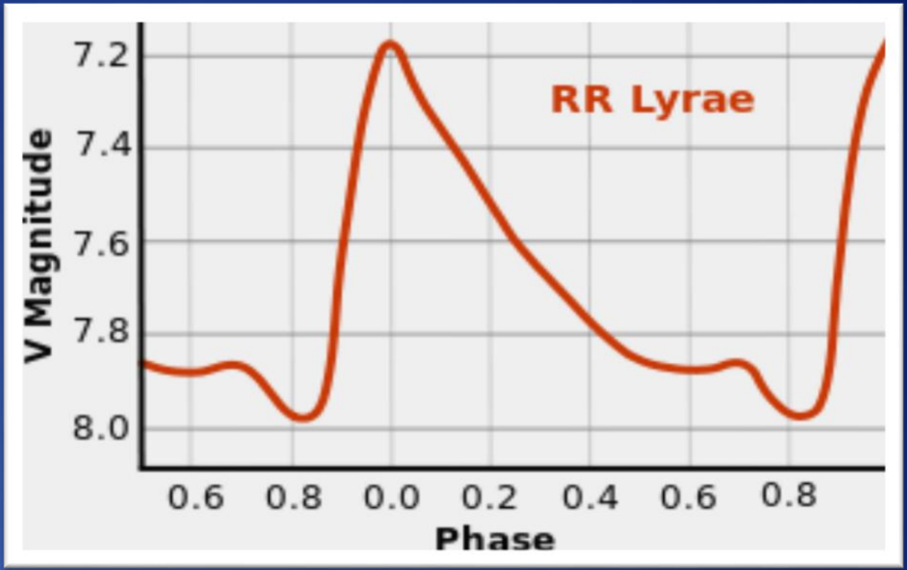
Parallax

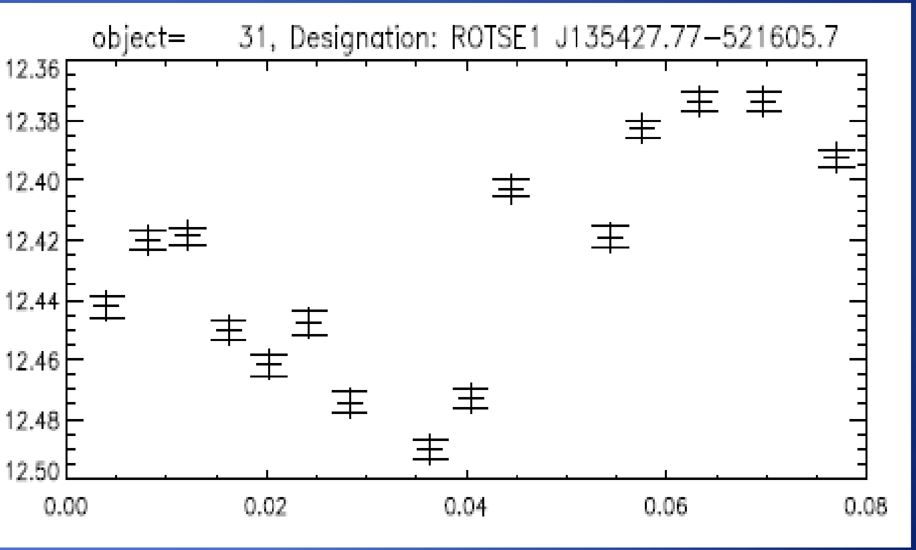
- Distance Units:
  - 1 AU = 1.49597870700 x 10^{11} m
  - 1 ly = 9.46 053 x 10^{15} m = 6.324 x 10^{4} AU
  - 1 pc = 3.085678 x 10^{16} m = 3.261633 ly = 206 264.81 AU
- 1 parsec (pc): Distance from the Sun to an astronomical object for which the parallax angle is one arcsecond
- Stellar parallax: A nearby star's apparent movement against the background of more distant stars as the Earth revolves around the Sun
- By taking measurements of the same star 6 months apart and comparing the angular deviation, distance to the star can be calculated
- 1st performed by Friedrich Wilhelm Bessel (1838)
- Limit of measurement with Earth based telescopes is about 20 pc -- includes around 2000 stars
- Hipparcos satellite (1989-1993) measured parallax accurately to about 200 pc – nearly a million stars
  - Precision parallax measurements of 273 Cepheid variables, 2 of them not previously observed



RR Lyrae Variables

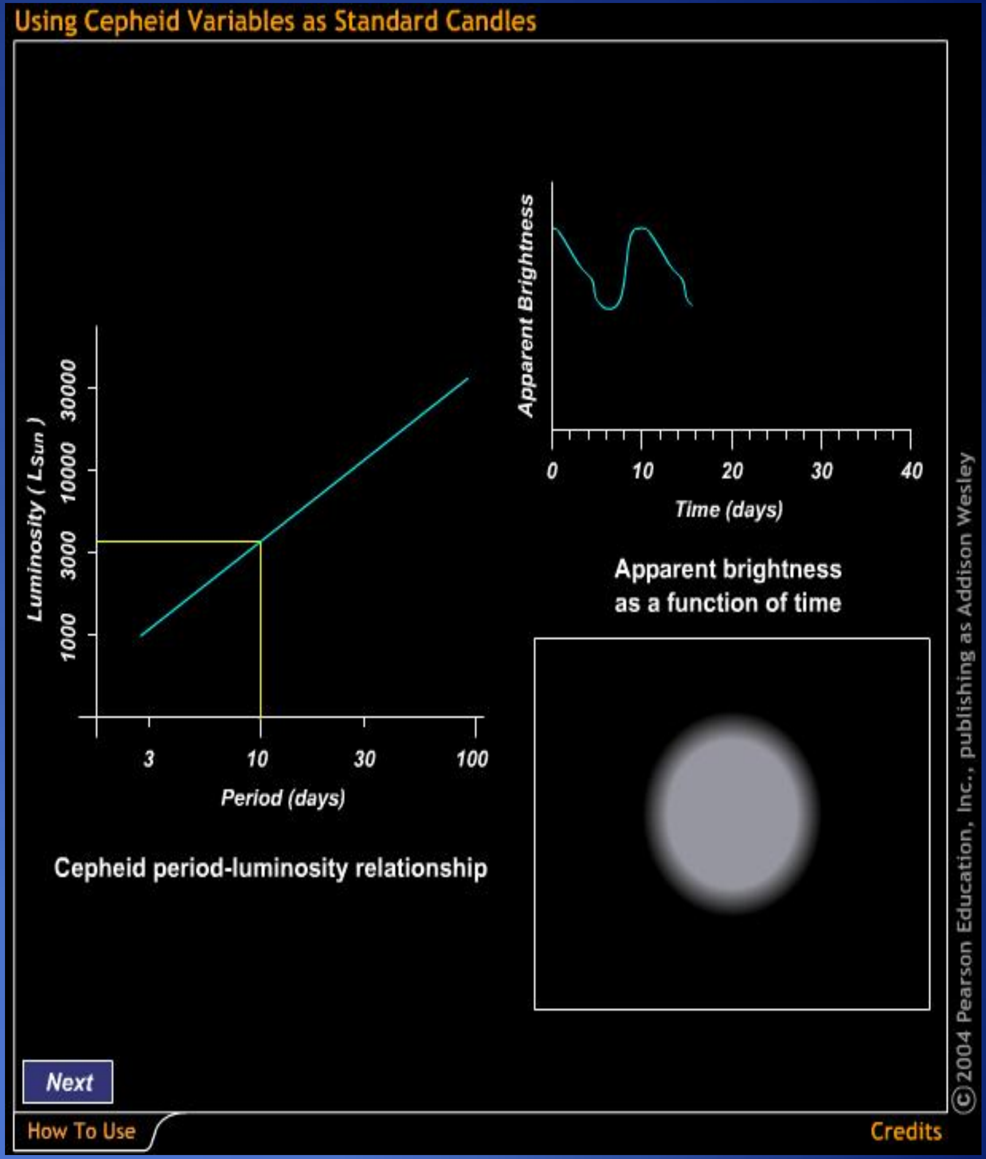
- Short period variable stars (< 1 day)
- Commonly found in globular clusters
- Named after prototype RR Lyrae in Lyra
  - Consumed H at core
  - Evolved off of main sequence & passed through red giant stage
  - Fusion of He in core
- Pulsating horizontal branch stars
  - Spectral class A (F occasionally)
  - Mass ≈ 0.5 solar mass; originally about 0.8 solar mass but shed mass during evolution
- Pulse in a manner similar to Cepheids
  - Old, low mass, metal–poor, Population II stars
  - More common but less luminous than Cepheids
  - Absolute mag = 0.75 (40-50 times solar luminosity)
- Good standard candles for relatively near objects (within Milky Way)
- Also used in globular cluster studies & to study chemical properties of older stars





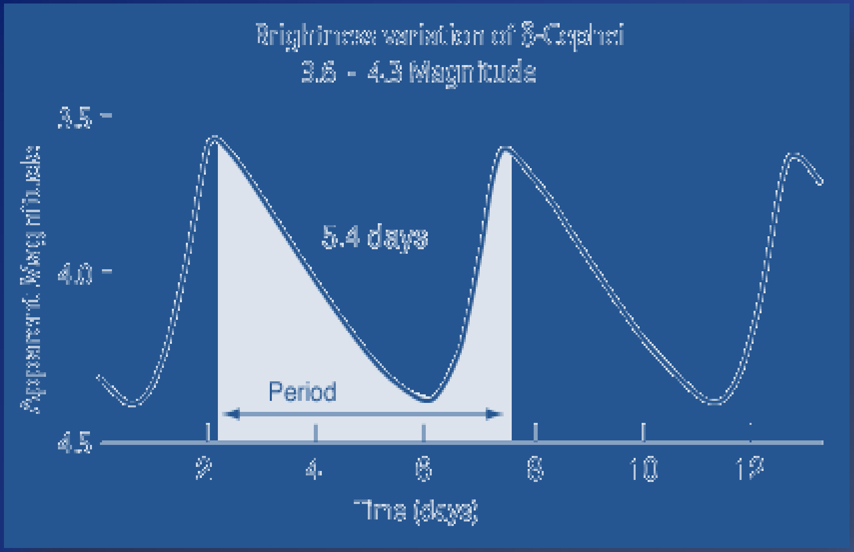
Cepheid Variables

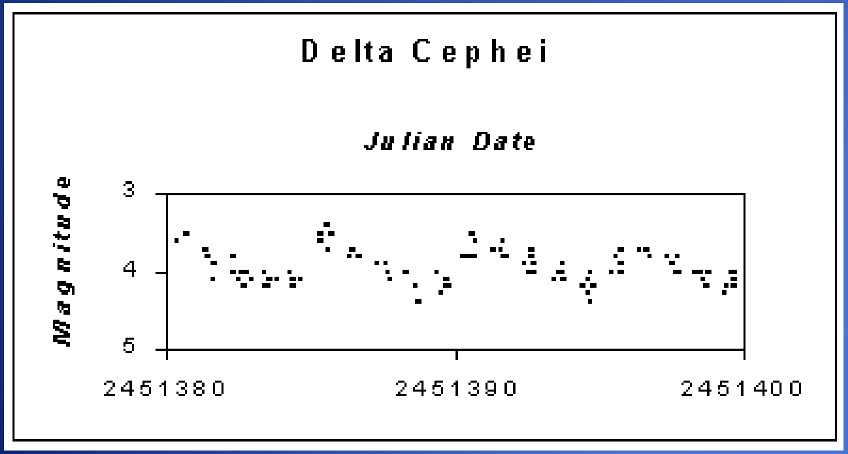
- Cepheid variables (Population I stars) make good standard candles because:
    - Long period variables
    - Follow a well-defined period-luminosity relationship
    - Bright giants -- luminous enough to see at great distances
- Henrietta Swan Leavitt (1868-1921): Observed a certain class of stars that oscillated in brightness periodically
- Plotting absolute brightness vs periodicity yielded a precise relationship
- Provided another way to obtain absolute brightness, & hence observed distances
- Because Cepheids are so bright, this method works up to 13 Mly
- Most galaxies have at least one Cepheid in them, so distances to all galaxies out to a reasonably large distance can be determined

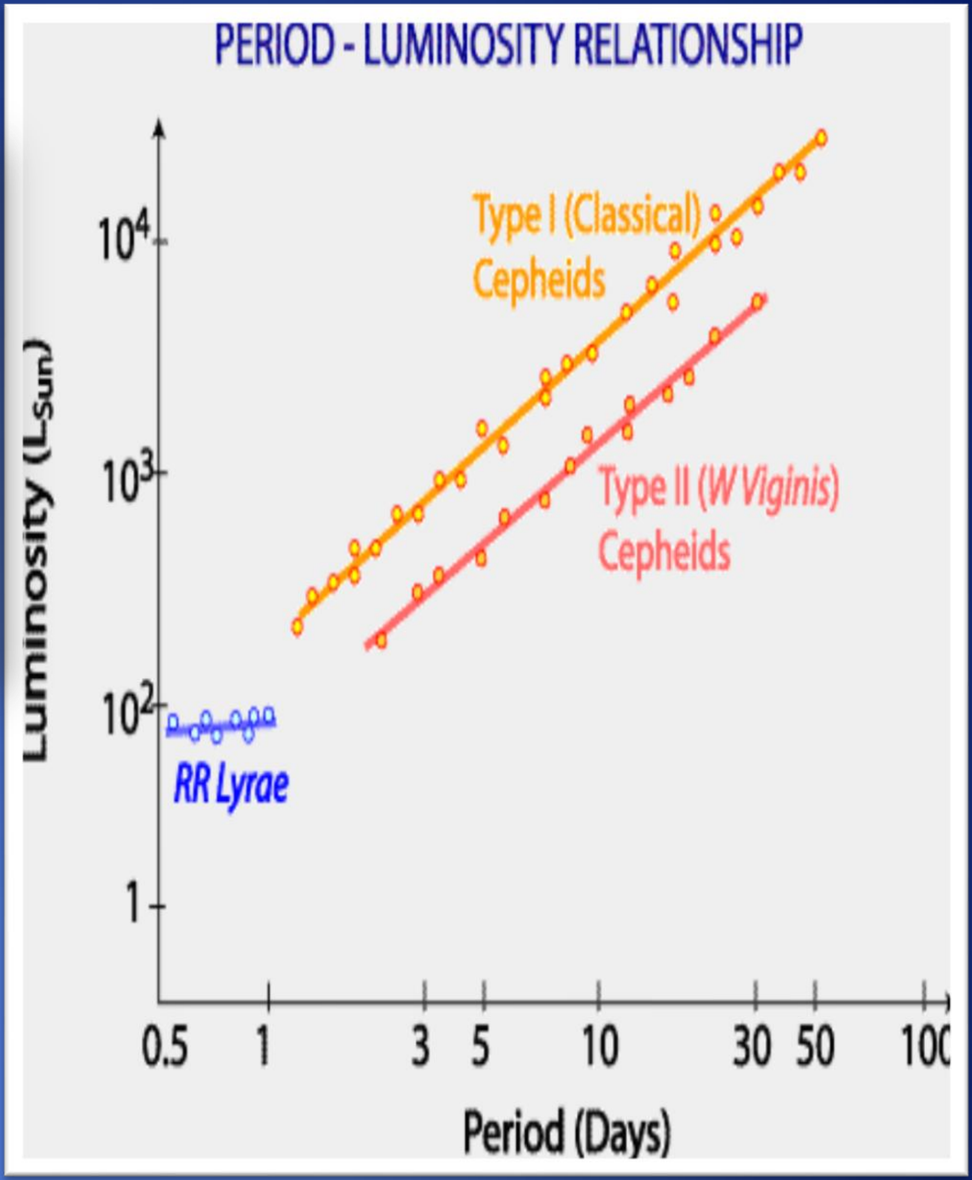


Cepheid Variables

- δ Cephei

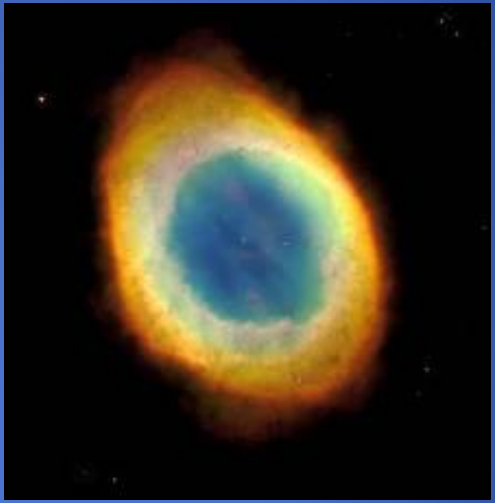






Planetary Nebulae

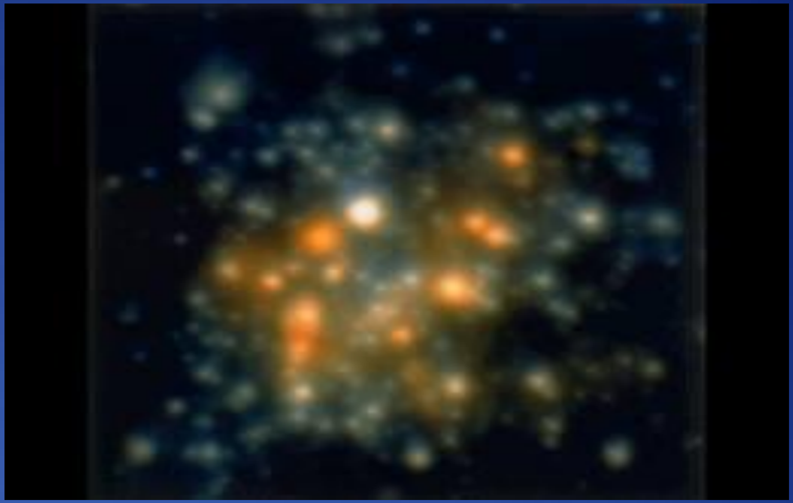
- Planetary nebula luminosity function (PNLF) is a secondary distance indicator used in astronomy
- Uses the [O III] λ5007 forbidden line found in all planetary nebula which are members of old stellar populations (Population II)
- Works well for both spiral and elliptical galaxies despite completely different stellar populations
- Part of the Extragalactic Distance Scale



The Ring Nebula (NGC 6720)

Most Luminous Supergiants

- Brightest supergiants in a given galaxy will have about the same absolute magnitudes:
  - About -8 for red supergiants
  - About -9 for blue supergiants
- These two types of supergiants can be seen out to about 50 Mly & 80 Mly respectively
- Compared to a maximum distance of about 20 Mly for Cepheid variables



Galactic center: Sgr A is located near the center of this image. Most of these stars are very young and massive and heavily reddened . Spectroscopic studies indicate that the stars are luminous super giants and only a few 10s of millions years old.*

VY Canis Majoris (Class M hypergiant) : 3 x 10^5 times solar luminosity; about 25 times solar mass.

Most Luminous Globular Clusters

- Beyond 80 Mly, even the brightest blue supergiants fade from view
- Must turn to entire star clusters & nebulae for luminosity measurement
- Brightest globular clusters have total luminosity of about magnitude -10 and can be observed out to 130 Mly

The Messier 80 globular cluster in the constellation Scorpius is located about 28,000 ly from the Sun and contains hundreds of thousands of stars.

H II Regions

- H II regions: Areas in space which are luminous with the emission spectrum of ionized
- Brightest H II regions have absolute magnitudes of ≈ -12 & can be detected out to about 300 Mly
- Compared to ≈ 130 Mly for the brightest globular clusters
- Associated with the presence of massive O-type & B-type stars
  - Surface temperatures in the range 15 000 – 60 000 K
  - Characteristic blackbody radiation curves peak in UV
- These stars will often be surrounded by vast clouds of H gas
- UV can ionize the H atoms:
  - H atoms tend to attract electrons & reassemble
  - Captured electrons cascading down through the quantum states of the H atom
  - Emit characteristic photons of light upon each downward jump

Eagle Nebula (M16): "The Pillars of Creation"

Supernovae (Sne)

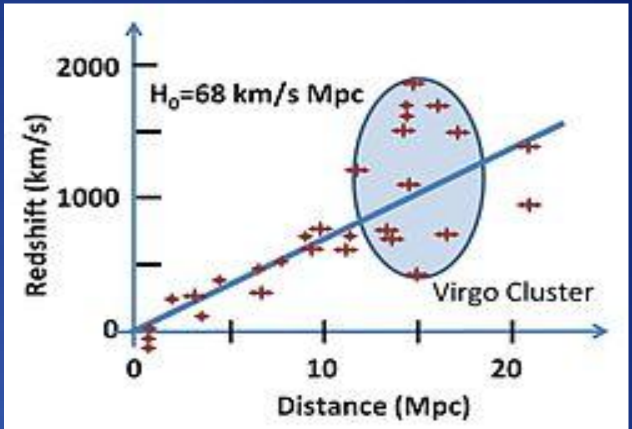
- Beyond 300 Mly where even the brightest HII regions are indistinct, the only individual standard candles are supernovae which can reach a peak magnitude = -19
- In theory, such magnitudes should be visible to 8 Gly
- However, supernovae types Ib, Ic & II show large brightness variations; intervening matter absorbs light
- Supernova classified as Type 1a are of great usefulness
  - Provide a distance measurement uncertainty approaching 5% over vast distance ranges of ≈ 1 000 Mpc

Nearby Supernova in Whirpool Galaxy (M51)

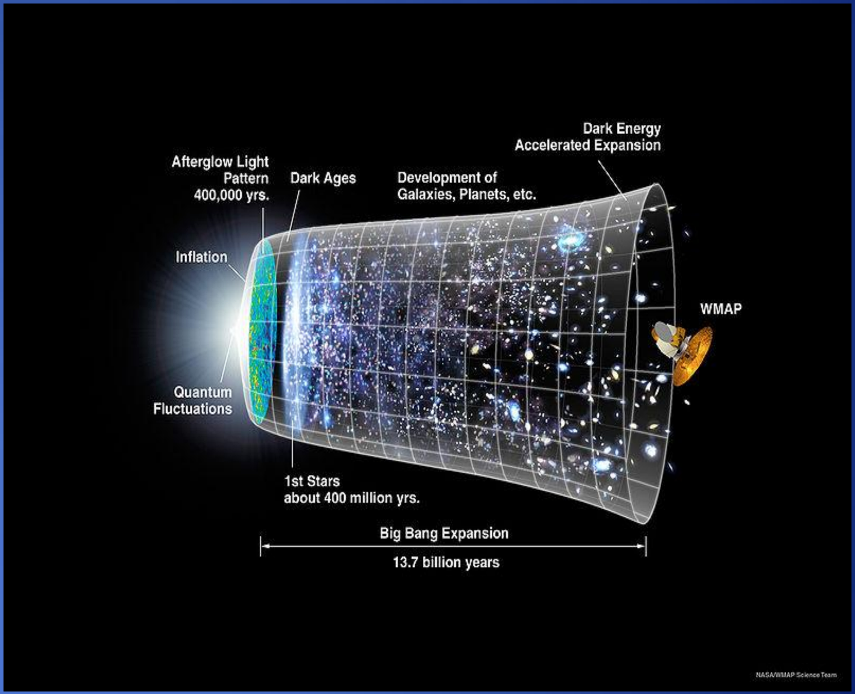
Hubble Constant & Red Shift

- Edwin Hubble (1889-1953) formulated the law relating velocity (as observed by red shift) with distance
  - Led in turn to the famous “Big Bang” model of the expanding universe.

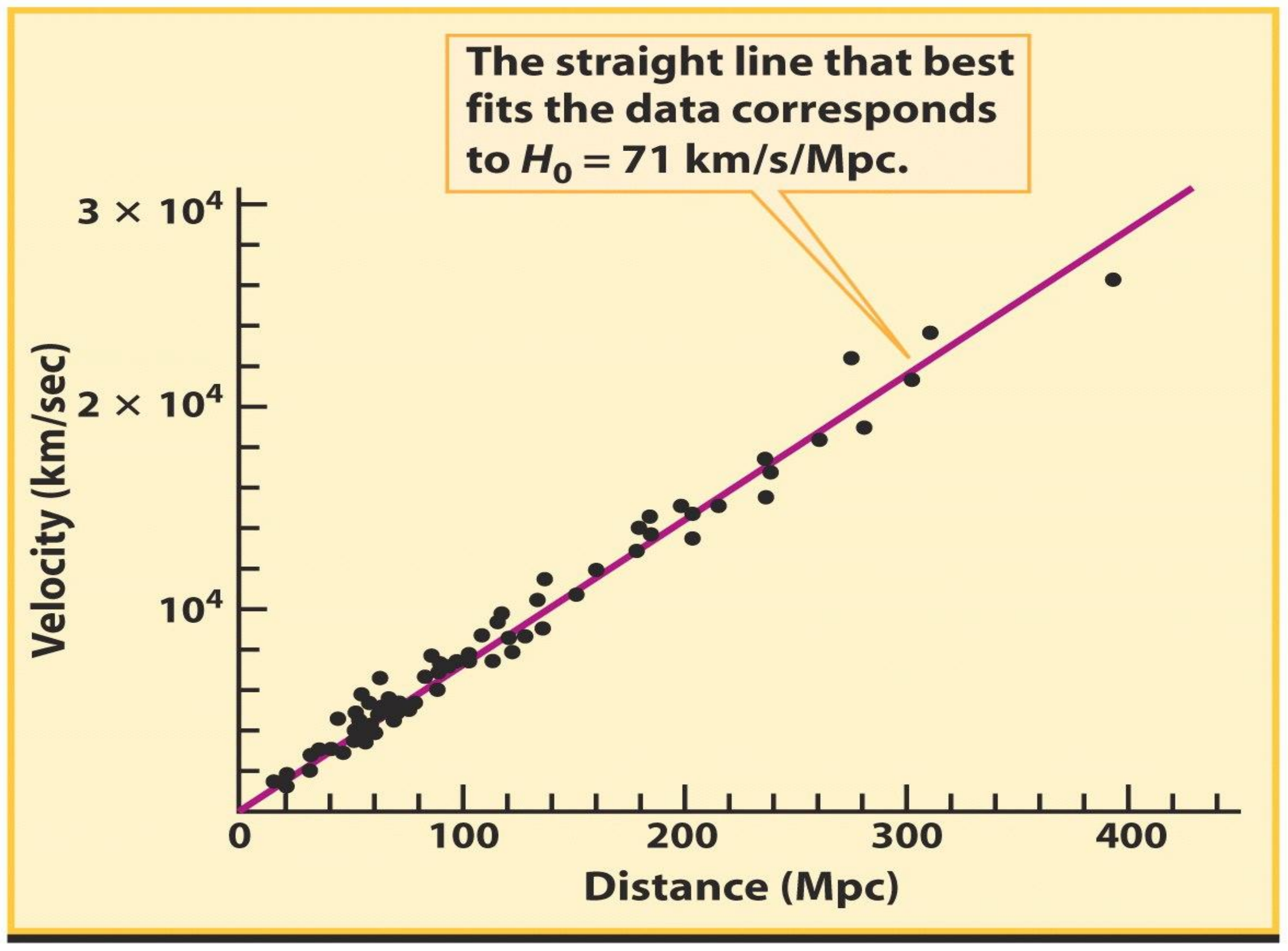
$$v = H_0 D$$



- Combined existing data against more precise red-shift measurements & known speed of light
- Hubble’s law can then be used to give another measurement of distance at the largest scales
- These measurements have led to accurate maps of the universe at very large scales
  - Led to many discoveries of very large-scale structures not otherwise possible
  - Ex: Great Wall, Great Attractor, etc.
- Hubble constant:
  - Particle Data Group "best modern value" of the Hubble constant: H_0 = 72 km/s per Mpc (∓ 10%).
  - Comes from the use of type Ia supernovae (which give relative distances to about 5%) along with data from Cepheid variables gathered by the HST
  - WMAP mission data Hubble constant:
    - H_0 = 71.0 2.5 km/s per Mpc



Hubble Constant & Red Shifts



Age of Universe = $1/H_0$ = 13.75 ∓ 0.11 Gy

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