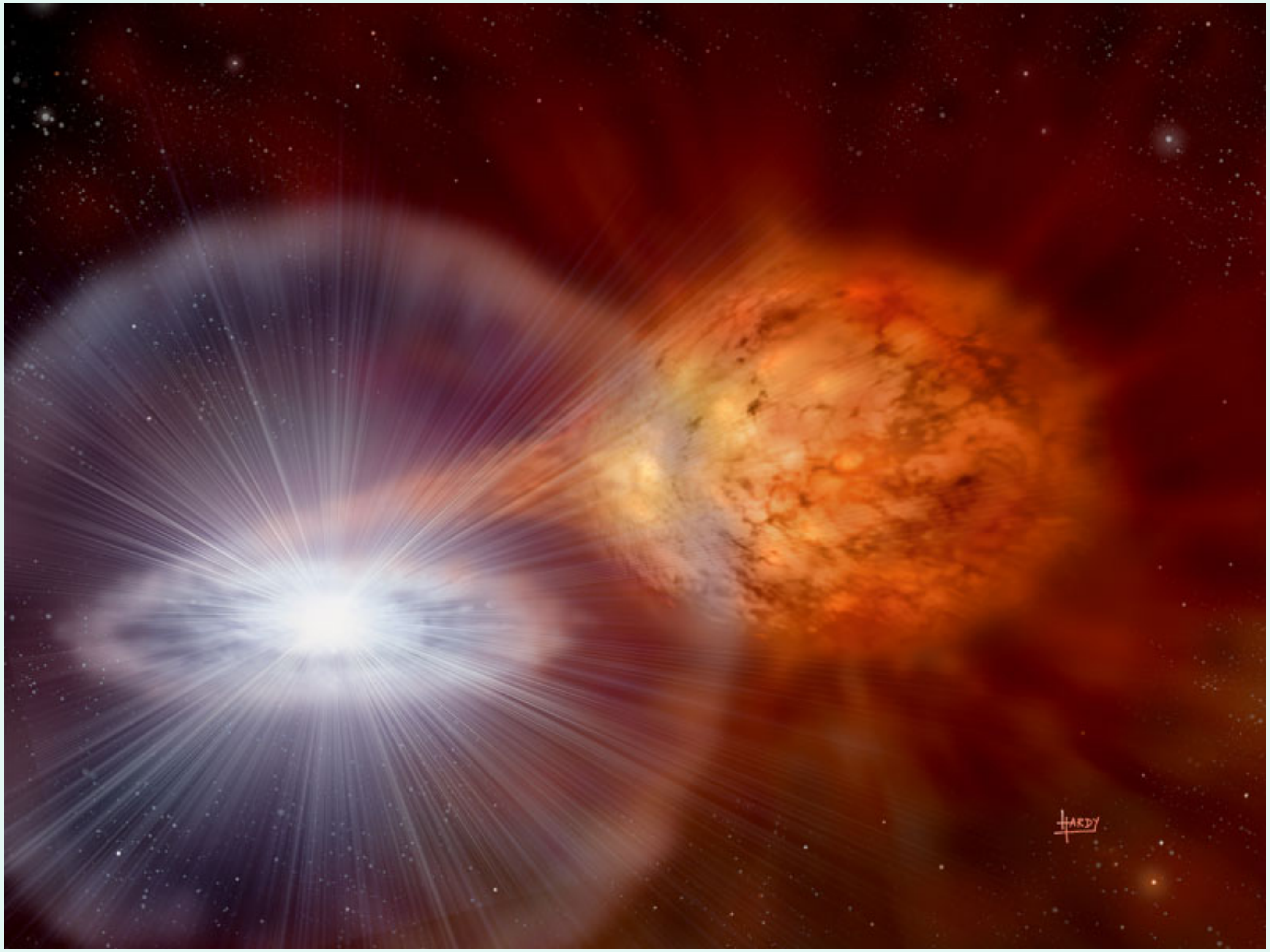
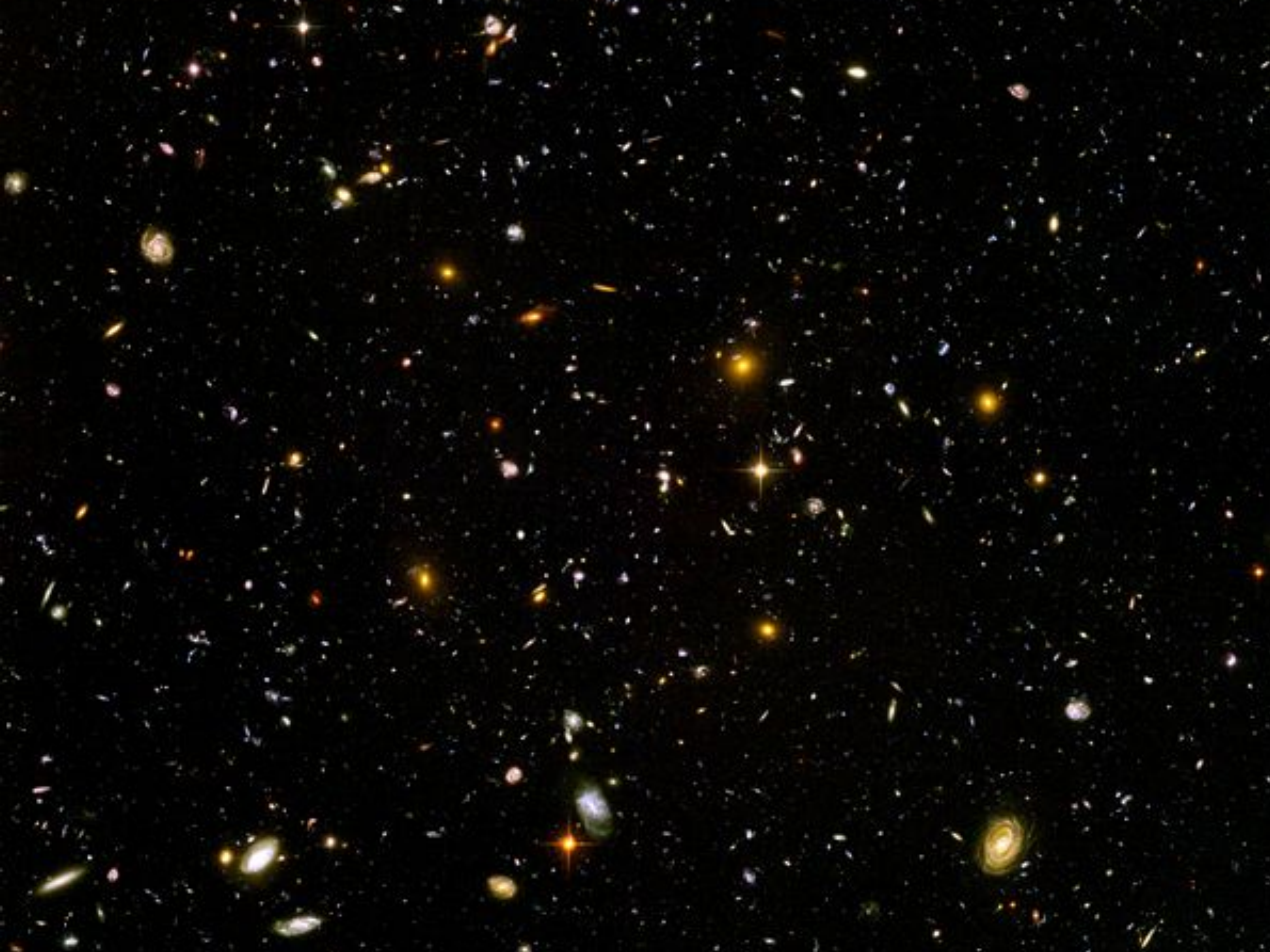
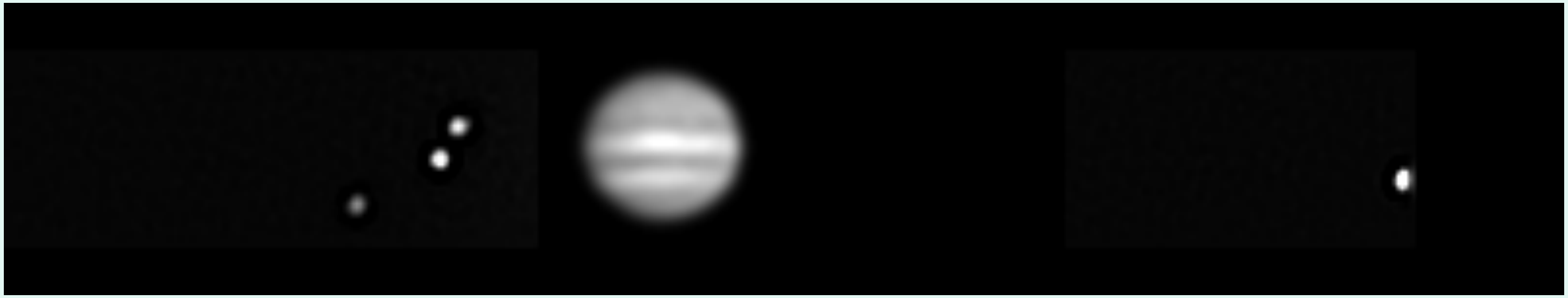
# Astronomy 120

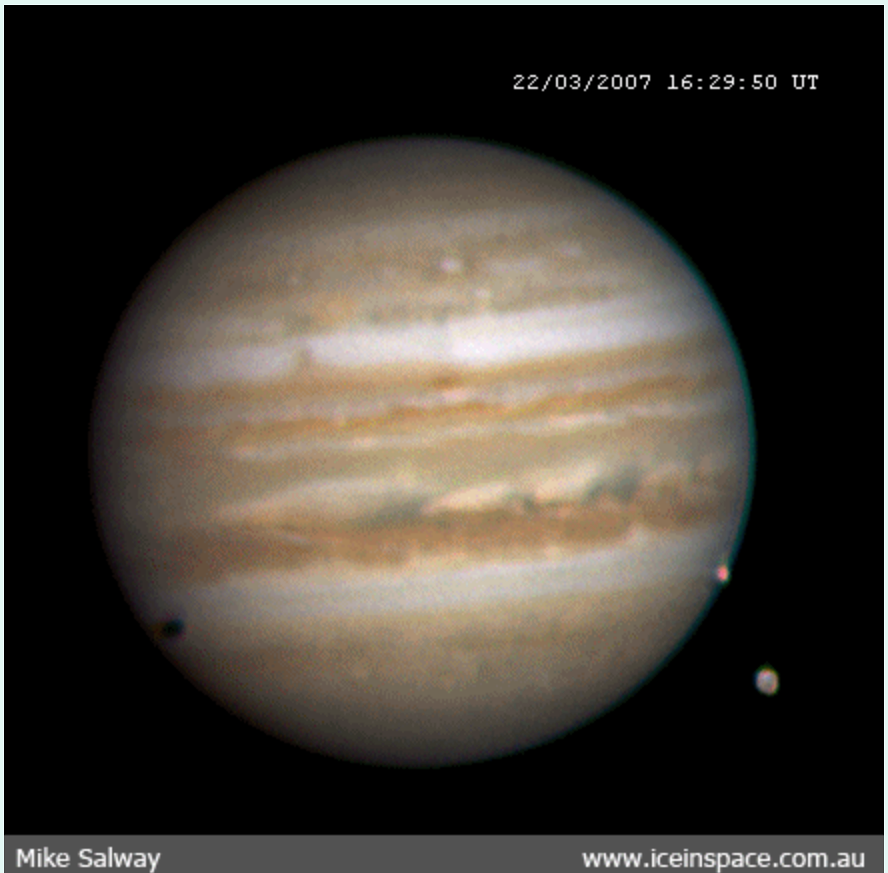



Prof. Jeff Kenney    Class 9    June 7, 2018



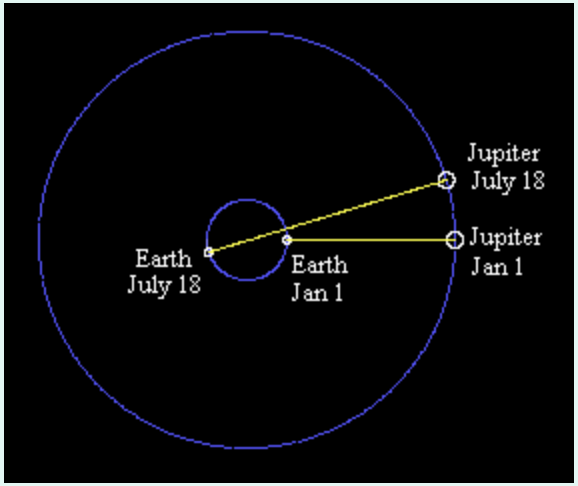
# How do we know earth-sun distance?






Jupiter's orbiting moons can be used as a clock

like looking at accurate clock thru a telescope

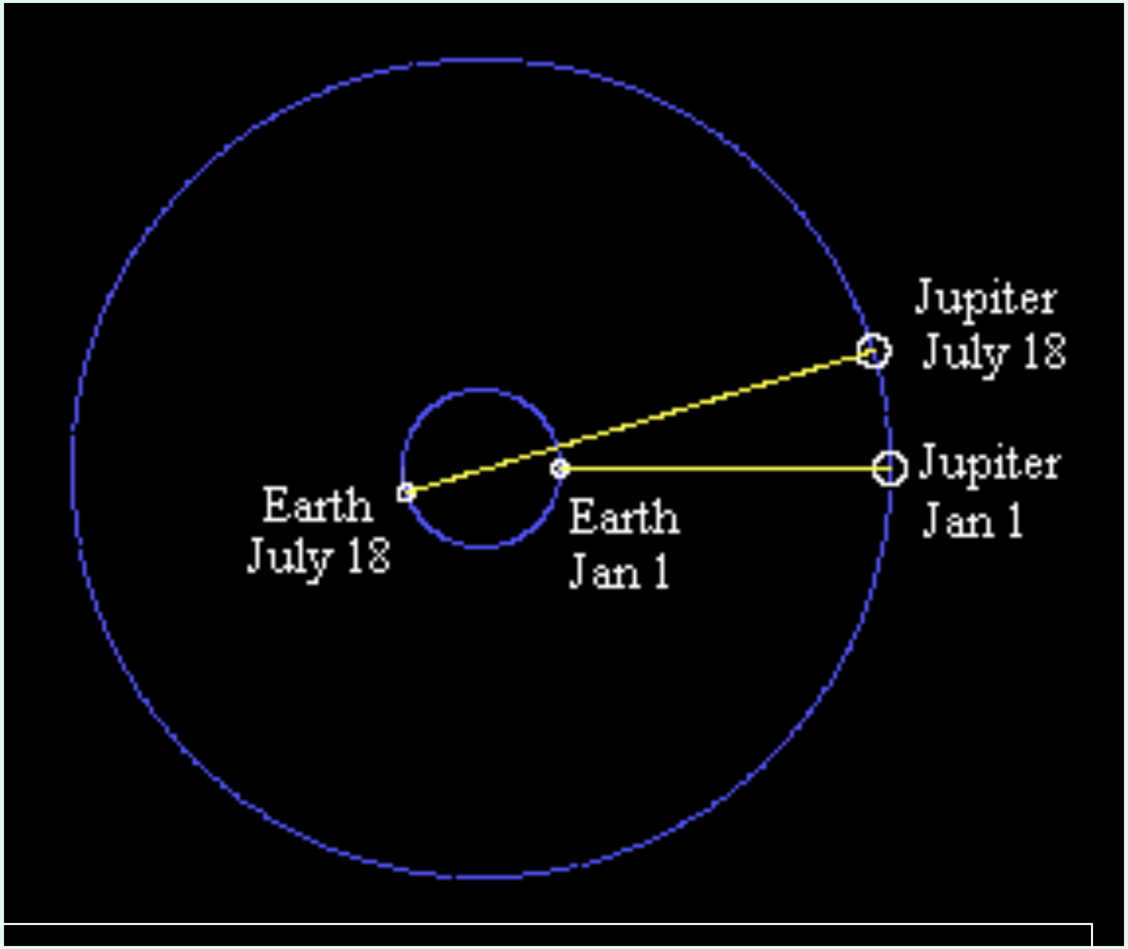



# Time delay in transits of Jovian moons

- A delay when Jupiter is furthest from earth, compared to when it is closest to the earth
- Time delay is due to extra distance & light travel time across inner solar system
- Can use this to measure earth-sun distance, if you know the speed of light

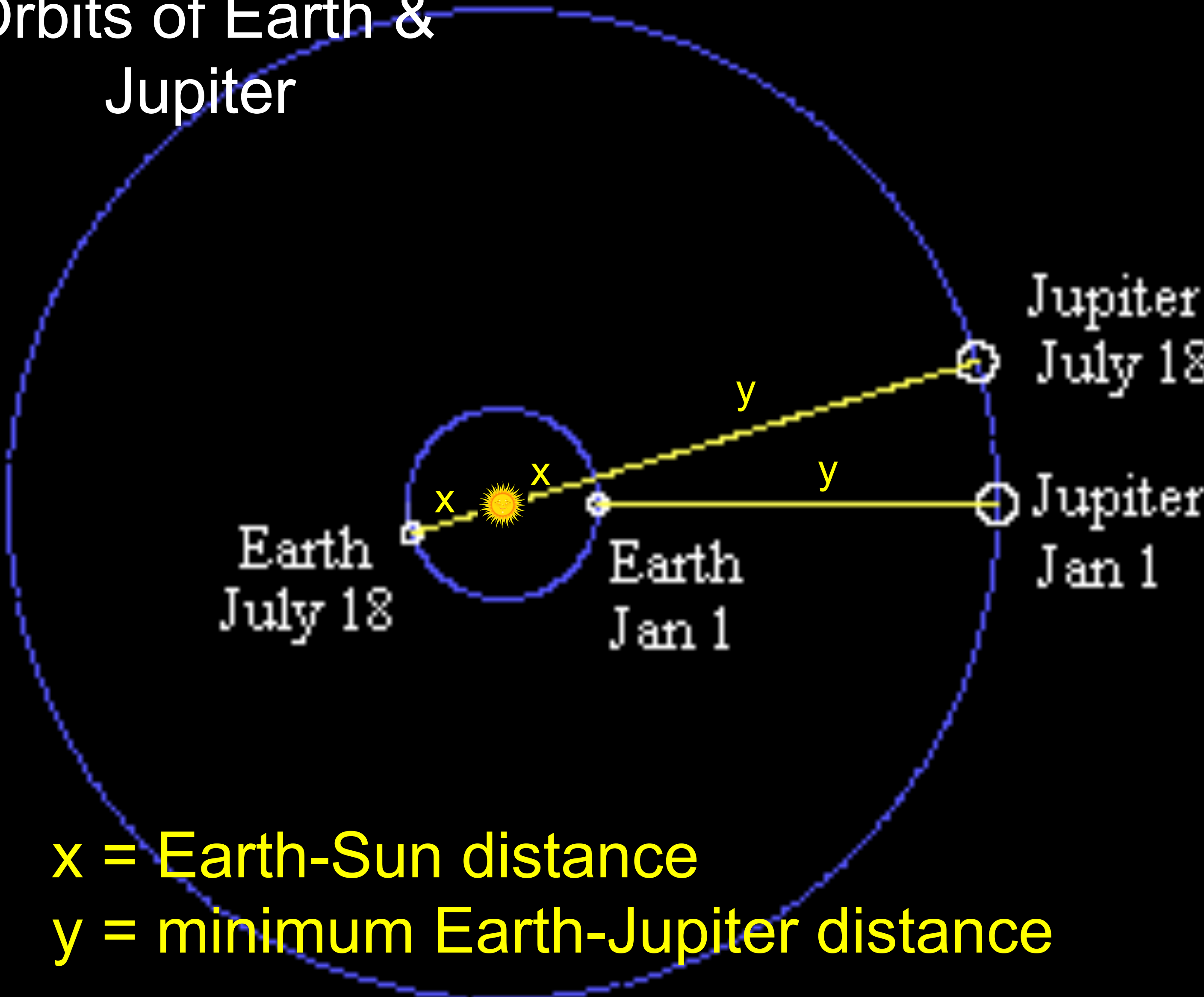
# Orbits of Earth & Jupiter

nice wig!




Roemer (1676)
observed a time delay of 16.6 minutes in the orbital transits (eclipses) of Jovian moons at 6.3-month intervals
*time delay due to the extra distance & light travel time across the inner solar system.*

Orbits of Earth & Jupiter




x = Earth-Sun distance

y = minimum Earth-Jupiter distance

From the diagram…

$2x = 2d_{ES}$ = 16.6 light-minutes

$d_{ES}$ = 8.3 light-minutes

Romer didn't know the speed of light so he couldn't convert to km (or other units) … but we do!

(Romer actually used this to make one of the first good estimates of the speed of light)

$d = vt$ (in general, if no acceleration) d= distance v=velocity t=time

$d_{ES} = ct$ = (300,000 km/sec) (8.3 minutes) (60 sec/min)

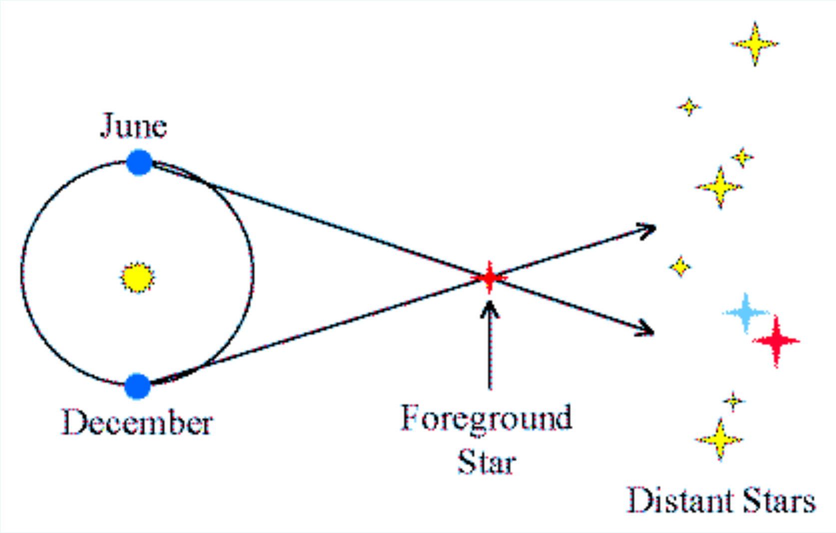
$d_{ES}$ = 150,000,000 km

= 1 astronomical unit

= 1 A.U.

*note: don't need to know $d_{EJ}$ to solve problem!*

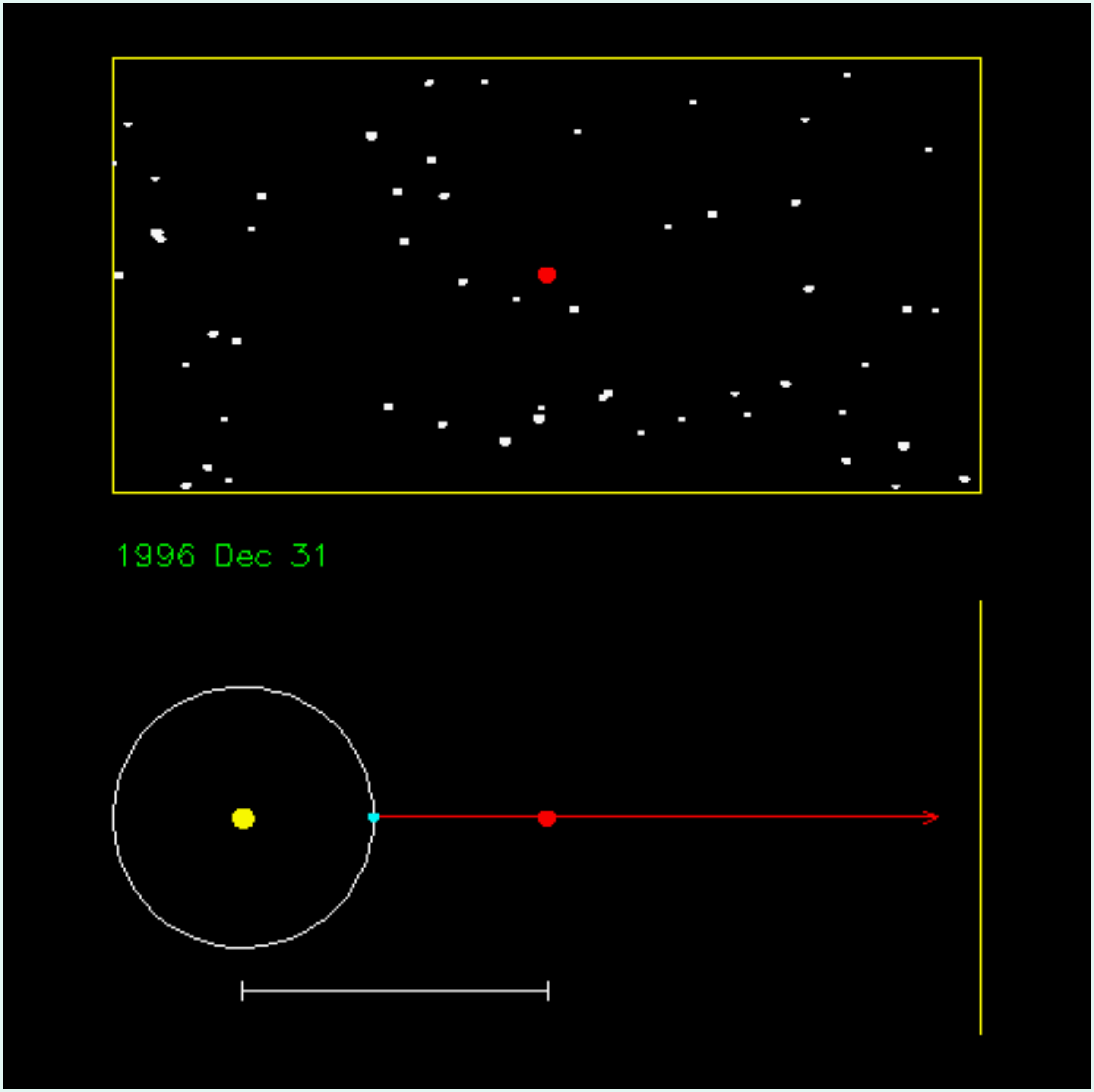
# Measuring Distances to Nearest Stars with Stellar Parallax




Stellar parallax: apparent motion of nearby stars against background of more distant stars and galaxies

*caused by earth's orbital motion around sun*

# Stellar parallax

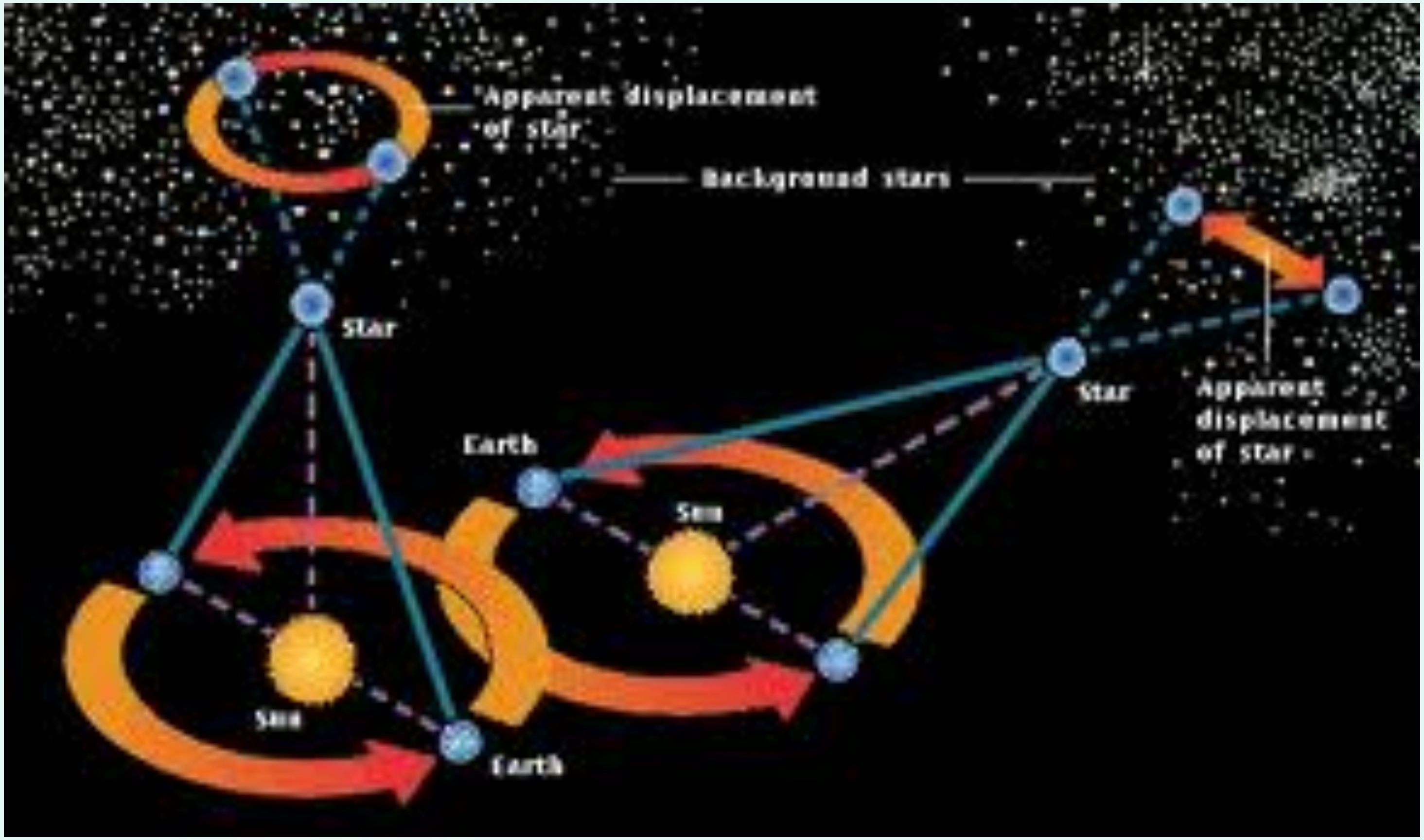



Sky view
(from earth)

Side view
(from above solar system)

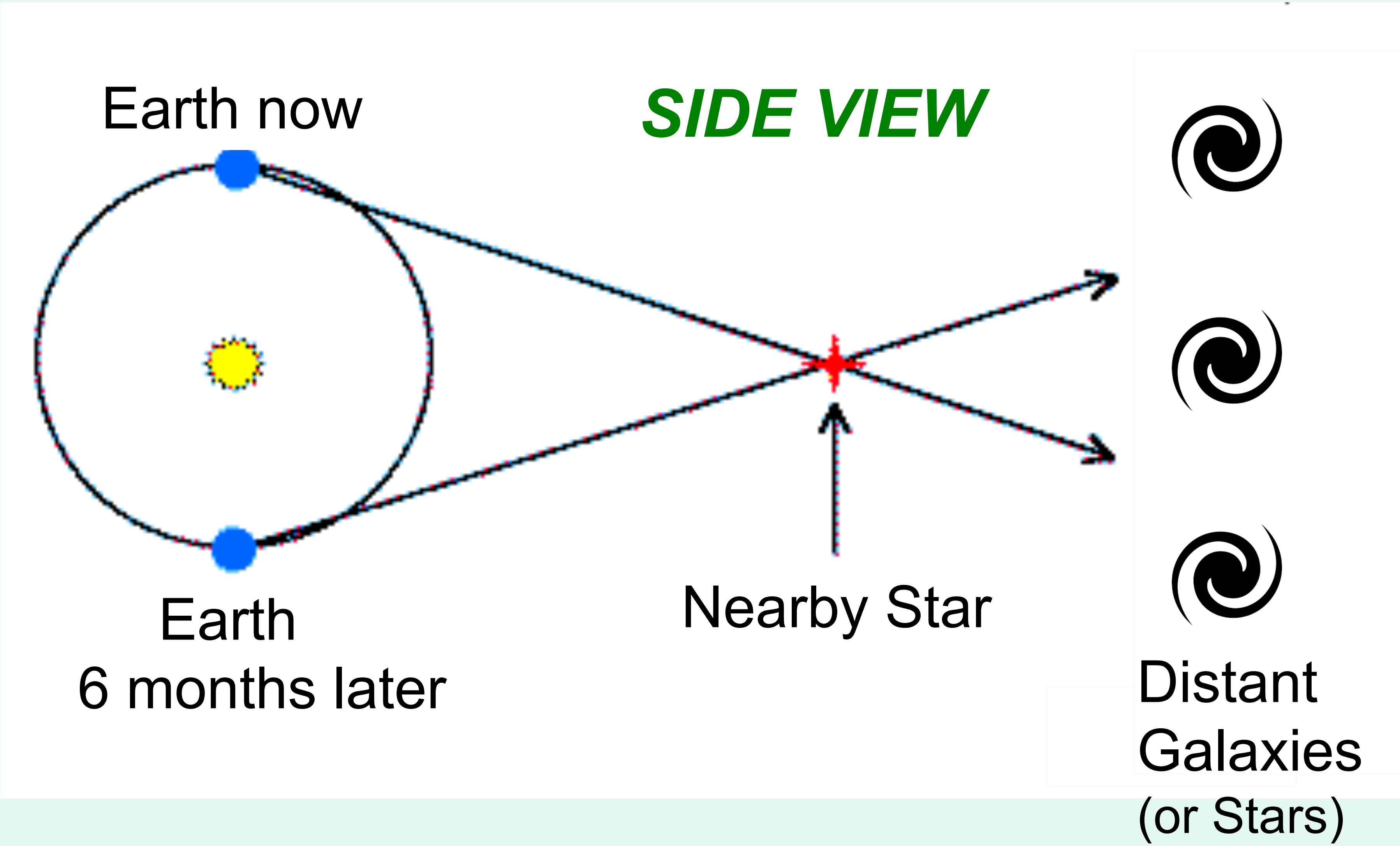
Parallax effect exaggerated by 100,000x

# Parallax in different directions

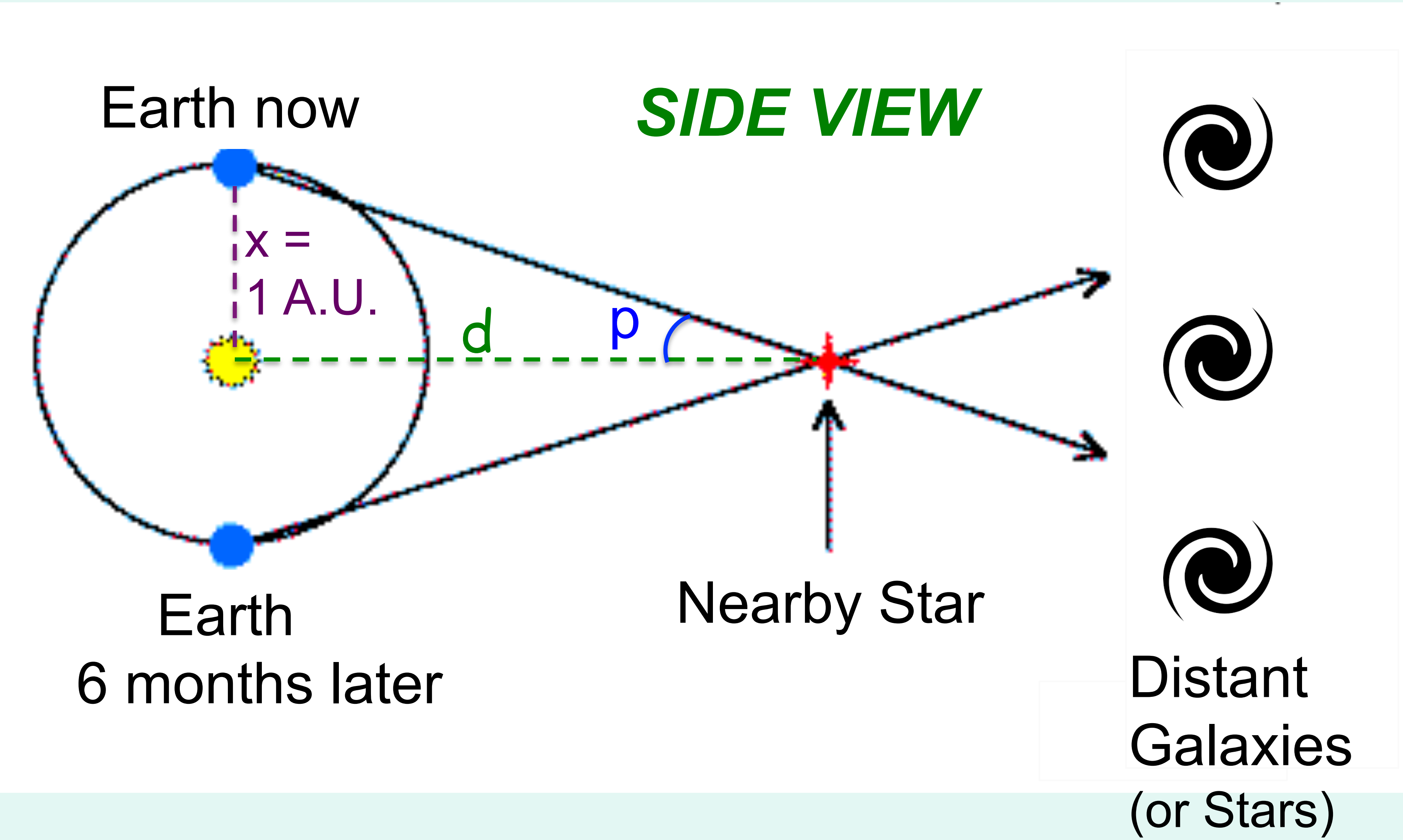



In earth's orbital plane, parallax motion traces out lines
Perpendicular to earth's orbital plane, parallax motion traces out circles
In other directions, parallax motion traces out ellipses

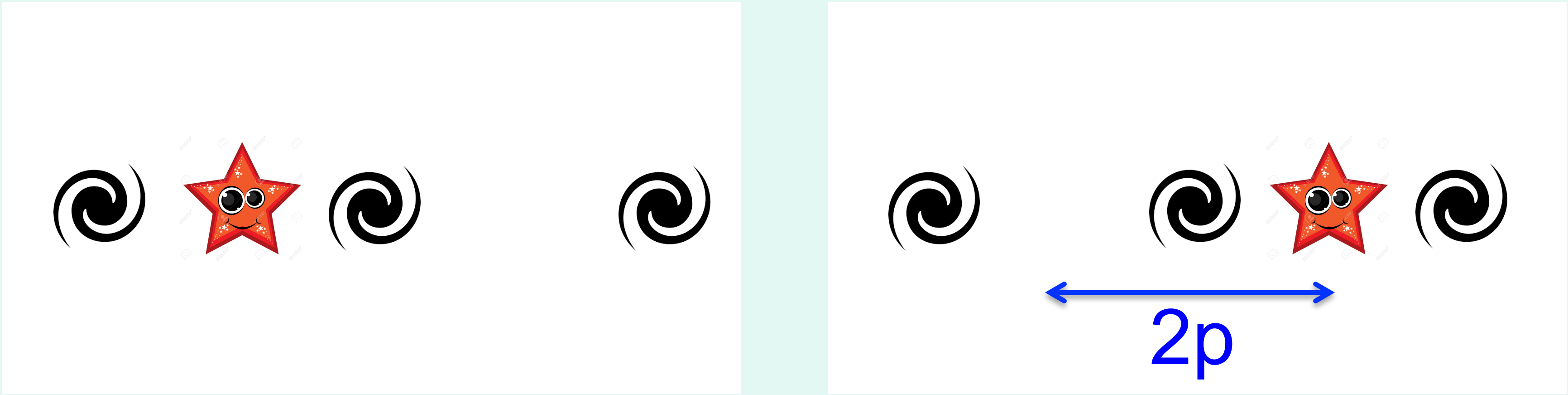
# Measuring Distances to Nearest Stars with Stellar Parallax



# Measuring Distances to Nearest Stars with Stellar Parallax



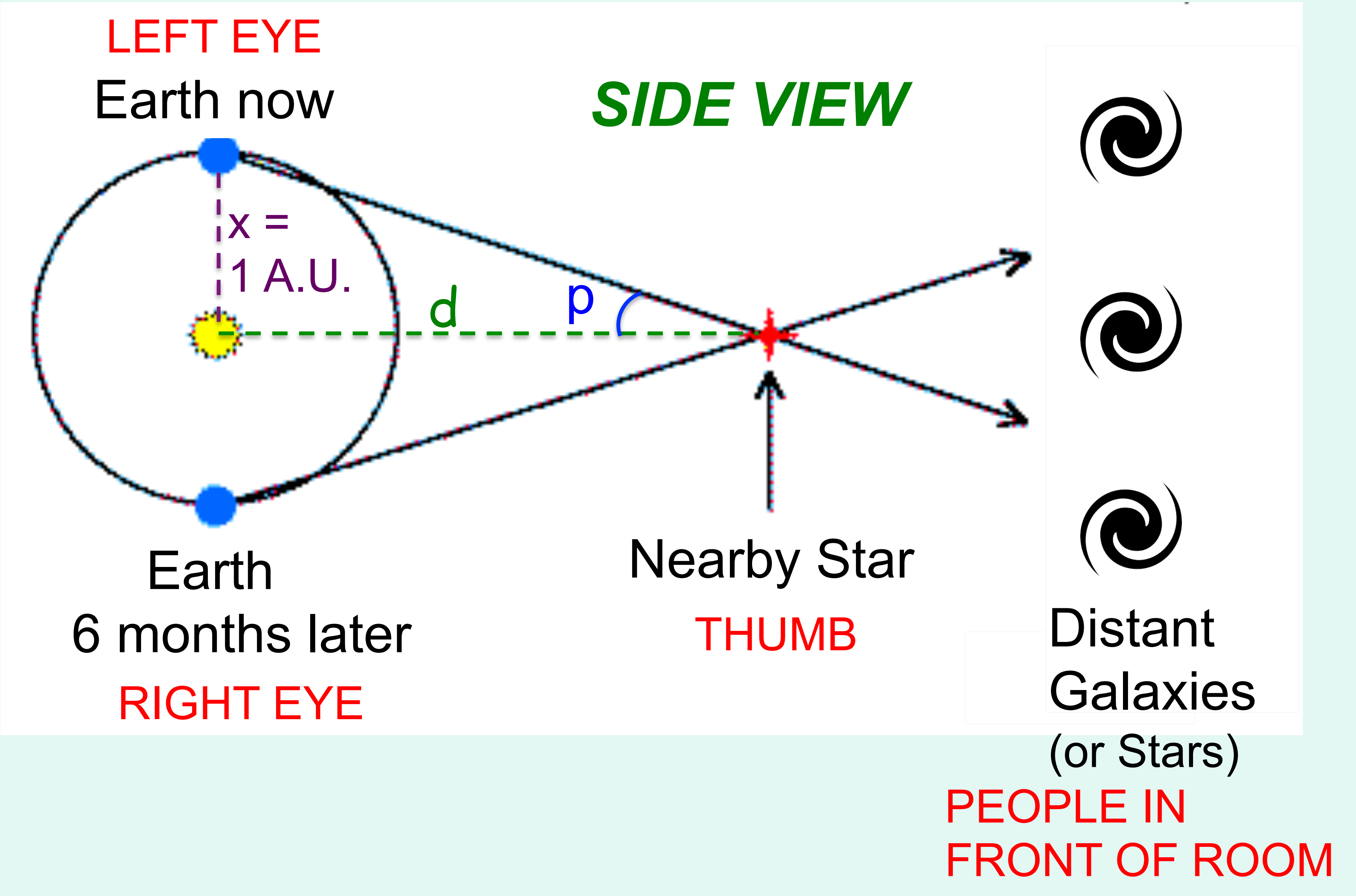
## WHAT WE SEE IN SKY VIEW




NOW

6 MONTHS LATER

Measuring Distances to Nearest Stars with Stellar Parallax



# P = Parallax angle: half the measured shift in star's position over 6 month interval

From simple geometry:

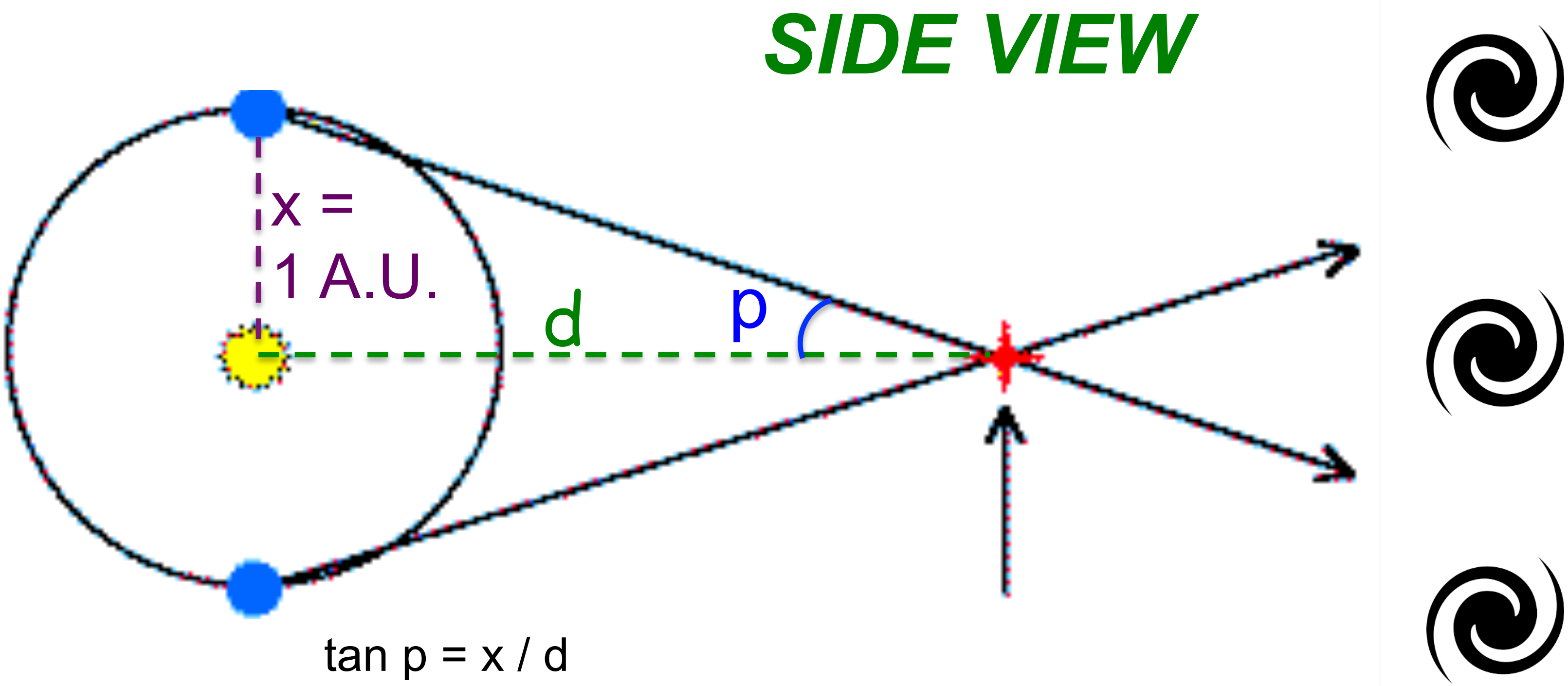
$d = 1 / p$ where

$d$ = distance, in parsecs

$p$ = Parallax angle, in arcseconds

or $d\ (\mathrm{pc}) = 1 / p\ (\mathrm{arcsec})$

# Measuring Distances to Nearest Stars with Stellar Parallax




tan p = x / d

for very small angles, tan p ≈ p  if p measured in radians

p = x / d if p measured in radians

p = 1 AU / d  if p measured in radians, d in AU

d = 1 AU / p  if p measured in radians, d in AU

d = 1 pc / p  if p measured in arcseconds, d in parsecs

1 radian = 206,265 arcseconds

1 parsec = 206,265 AU

# P = Parallax angle: half the measured shift in star's position over 6 month interval

From simple geometry:

d = 1 / p    where

d = distance, in parsecs

p = Parallax angle, in arcseconds

or d (pc)  = 1 / p (arcsec)

in order to get such a simple equation, we define a new distance:

1 parsec = 206,265 AU

1 parsec = 3.26 light-years

*a parsec is that unit of distance that makes this equation as simple as possible!*

# P = Parallax angle: half the measured shift in star's position over 6 month interval

From simple geometry:

**d = 1 / p** where

d = distance, in parsecs

p = Parallax angle, in arcseconds

or **d (pc) = 1 / p (arcsec)**

in order to get such a simple equation, we define a new distance

define 1 parsec = 206,265 AU

1 pc = 3.26 light-years

a parsec is that unit of distance that makes this equation as simple as possible!

A star with a parallax angle of p=1" has distance of d=1 pc

A star with a parallax angle of p=0.1" has distance of d=10 pc

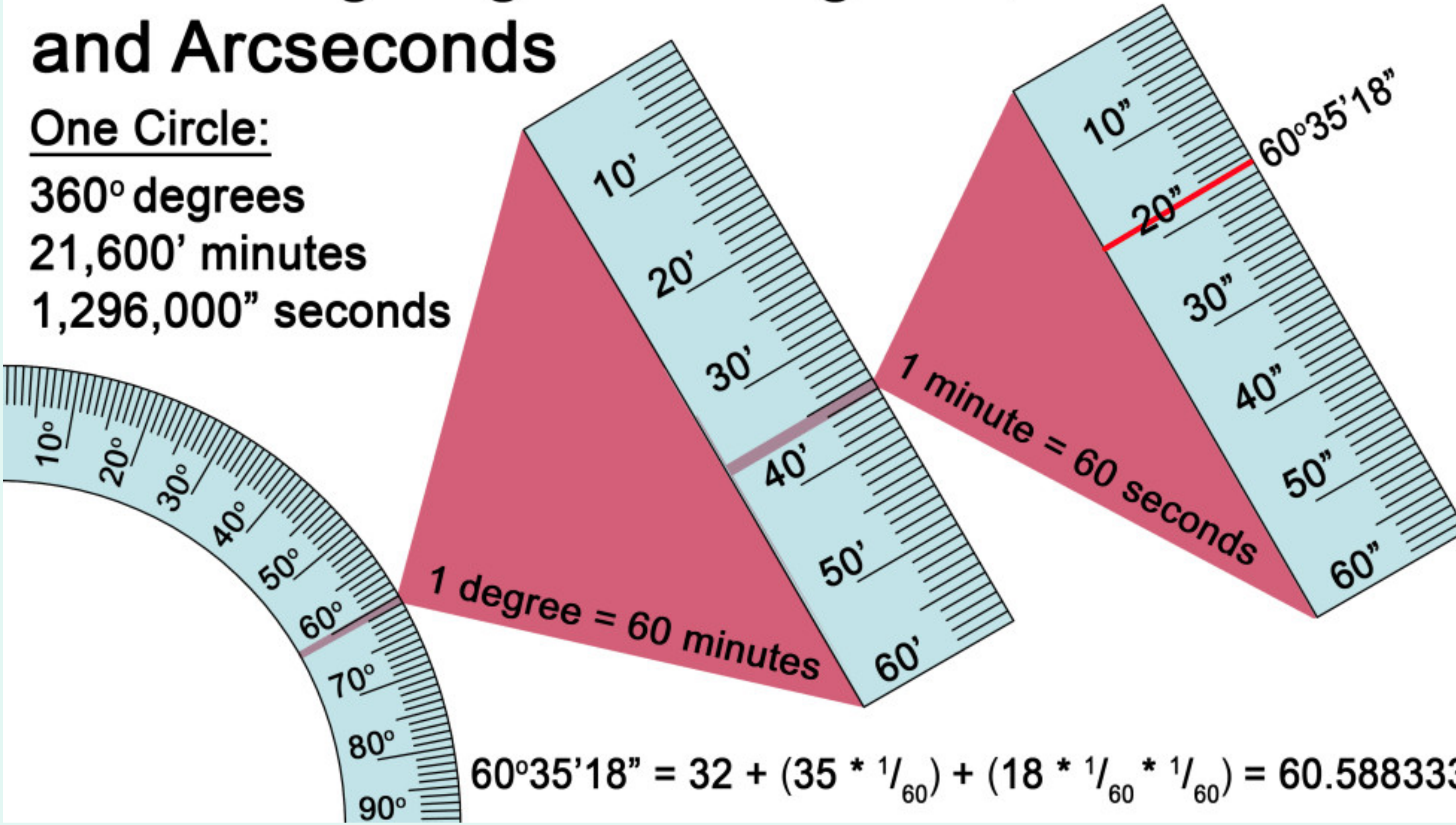
# Measuring Angles in Degrees, Arcminutes and Arcseconds

<u>One Circle:</u>

360° degrees

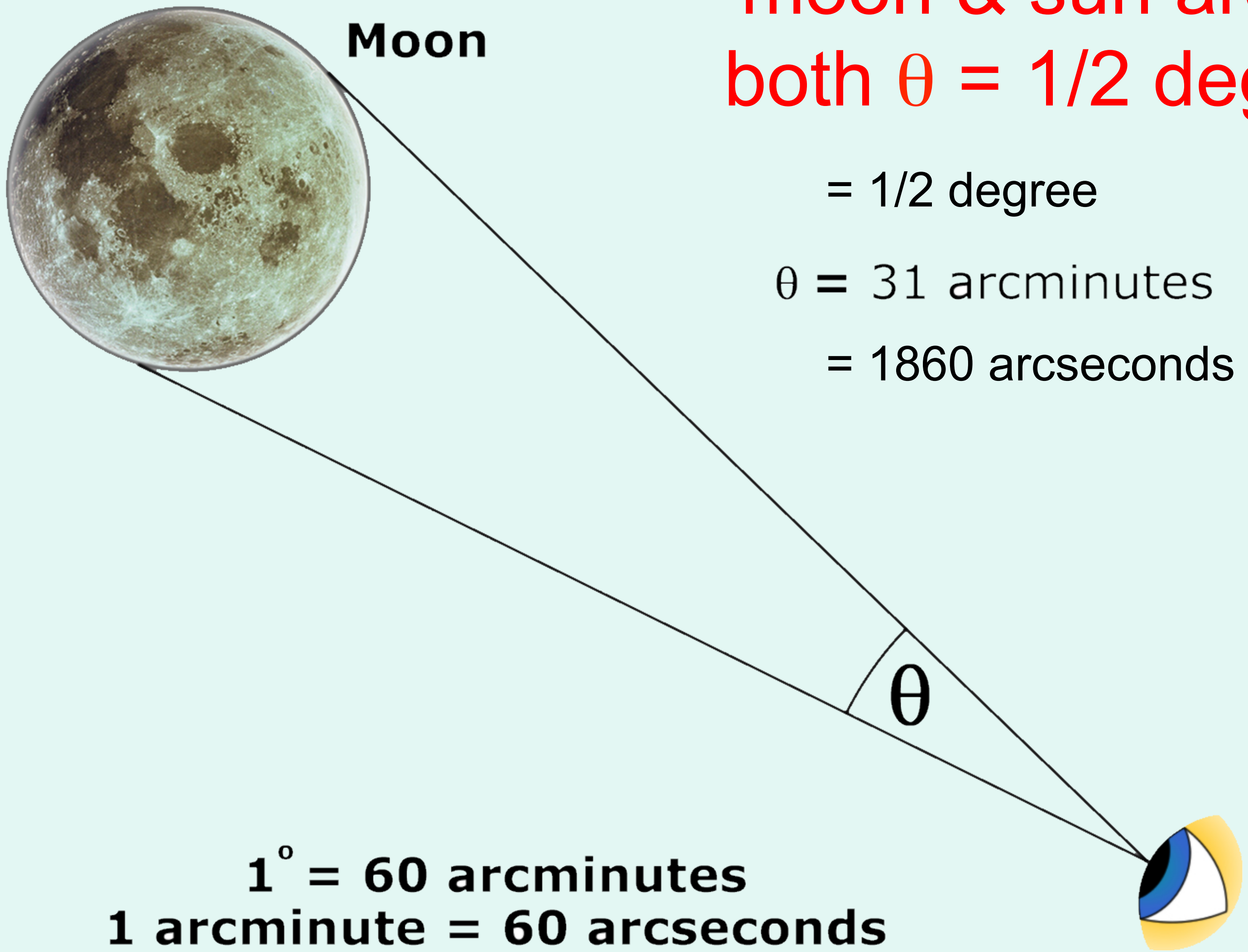
21,600' minutes

1,296,000" seconds




$$60^\circ 35' 18'' = 32 + (35 * {}^{1}/_{60}) + (18 * {}^{1}/_{60} * {}^{1}/_{60}) = 60.588333^\circ$$

# moon & sun are both $\theta$ = 1/2 deg !




= 1/2 degree

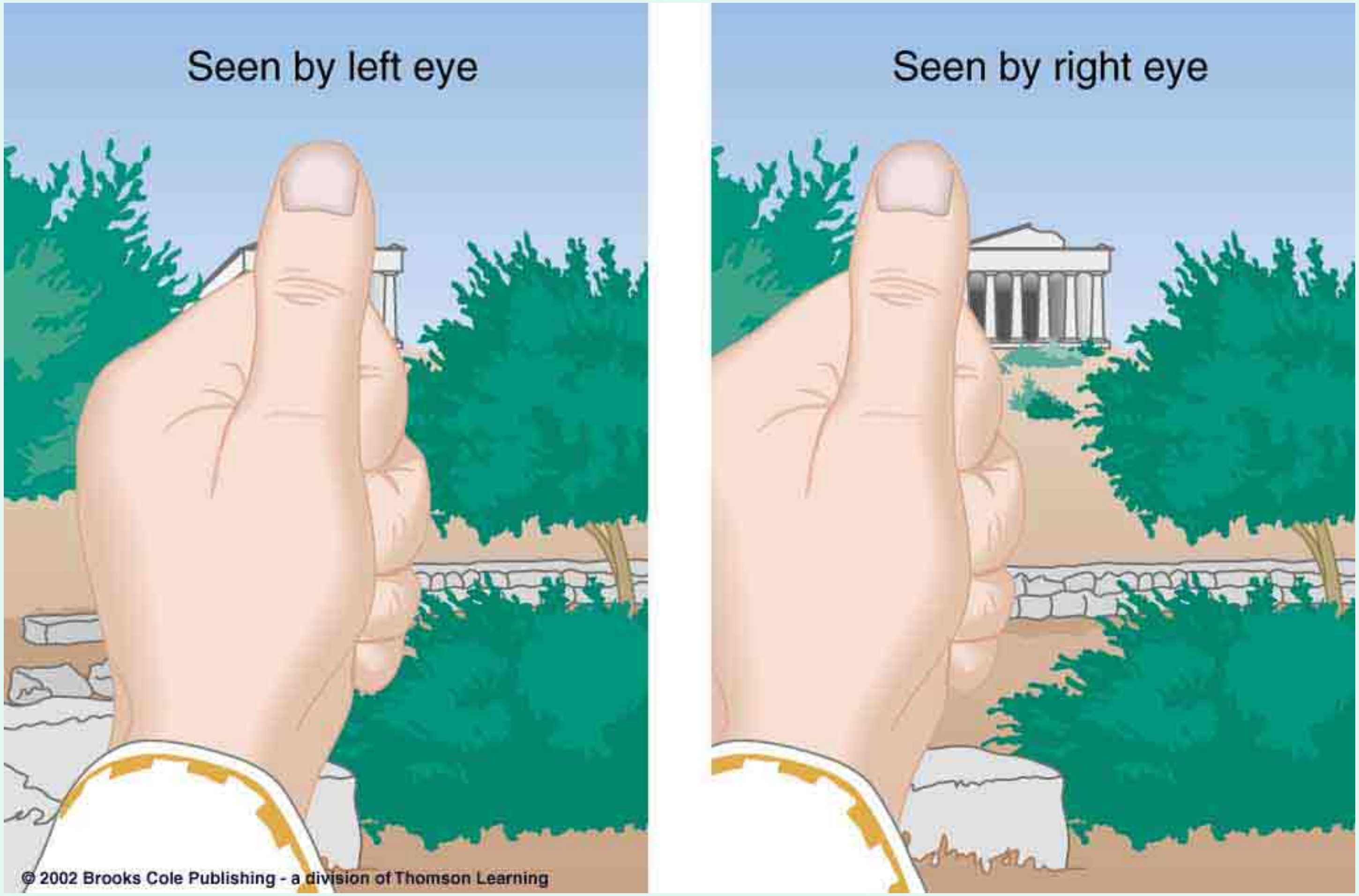
$\theta$ = 31 arcminutes

= 1860 arcseconds

**1° = 60 arcminutes**
**1 arcminute = 60 arcseconds**

1” ~ dime at 2 miles
1 milliarcsecond ~ dime in California

# Parallax with your 2 eyes & thumb…



# Why can't we use parallax to measure very large distances?

A. The stars become too faint

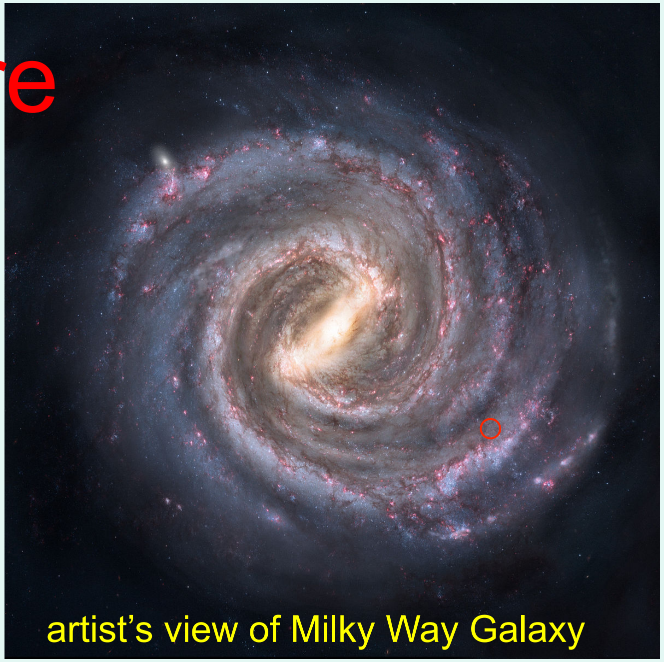
B. There are no good background sources

C. The parallax angle becomes too small to measure

D. The parallax angle shift becomes distorted by other effects

E. Budget cuts

# how far out can we measure distances with parallax?




From space, with HST or Hipparcos satellite, smallest measurable angle is presently p = 0.004"

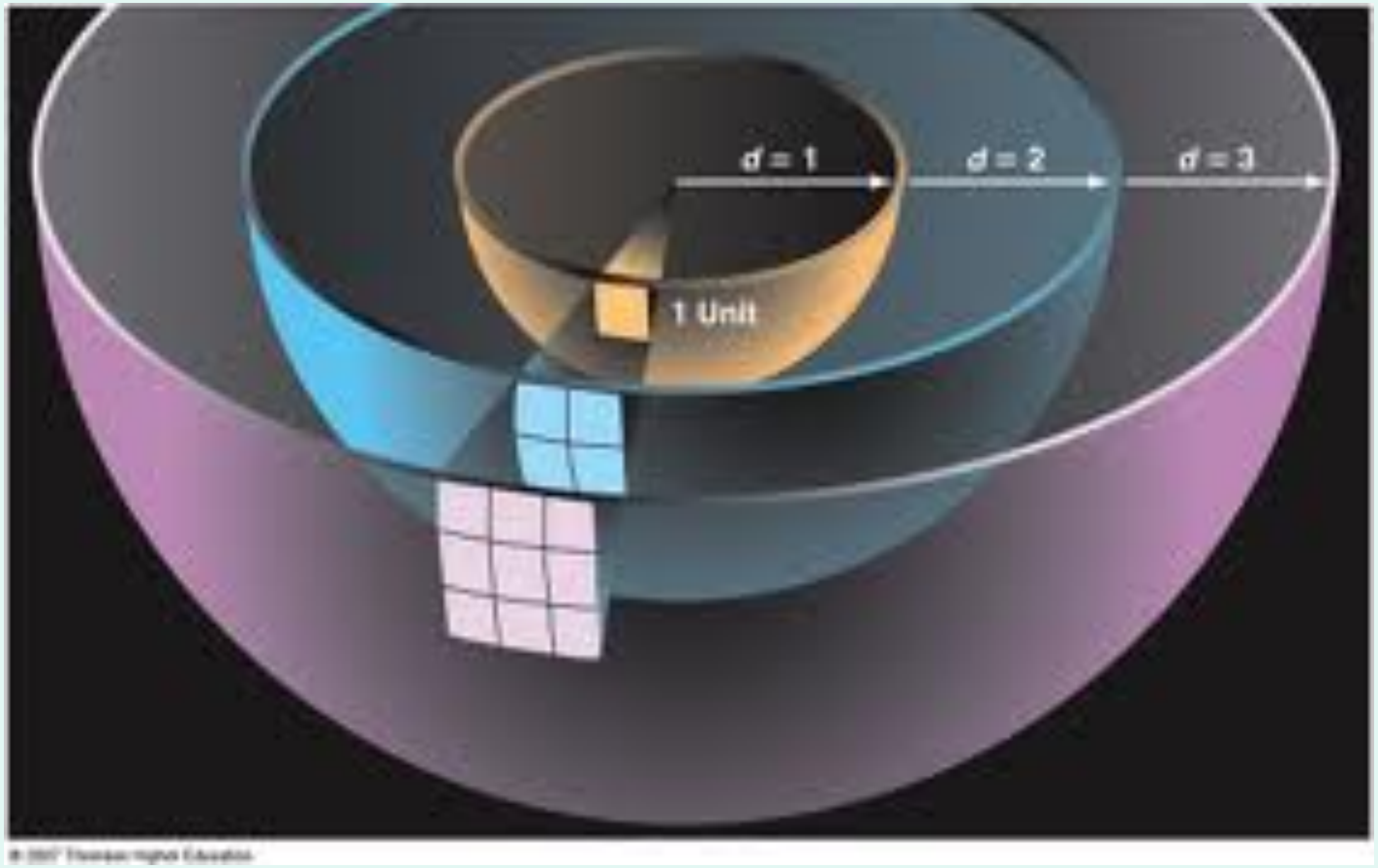
(not this good from the ground, since's earth's atmosphere blurs the images)

We can't directly determine distances greater than d = 1/0.004" = 250 pc = 800 LY using parallax.

This is not very far!! Our galaxy diameter is ~100,000 LY!

*So we need some other way to estimate larger distances ->* **standard candles**

# Inverse square law




At distance d from star, entire luminosity is spread out over an imaginary sphere of surface area $A = 4\pi d^2$

brightness = luminosity per area

# Inverse square law

$$b = \frac{L}{4\pi d^2}$$

$$b = apparent\ brightness\ in\ W / m^2$$ = J $s^{-1}$ $m^{-2}$

$$L = Luminosity\ in\ W$$ = Joule $s^{-1}$

$$d = distance\ in\ meters$$

# Luminosity, brightness & distance

## Luminosity

- –a property of source
- –doesn't depend on you
- –*you can't directly measure it, need to calculate it*

## Brightness

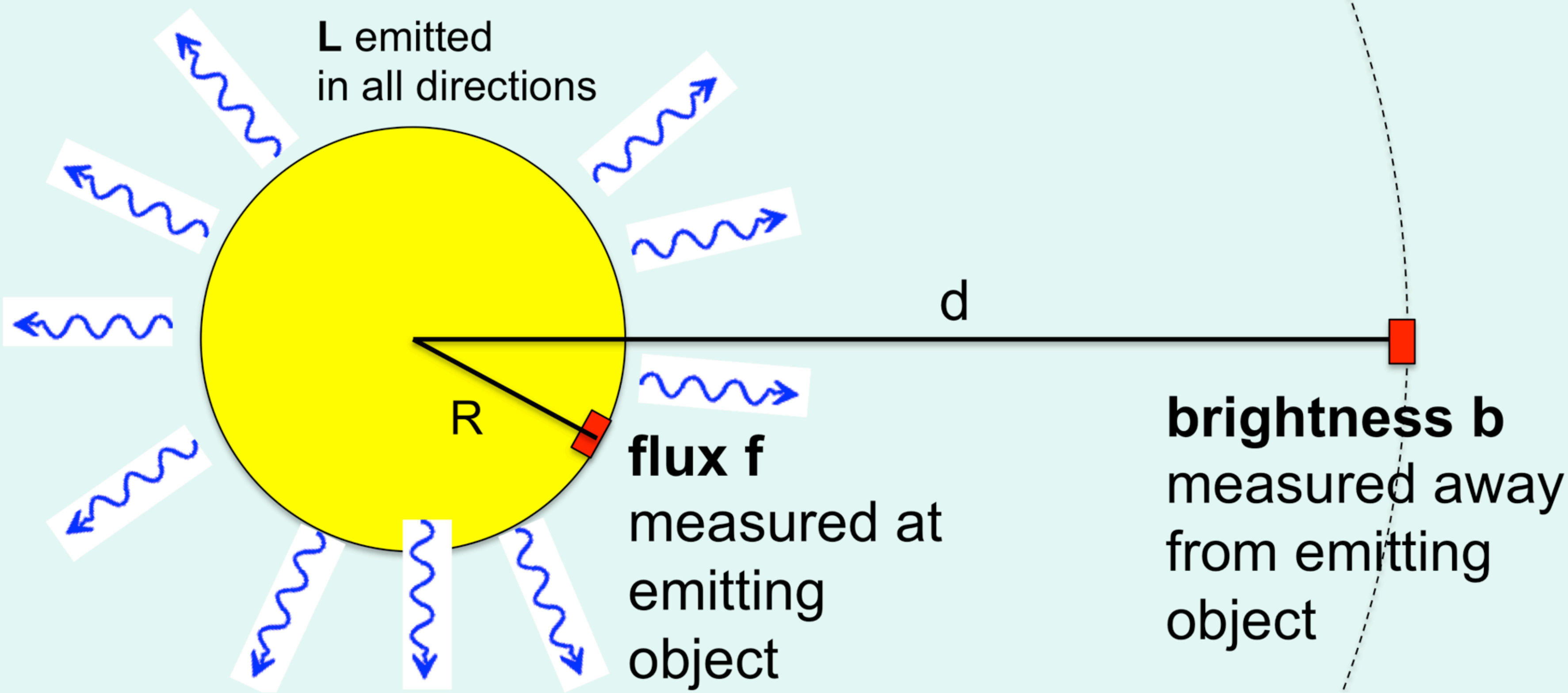
- –depends on the source and you
- –depends on Luminosity and Distance between you and source
- –*you directly measure it*

# Flux vs. Brightness

very similar quantities, same units of J s-1 m-2

amount of energy passing each second through unit area of:

- ***emitting object*** with radius R is **flux** $f = L / 4\pi R^2$
- ***detector***, at some distance d from emitting object is **brightness** $b = L / 4\pi d^2$



# Inverse square law

$$b = \frac{L}{4\pi d^2}$$

$$b = apparent\ brightness\ in\ W / m^2$$
$$L = Luminosity\ in\ W$$
$$d = distance\ in\ meters$$

One measures brightness b with telescope.
In general, might not know either L or d ….. BUT!

1. If distance known, one can calculate L

$$L = 4\pi d^2 b$$

# Inverse square law & *standard candles*

2. If luminosity known, one can calculate d:

$$d = (L/4\pi b)^{1/2}$$

In general, we don't directly know luminosities of stars.

BUT! There are certain types of stars which all have about the same luminosity…
AND we think we know their luminosity…

These are **STANDARD CANDLES**

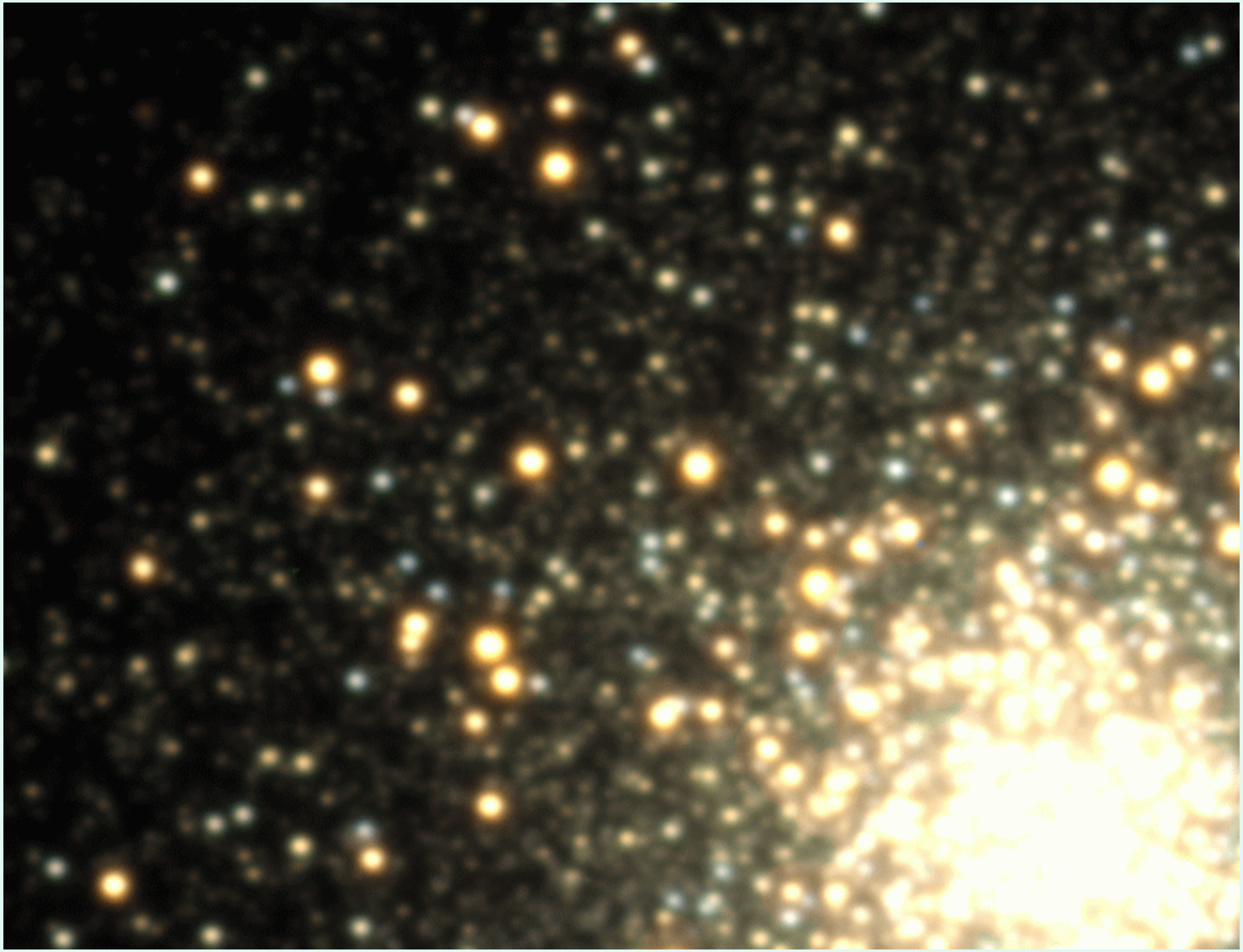
# Standard candles: 2 important examples

1. Cepheid Variable stars

(there are other variable stars, and some of them have regular variations & so are useful as distance indicators – e.g. RR Lyrae variable stars – but Cepheids are the most important)

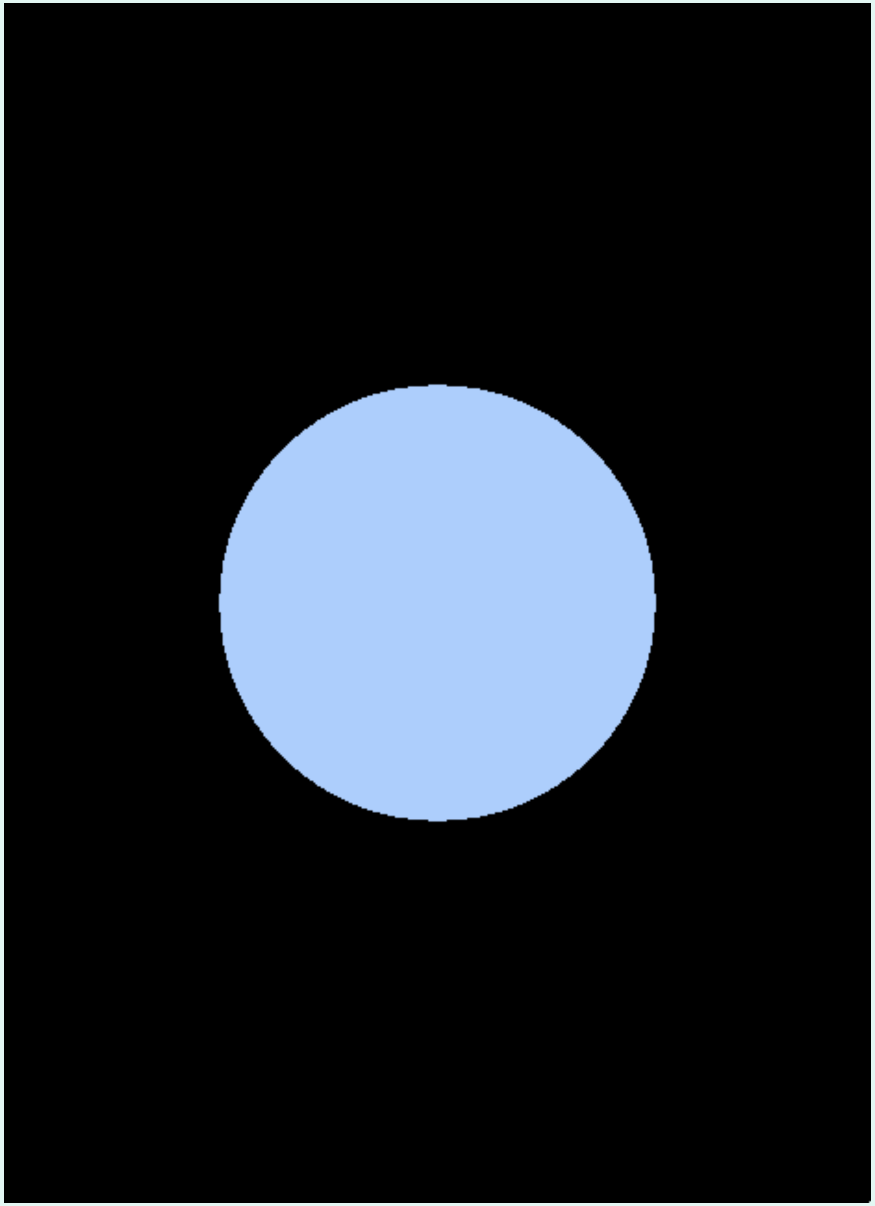
2. TYPE Ia supernovae

# Variable stars in globular cluster M3



Elapsed time 8 hours

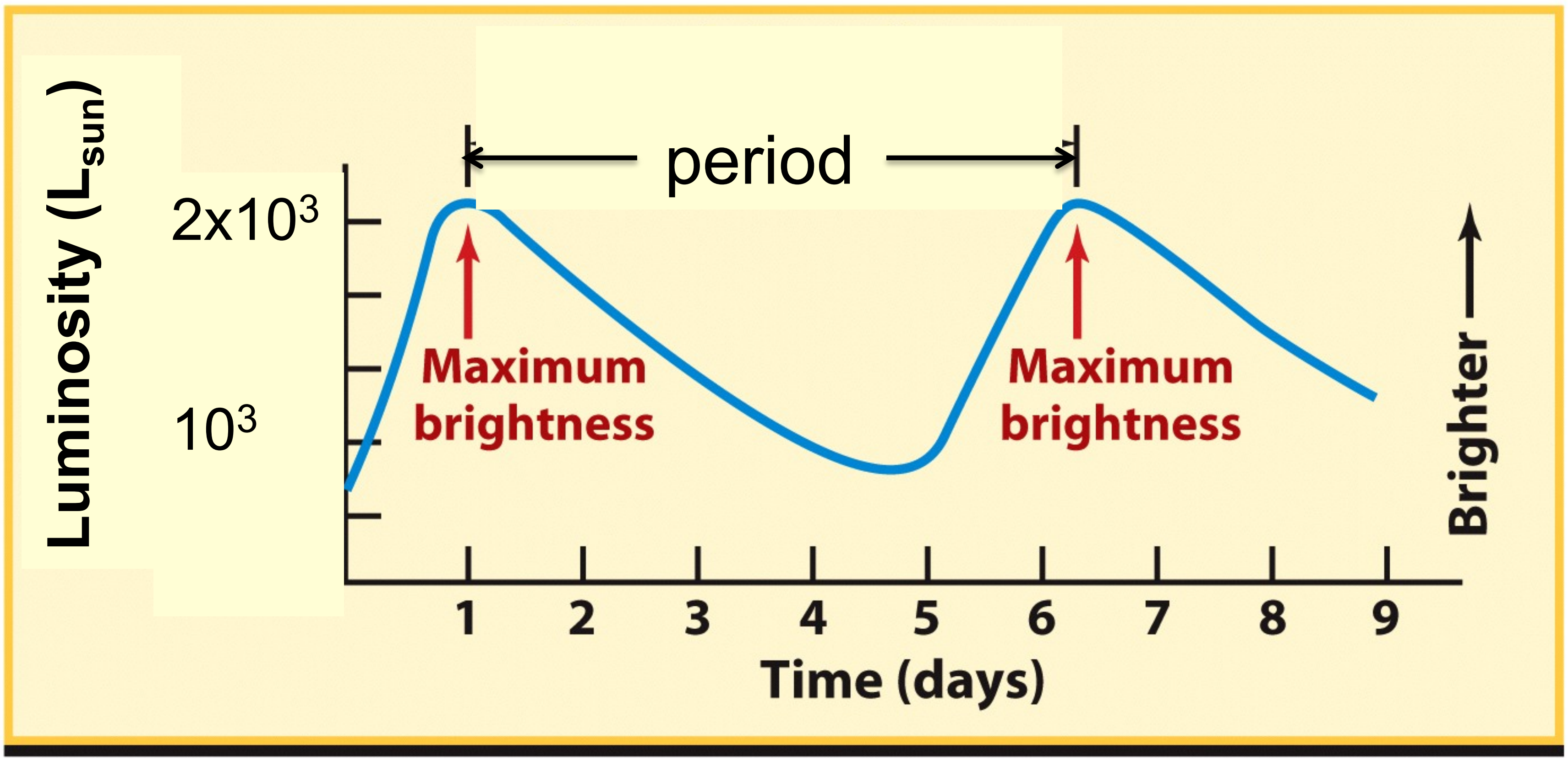
animation of Cepheid pulsation



## Cepheid variable:

a class of evolved/
post-main sequence/
giant star which
*pulsates*, and whose
*luminosity therefore
varies in a regular way*

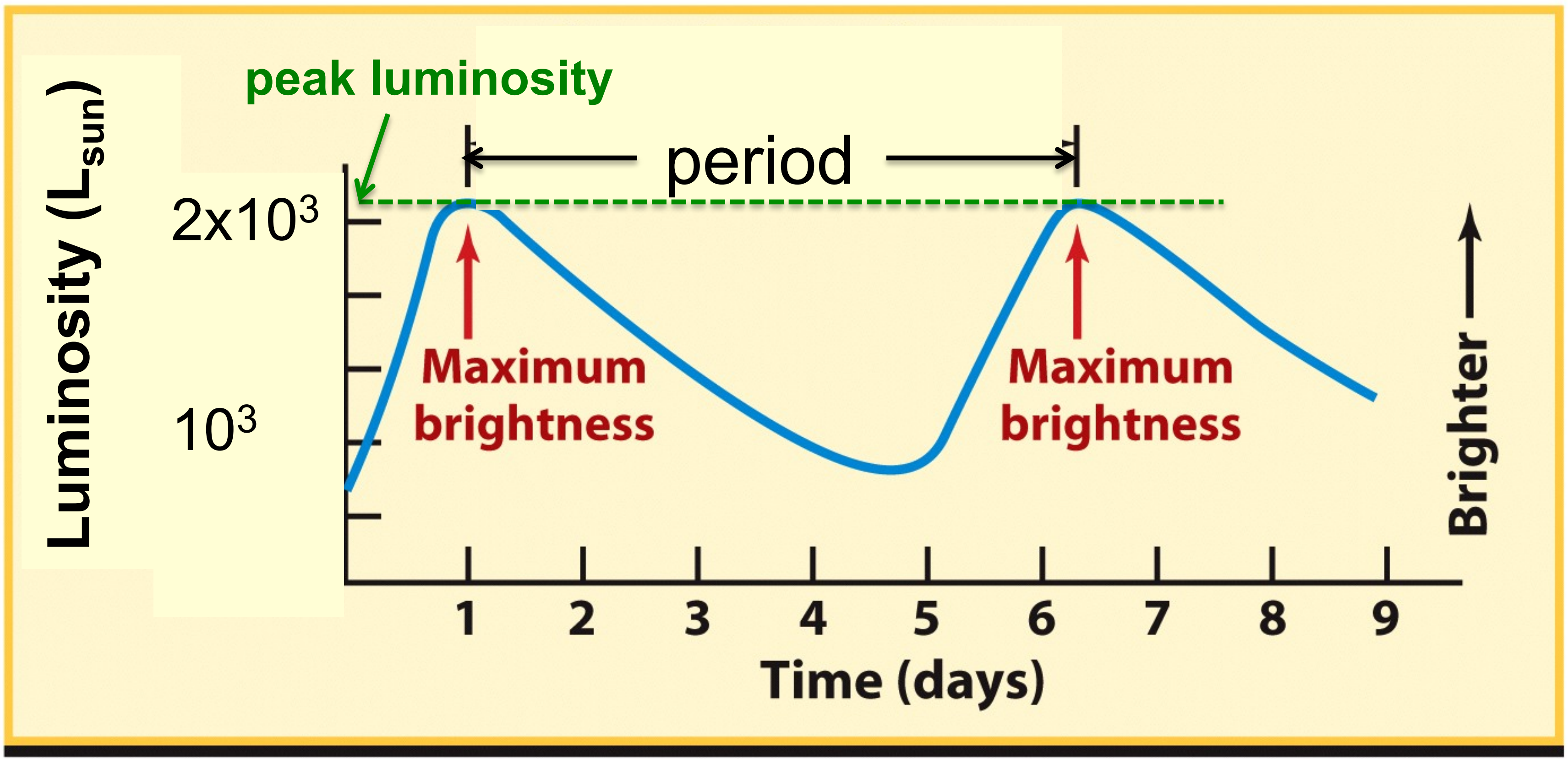
# light curve of Cepheid Variable star δ Cephei




light curve = luminosity (or brightness) versus time

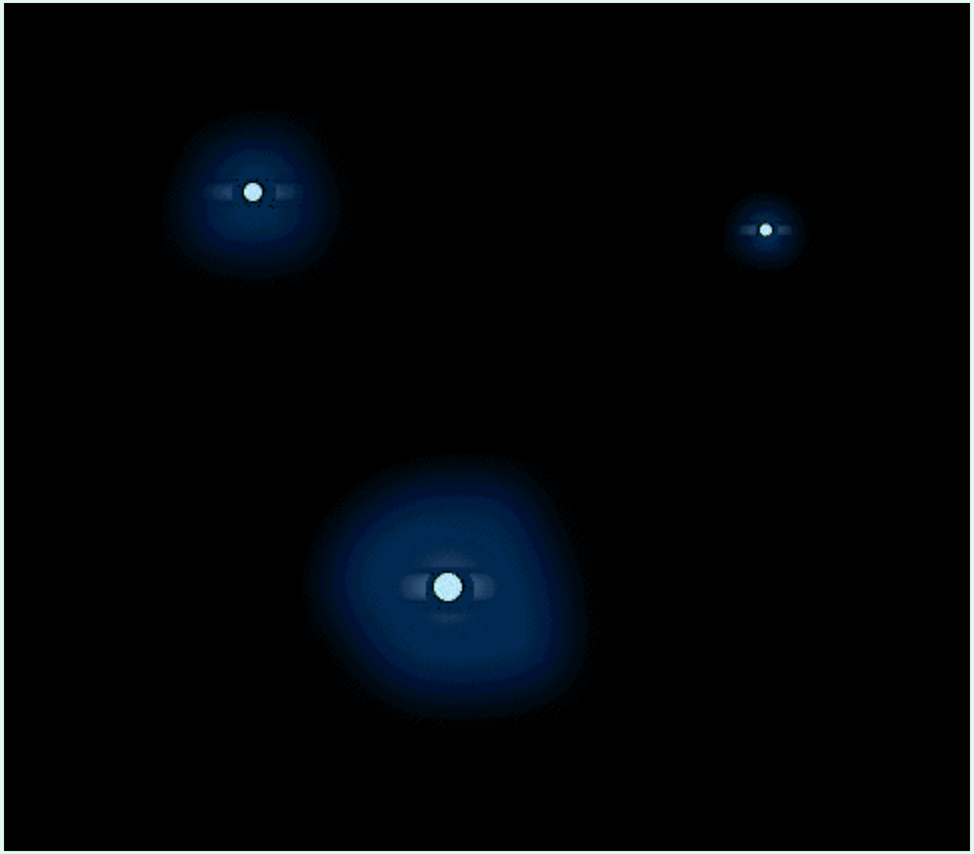
luminosity (& brightness) reaches maximum every 5.4 days for this particular star δ Cephei

# light curve of Cepheid Variable star δ Cephei

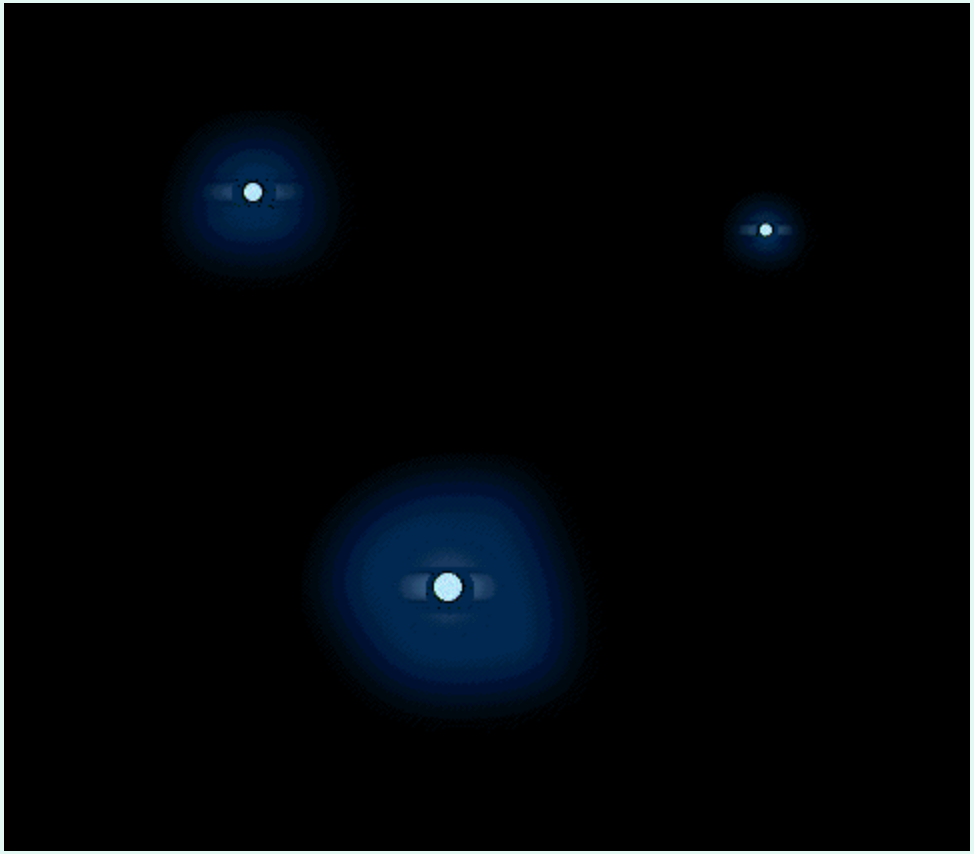



Cepheid Variable stars are important distance indicators since period and peak luminosity are tightly coupled!

# animation of 3 Cepheid variables with different peak luminosities



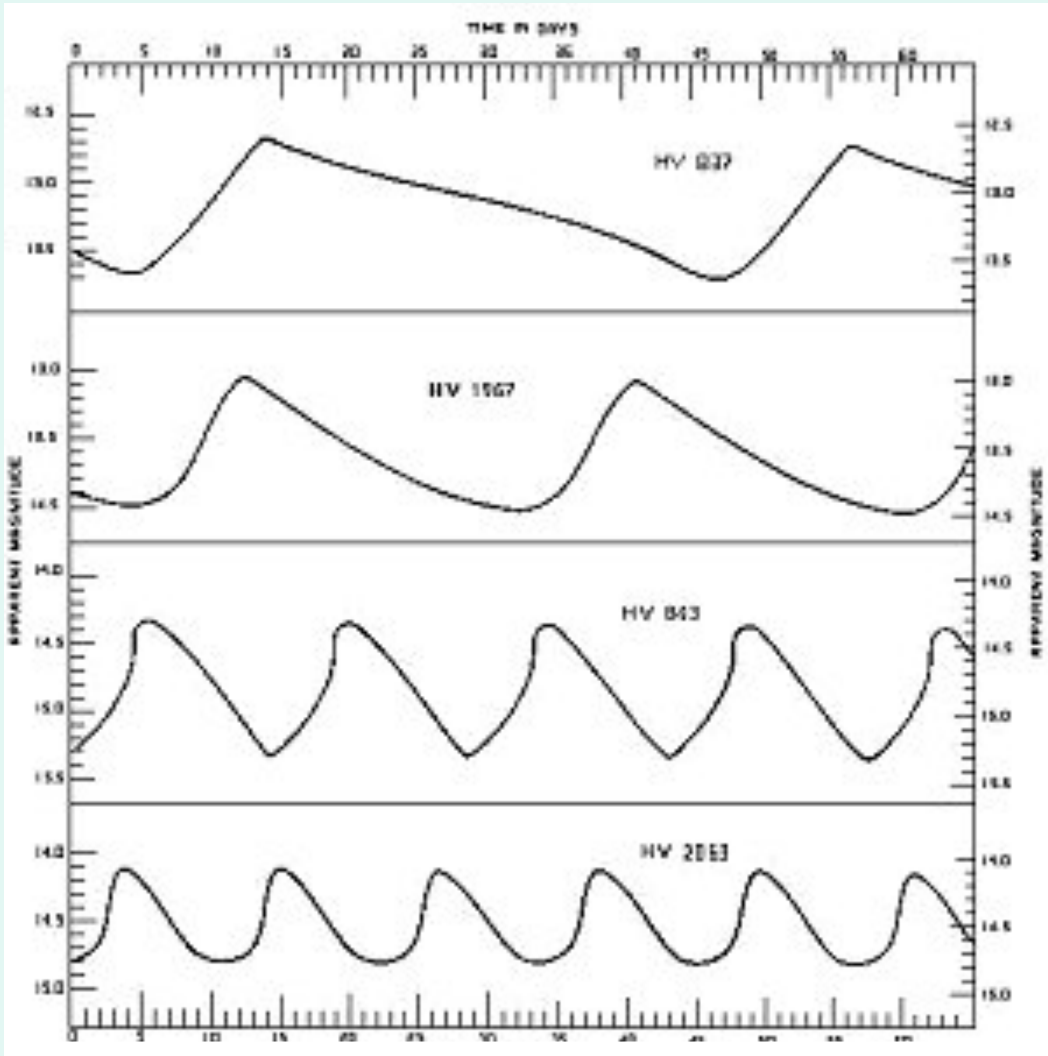
# animation of 3 Cepheid variables with different peak luminosities



The period is longer if the peak luminosity is higher!

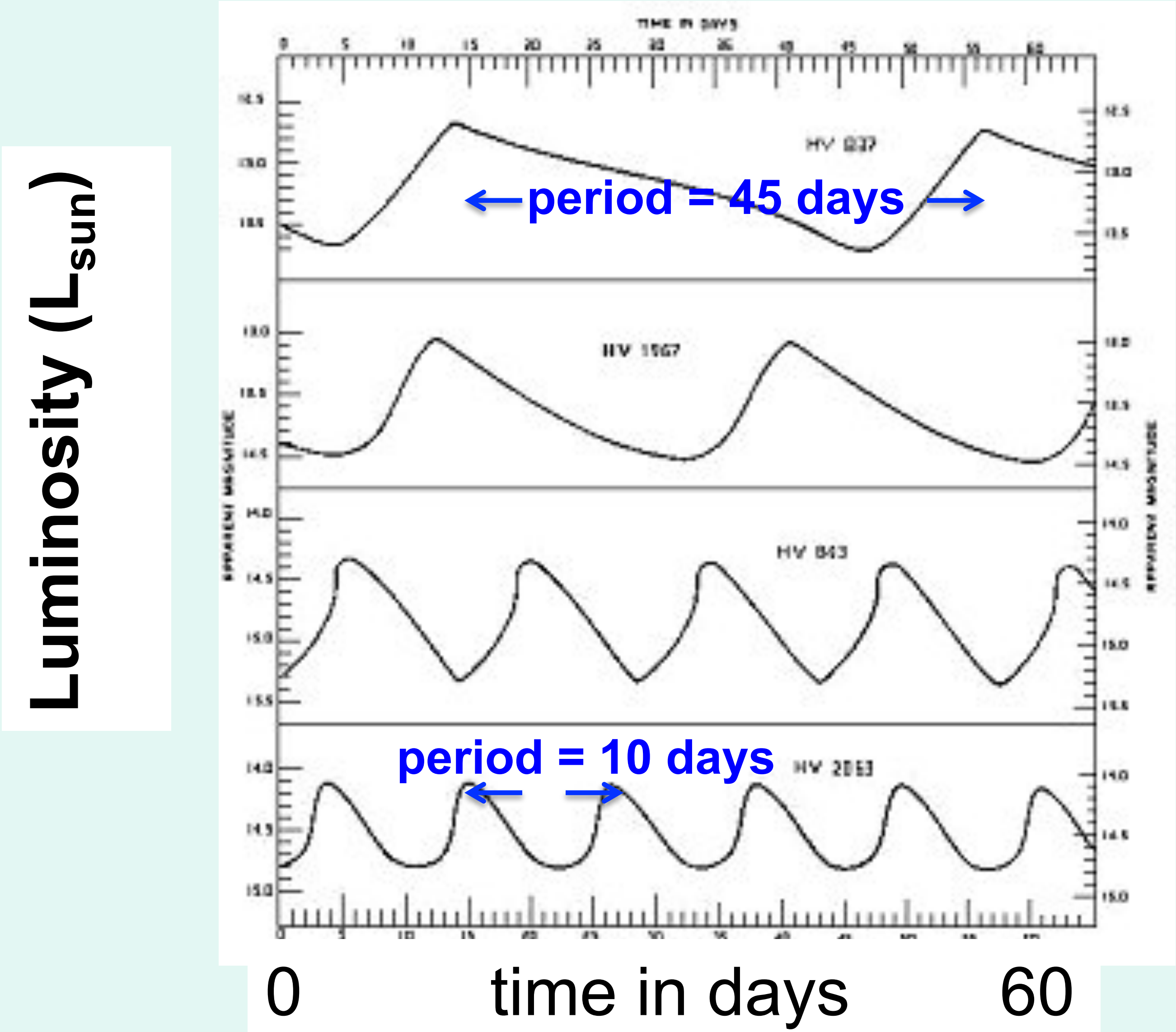
# Cepheid Variables with different periods and (peak) luminosities

**Luminosity ($L_{sun}$)**

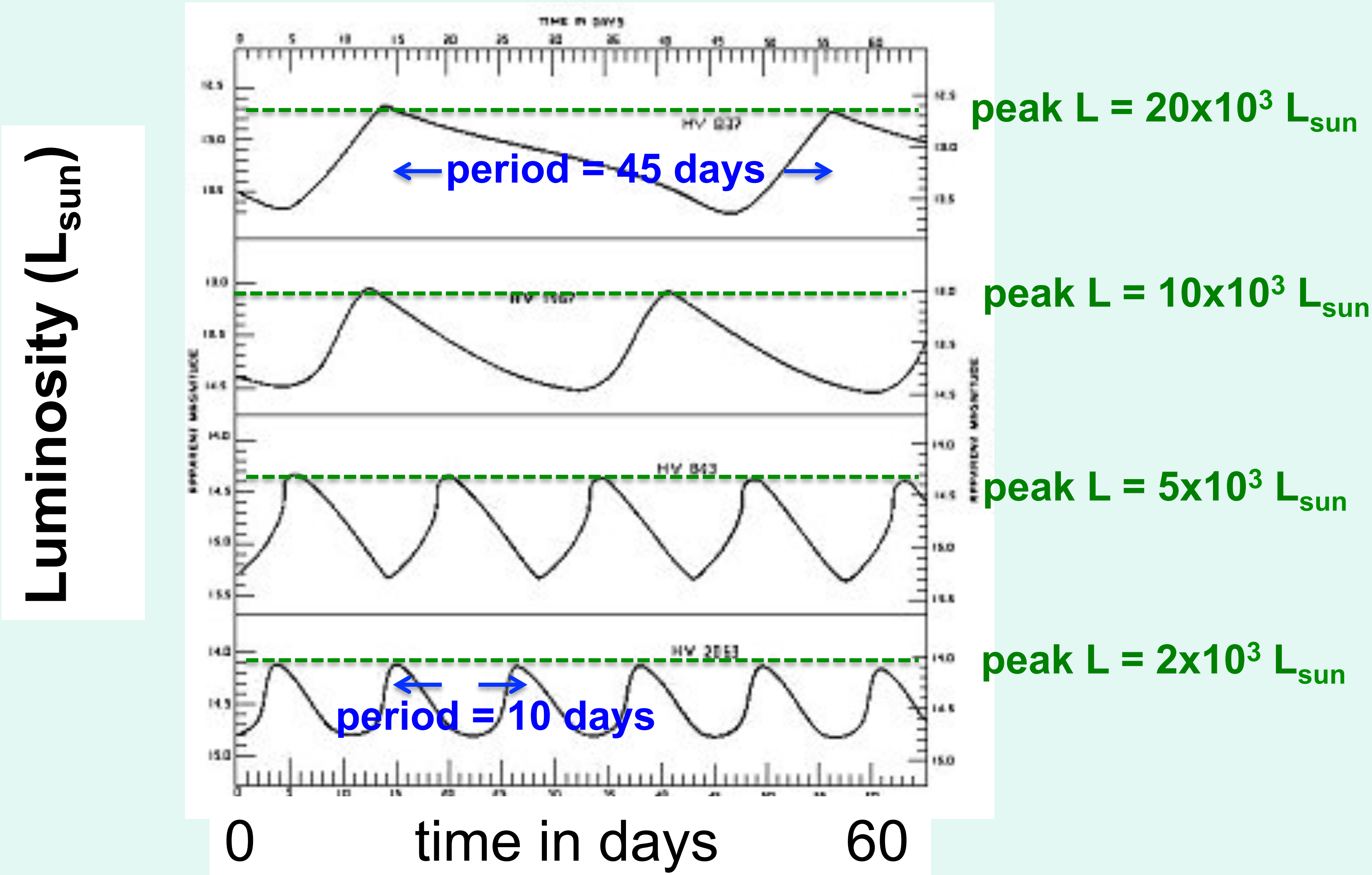


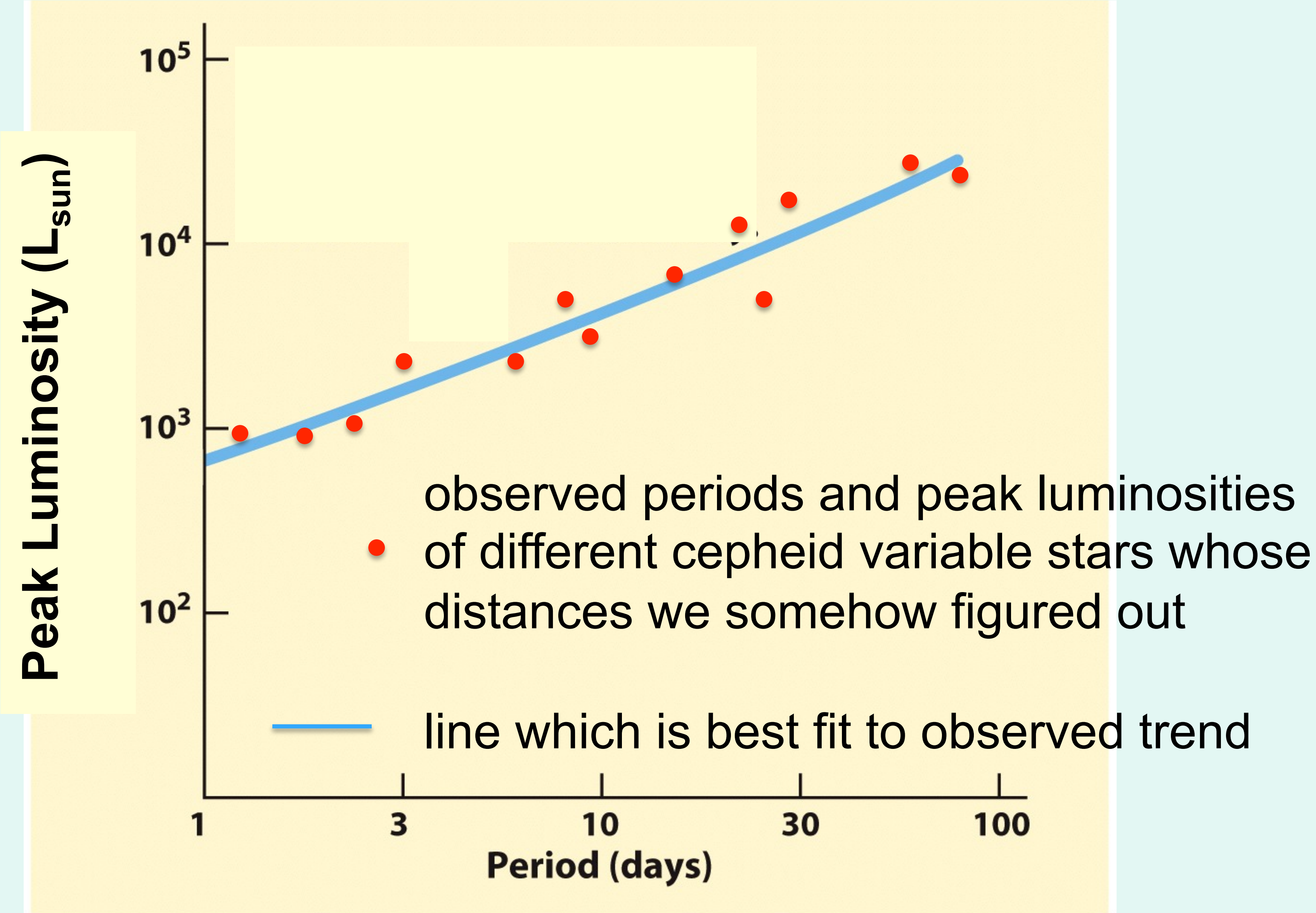
0 time in days 60

# Cepheid Variables with different periods and (peak) luminosities



# Cepheid Variables with different periods and (peak) luminosities

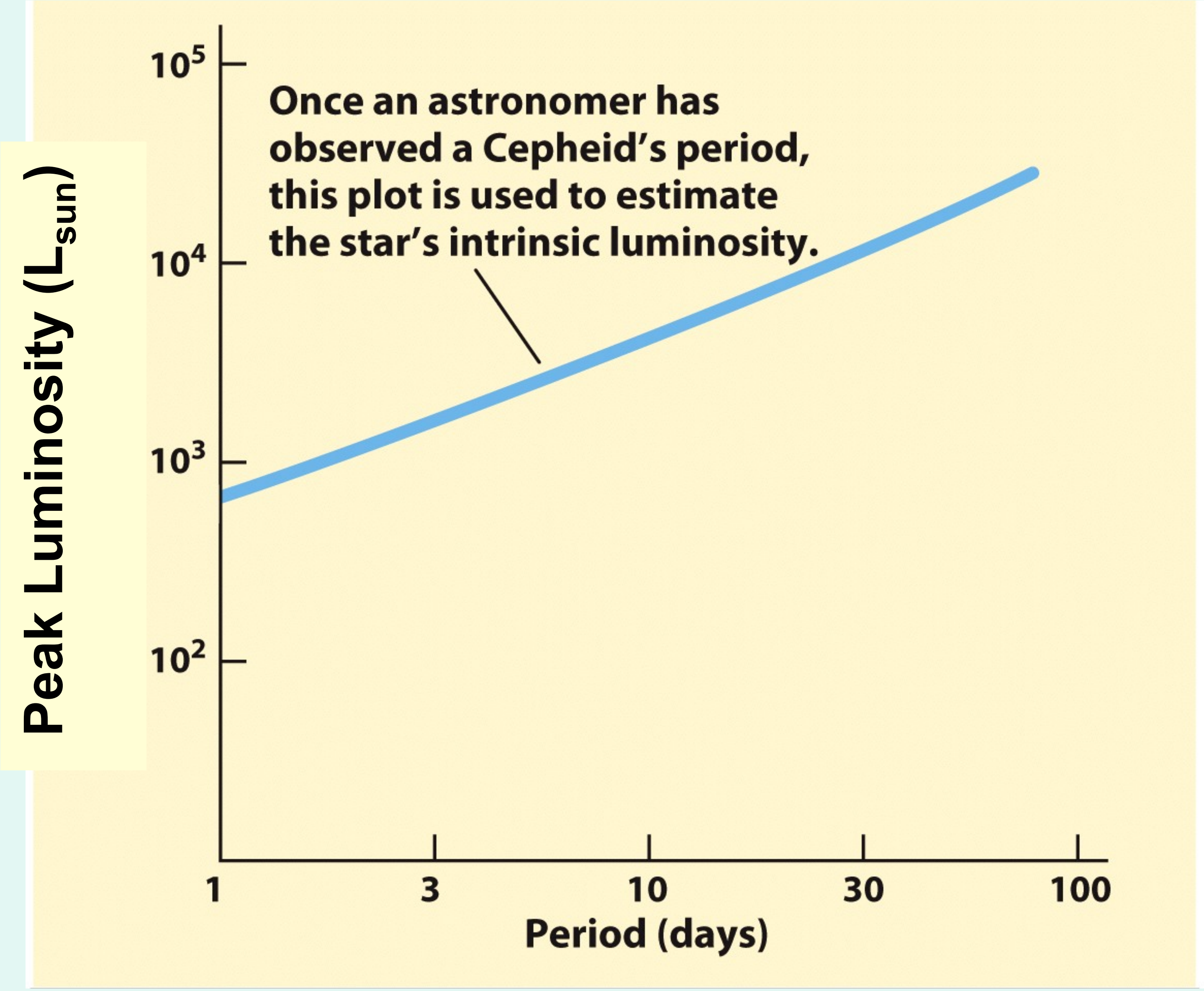




Peak Luminosity ($L_{sun}$)
$10^5$
$10^4$
$10^3$
$10^2$
1
3
10
30
100
Period (days)
observed periods and peak luminosities of different cepheid variable stars whose distances we somehow figured out
line which is best fit to observed trend

# How do we use Cepheids to get distances?

- measure period -> infer L from “known” period-luminosity relation
- measure brightness b with telescope
- calculate distance from d = sqrt{L/4$\pi$b}



Peak Luminosity ($L_{sun}$)
$10^5$
$10^4$
$10^3$
$10^2$
Once an astronomer has observed a Cepheid's period, this plot is used to estimate the star's intrinsic luminosity.
1
3
10
30
100
Period (days)

# Why can't we use Cepheid variable stars to measure the distances to the most distant galaxies?

A. Their brightness is too small to be detected

B. There aren't any in the most distant galaxies

C. Their period is too long to measure in a human lifetime

D. The Galactic period-luminosity relation breaks down in the early universe

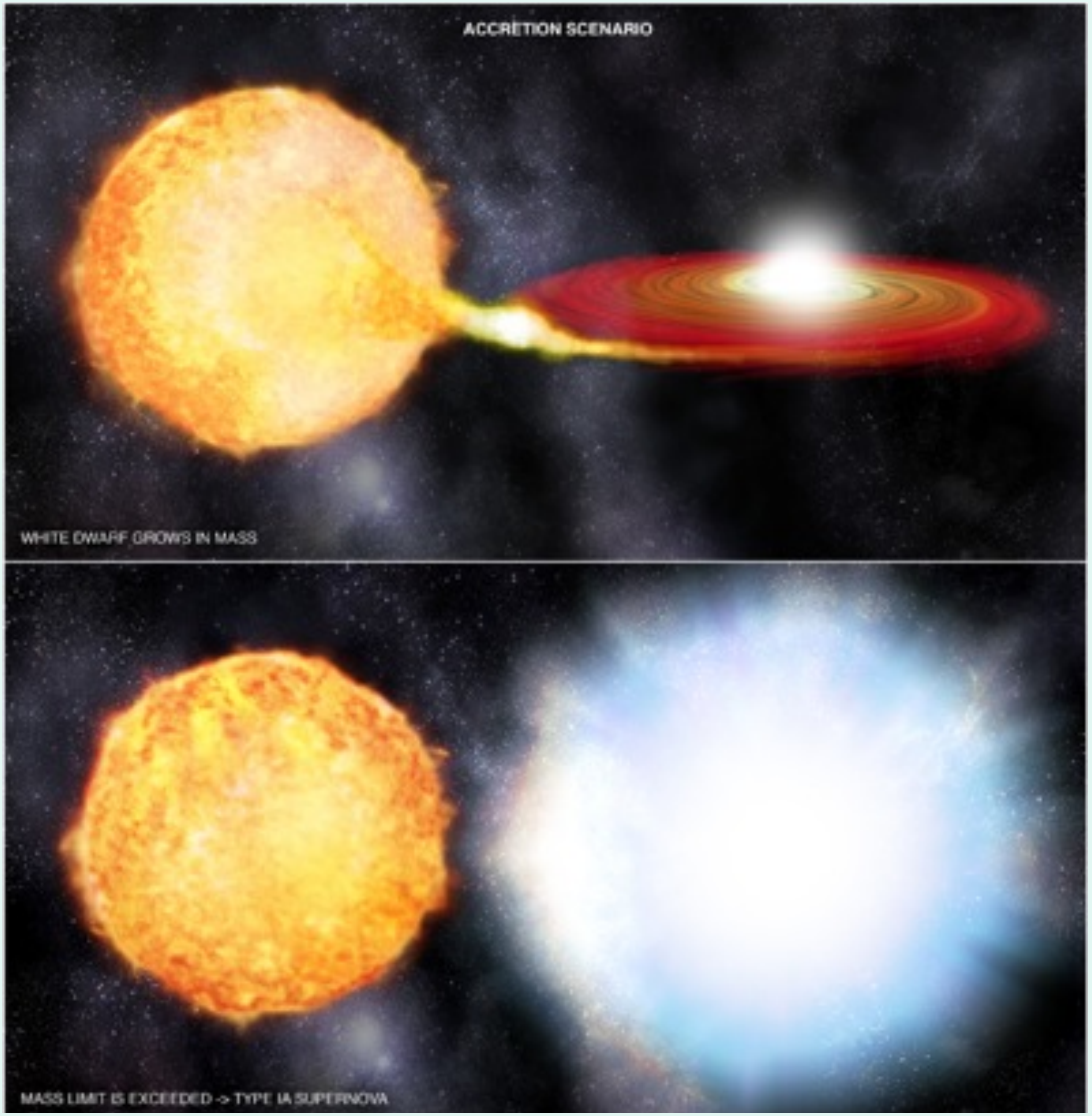
E. Putin won't allow it

# Standard candles: 2 important examples

1. Cepheid Variable stars

(there are other variable stars, and some of them have regular variations & so are useful as distance indicators – e.g. RR Lyrae variable stars – but Cepheids are the most important)

2. TYPE Ia supernovae




# Type Ia Supernova

(from intermediate mass stars M ~ 3-8$M_{sun}$)

White dwarf in binary pair accretes mass from companion, causing it to explode as supernova *if its mass exceeds "Chandrasekhar limit"*

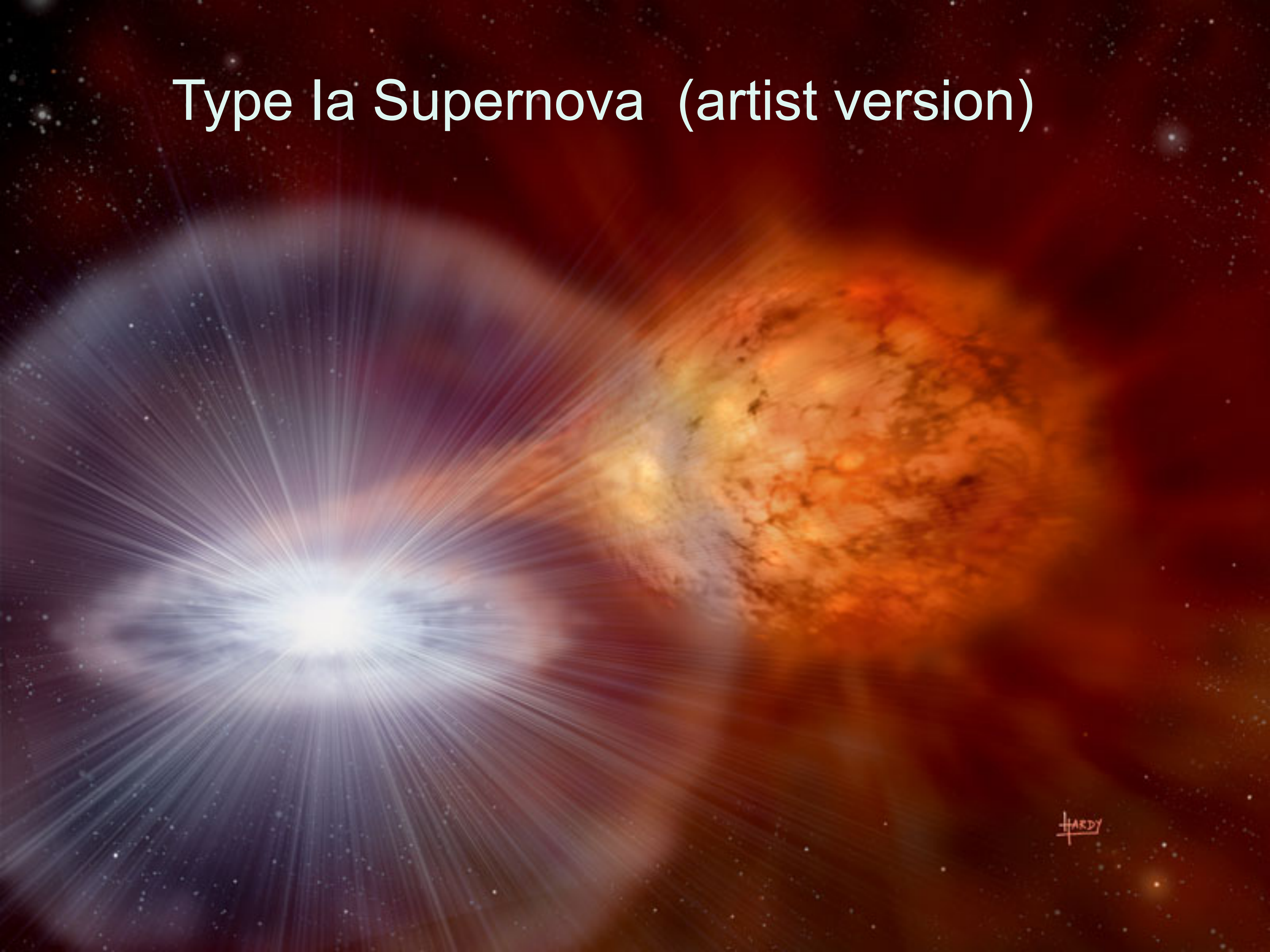
*All explosions have about the same luminosity of $L \sim 10^{10}\ L_{sun}$*

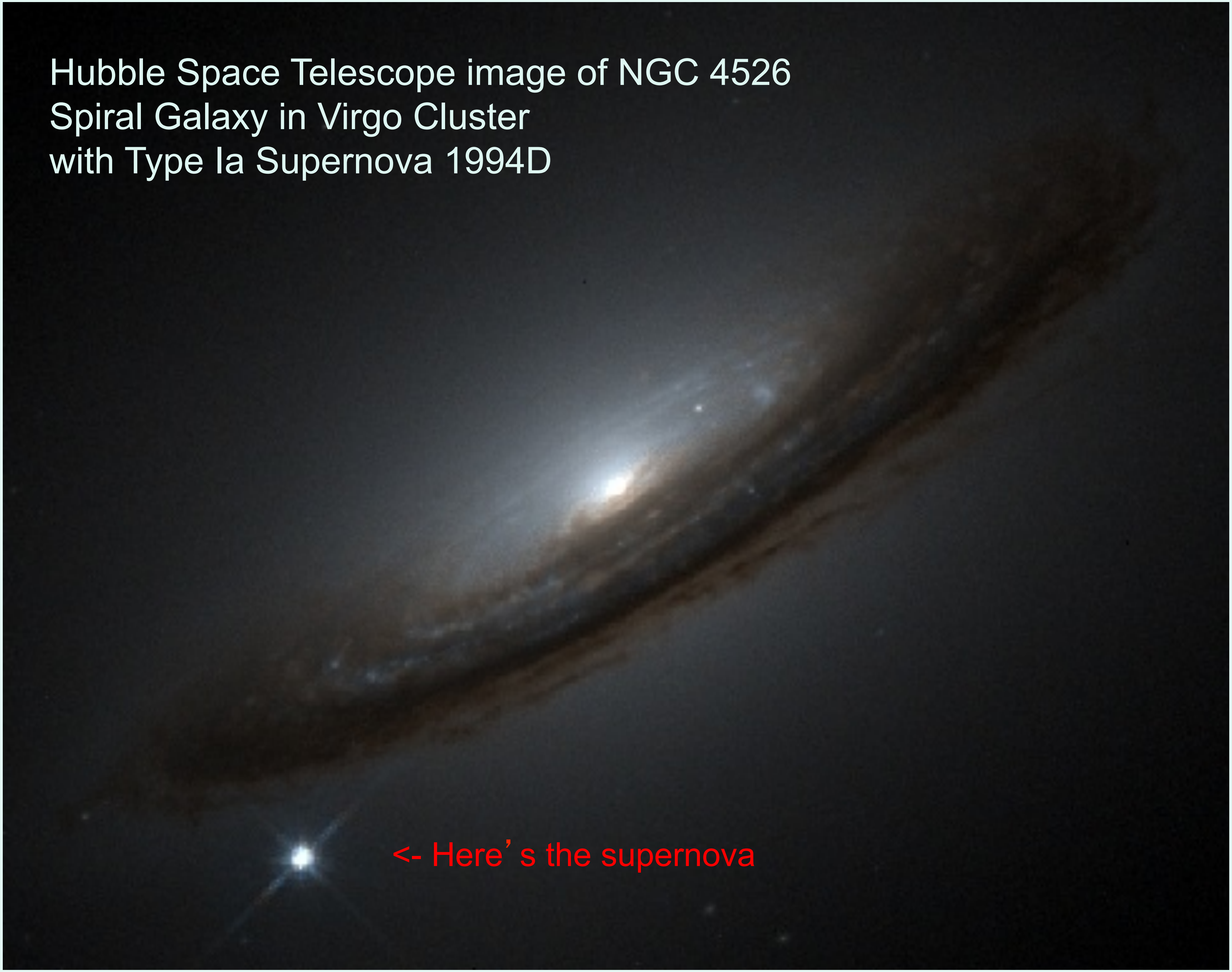
# Type Ia Supernova

White dwarf in binary system accretes mass from companion & explodes

*All explosions have about the same luminosity of $L \sim 10^{10}\ L_{sun}$*

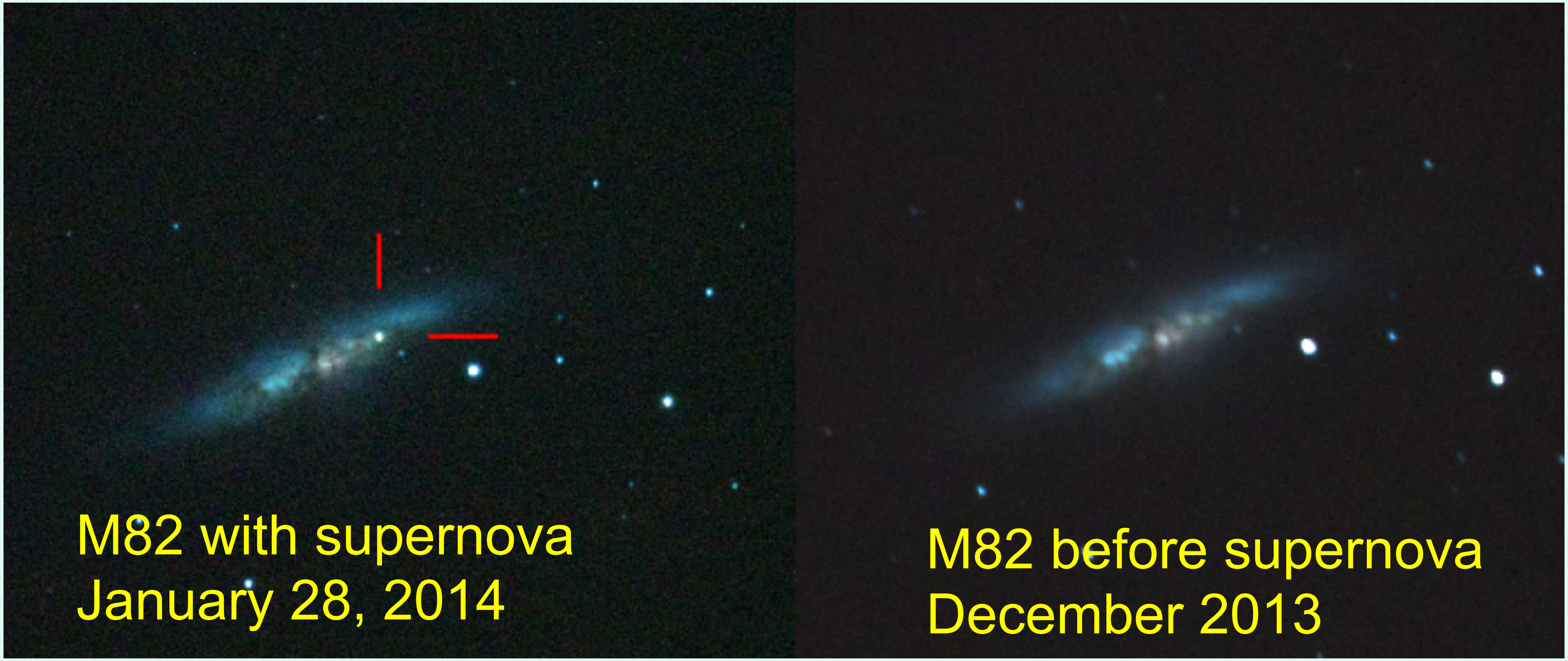
# Type Ia Supernova  (artist version)




Hubble Space Telescope image of NGC 4526
Spiral Galaxy in Virgo Cluster
with Type Ia Supernova 1994D
<- Here's the supernova

# Nearby Supernova in Galaxy M82!!

The closest supernova in 27 years (only 12 million light years away)




*measure brightness b of supernova in galaxy*
*obtain spectra to confirm supernova is Type Ia*
*use known luminosity of Type Ia supernovae together with inverse square law to learn distance to supernova*
*supernova is in galaxy, so we also learn distance to host galaxy*

# Why can’t we use supernovae to measure the distances to stars in our Galaxy?

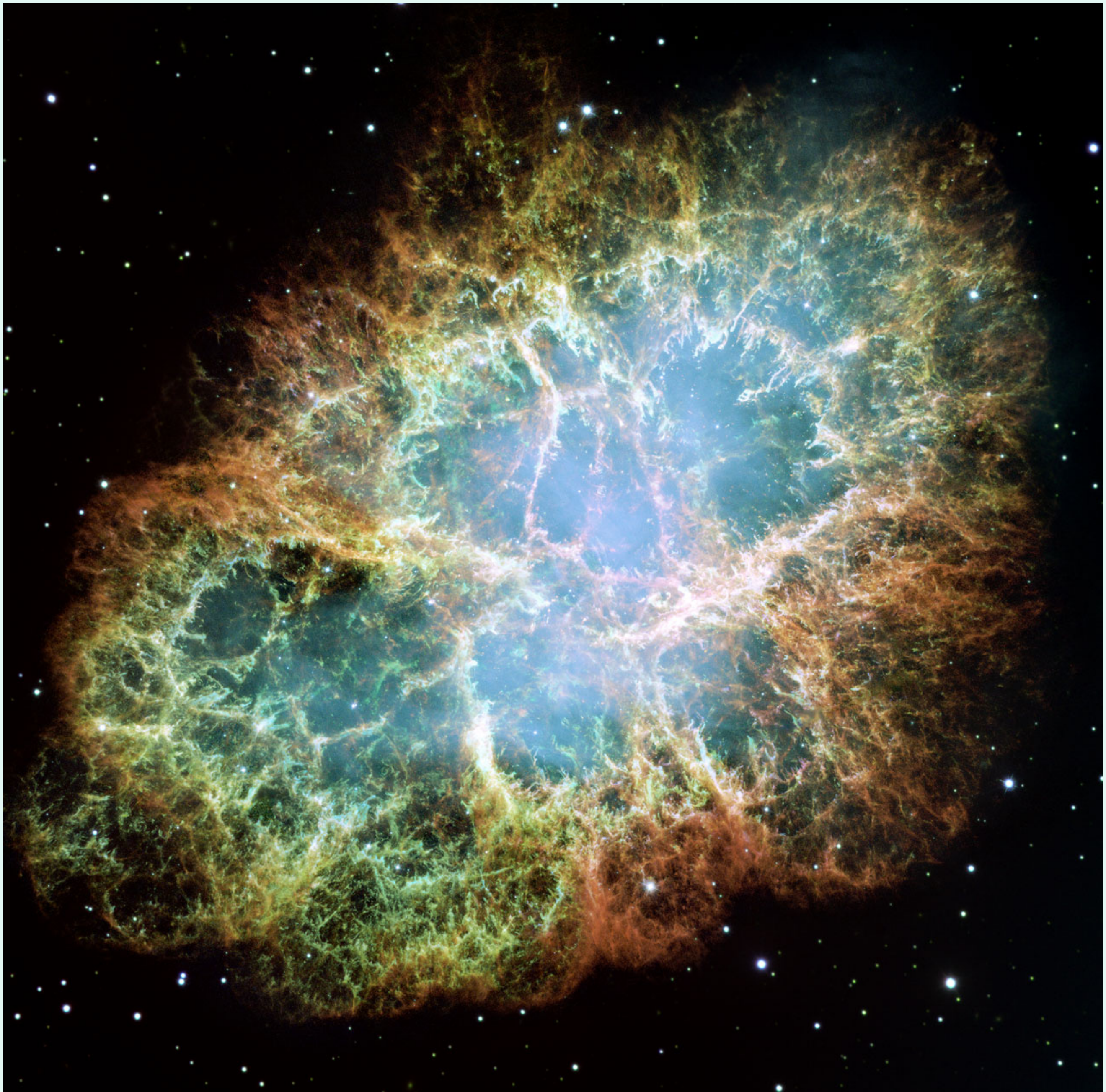
A. Their brightness is too large for present detectors

B. They don’t happen in our type of Galaxy

C. There aren’t enough of them

D. There haven’t been any in our Galaxy recently

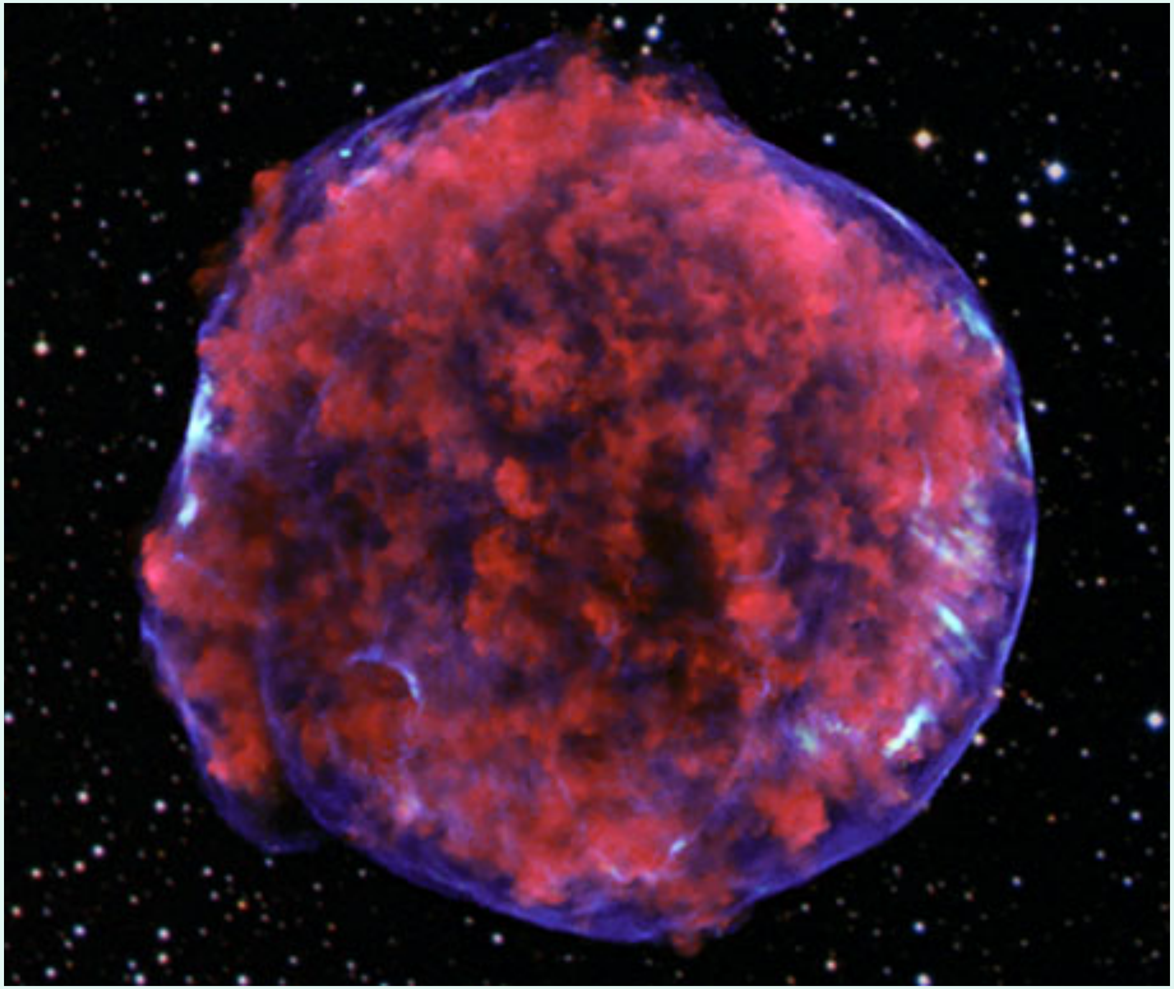
E. We can measure the distance to the supernova but that doesn’t tell us the distances to other stars in the Galaxy



# Crab Nebula Supernova Remnant

produced by Type Ia supernova explosion in 1054 A.D.

# Tycho's Supernova Remnant
## from Type Ia Supernova in 1572 A.D.



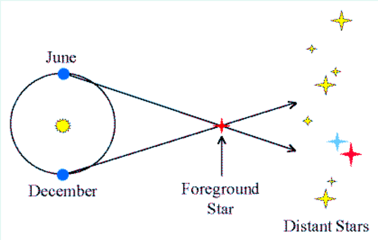
X-Ray image from Chandra telescope

Red: low energy x-rays from debris of star

Blue: high energy x-rays from blast wave – high energy electrons

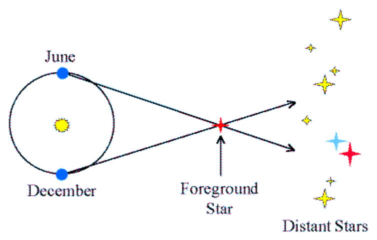
# Comparison of distance techniques

Parallax




- foolproof
- very simple and direct (based on simple geometry)
- no systematic error

# Comparison of distance techniques




Parallax

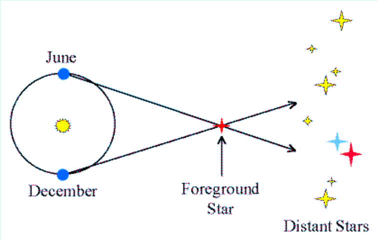
- foolproof
- very simple and direct (based on simple geometry)
- no systematic error

Standard candles

- possible systematic errors
- *how do we know a certain object is really a "standard candle"?*

# Comparison of distance techniques

Parallax

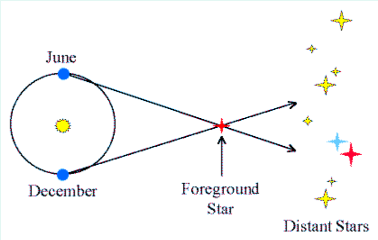



- foolproof
- very simple and direct (based on simple geometry)
- no systematic error

Standard candles

- possible systematic errors
- *how do we know a certain object is really a "standard candle"?* → light curve or spectra
- *how do we know the true luminosity of a std candle?*

# Comparison of distance techniques



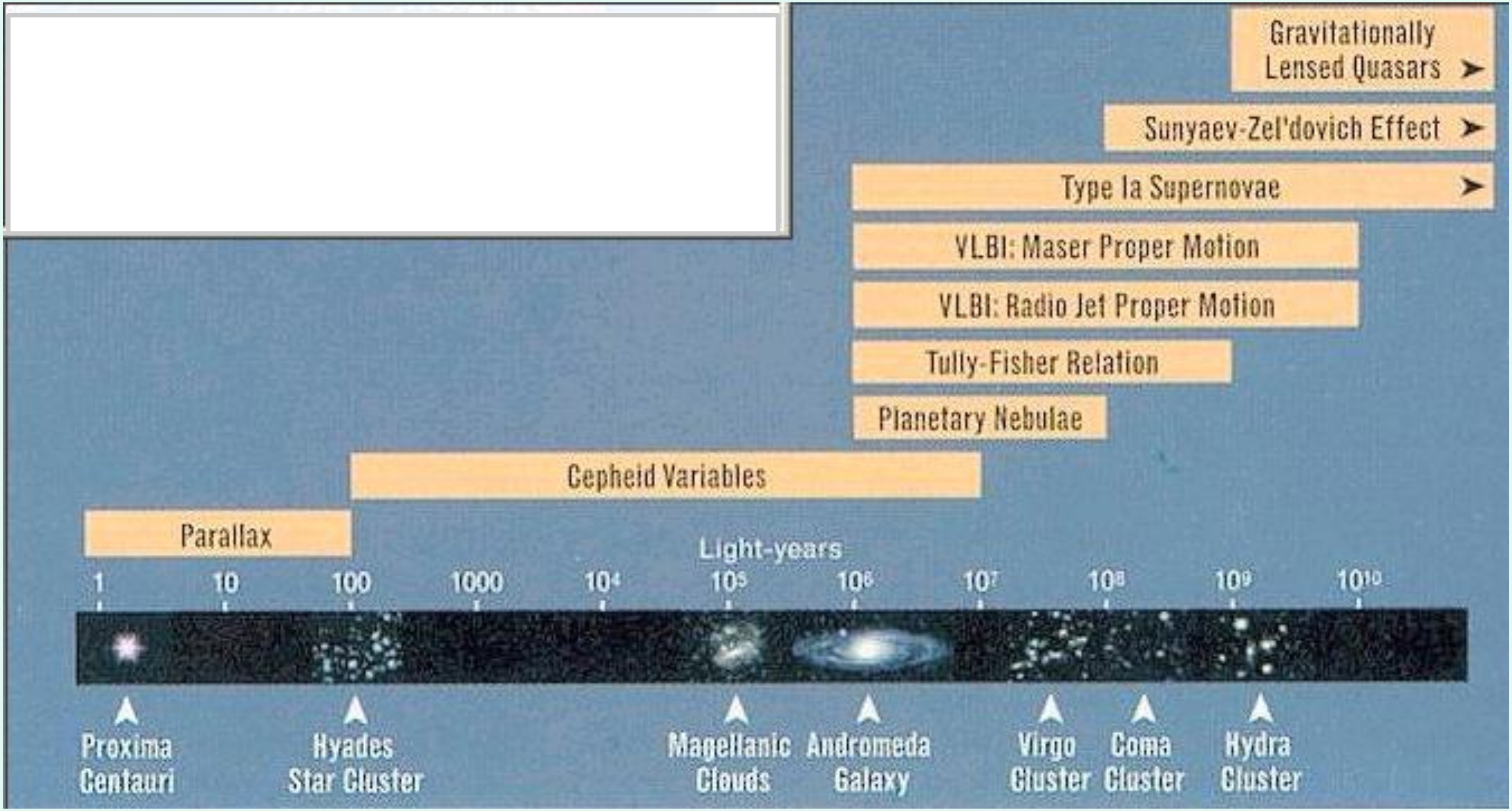

## Parallax

- foolproof
- very simple and direct (based on simple geometry)
- no systematic error

## Standard candles

- possible systematic errors
- *how do we know a certain object is really a "standard candle"?* → light curve or spectra
- *how do we know the true luminosity of a std candle?* → need to measure distance to some of these with some direct method e.g . parallax → distance ladder

# Cosmic distance ladder




Each technique only works over a limited range in distance, so we need to cobble together different techniques to cover the whole universe