
Galaxies and Cosmology
A Historical Approach
From the Milky Way to the Big Bang, and everything in between

Galaxies and Cosmology - References

- Chaisson and McWilliam – Ch 23-27 (parts)
- Freedman and Kauffman - Ch 23,24,26
- Berendzen, Hart, & Seeley - “Man Discovers the Galaxies”
- J.D. Fernie (1970) - “The Curtis-Shapley Debate”, PASP (online)
- Gale Christiansen - “Edwin Hubble”
- Allan Sandage - *http://apod.nasa.gov/diamond_jubilee/1996/sandage_hubble.html*


The Milky Way

If we could observe the Milky Way from a great distance, it might look a bit like this (edge-on and face-on).

The Milky Way [AT Ch 23]

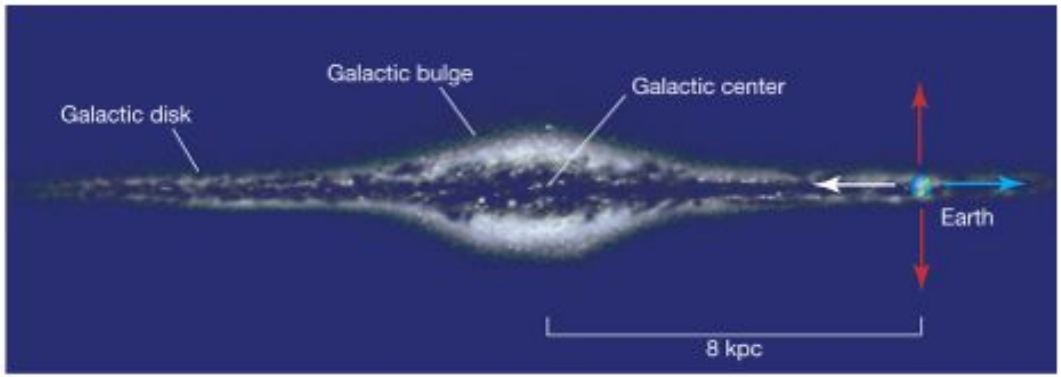
- the Milky Way is a galaxy
- the sun is one of 10-100 billion stars in the Milky Way
- 10^{12} solar masses, mostly "dark matter"
- bright part about 30,000 pc = 100,000 light years across
- the sun is located 8,000 pc = 24,000 light years from the centre

Galaxies Similar to the Milky Way

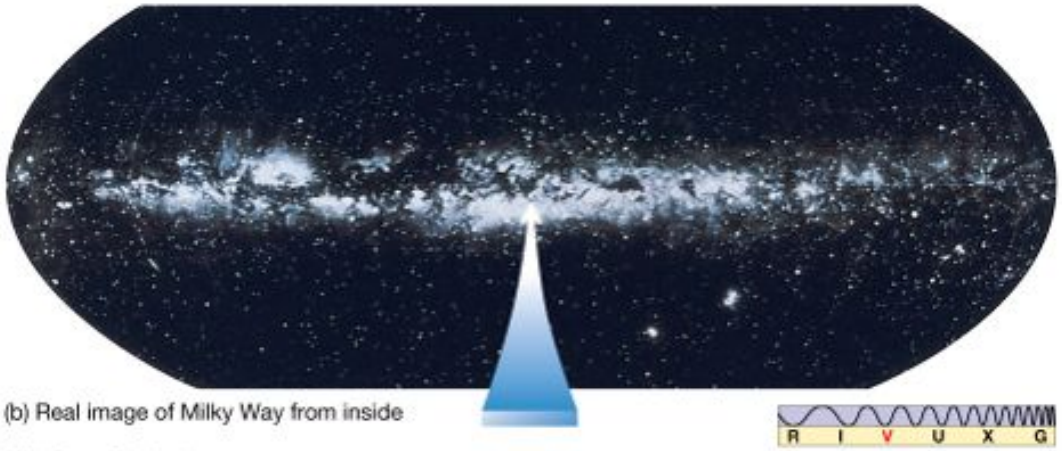
"Andromeda"

The Milky Way

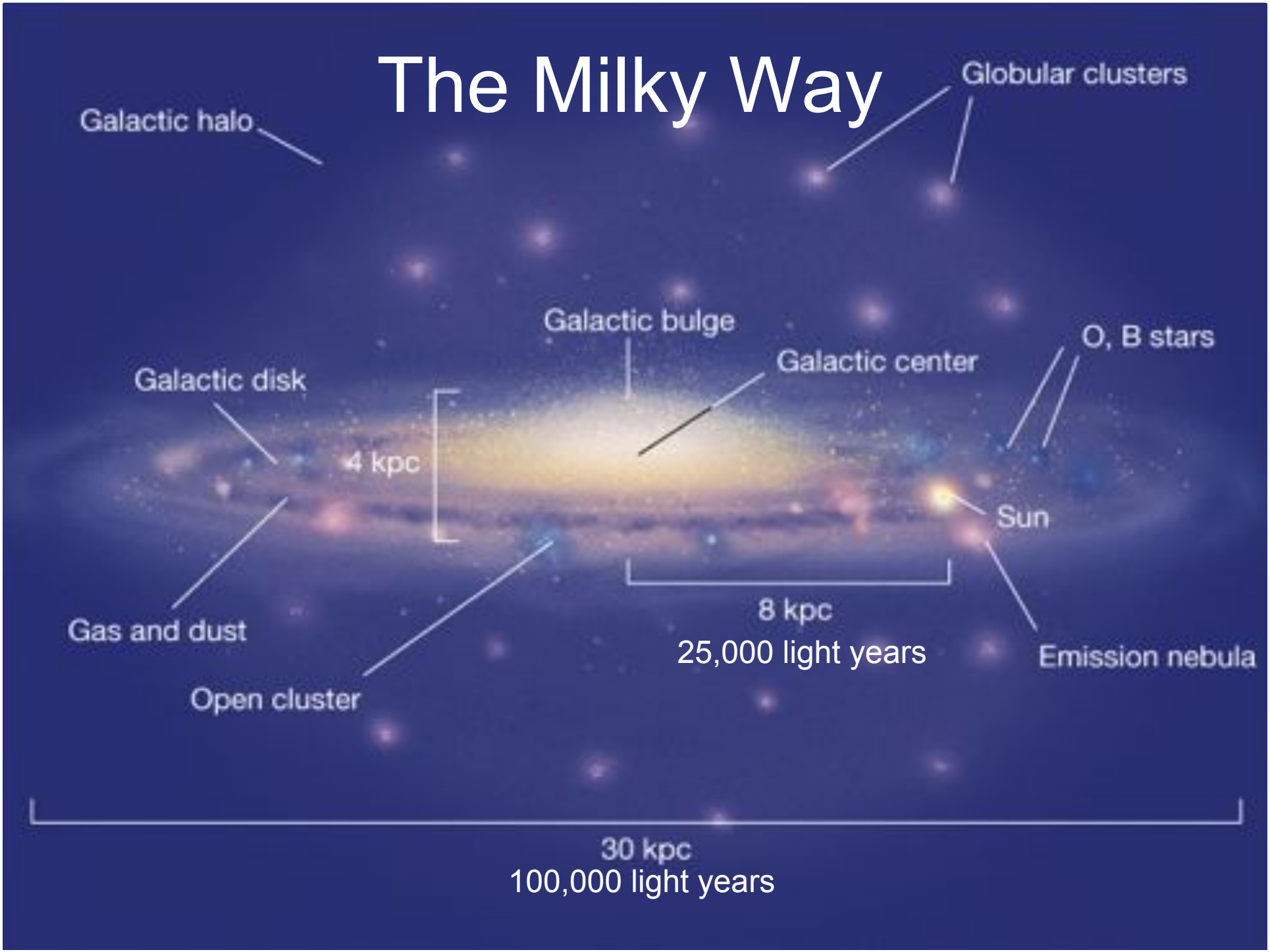
From Earth, we see few stars when looking out of our galaxy (red arrows) and many stars when looking in (blue arrows). Milky Way is what our galaxy appears to be in the night sky.



(a) Artist's view of Milky Way from afar

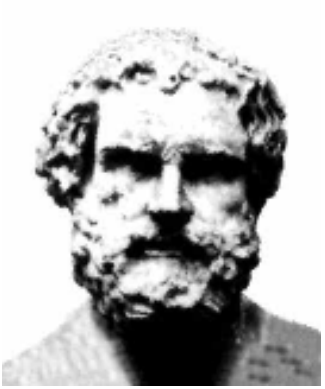


(b) Real image of Milky Way from inside


The Milky Way
Galactic halo
Globular clusters
Galactic bulge
Galactic center
O, B stars
Galactic disk
4 kpc
Sun
Gas and dust
8 kpc
25,000 light years
Emission nebula
Open cluster
30 kpc
100,000 light years

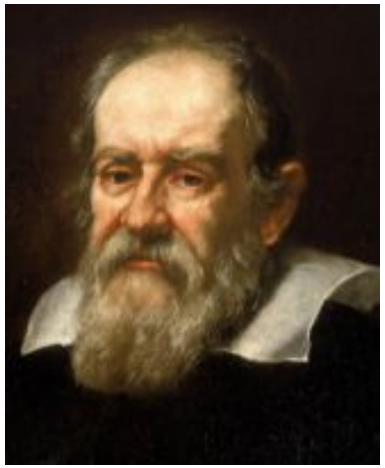
Historical Introduction to the Milky Way and Galaxies

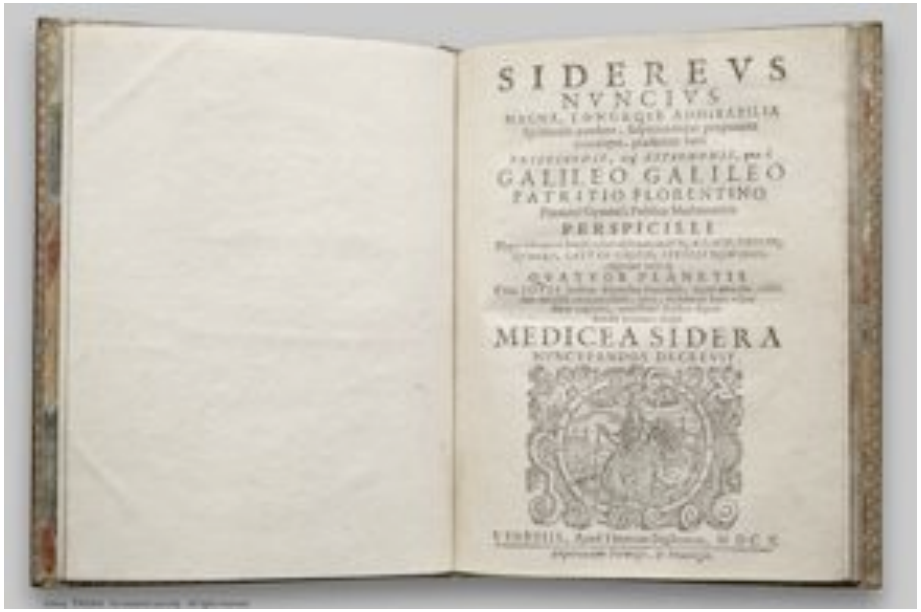
- Pre-1609:
  - Democritus (460-370BC): the “Milky Way” is an aggregate of unresolved light from countless stars
  - Aristotle later argued against this



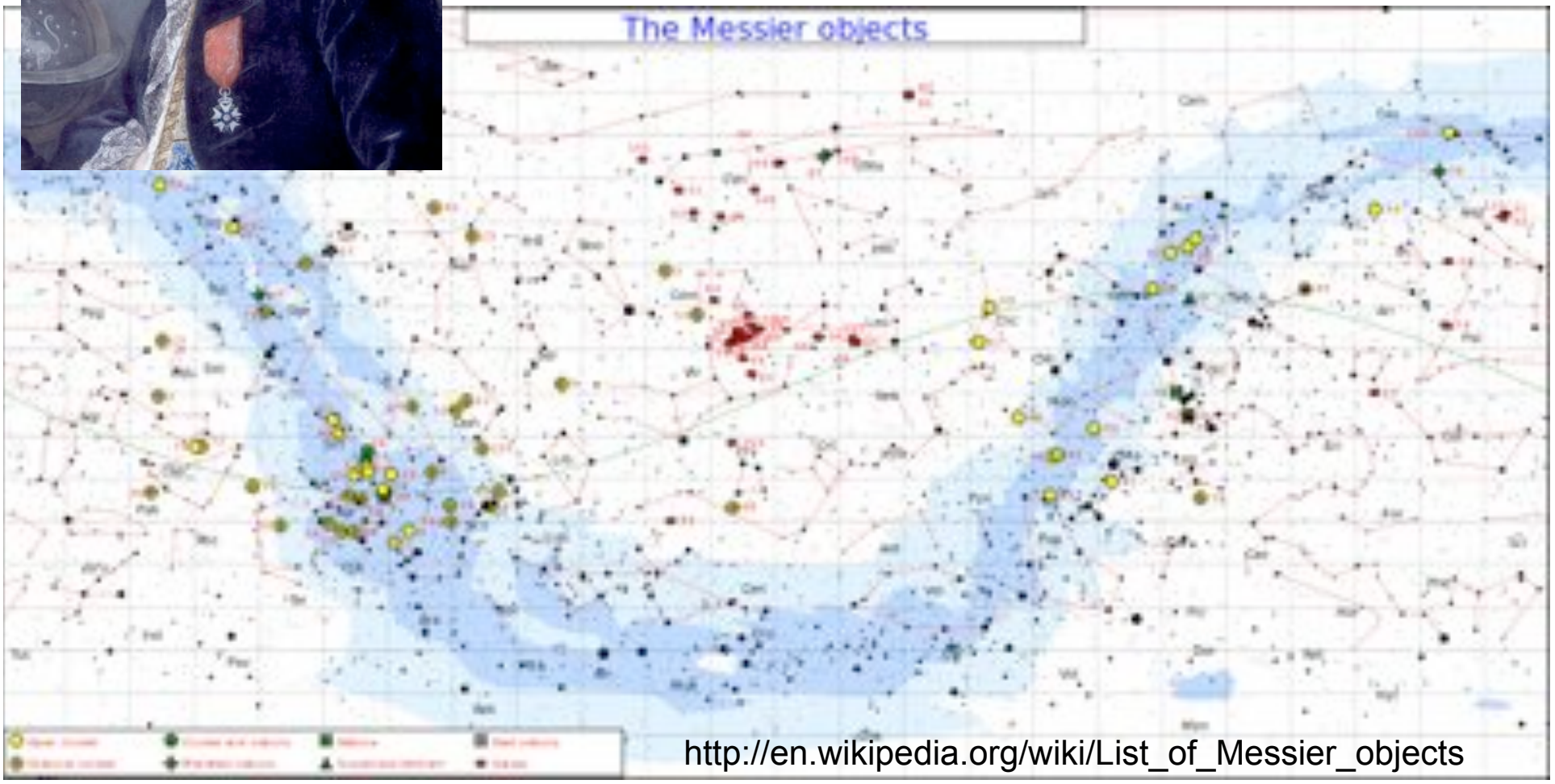
Galileo 1609

- Milky Way is a blur of unresolved stars
- telescopic confirmation of Democritus



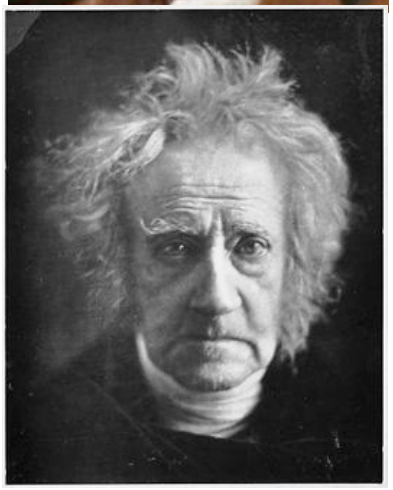


- Messier (1730-1817)
  - Made list of 110 non-stellar objects (a few not real)



http://en.wikipedia.org/wiki/List_of_Messier_objects

- William (c. 1800), John Herschel (c. 1830)
  - Catalogued many non-stellar telescopic objects
  - culminated with NGC Catalogue – Dreyer c.1890 (still used)



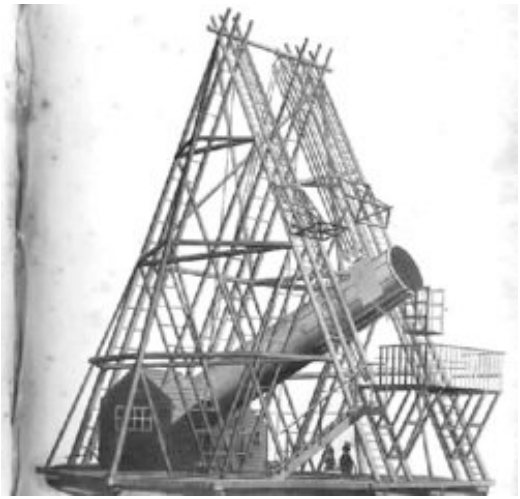


Photo of John Herschel's 48" telescope in Slough, just before it was demolished in 1839

See "The Age of Wonder" by Richard Holmes

Non-stellar objects

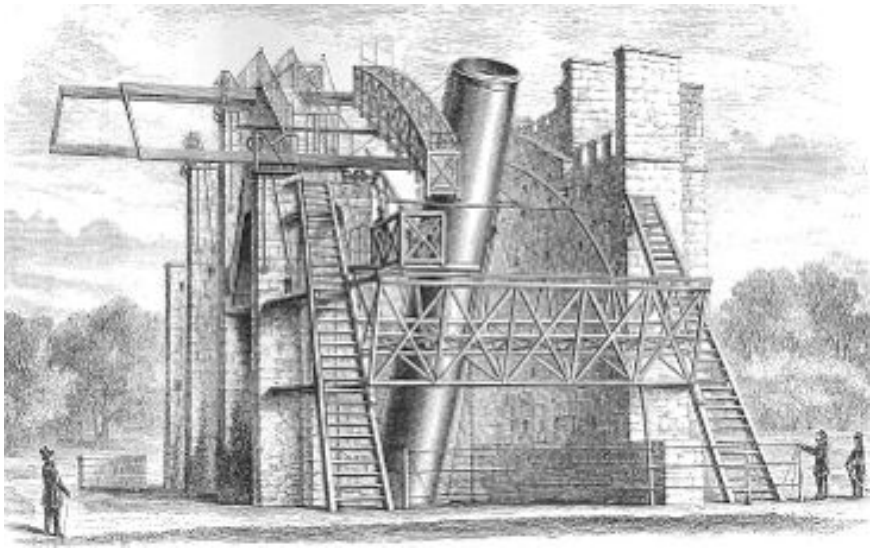
- Star clusters and nebulae
- Nebulae now known to be either
  - nearby gas clouds, or
  - distant galaxies like the Milky Way containing millions-billions of stars, gas and dust
- Distinction was not appreciated in the 19th century

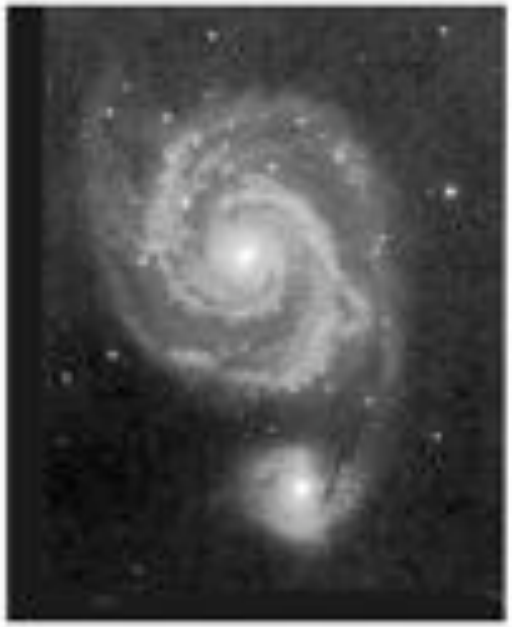

Non-stellar objects

Non-stellar objects

Andromeda Galaxy

- Earl of Ross
  - “Leviathan of Par-sonstown” – 72” telescope outside Birr, Ireland
  - Detailed drawings of “spiral nebulae”





Nature of Milky Way from Star Counts

- William Herschel c. 1800
  - Star counts show MW to be roughly centred on sun (wrong!)

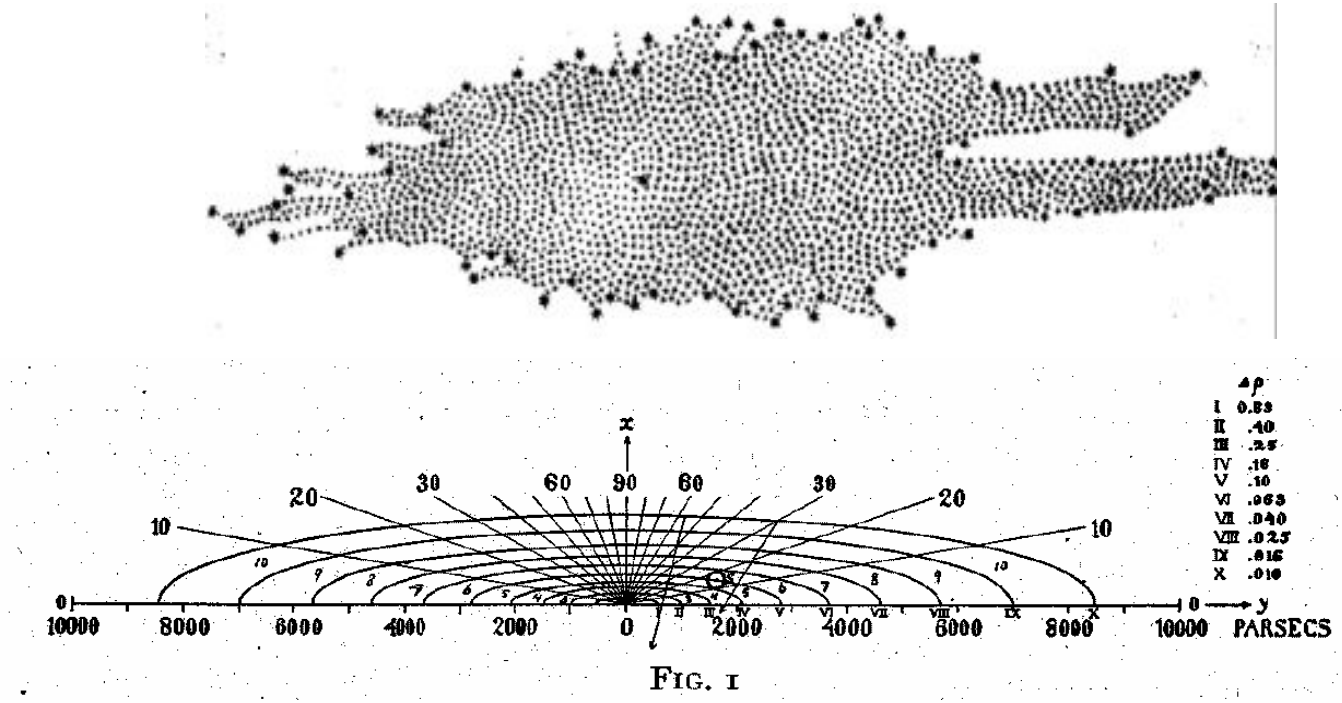
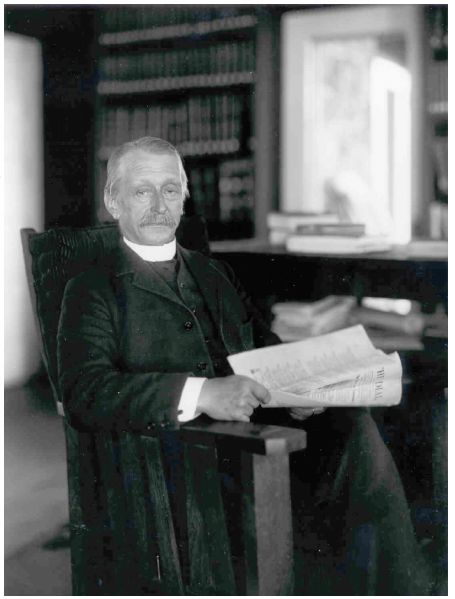


FIG. 1

AT 23.2



Kapteyn, c. 1900

AT Ch 17.1

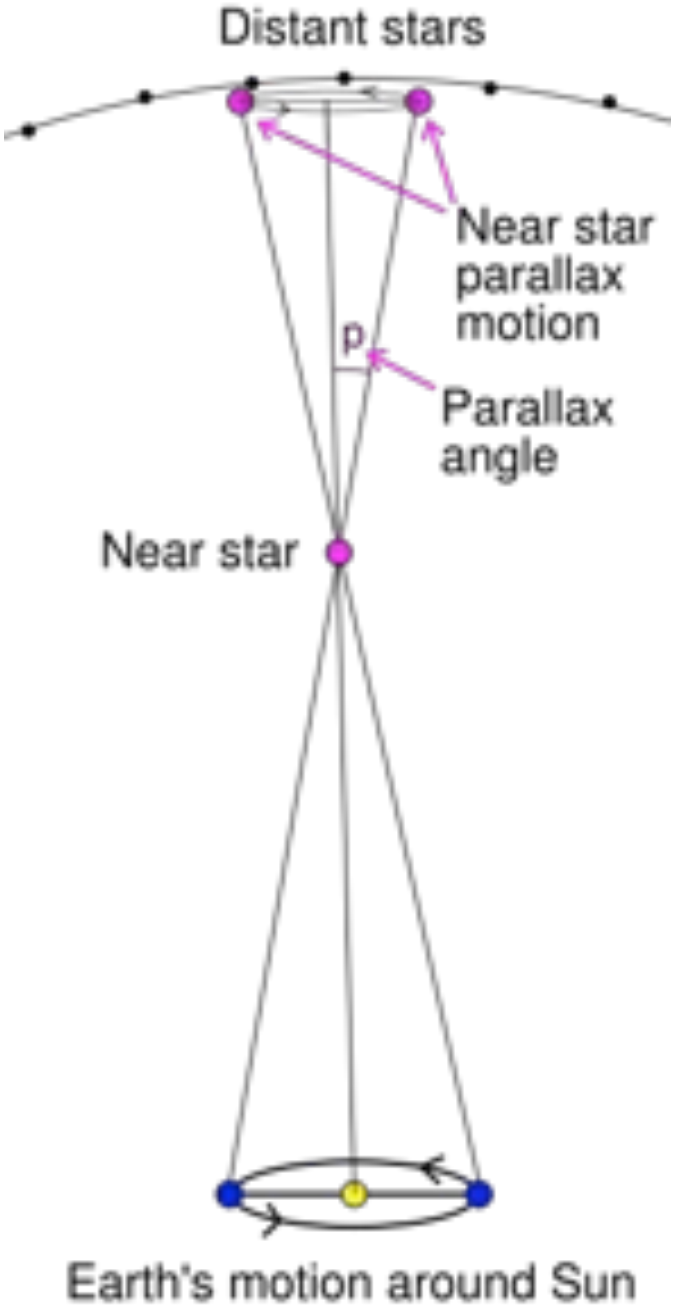
Stellar Parallax

- http://sci.esa.int/interactive/media/flashes/2_1_1.htm
  - Slider for different distances
- As distance increase, parallax decreases
- D= 1 parsec = 3.26 light years means parallax angle = 1 arcsec

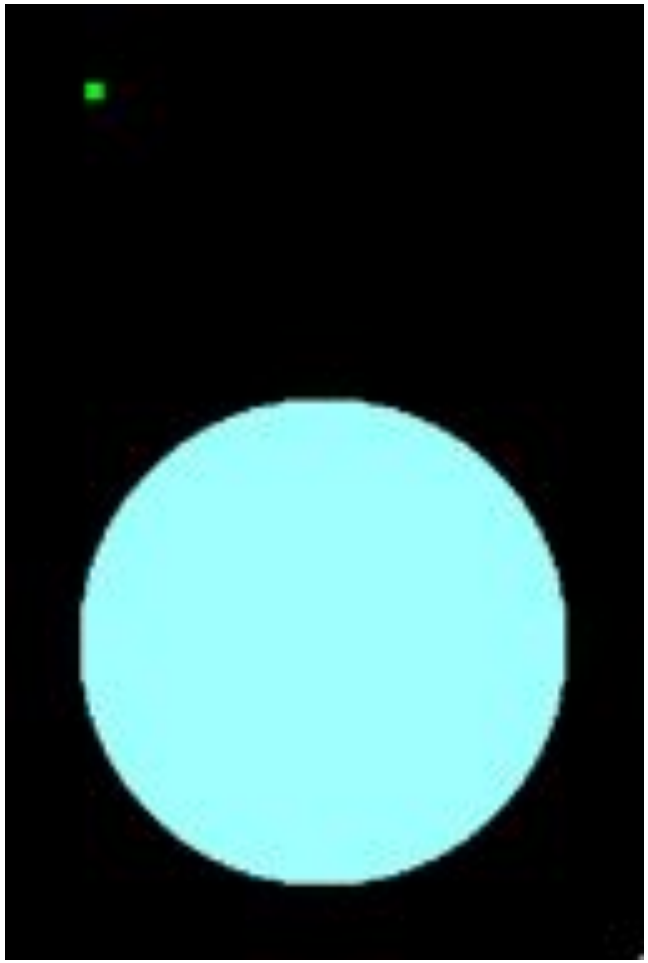
Discovery of parallax - Bessel 1838

"Bessel was able to achieve the feat for which he is best remembered today: he is credited with being the first to use parallax in calculating the distance to a star. Astrono-mers had believed for some time that parallax would provide the first accurate measurement of interstellar distances—in fact, in the 1830s there was a fierce competition between astro-nomers to be the first to measure a stellar parallax accurately. In 1838 Bessel won the race, announcing that 61 Cygni had a para-llax of 0.314 arcseconds; which, given the diameter of the Earth's orbit, indicated that the star is 10.4 ly away. If the currently accep-ted figure of 11.4 ly (see 61 Cygni and discus-sion page) is correct, Bessel's figure had an error of 8.8%. He narrowly beat Friedrich Struve and Thomas Henderson, who measured the parallaxes of Vega and Alpha Centauri in the same year." - Wikipedia

AT Ch 17.1



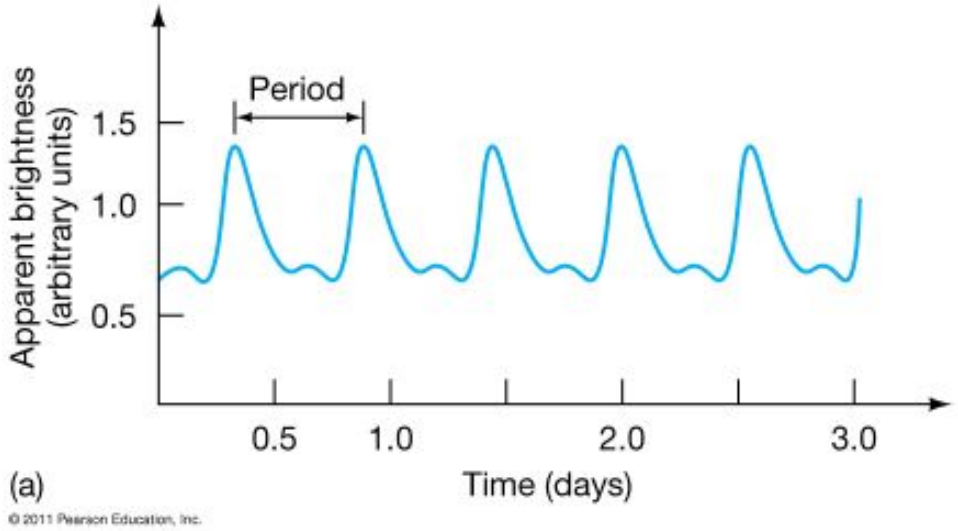
Pulsating Variables AT 23.2



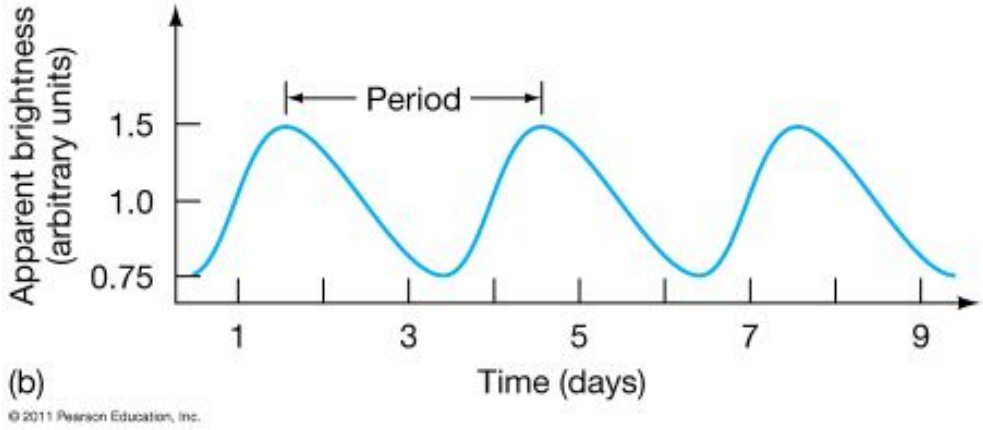
- Most stars are stable!
- A tiny fraction pulsate and vary in brightness
  - Cepheids (named after δ Cephei) – mostly young massive stars.
  - RR Lyrae stars – mostly old, low mass

Pulsating Variables

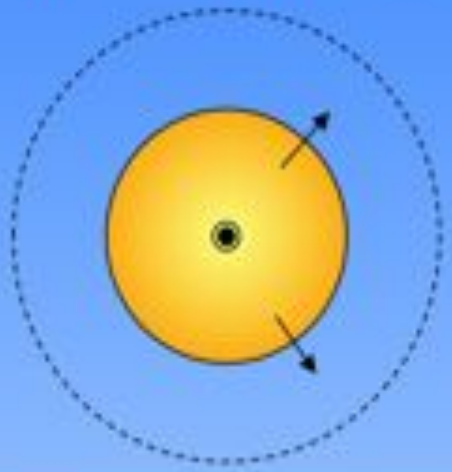
RR Lyrae star - periods from 0.5 to 1 day.



Cepheid variable - periods range from about 1 to 100 days.



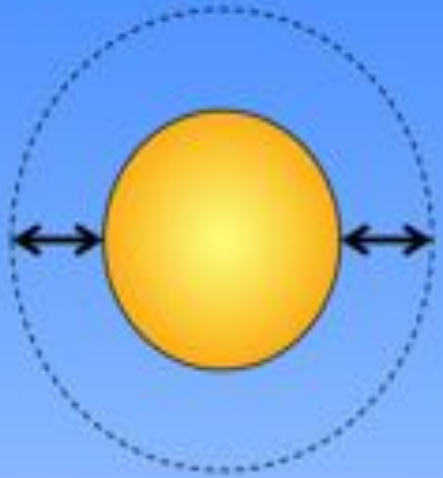
- Vélocimétrie radiale

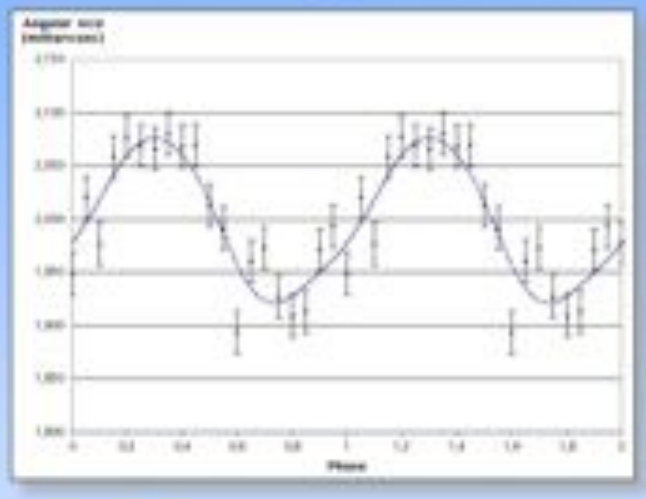


Perpendiculairement au plan du ciel

Distance

- Interférométrie





Dans le plan du ciel

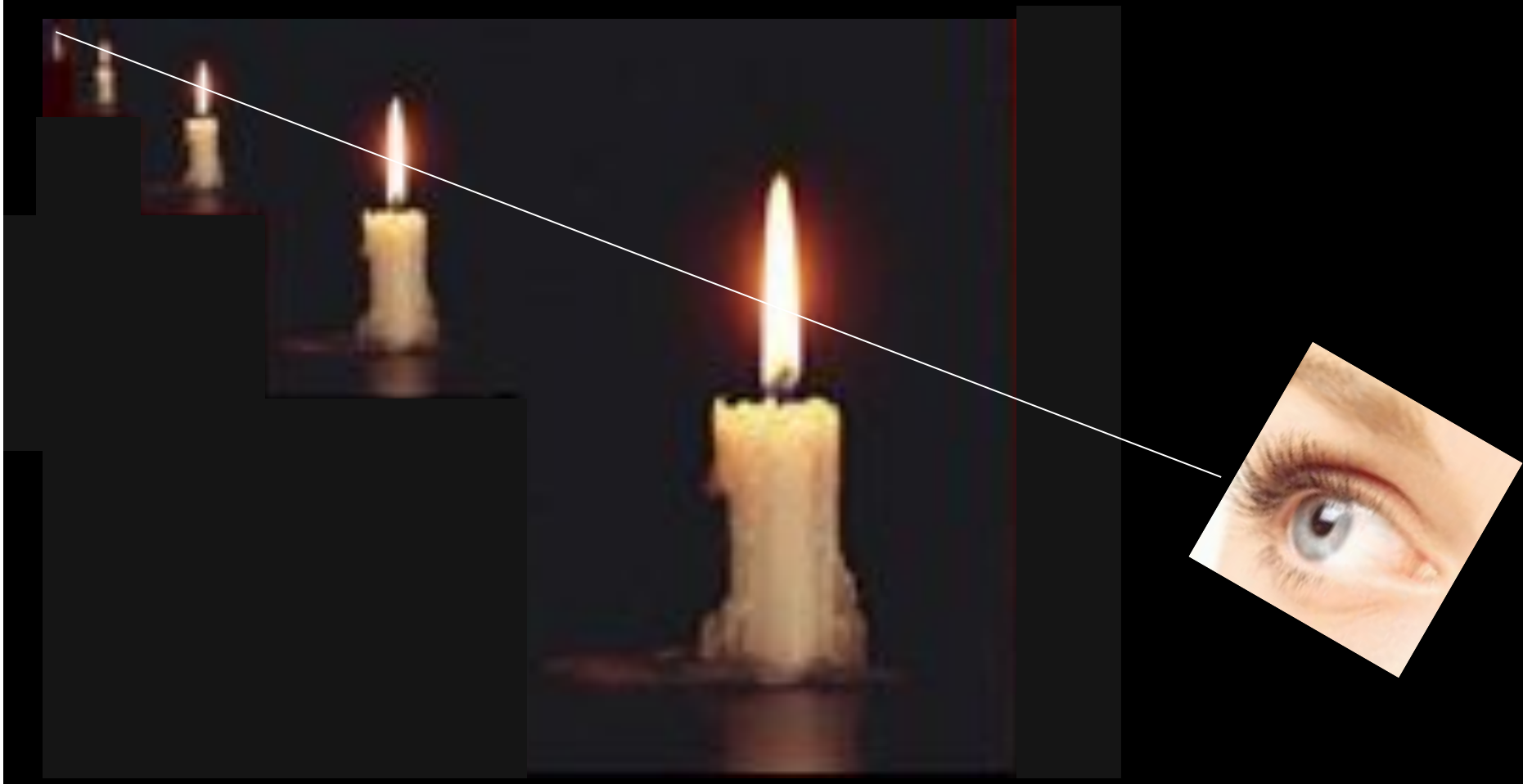
http://www.obspm.fr/actual/nouvelle/dec01/kervella.en.shtml

What determines the apparent brightness of objects in the sky?

- Distance
- Power output or "intrinsic luminosity"

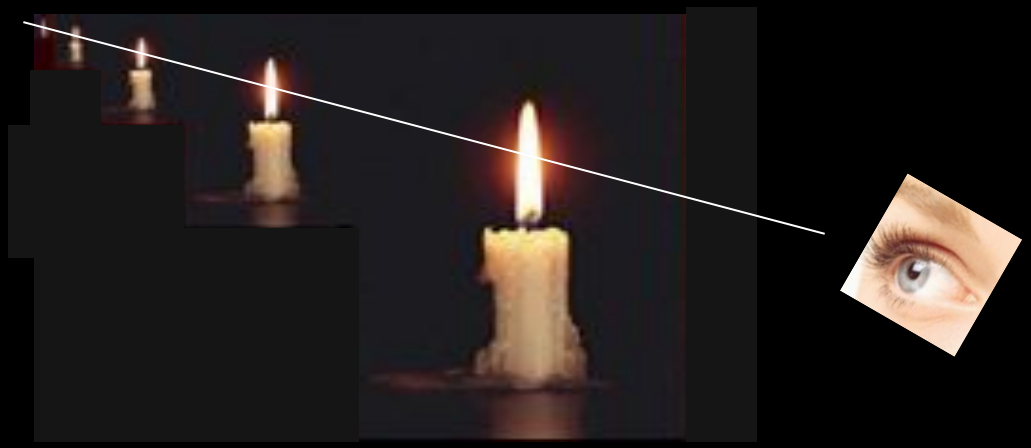

Apparent brightness
vs.
“power” or “luminosity”
or “absolute brightness”

Standard Candle



Could you determine distance with these candles?

Standard Candle



Standard Candle:

- an object with constant power output
- everywhere
- can be used to determine distances

NOT Standard Candles

Could you determine distance with these candles?

NOT Standard Candles

Could you determine distance with these stars?

Henrietta Leavitt 1912

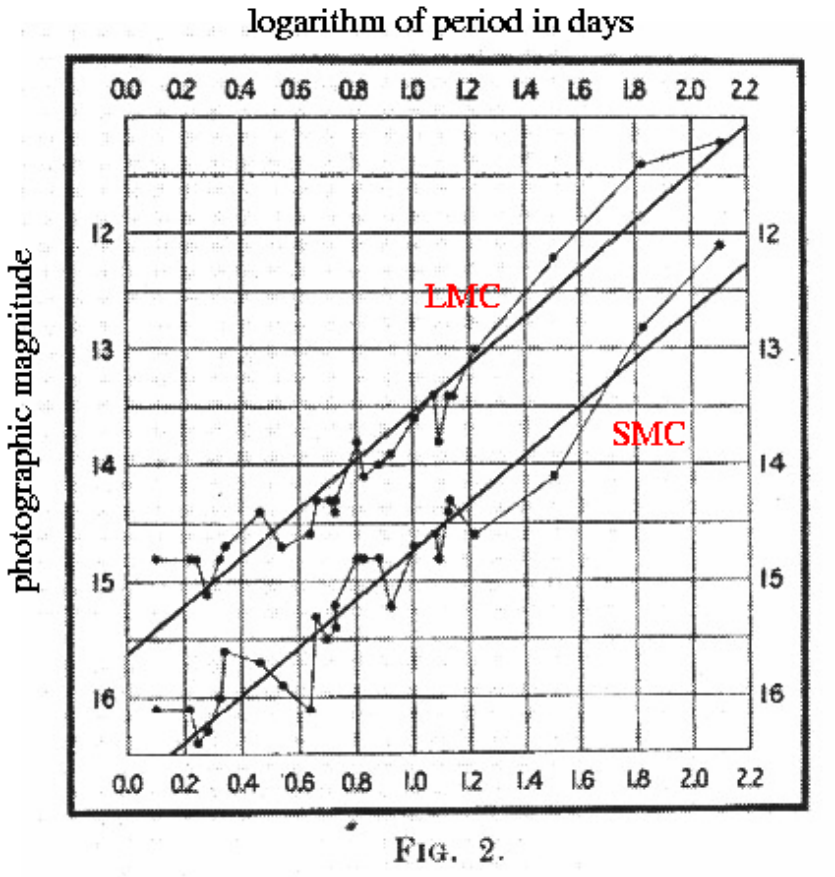
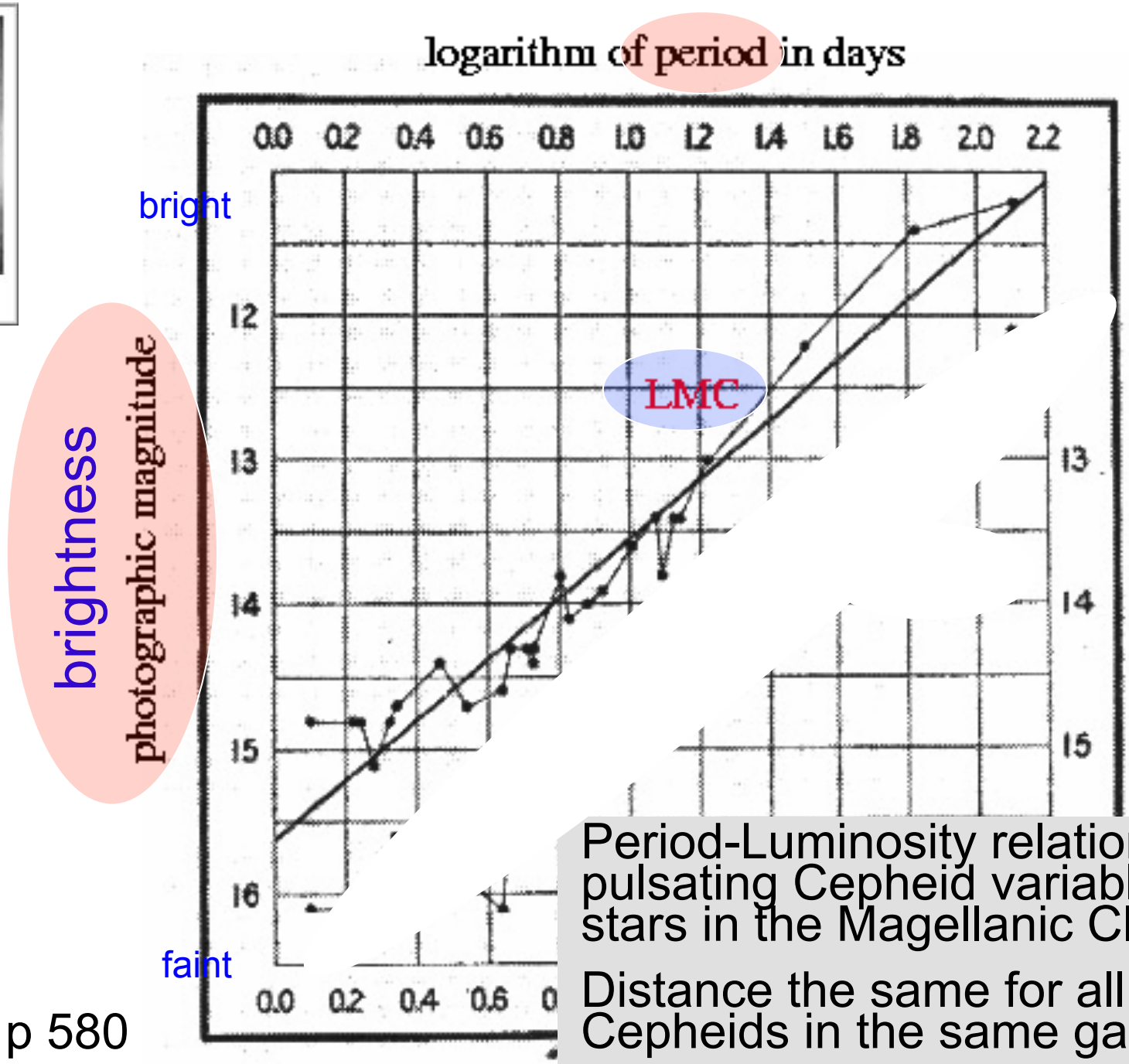


FIG. 2.

Period-Luminosity relation for pulsating Cepheid variable stars in the two Magellanic Clouds

Distance the same for all stars in each galaxy.

- AT 23.2 p 580

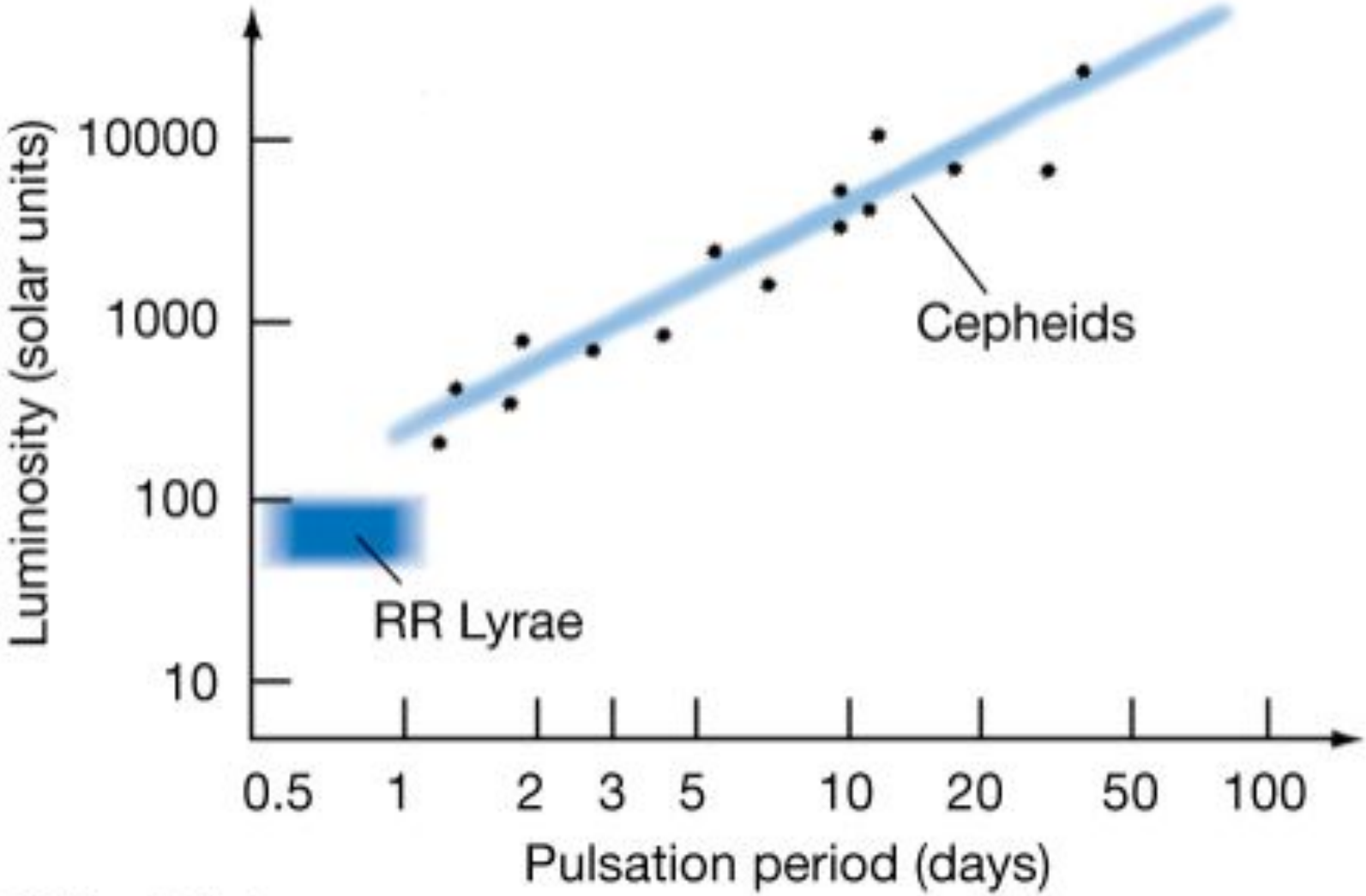


Period-Luminosity relation for pulsating Cepheid variable stars in the Magellanic Clouds

Distance the same for all Cepheids in the same galaxy

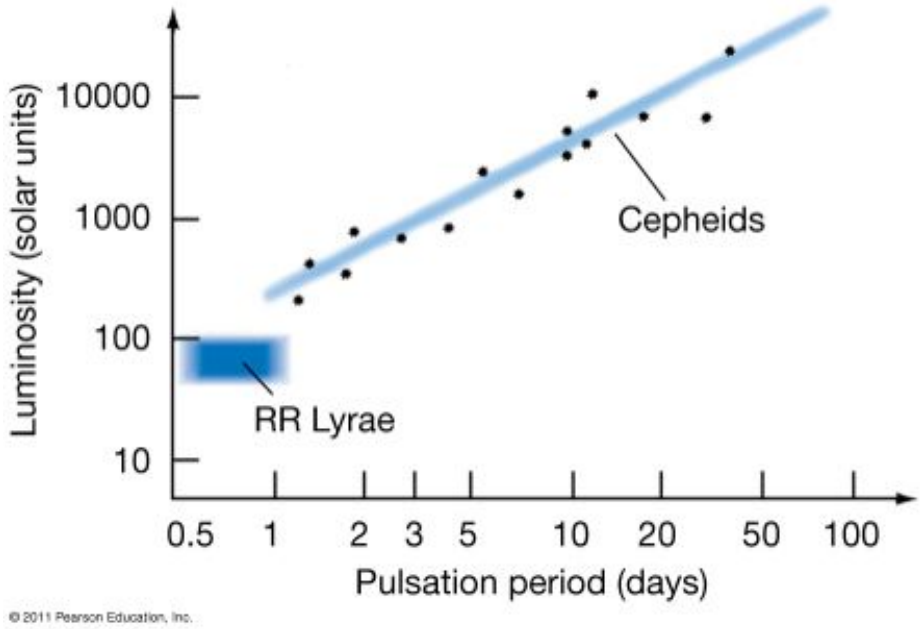
AT 23.2 p 580

Pulsating Variables



AT 23.2 p 580

Pulsating Variables

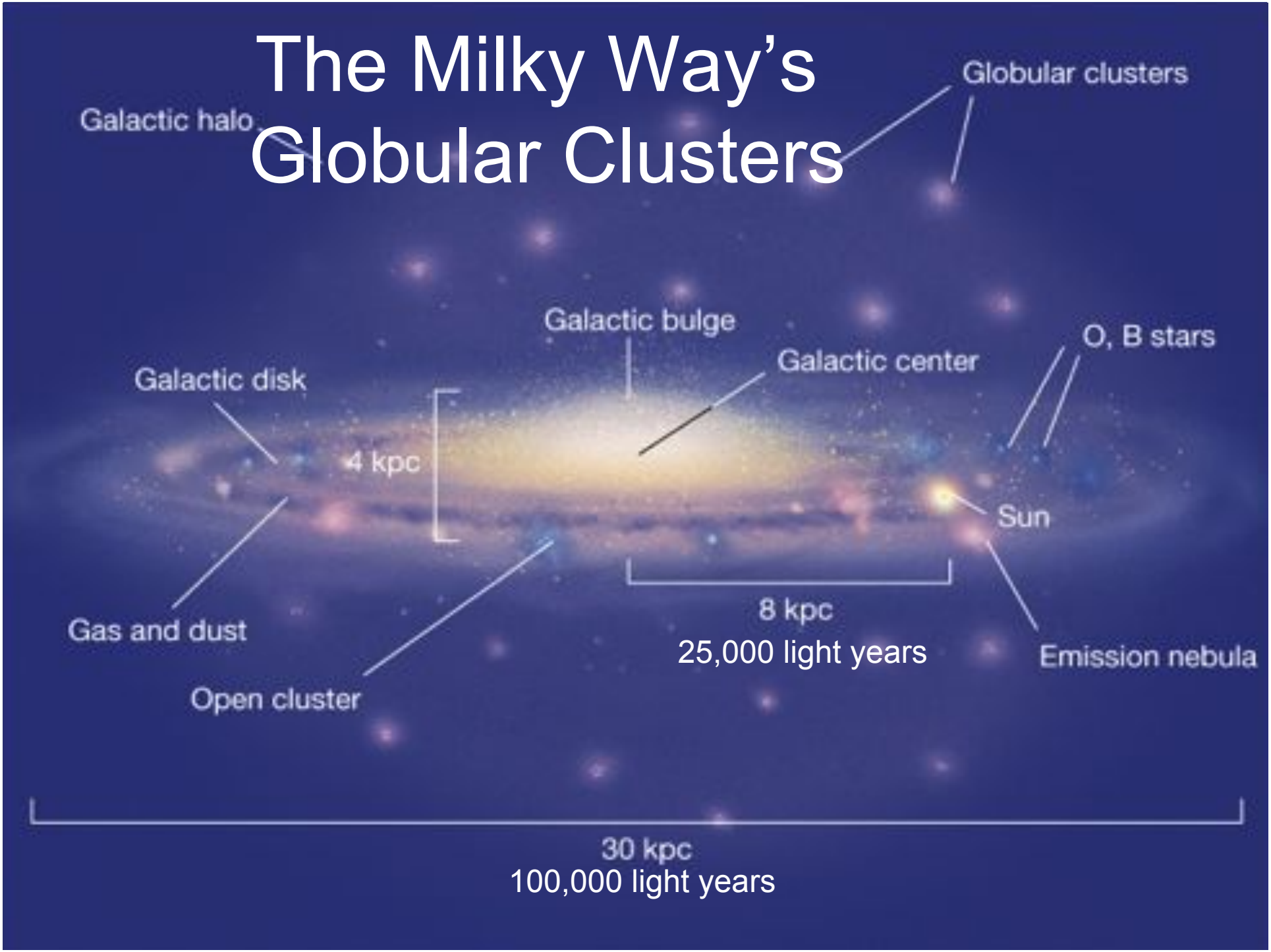


- Pulsating Cepheids of a given period, and all RR Lyrae stars, are standard candles.
- *Given a measurement of the period of a pulsating variable, and its apparent brightness, you can tell how far away it is!*

Distances

- Some classes of objects are **standard candles.**
- If you measure how bright they **appear,** you can derive their **distance**.

The Milky Way's Globular Clusters

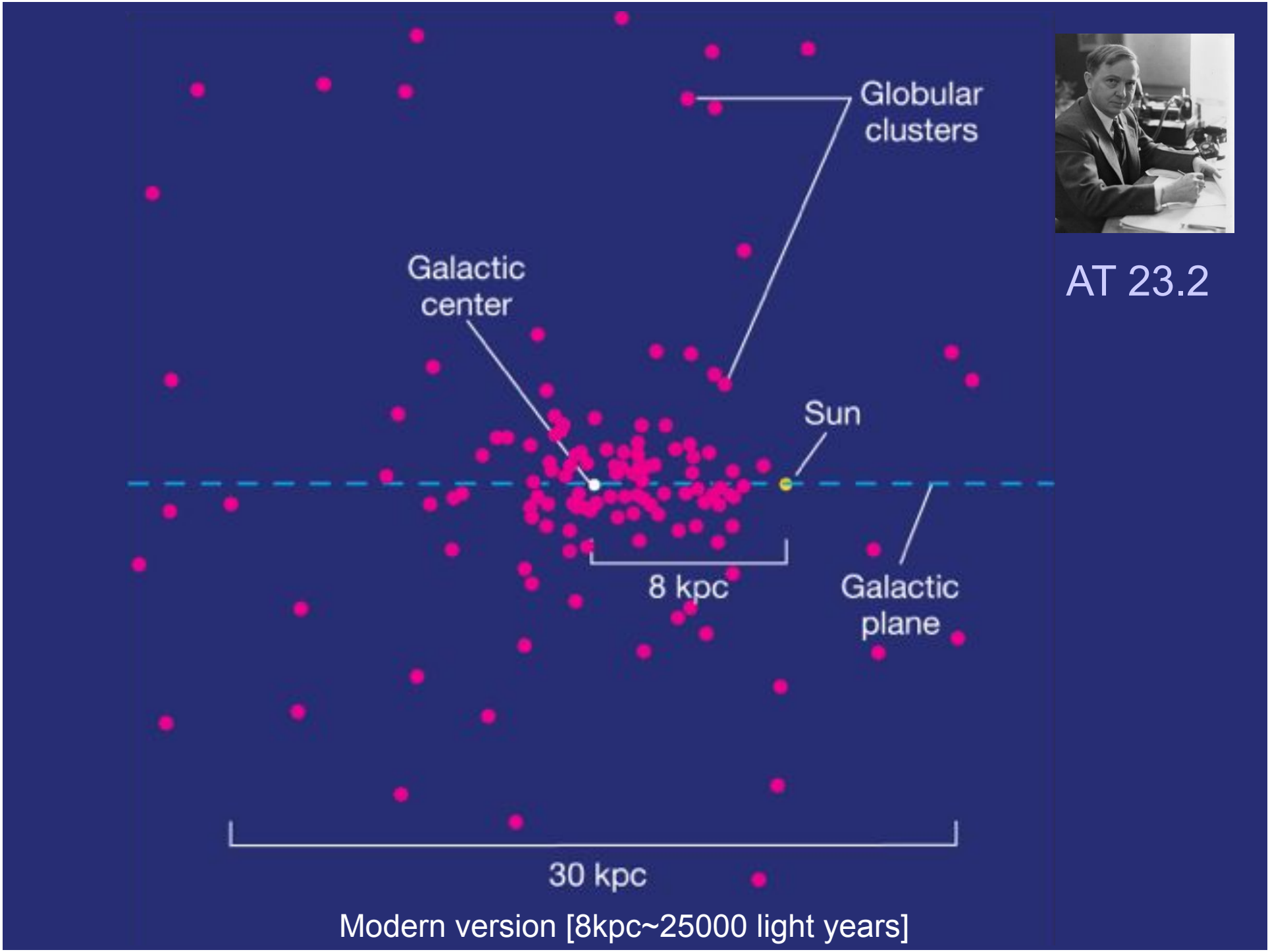


Quick aside: Globular Clusters

Millions of stars!
Outer regions of galaxies
Milky Way has around 150

Harlow Shapley 1918 AT 23.2

- Distances of pulsating variables (RR Lyrae stars) in globular clusters

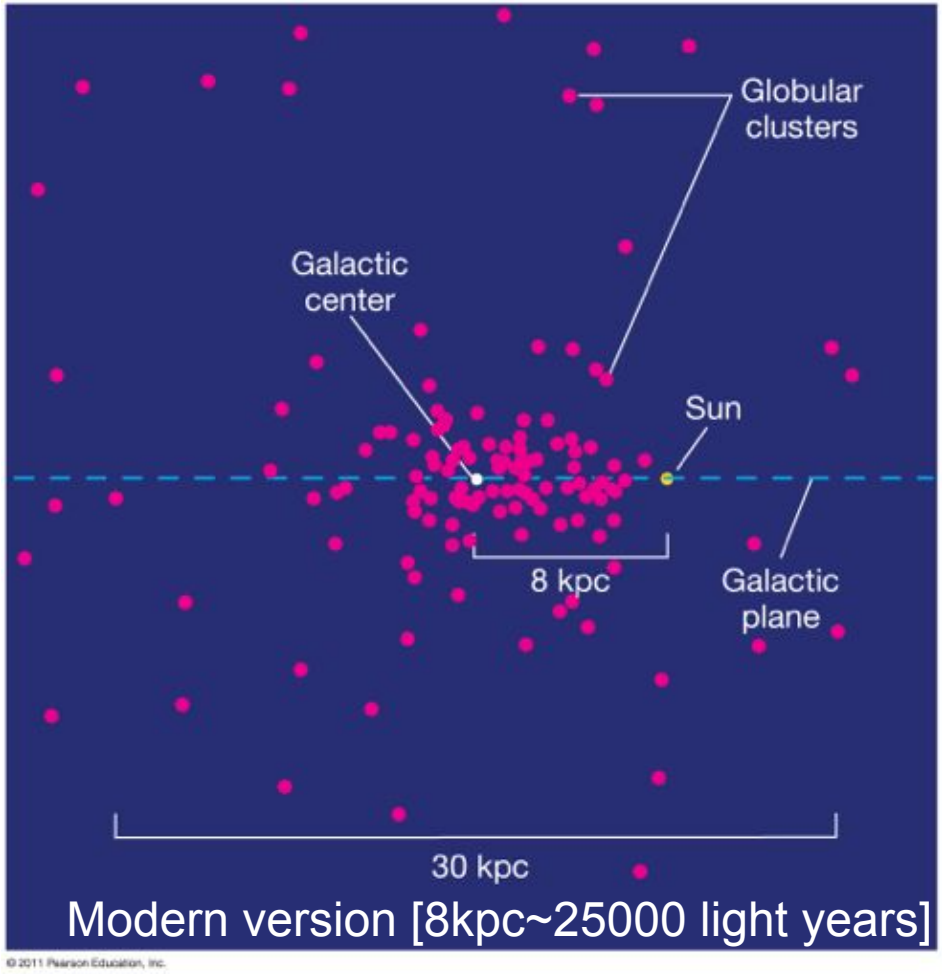


AT 23.2

Modern version [8kpc~25000 light years]

Harlow Shapley 1918 AT 23.2

- Distances of pulsating variables (RR Lyrae stars) in globular clusters
- Globular clusters define a roughly circular system centred 40,000 light years from sun
- Sun is not at centre of Milky Way
- Final death of geocentricism!

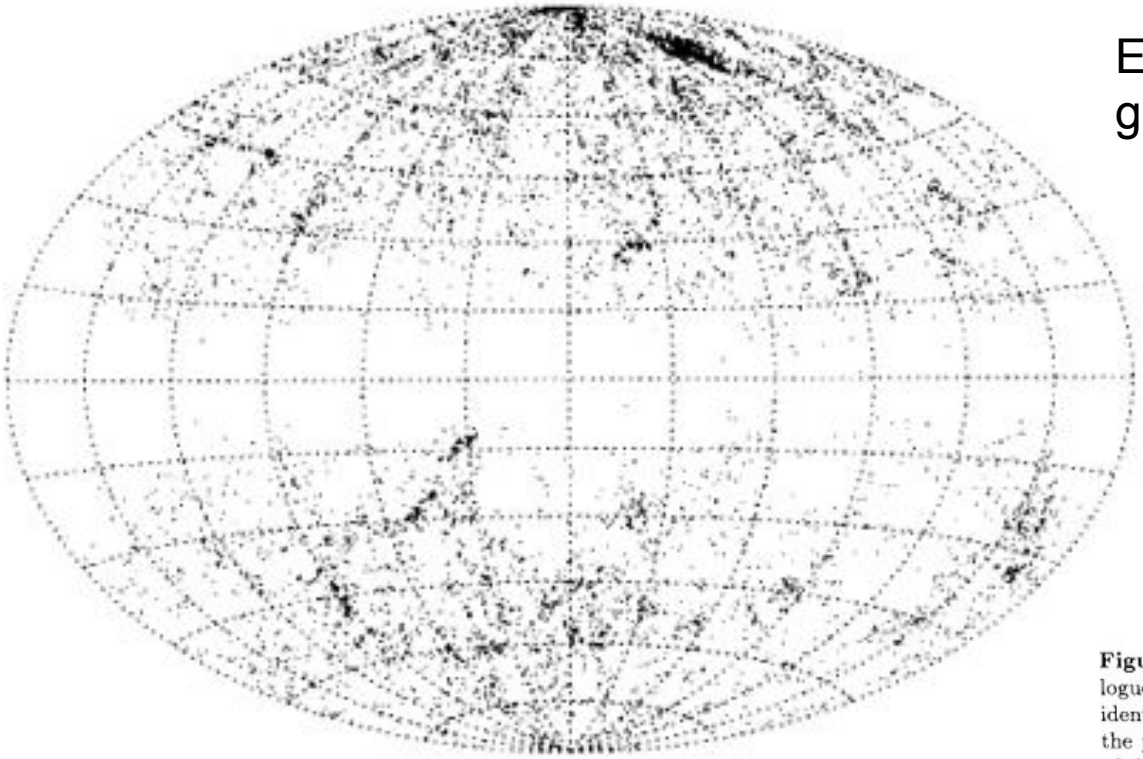


Modern version [8kpc~25000 light years]

Dust – Trumpler 1930

Dust – Trumpler 1930

- Explains Hubble's "zone of avoidance" of galaxies.



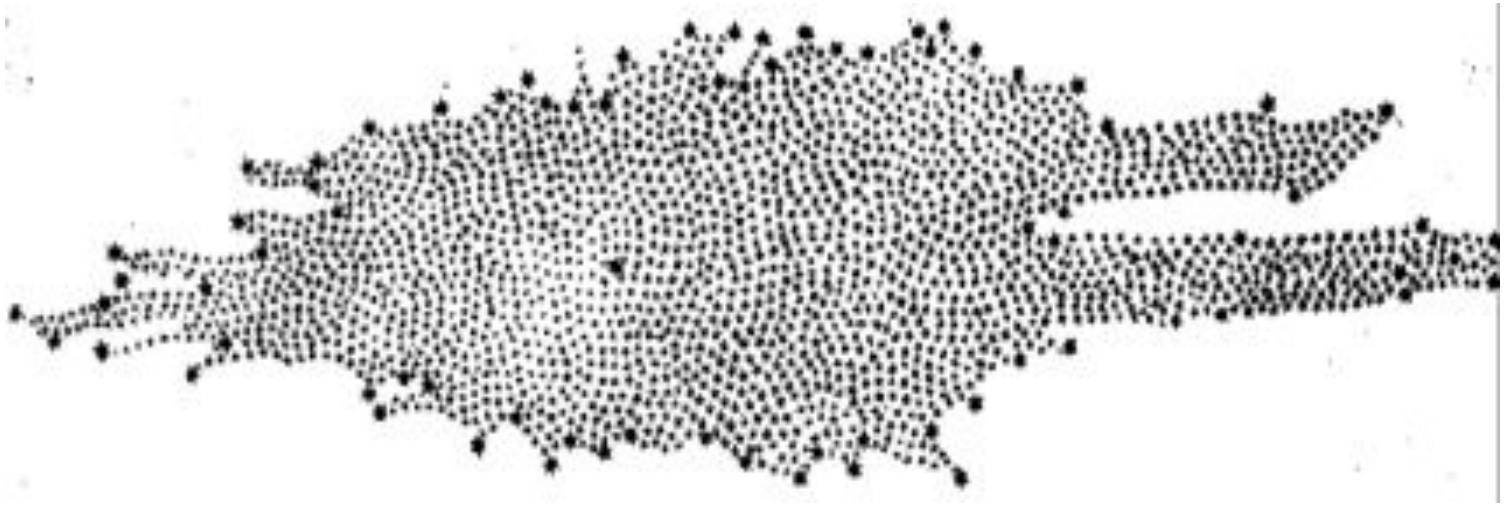
Each point is an NGC galaxy. Entire sky shown.

Plane of Milky Way

Figure 1.5 Map showing the distribution of New General Catalogue (NGC) and Index Catalogue (IC) objects which have been identified as spiral or elliptical nebulae. In this Aitoff projection, the plane of the Milky Way runs horizontally through the center of the map. Note the dearth of objects in the "zone of avoidance" within fifteen degrees of the plane.

Dust – Trumpler 1930

- Explains star count results (below) - how?



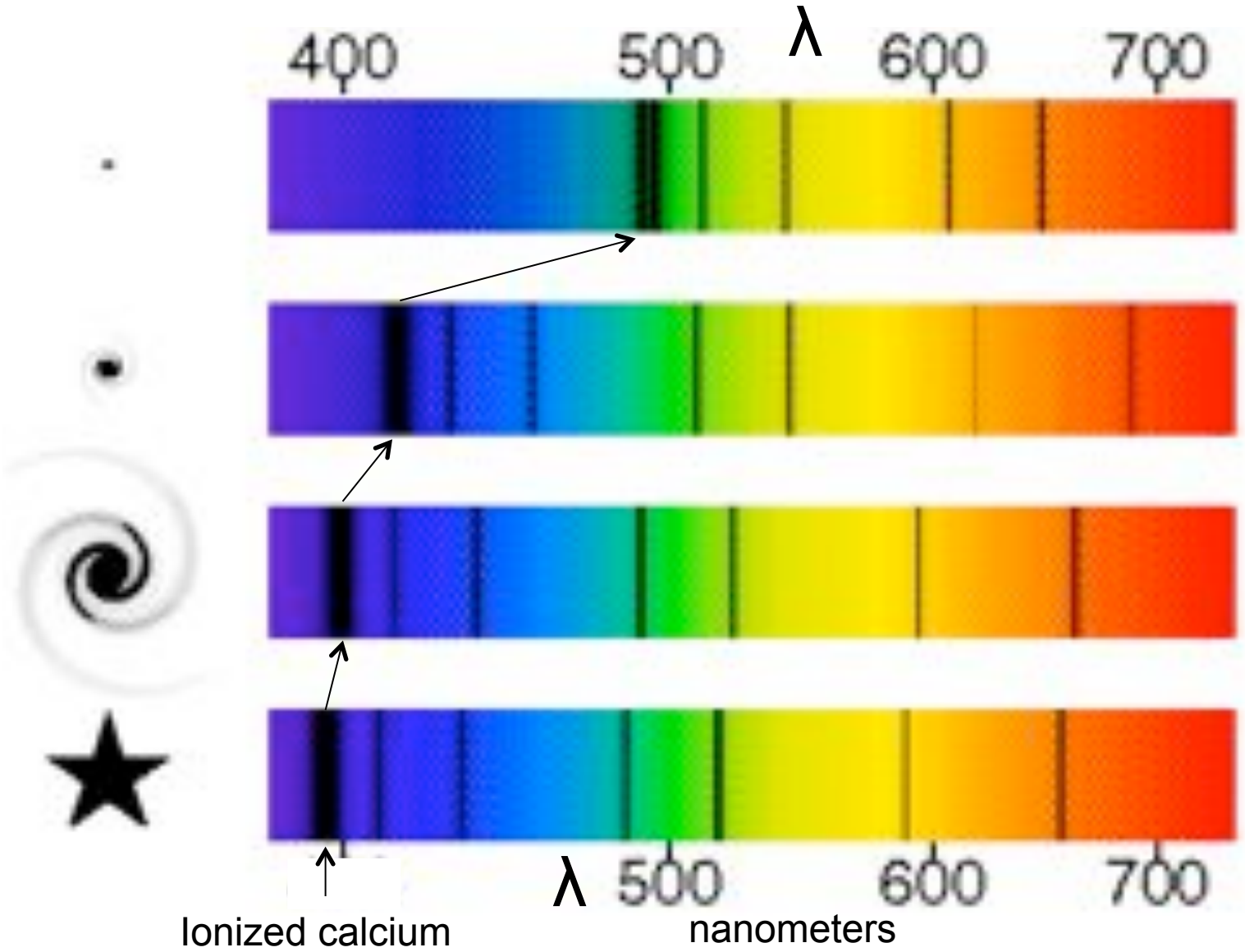
Herschel 1800

Galaxy Velocities AT 24.3

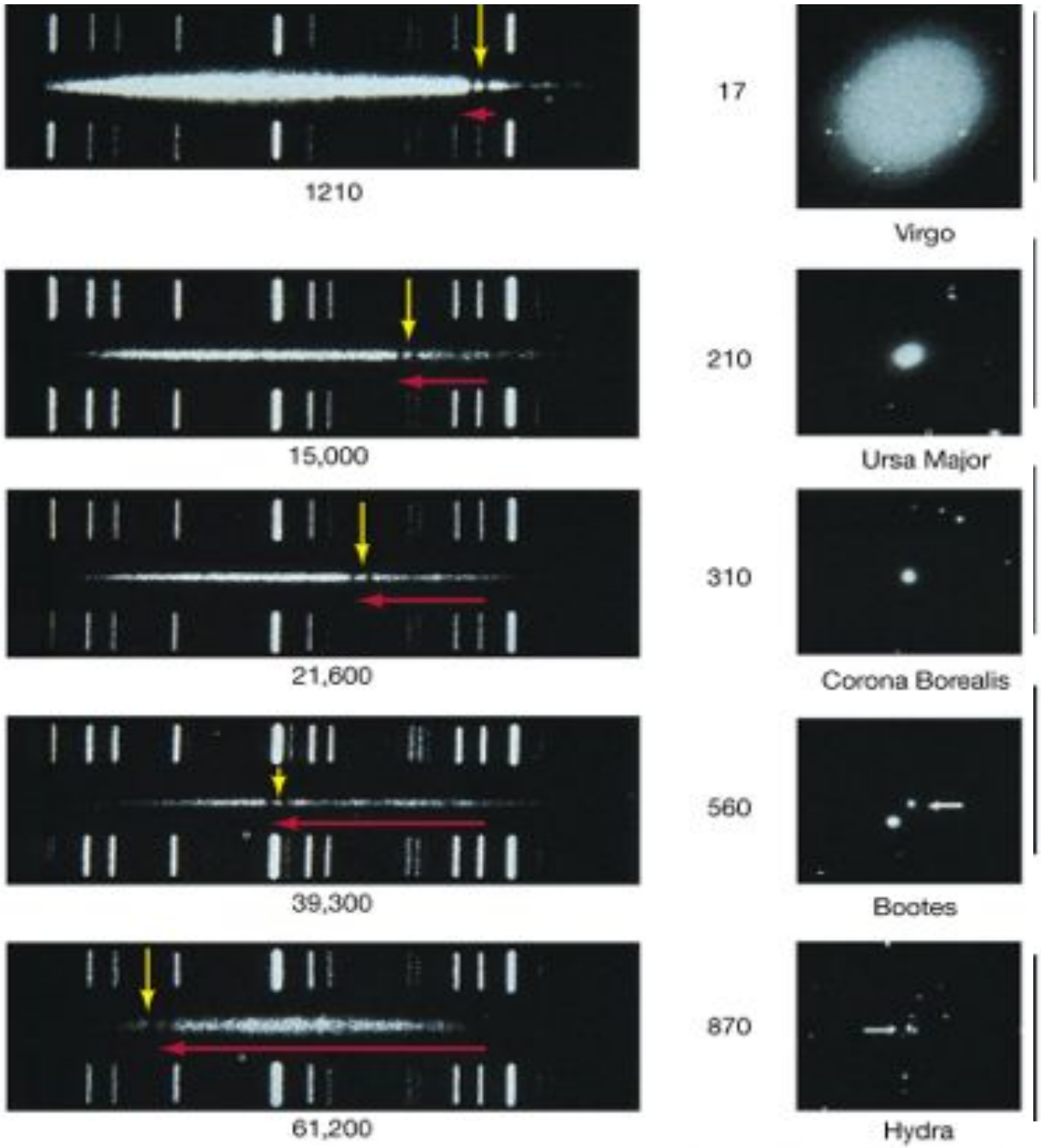
- Vesto Slipher at Lowell Observatory
  - Heroic efforts to obtain radial velocities (Doppler shifts) of nebulae starting in 1912
  - 1924: 36/41 were > 0! – some had v of thousands of km/s!
  - Result found its way into a book on general relativity by Eddington 1924 - a sense that it was “relevant”

Vesto Melvin Slipher
1875-1969

Galaxy Velocities

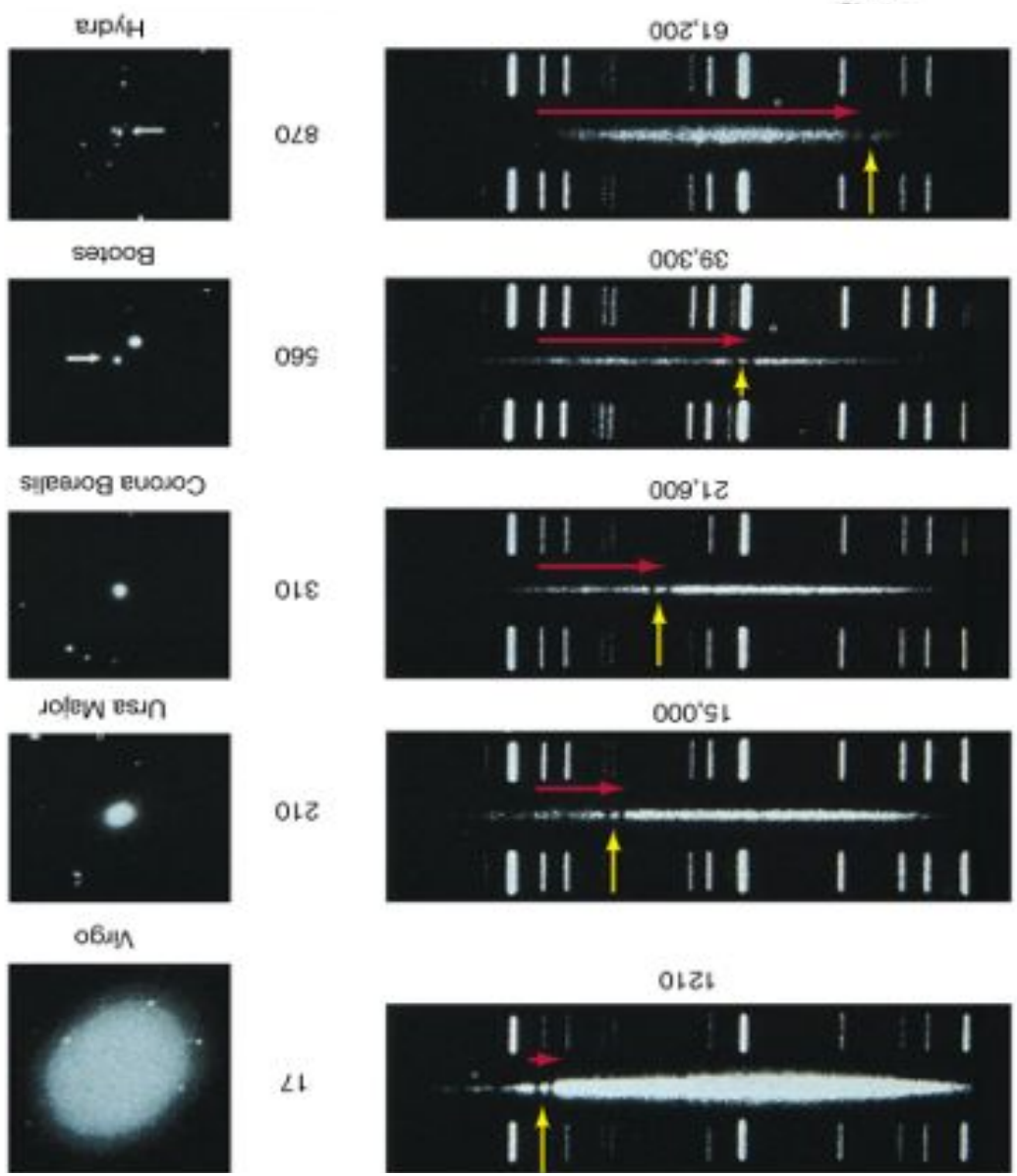


Galaxy Velocities



Galaxy Velocities

- *Slipher:* all galaxies (with a couple of nearby exceptions) seem to be moving away from us.
- The velocities and Doppler shifts can be huge!



This diagram uses modern data: Slipher's velocities extended only to 3000 km/s.

Nature of “Nebulae” [Galaxies]

- Basically fuzzy, little resolution with telescopes available around 1900

- Two distinct views of “nebulae” c1920:
  1. The nebulae are huge “island universes” much like the Milky Way, billions of stars, but at great distance; **or**
  2. The nebulae are small objects embedded in or near the Milky Way – the Milky Way is “the Universe”.

AT 23.2

Nature of "Nebulae"

- Difficult problem:
  - lack of resolution into stars
  - We now know that many fuzzy objects *are* local and gaseous!
- The Great Debate (Washington 1920) - Curtis vs. Shapley
  - Fernie, PASP 1970; Trimble PASP 1995

Nature of "Nebulae"

- For the Island Universe hypothesis (Curtis):
  - Nebulae had large velocities and would escape the Milky Way - hence external
  - Novae in M31 (Andromeda galaxy) - similar to novae in MW, brightness puts them at ~10^6 light years

standard candle!

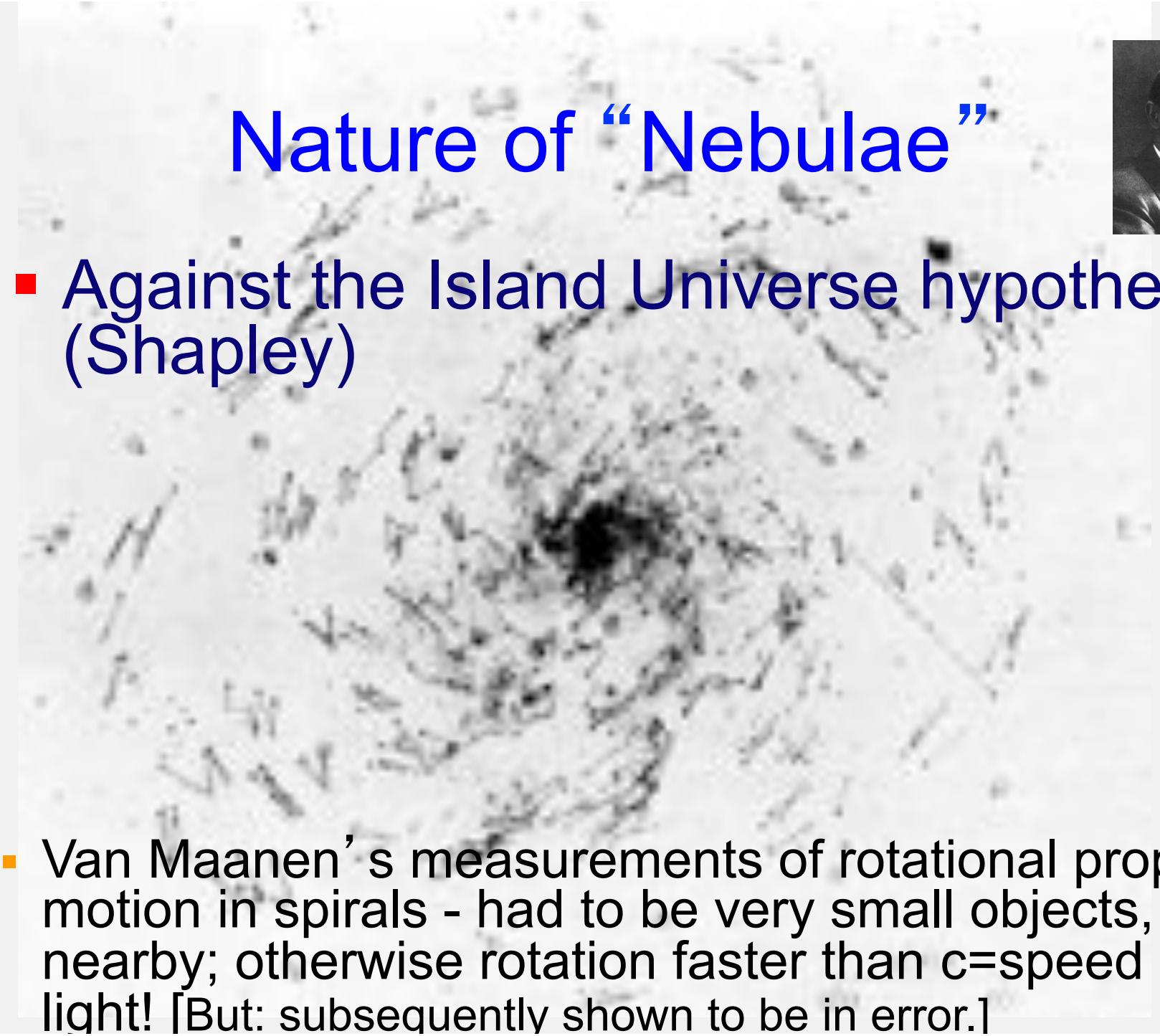
Nature of "Nebulae"

- Against the Island Universe hypothesis (Shapley):
  - "Nova" S And 1884 in M31 - reached almost naked eye brightness → near MW [But not a nova!]

standard candle!

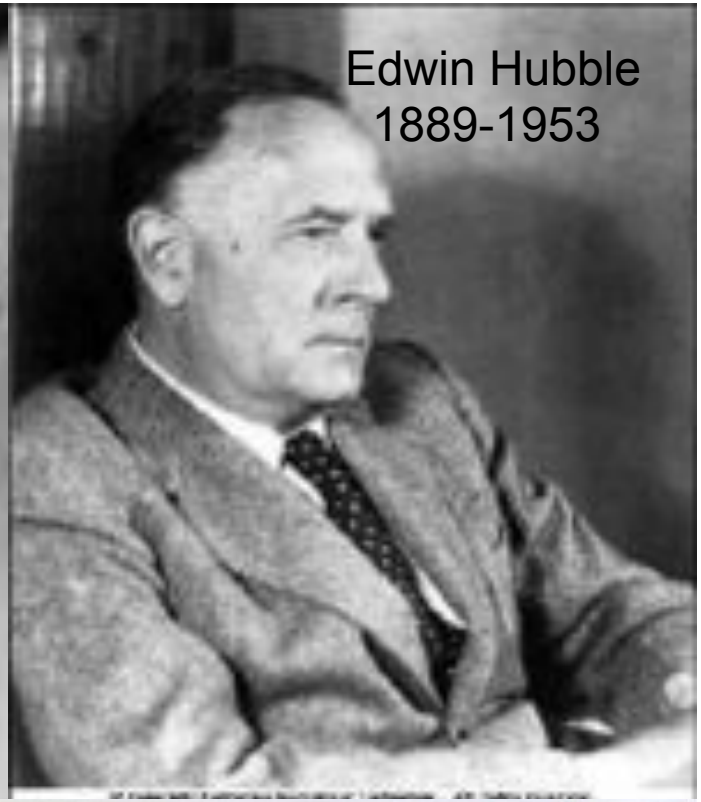
Nature of "Nebulae"

- Against the Island Universe hypothesis (Shapley)

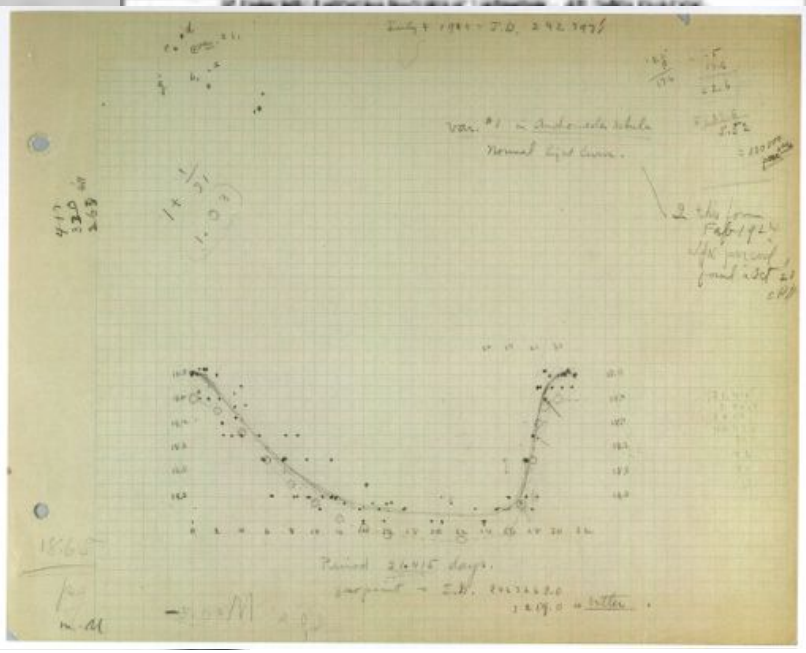


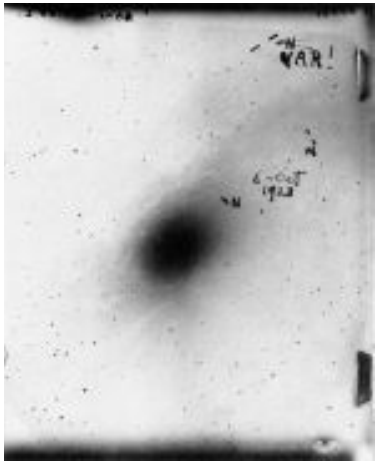
- Van Maanen's measurements of rotational proper motion in spirals - had to be very small objects, nearby; otherwise rotation faster than c=speed of light! [But: subsequently shown to be in error.]

Nature of "Nebulae"



Edwin Hubble
1889-1953



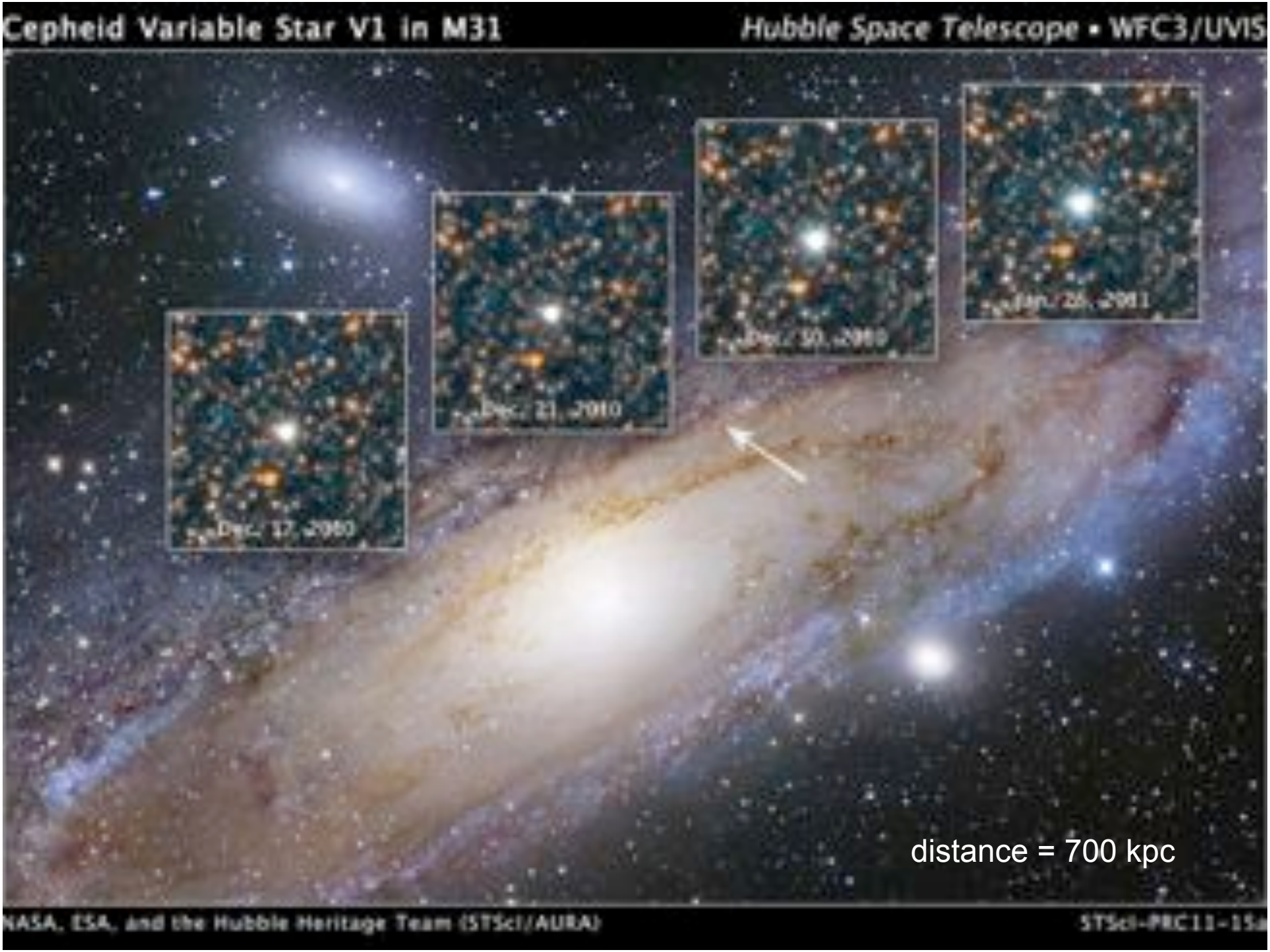


Nature of "Nebulae"

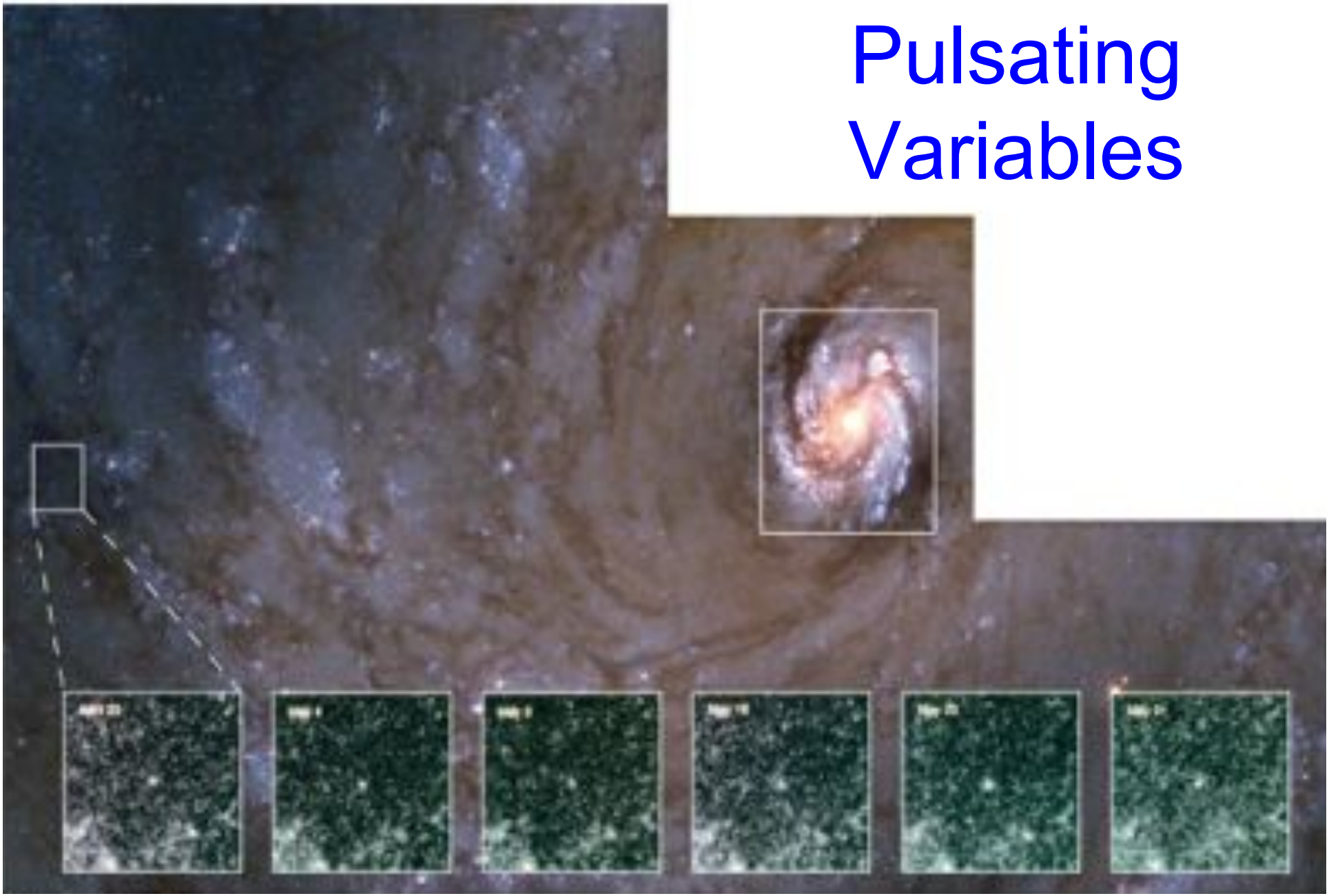
Edwin Hubble

- Settled in late 1923 by Edwin Hubble
  - Newly commissioned Mt Wilson 100" - showed resolution into stars for nearby galaxies
  - Pulsating variables (Cepheids) discovered in M31, M33, NGC 6822
- Distance of the Andromeda about a million light years (modern: 2 million l.y.)– a true "island universe" just like the Milky Way

http://www.youtube.com/watch?v=TEHHFLxmazI


Cepheid Variable Star V1 in M31
Hubble Space Telescope • WFC3/UVIS
distance = 700 kpc
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
STScI-PRC11-15a

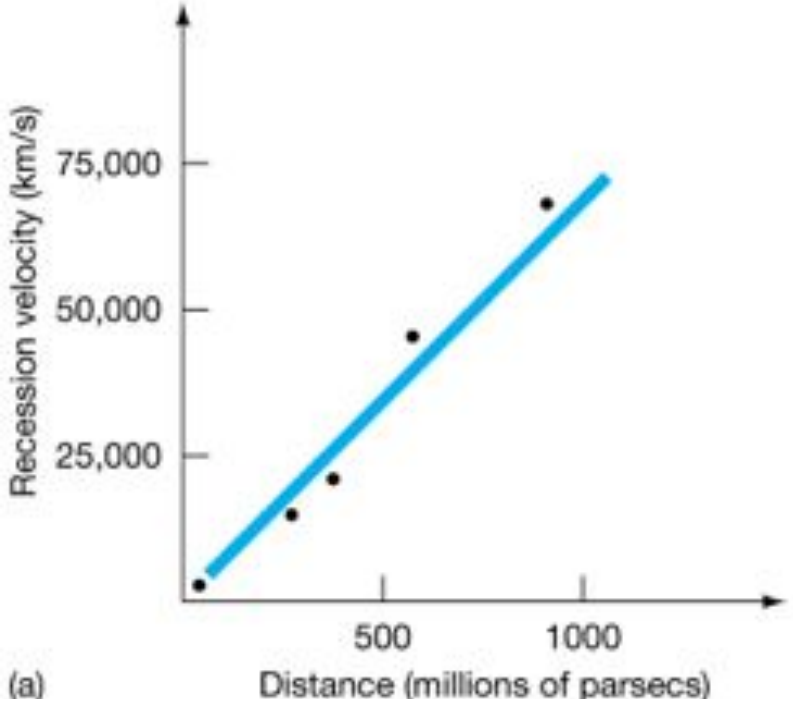
Pulsating Variables

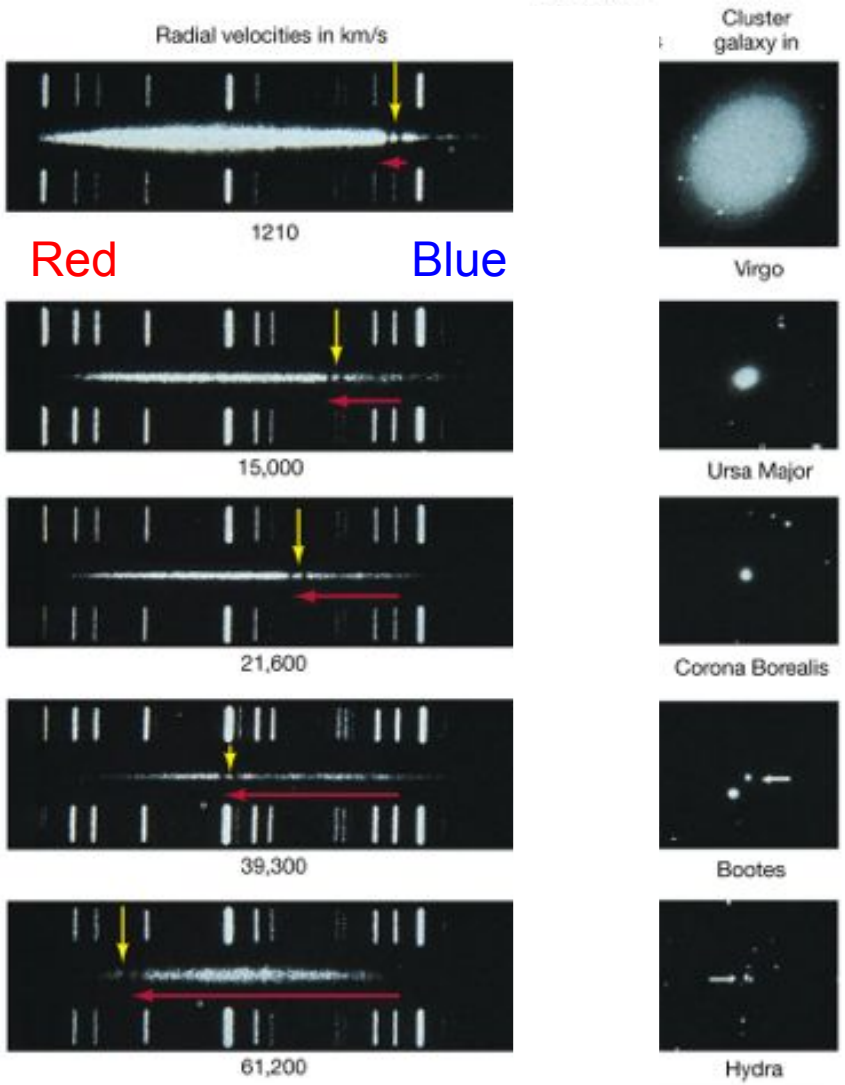


Cepheid variable at a distance of 25 Mpc=75 million light years!

Expansion of the Universe (Hubble 1929)

Hubble: Galaxies further away from the Milky Way are moving away faster





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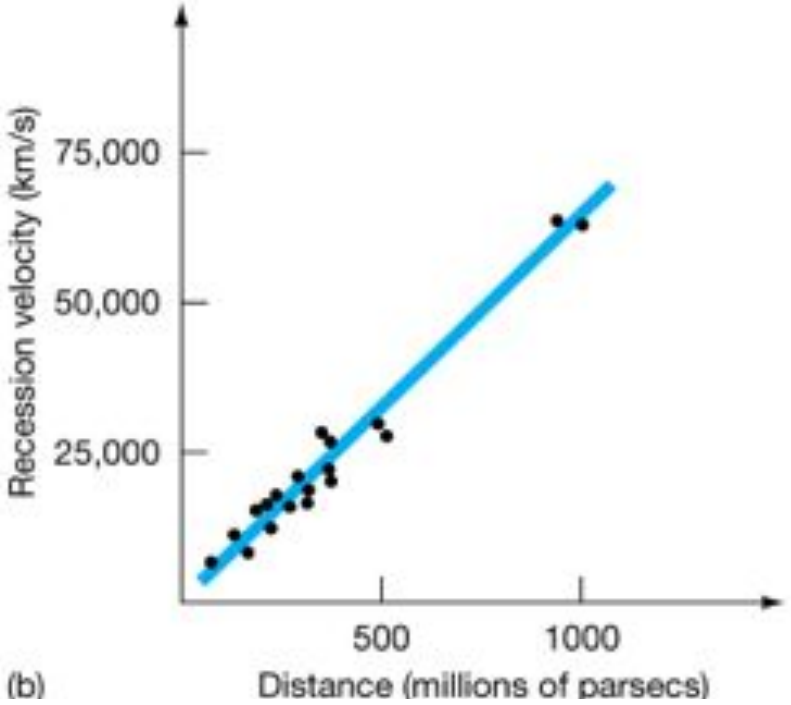
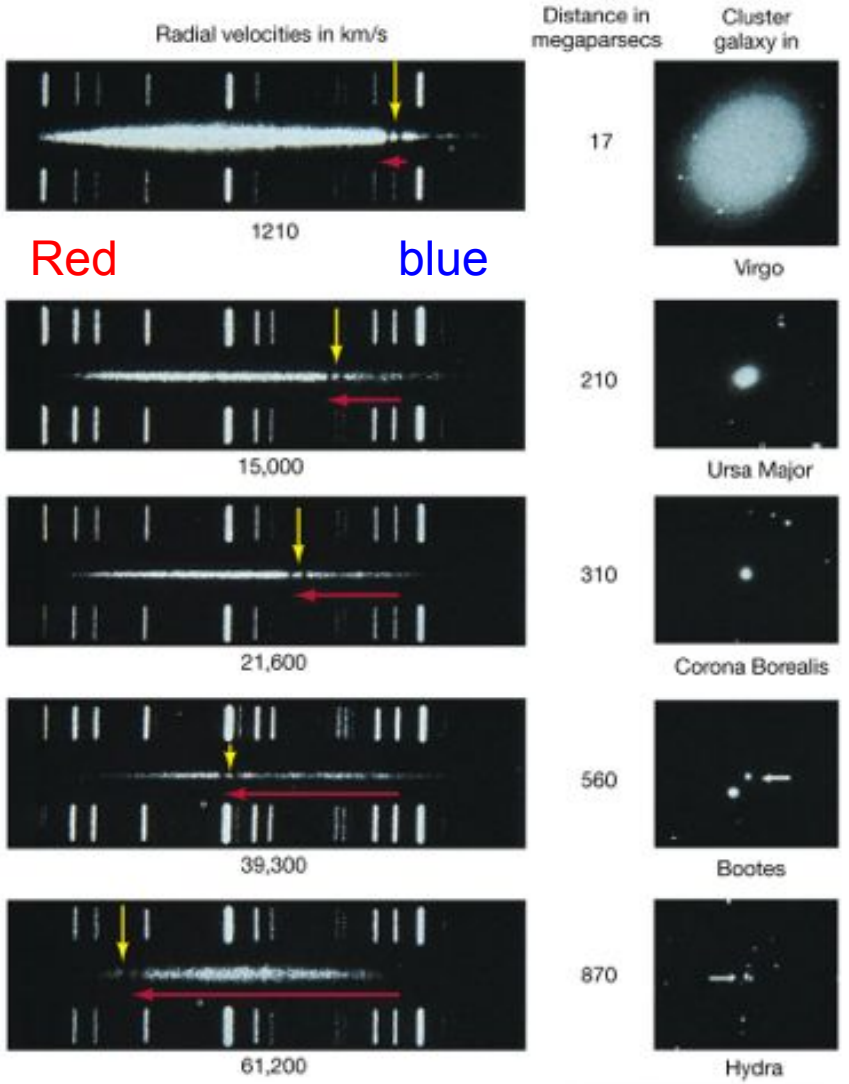




The Expansion of the Universe (Hubble 1929)

AT 24.3

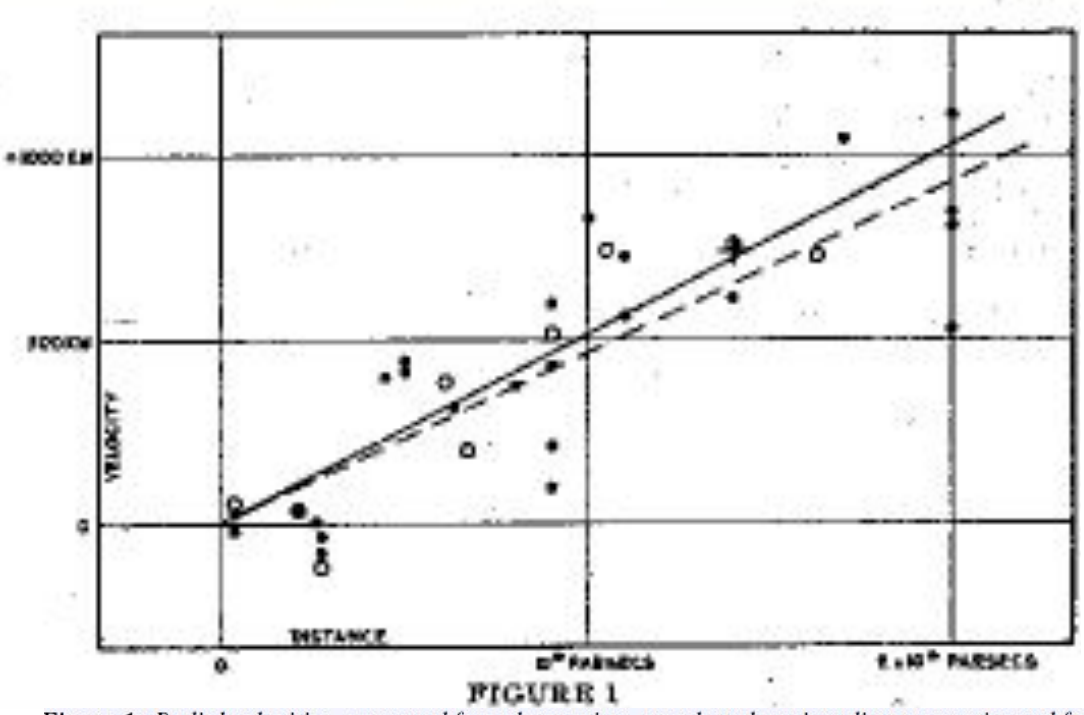


FIGURE 1

Figure 1: *Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.*

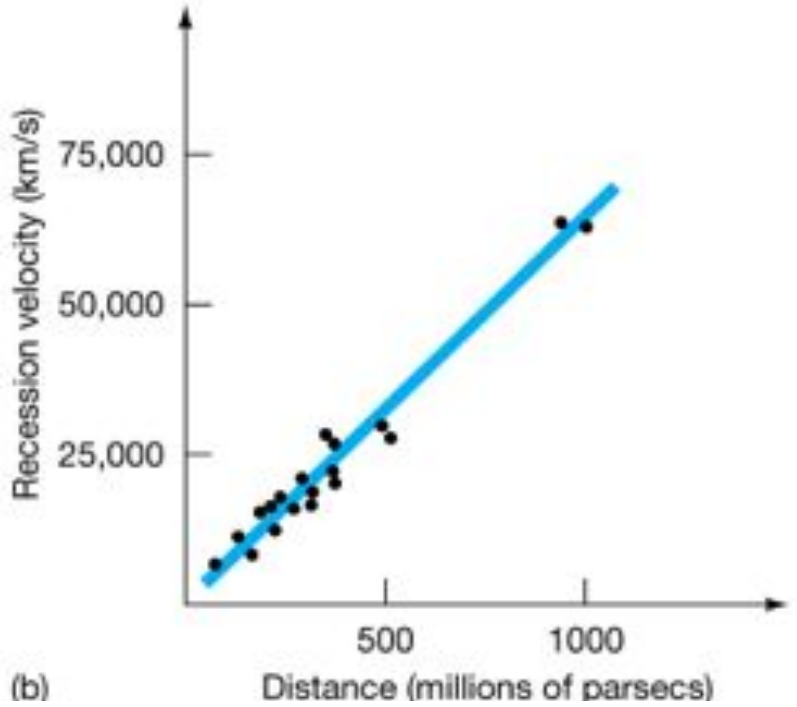
- Distances of 24 galaxies (from Cepheids, novae, brightest stars…)
- Velocities from Slipher (not acknowledged)

But see http://phys.org/news/2013-04-textbooks-wrong-astronomers-clash-hubble.html

Hubble's Law AT 24.3

The relationship (slope of the line) is characterized by Hubble's constant H_0:

$$\text{recessional velocity} = H_0 \times \text{distance}$$



$$v = H_o d,$$

$$H_0 = 513 \pm 60 \text{ km/s/Mpc} \quad (1929)$$

$$= 73 \pm 3 \text{ km/s/Mpc} \quad (2010)$$

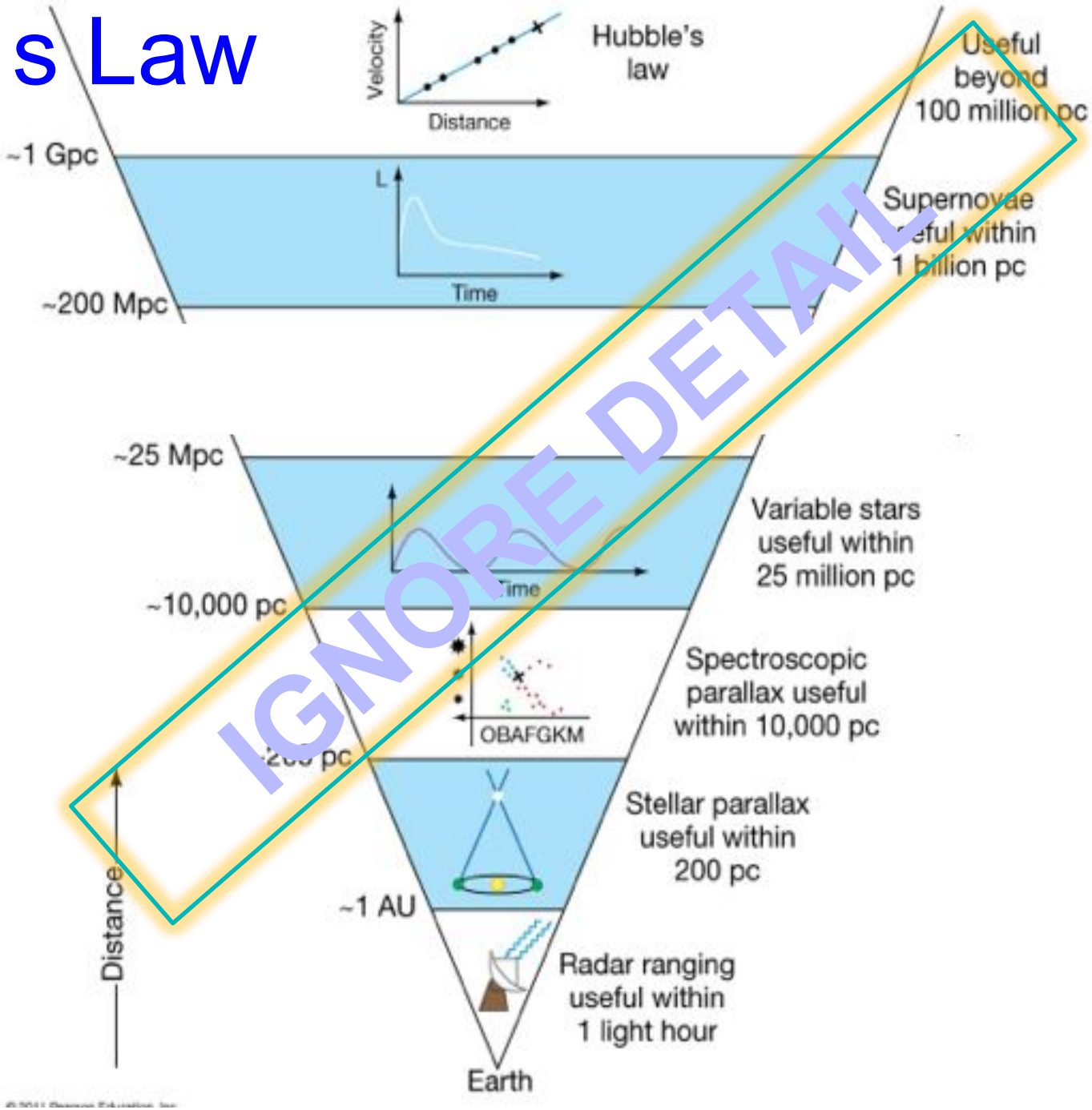
Measuring distances using Hubble's law actually works better on farther away objects; random motions are overwhelmed by the recessional velocity.

Hubble's Law

AT 24.3

final step in the distance ladder

[also super-novae!]



Hubble expansion

- Hubble seemed unaware of the implications for cosmology

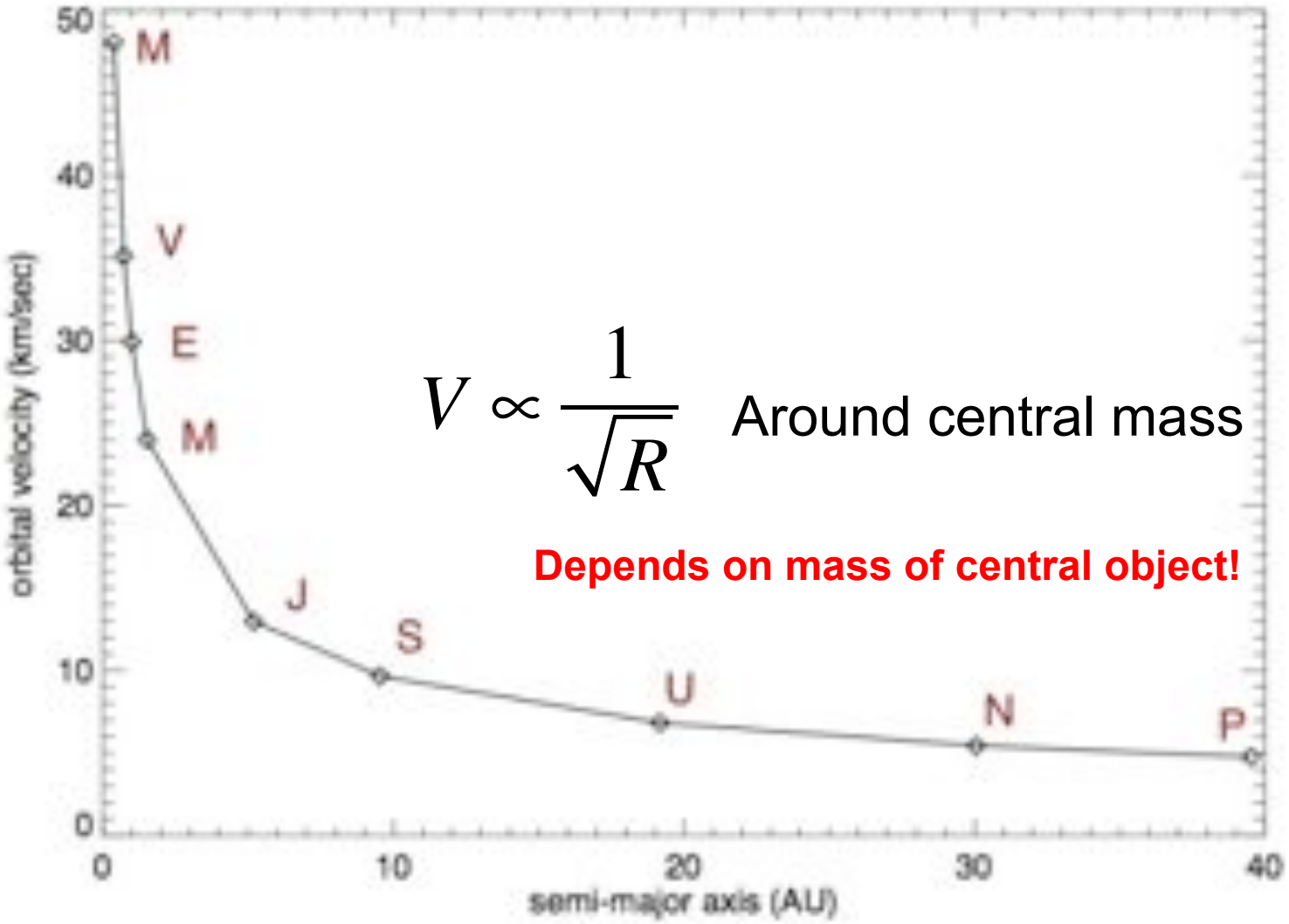
http://www.youtube.com/watch?v=hVApTLE7Csc

http://www.youtube.com/watch?v=hVApTLE7Csc

Dark Matter (AT 23.6, 25.1)

The Coma Cluster
d=100 Mpc (300Mly)
About ½ deg across (~1 Mpc)

Kepler – orbital velocity



$$V \propto \frac{1}{\sqrt{R}}$$ Around central mass

Depends on mass of central object!

Dark Matter - Fritz Zwicky 1933

- Doppler shifts of individual Coma galaxies
- gives mass of Coma - why?
- about 10X that expected from light from galaxies (starlight)!

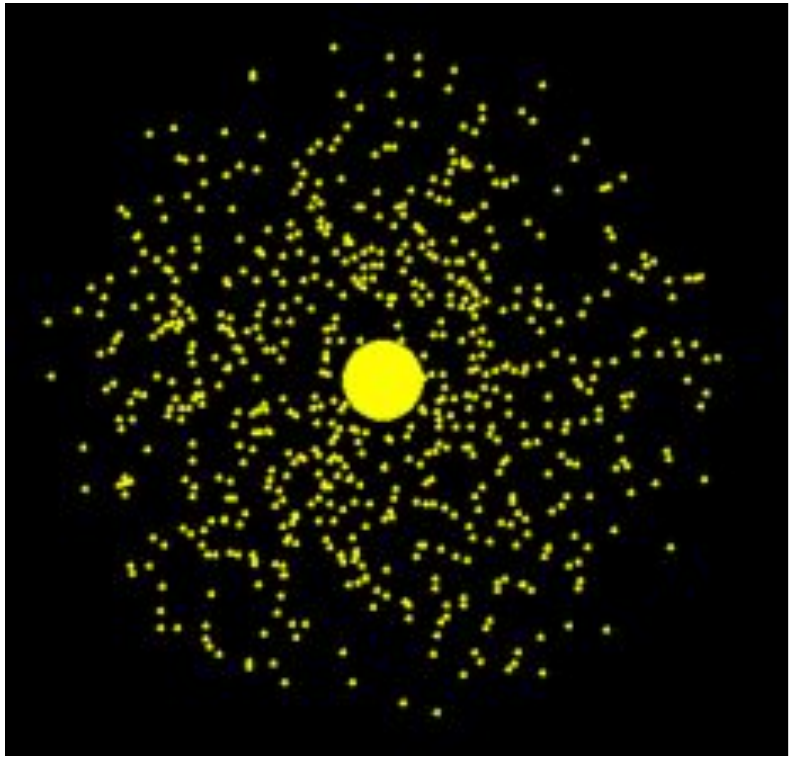
Dark Matter - Ignored for 40 years!

Year	No. of citations
1955-59	2
1960-64	6
1965-69	5
1970-74	2
1975-89	63
1990-99	71

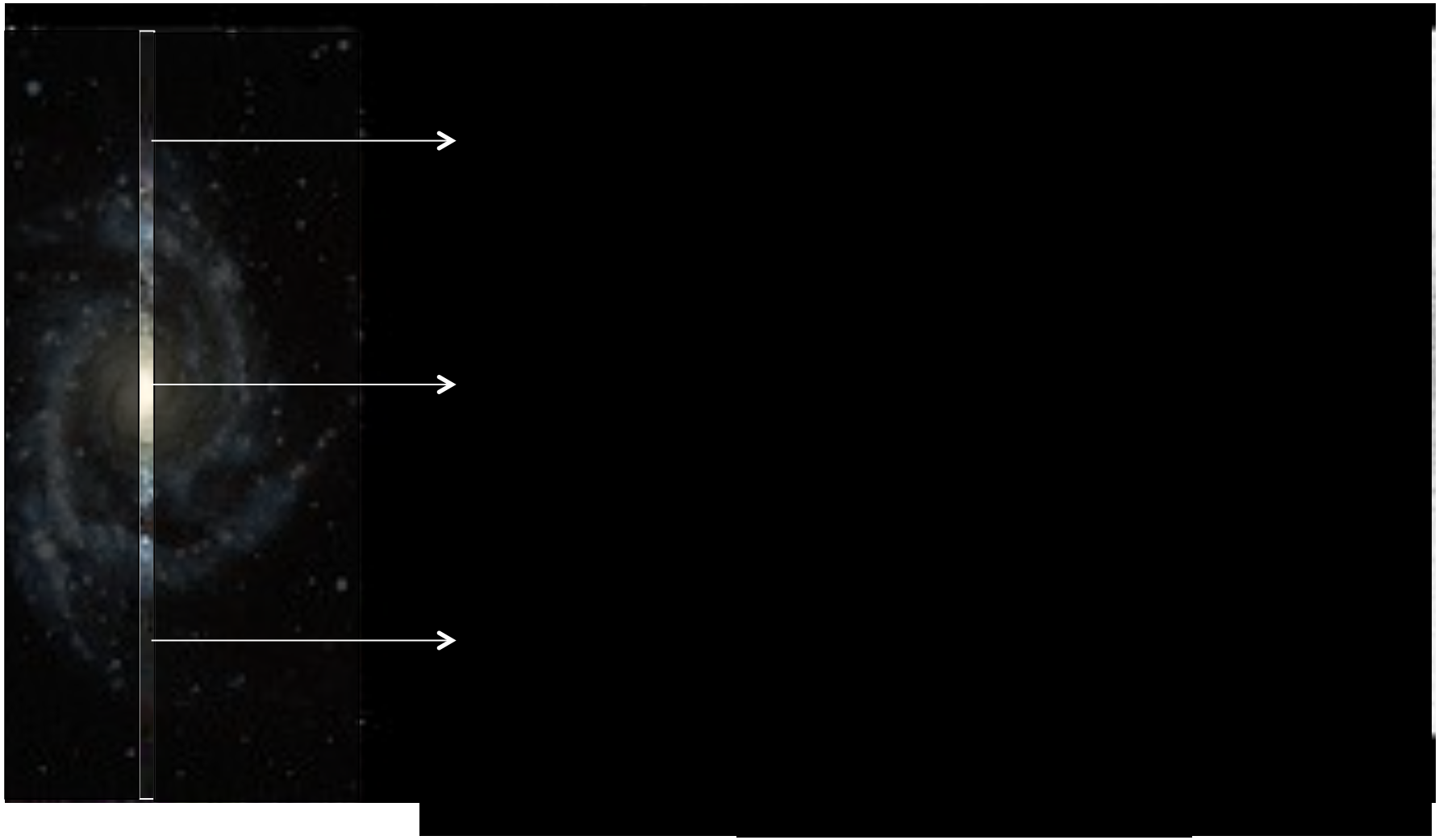
Zwicky 1933 citations
(van den Bergh 2001)

Dark Matter - Galaxy Rotation

- Known since the 1920's that galaxies like the Milky Way rotate



Dark Matter - Rotation curves of galaxies



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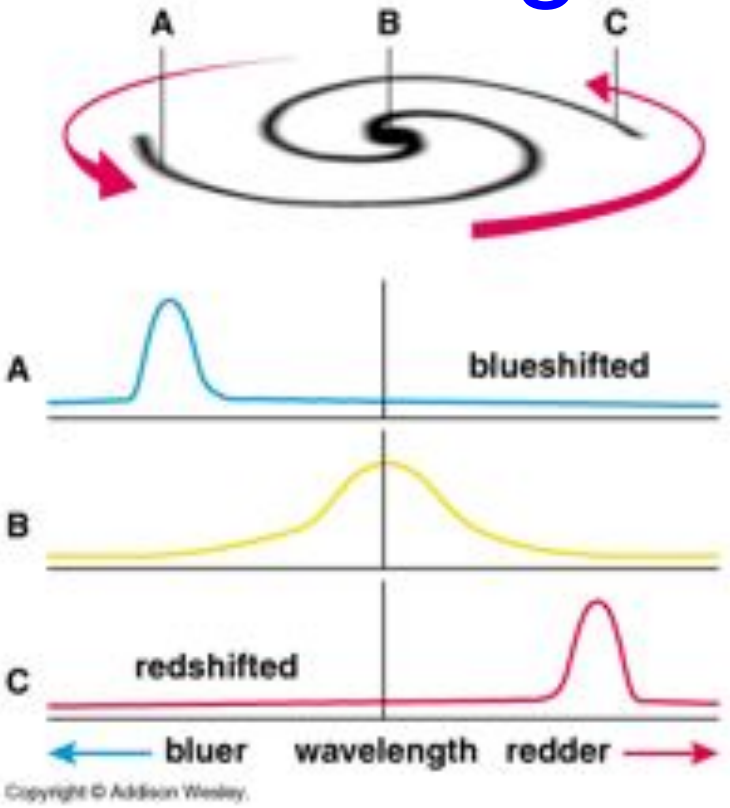
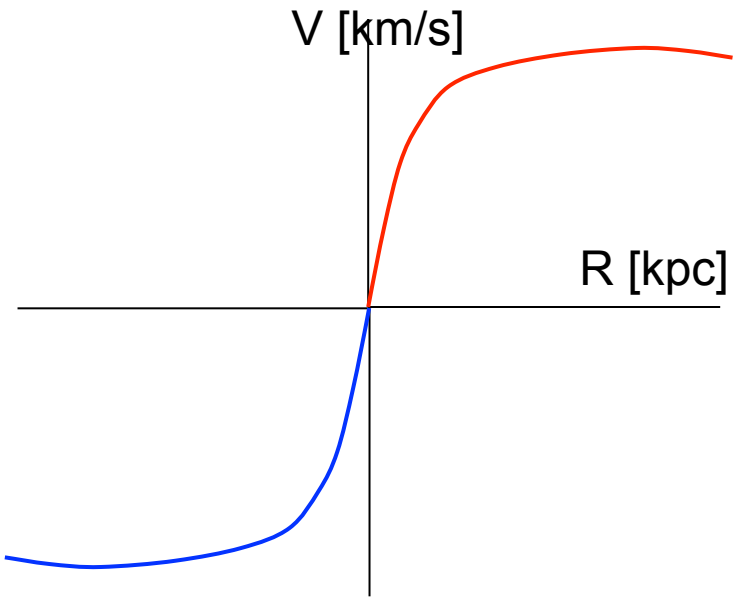
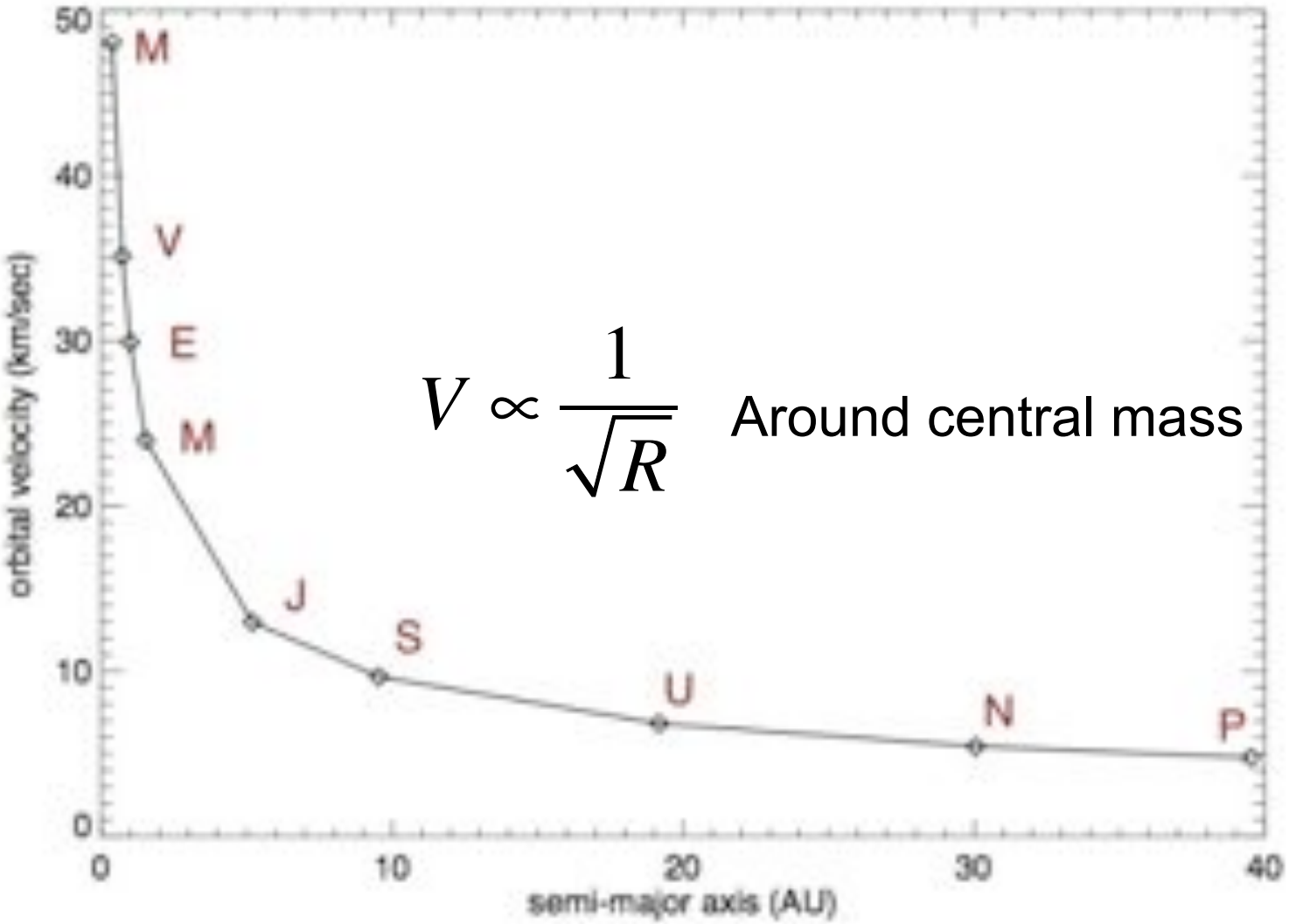




Newton's laws of gravity – derive mass from rotation velocity!

Kepler – orbital velocity



$$V \propto \frac{1}{\sqrt{R}}$$

Around central mass

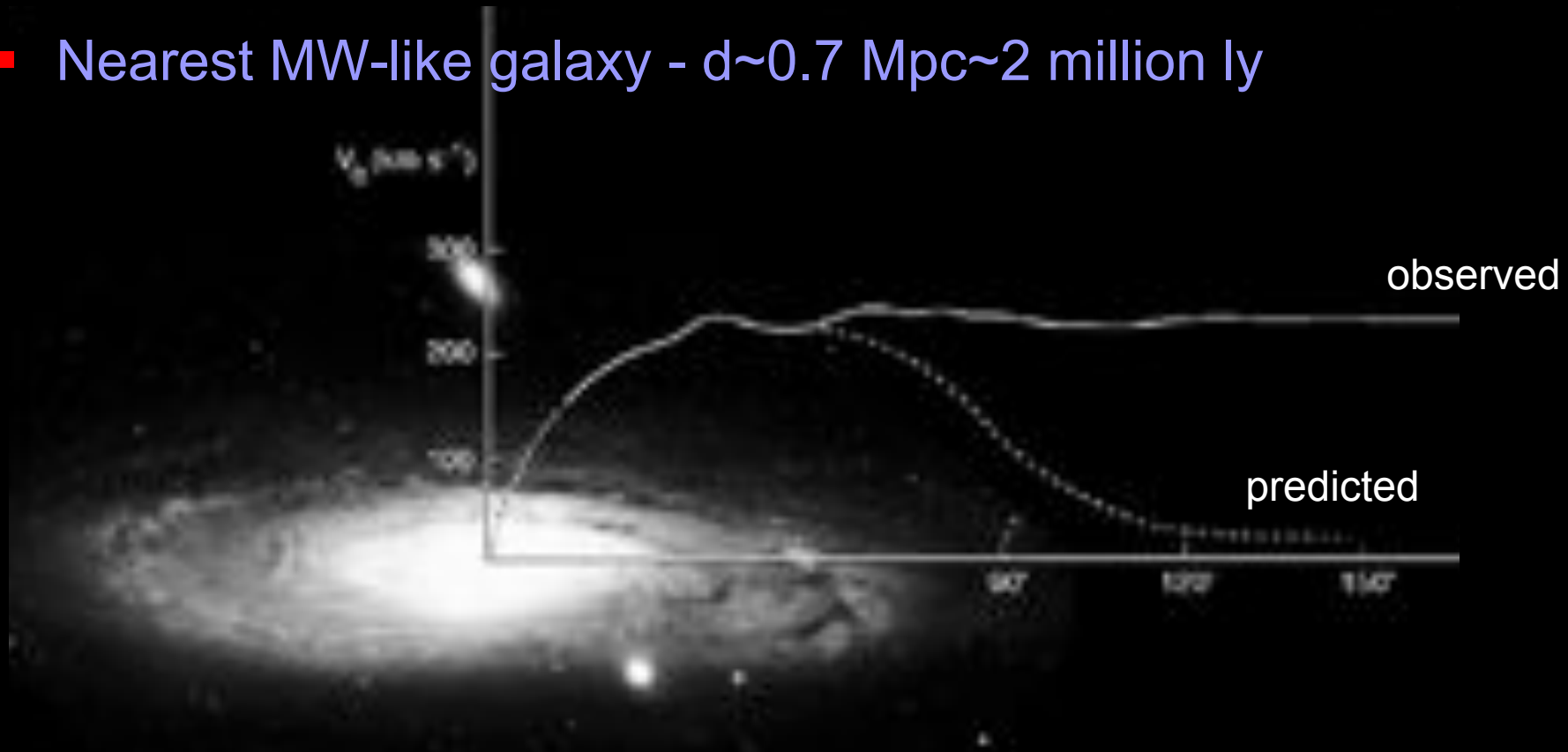
Dark Matter - Andromeda nebula

- Nearest MW-like galaxy - d~0.7 Mpc~2 million ly

- Must be a huge amount of invisible matter in the outer regions - it is ***DARK!***

Dark Matter - Andromeda nebula

- Nearest MW-like galaxy - d~0.7 Mpc~2 million ly

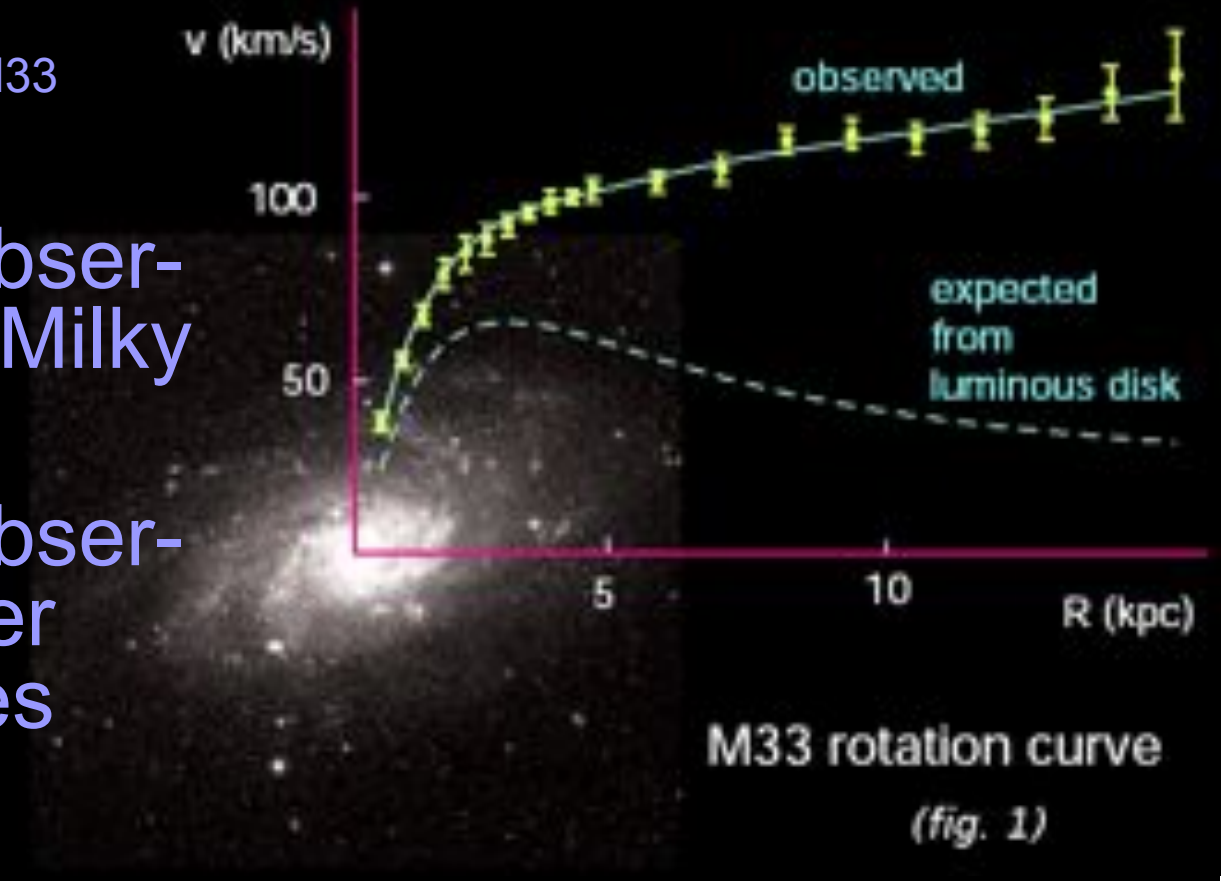


- Must be a huge amount of invisible matter in the outer regions - it is ***DARK!***

Dark matter from rotation curves - 1975

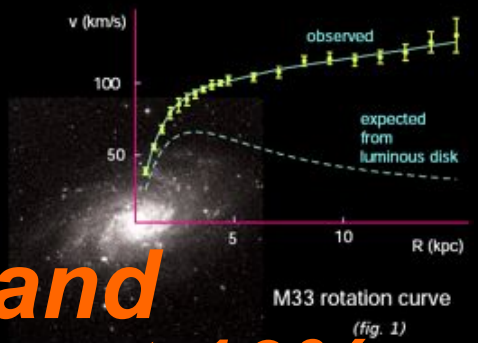
Another example - M33

- Agrees with observations in the Milky Way
- Agrees with observations of other similar galaxies



90% of matter in galaxies and clusters is "dark", only 10% is "luminous" - e.g. stars.

Dark matter

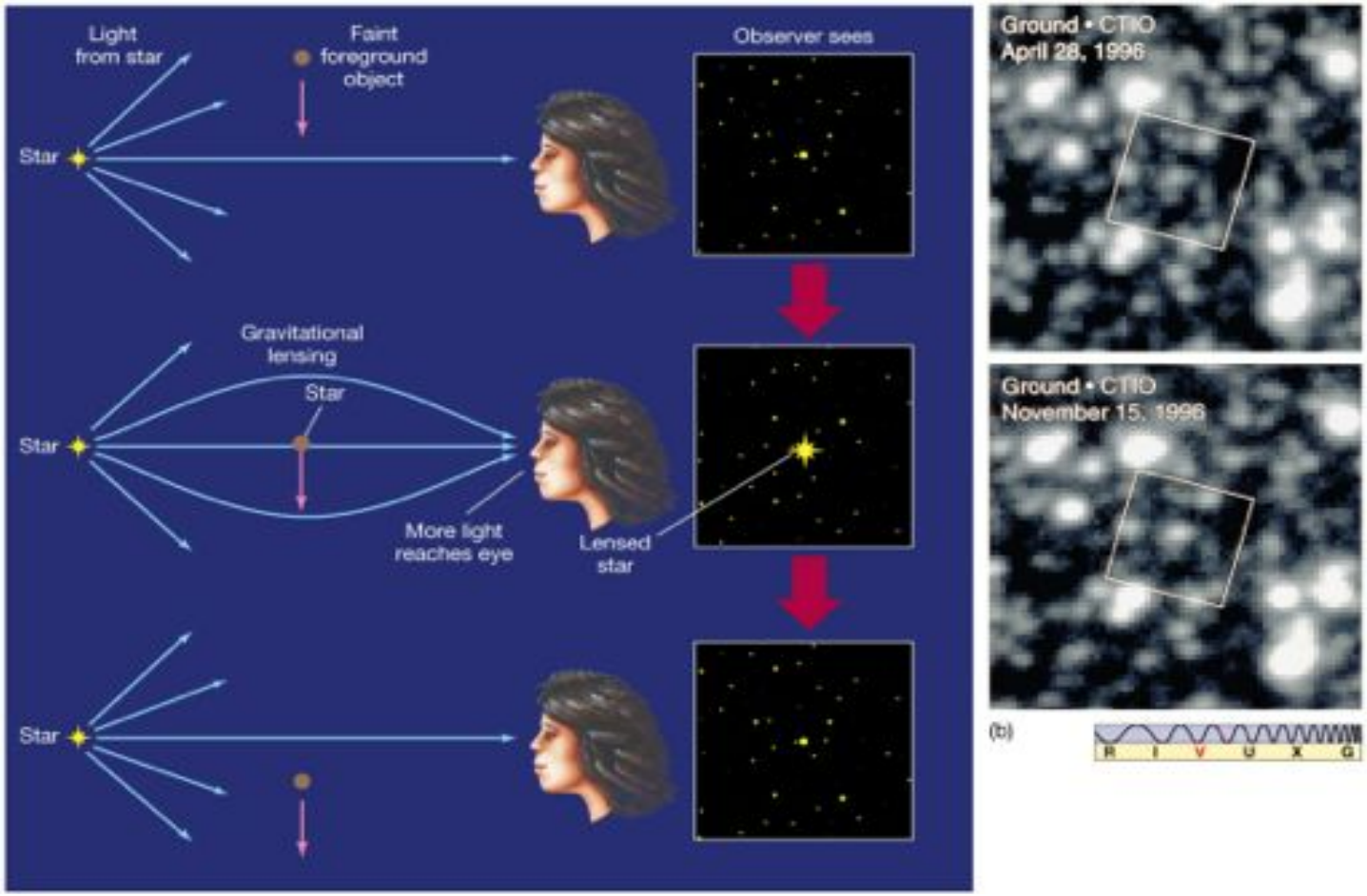


- *90% of matter in galaxies and clusters is "dark", only about 10% is "luminous" - e.g. stars.*
  - *From motions in clusters of galaxies, and from rotation curves of individual galaxies*
- *Dark matter is associated with individual objects like galaxies and clusters, and not just spread diffusely through the Universe*

The Dark Matter is **not** …

- **Not**: stars gas rocks baseballs mini-blackholes blah blah blah

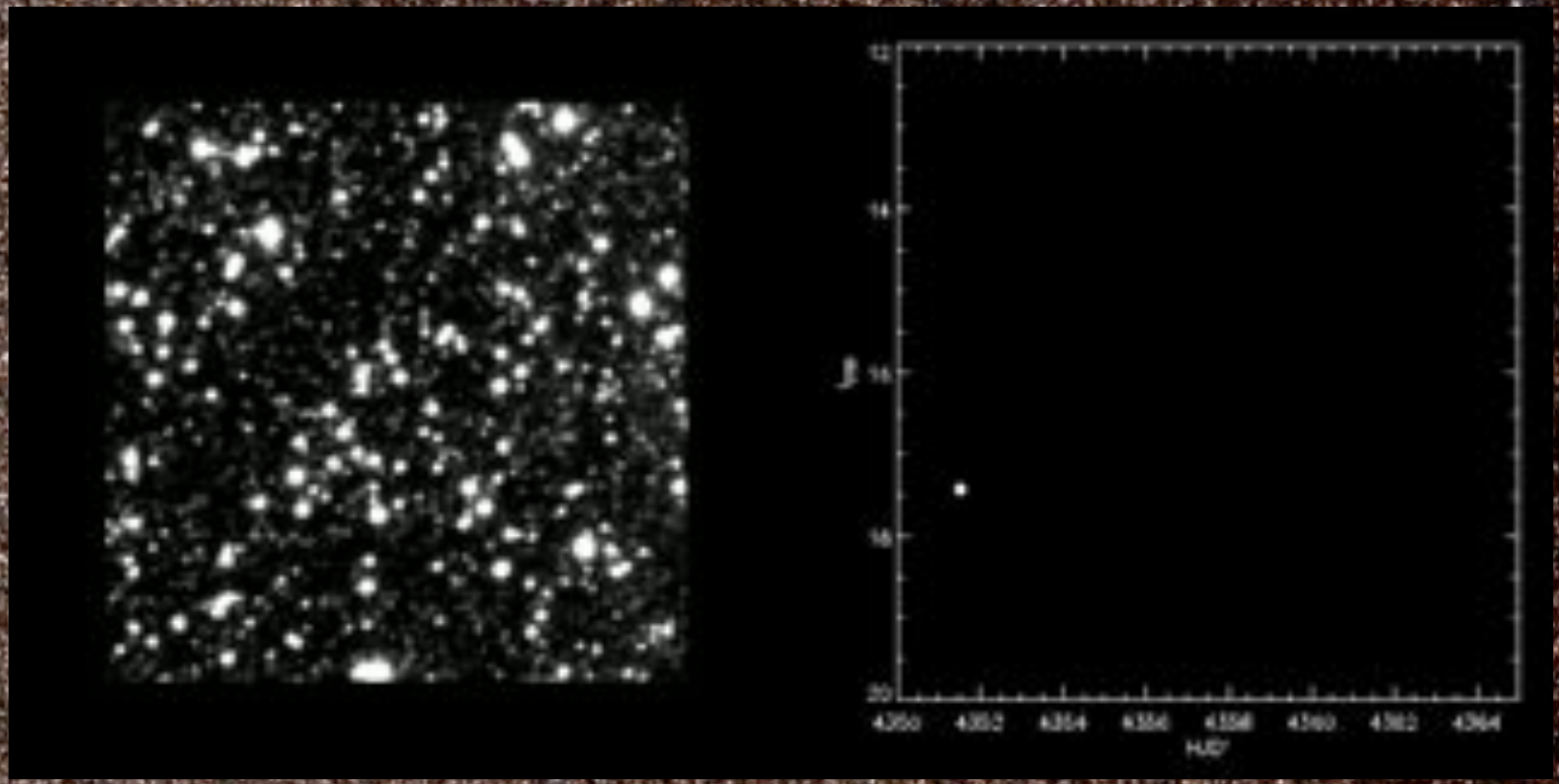
Gravitational Lensing [AT 23.6]



- The bending of space-time can allow a large compact mass to act as a gravitational lens. These events can be seen in areas of the sky with lots of stars.

Gravitational lensing

Gravitational lensing



http://www.youtube.com/watch?v=J_w1OJlXTzg

The Dark Matter is **not** …

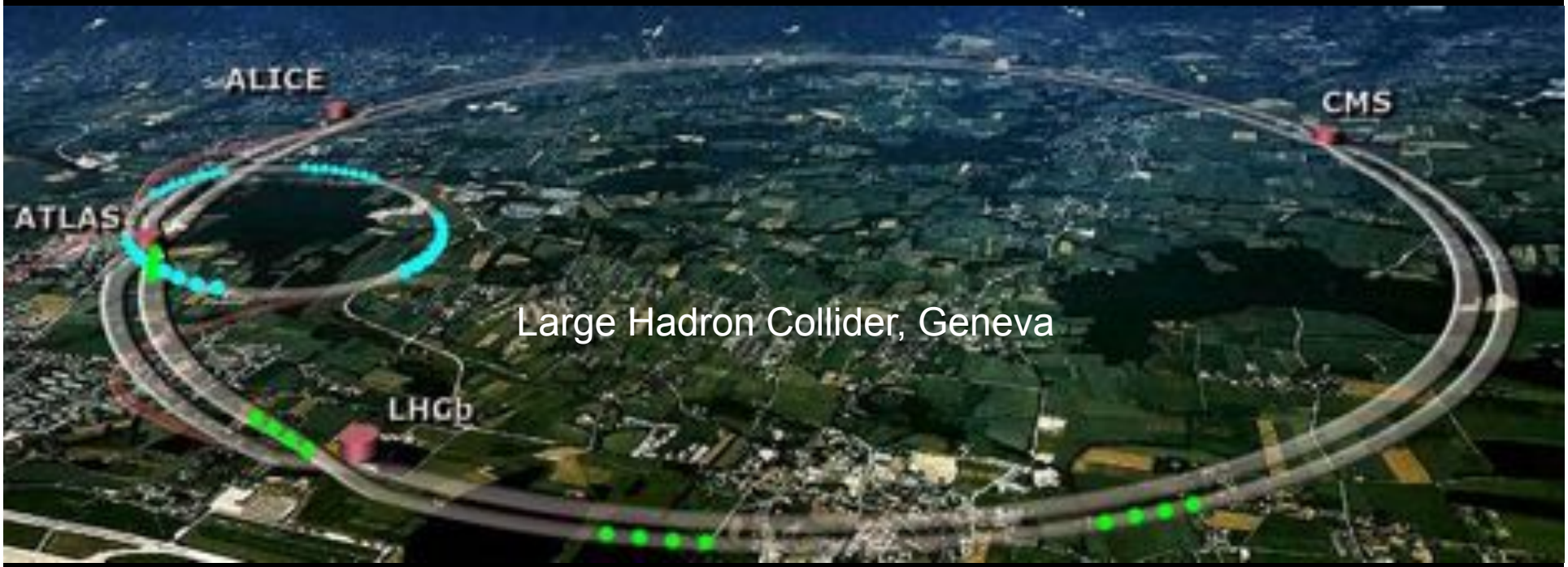
- **Not**: White dwarfs, neutron stars, stellar mass black holes!
  - MACHO, OGLE surveys for lensing events

http://www.youtube.com/watch?v=J_w1OJlXTzg

The Dark Matter is **not** …

- Not: Massive black holes?
  - Would see their effect - tides, X-rays, …

What is the Dark Matter?



Large Hadron Collider, Geneva

What is the Dark Matter?

- Exotic particles?
  - Probably, though what exactly? a number of candidates that could work …
  - almost certainly “weakly interacting” with ordinary matter (somewhat like neutrinos)

Dark Matter Summary

90% of the matter in the Universe is in a form that doesn't interact with ordinary matter. We don't know what it is, though there are some ideas from particle physics. It is contained in galaxies, and in clusters of galaxies

Evidence:

1. Motions of galaxies in clusters
2. Rotation curves of galaxies

Dark Matter Summary

During the Twentieth Century astronomers have discovered that the Universe contains ~10 times more mass than had previously been suspected; most of it in forms that are very difficult to observe (see Table 2). It is slightly disconcerting that perhaps only 0.001% of humanity is presently aware of the enormous paradigm shift towards a universe in which 99% is in invisible form. One of the reasons for this is, no doubt, that we live on Earth, which has a mean density that is almost 30 orders of magnitude greater than the mean density of the universe. In other words, we live in an atypical environment in which cold baryonic matter dominates over the dark energy of the vacuum by an overwhelming factor. In some ways the revolutionary discovery that ~99% of the mass of the universe is in invisible form was similar to the quantum revolution of the 1920s, of which Sam Treiman wrote: “There was no immediate commotion in the streets. Only a small band of scientists were participating in or paying close attention to these developments.”

van den Bergh 2001