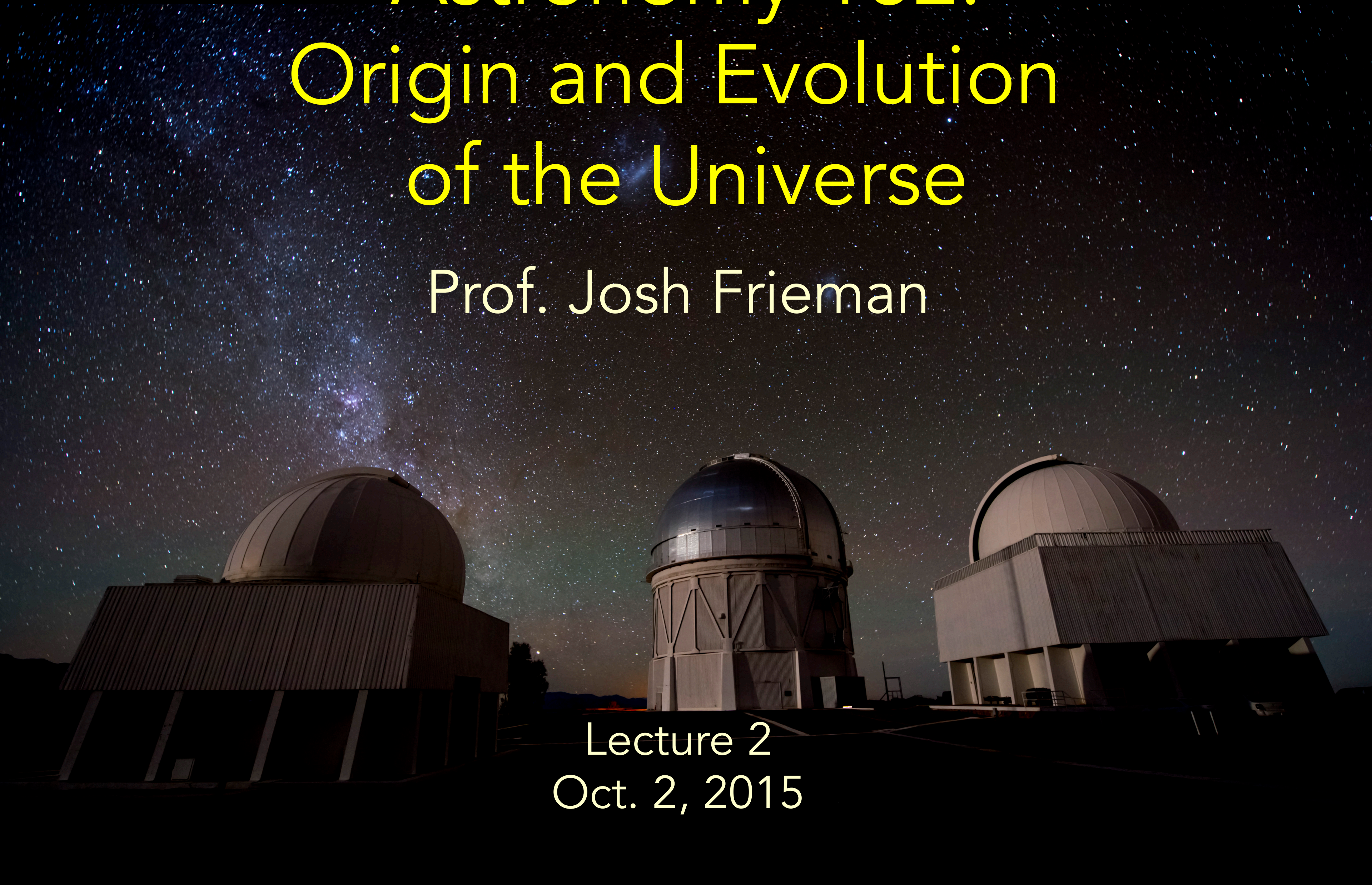
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 2
Oct. 2, 2015

Today

- The Universe in Time and Space
- The Expansion of the Universe
- The Cosmological Principle

- Next Wednesday: bring your laptops, Jason will go over Lab 1 with you.
- Next Friday: follow-up meeting on Lab 1 with Jason, as needed

The Universe in Time

- Creation Myths
  - Describe birth of the World in terms of the observed environment, extrapolating observed processes of change (in some cases).
  - The Universe had a beginning in time and is dynamic, changing.
- Pre-Socratics:
  - Heraclitus: change is fundamental to the world (“never step in same river twice”).
  - Parmenides: change is an illusion. Reality is fundamentally static.

The Universe in Time

- Aristotle (5th Century BC):
  - "On the Heavens"
  - The Universe began in time but is thereafter unchanging and everlasting into the future.

- Aristotelian view of a static Universe dominated scientific discourse into the early part of the 20th Century.
- Widely accepted and influential paradigm
  - Cf. T. Kuhn, *The Structure of Scientific Revolutions*

The Universe in Time

- Einstein:
  - Theory of General Relativity (GR, 1916)
  - GR predicts a dynamic Universe: expanding or contracting.
  - Prevailing (Aristotelian) assumption was that the Universe is static. At that time, "the Universe" meant the system of stars (in what we now know to be our Galaxy).
  - To resolve this conflict, Einstein introduced an ad hoc term into his GR equations, the Cosmological Constant, in order to obtain a static Universe solution.

The Universe in Time

- 1922: A. Friedmann showed that GR generically contains expanding and contracting Universe solutions (initially criticized but later accepted by Einstein).
- 1920's: Lemaitre, de Sitter, Robertson, Walker, … came to similar conclusions.
- Moreover, Einstein's static Universe is unstable: it will eventually expand or contract.
- 1929: Hubble discovers expansion of the Universe
- Einstein later called his introduction of the Cosmological Constant "the biggest blunder of my life" (according to Gamow), since he could have predicted the expanding Universe.

The Universe in Time

- 1998: Einstein has the last laugh. Discovery of cosmic acceleration brings the cosmological constant back into vogue:
  - The cosmological constant is the simplest example of what we now call Dark Energy, as we will discuss later in the course.

The Universe in Space

- Democritus (Greek atomists) and Chinese cosmologists of the Hsuan Yeh school posited an infinite Universe.
- Plato: the material world is finite but surrounded by an infinite void.
- Archytas (friend of Plato) (and later Lucretius): logical argument for an infinite Universe:
  - "If I am at the extremity of the heaven of stars, can I not stretch outward my hand? It is absurd to suppose I could not; if I can, what is outside must be either body or space."

The Universe in Space

- Aristotle:
  - The Universe is finite in extent, the heavens consisting of concentric crystalline spheres centered on and rotating about the Earth.
- Again, this view prevailed and became accepted dogma for nearly 2000 years.
- Giordano Bruno: burned at the stake in 1600 for espousing heresies, including that the Universe is infinite.

What is the Scale of the Universe?

- Eratosthenes (~250 BC):
    - Used shadow cast by stick at Alexandria to estimate Earth circumference ~40,000 km

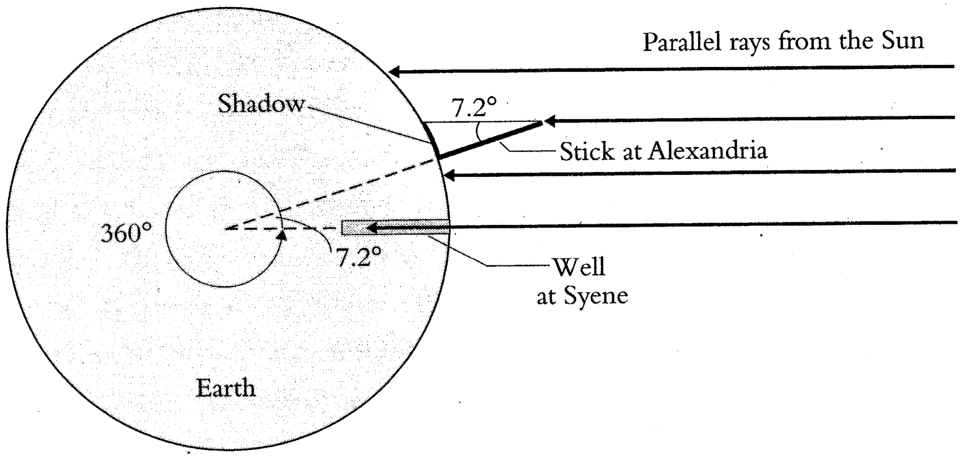


Figure 1 Eratosthenes used the shadow cast by a stick at Alexandria to calculate the circumference of the Earth. He conducted the experiment at the summer solstice, when the Earth was at its maximum tilt and when towns lying along the Tropic of Cancer were closest to the Sun. This meant that the Sun was directly overhead at noon at those towns. For reasons of clarity, the distances in this and other diagrams are not drawn to scale. Similarly, angles may be exaggerated.

S. Singh,
Big Bang

Size of Moon

Lunar Eclipse, Sept. 27, 2015

Size of Moon

circumference~10,000 km

S. Singh,
Big Bang

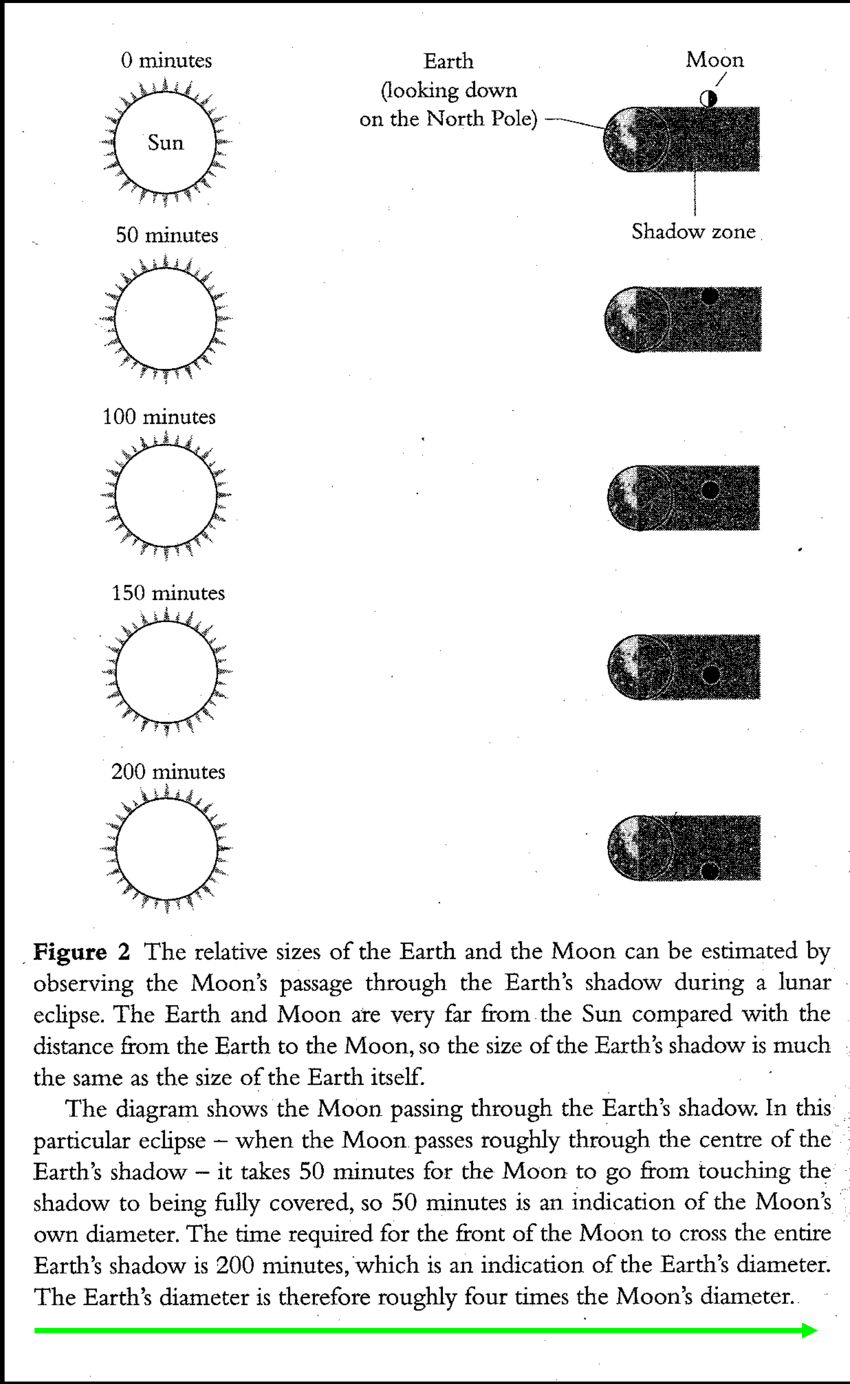


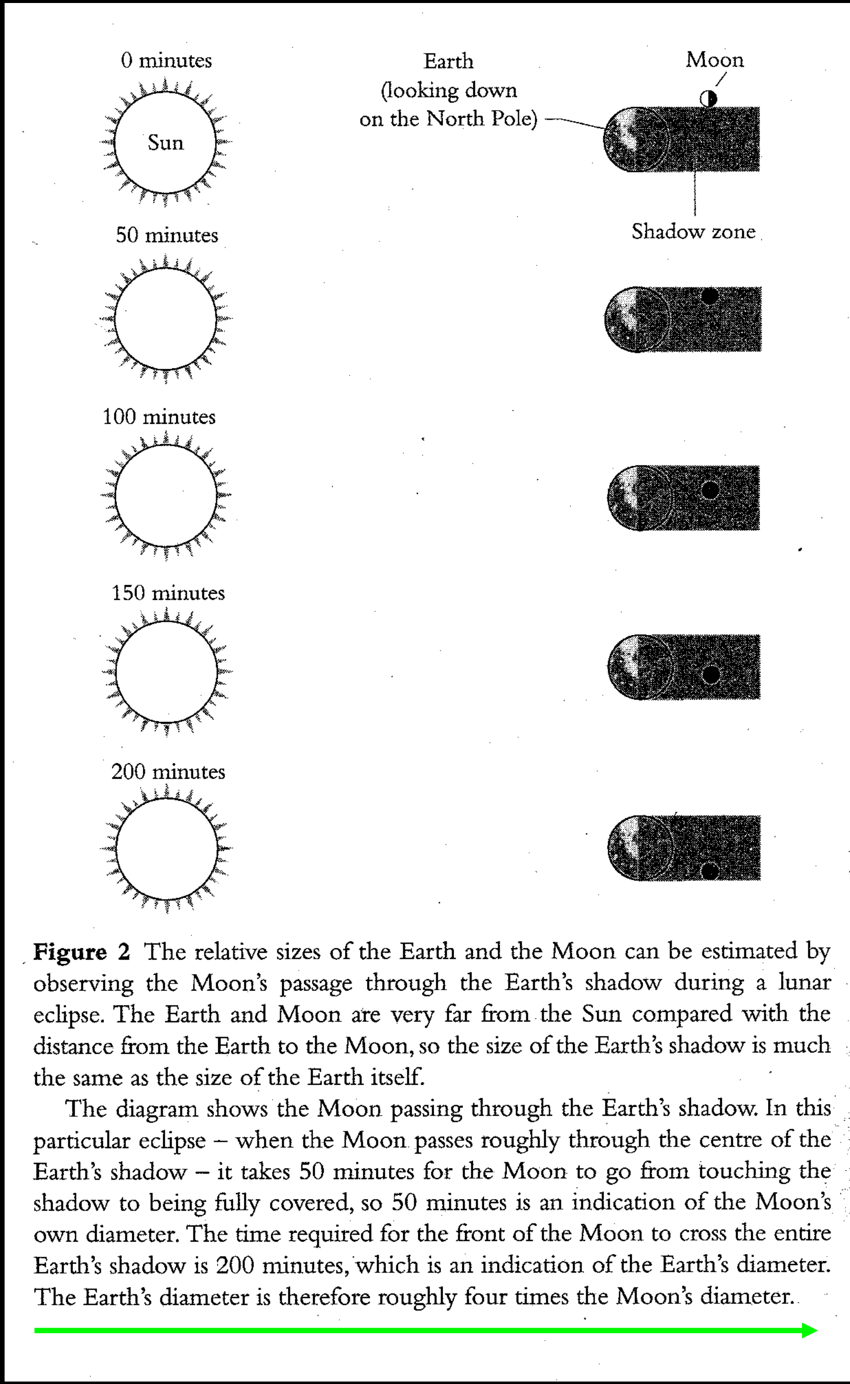
Figure 2 The relative sizes of the Earth and the Moon can be estimated by observing the Moon's passage through the Earth's shadow during a lunar eclipse. The Earth and Moon are very far from the Sun compared with the distance from the Earth to the Moon, so the size of the Earth's shadow is much the same as the size of the Earth itself.

The diagram shows the Moon passing through the Earth's shadow. In this particular eclipse – when the Moon passes roughly through the centre of the Earth's shadow – it takes 50 minutes for the Moon to go from touching the shadow to being fully covered, so 50 minutes is an indication of the Moon's own diameter. The time required for the front of the Moon to cross the entire Earth's shadow is 200 minutes, which is an indication of the Earth's diameter. The Earth's diameter is therefore roughly four times the Moon's diameter.

Size of Moon

Distance to Moon

Cover moon with thumb held at arm's distance:
~100:1 ratio
Earth-Moon distance
~380,000 km



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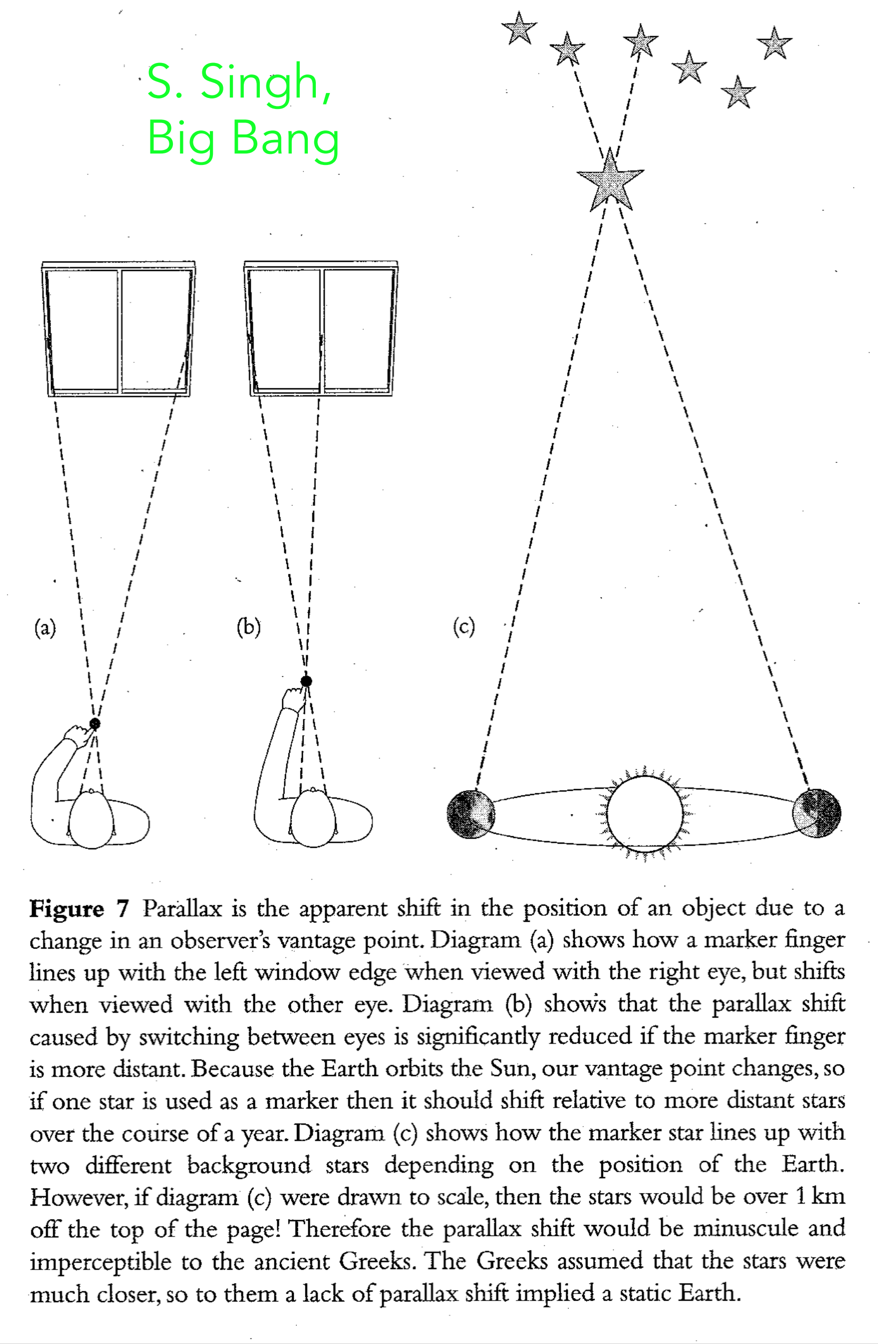
Distance to Stars: Parallax

Use distance of Sun to infer distances to brighter stars

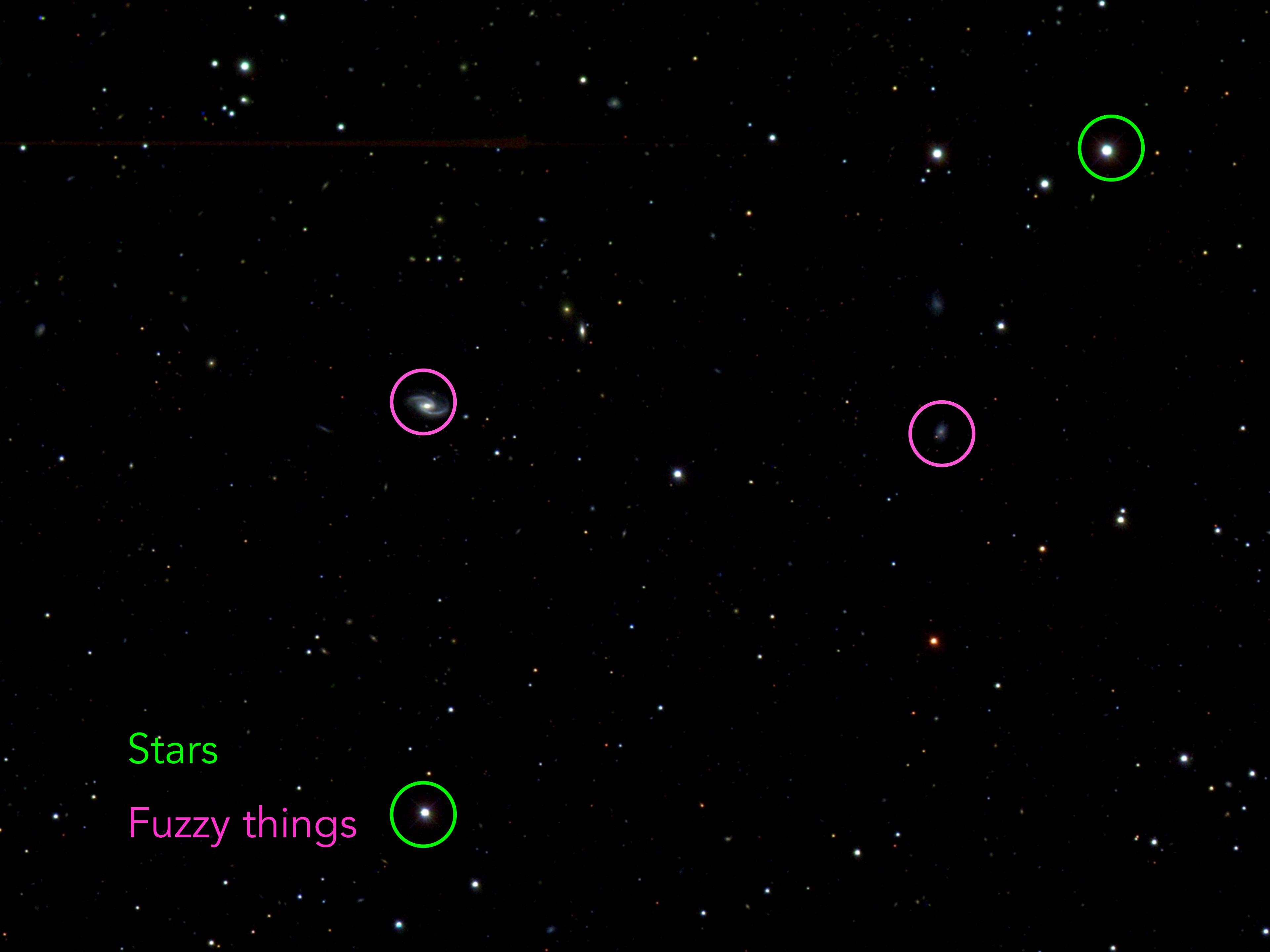
Bessel (1838): measured parallax of 61 Cygni:
0.3 arcseconds→11 light years
(lack of apparent parallax had been taken as argument against heliocentric model)

Hipparcos satellite:
Parallax distances to a million stars out to ~600 light years



S. Singh,
Big Bang

Figure 7 Parallax is the apparent shift in the position of an object due to a change in an observer's vantage point. Diagram (a) shows how a marker finger lines up with the left window edge when viewed with the right eye, but shifts when viewed with the other eye. Diagram (b) shows that the parallax shift caused by switching between eyes is significantly reduced if the marker finger is more distant. Because the Earth orbits the Sun, our vantage point changes, so if one star is used as a marker then it should shift relative to more distant stars over the course of a year. Diagram (c) shows how the marker star lines up with two different background stars depending on the position of the Earth. However, if diagram (c) were drawn to scale, then the stars would be over 1 km off the top of the page! Therefore the parallax shift would be minuscule and imperceptible to the ancient Greeks. The Greeks assumed that the stars were much closer, so to them a lack of parallax shift implied a static Earth.


Stars
Fuzzy things

Charles Messier (1730-1817)

Astronomer for French Navy

Discovered 20 comets

In the course of his search for comets, he catalogued fuzzy things that didn’t move:

110 nebulae and
star clusters

Messier 1

Remnant of Supernova of 1054, observed by Chinese and possibly by the Anasazi

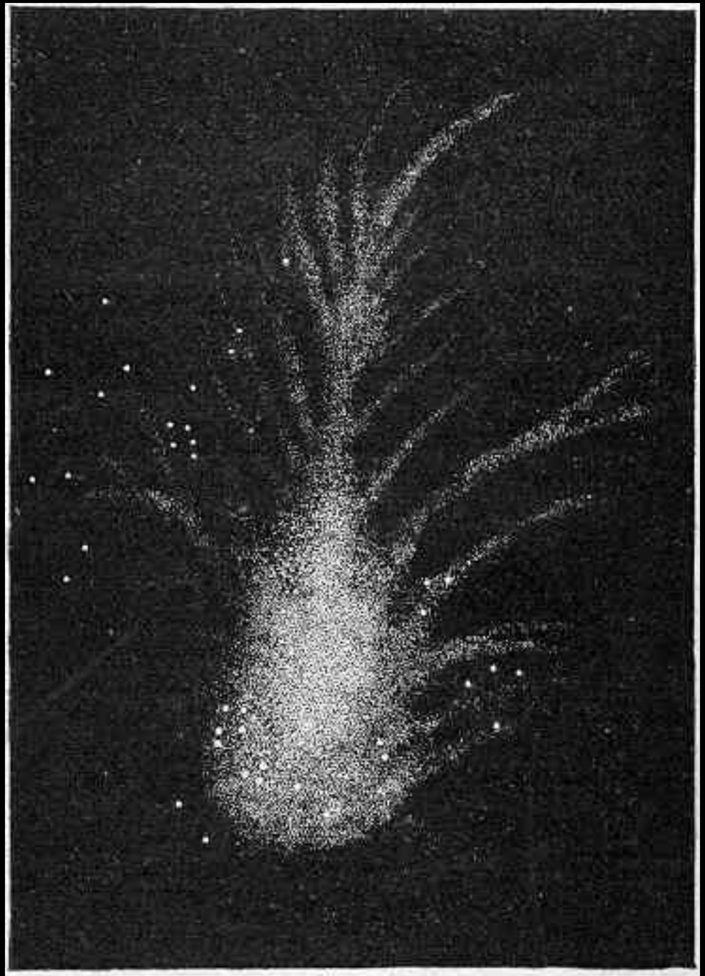
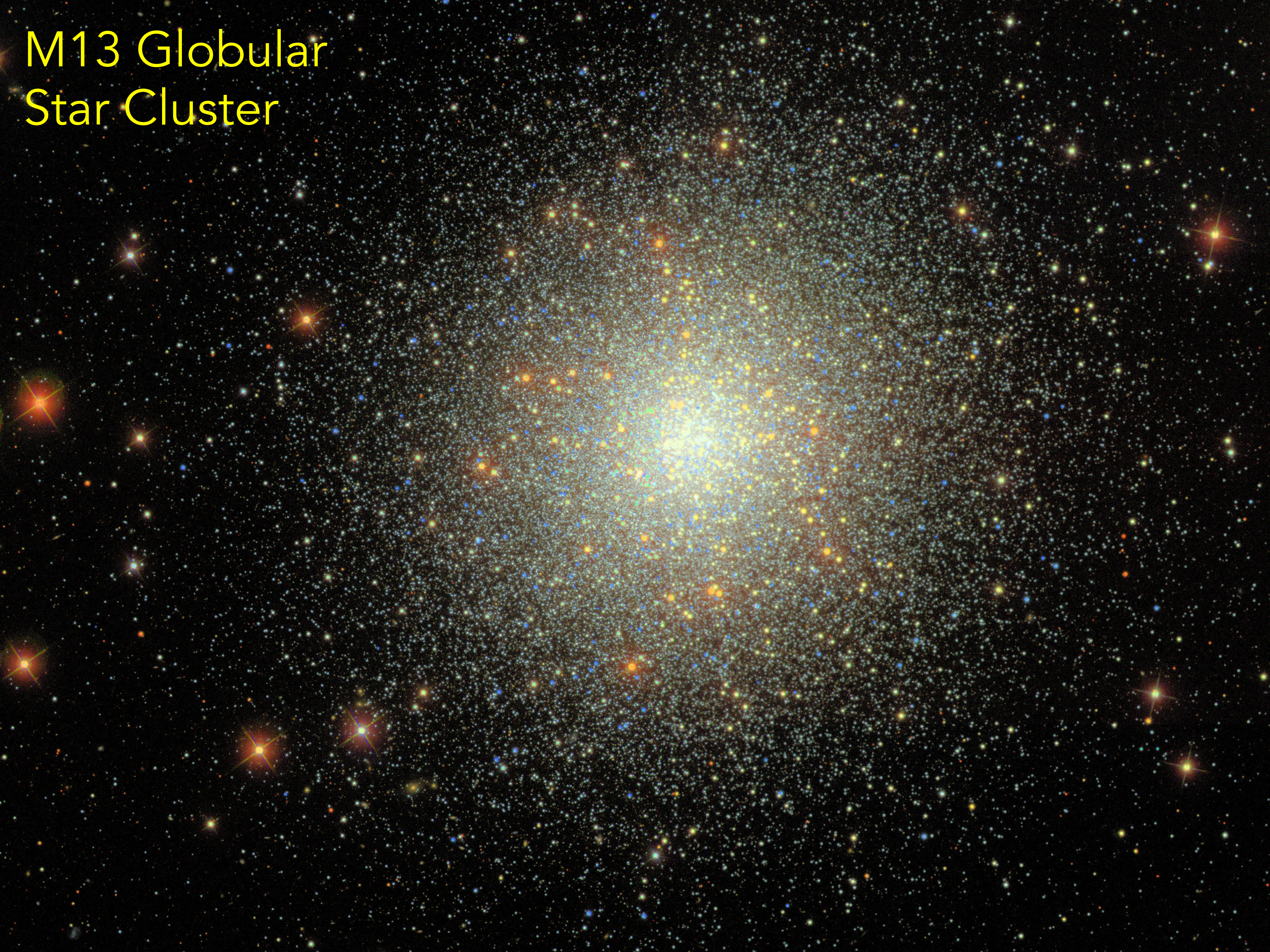


Fig. 438.

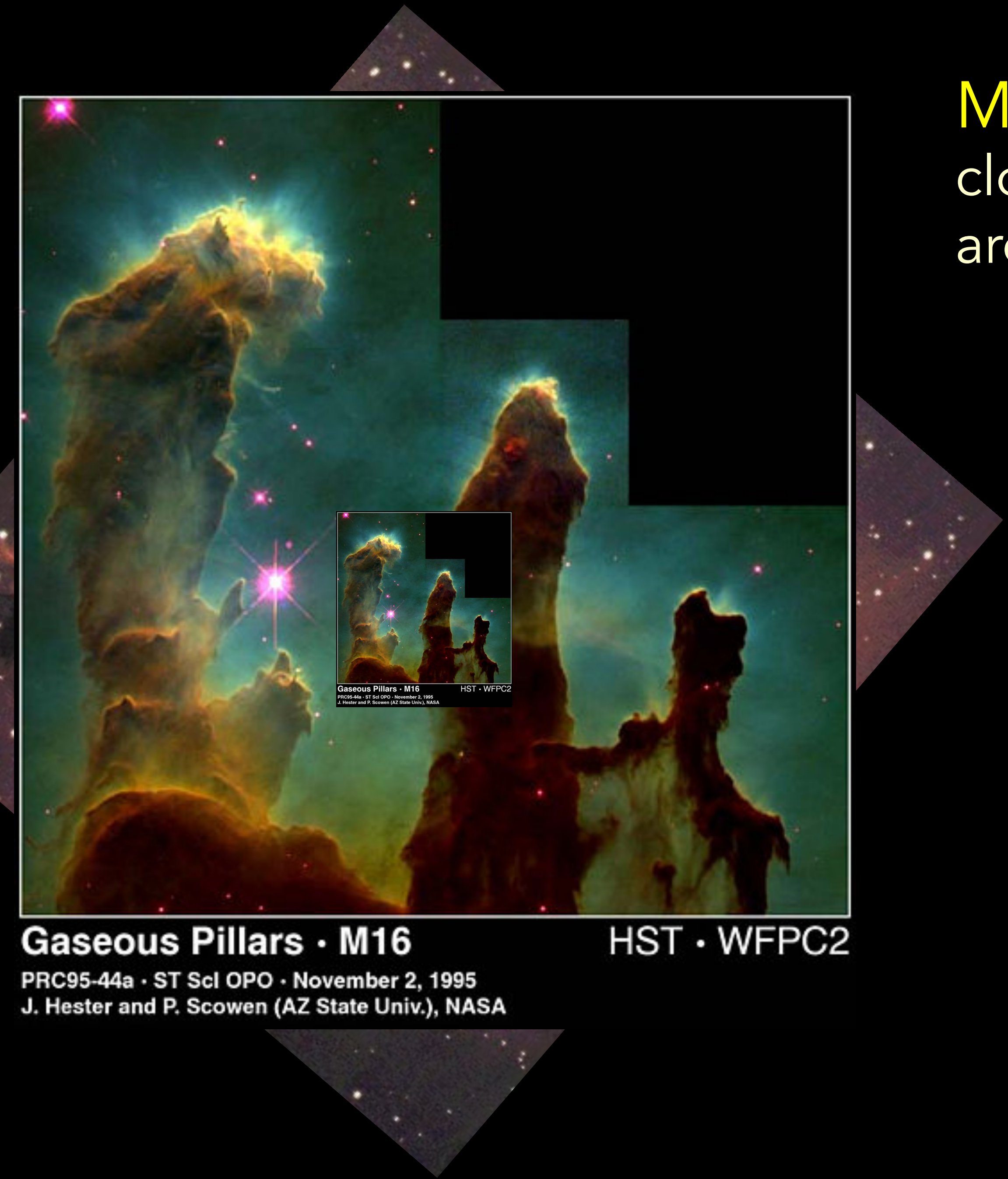
Drawing by Lord Rosse c. 1844

M13 Globular Star Cluster



M16, the Eagle Nebula:

clouds of gas & dust that are forming new stars



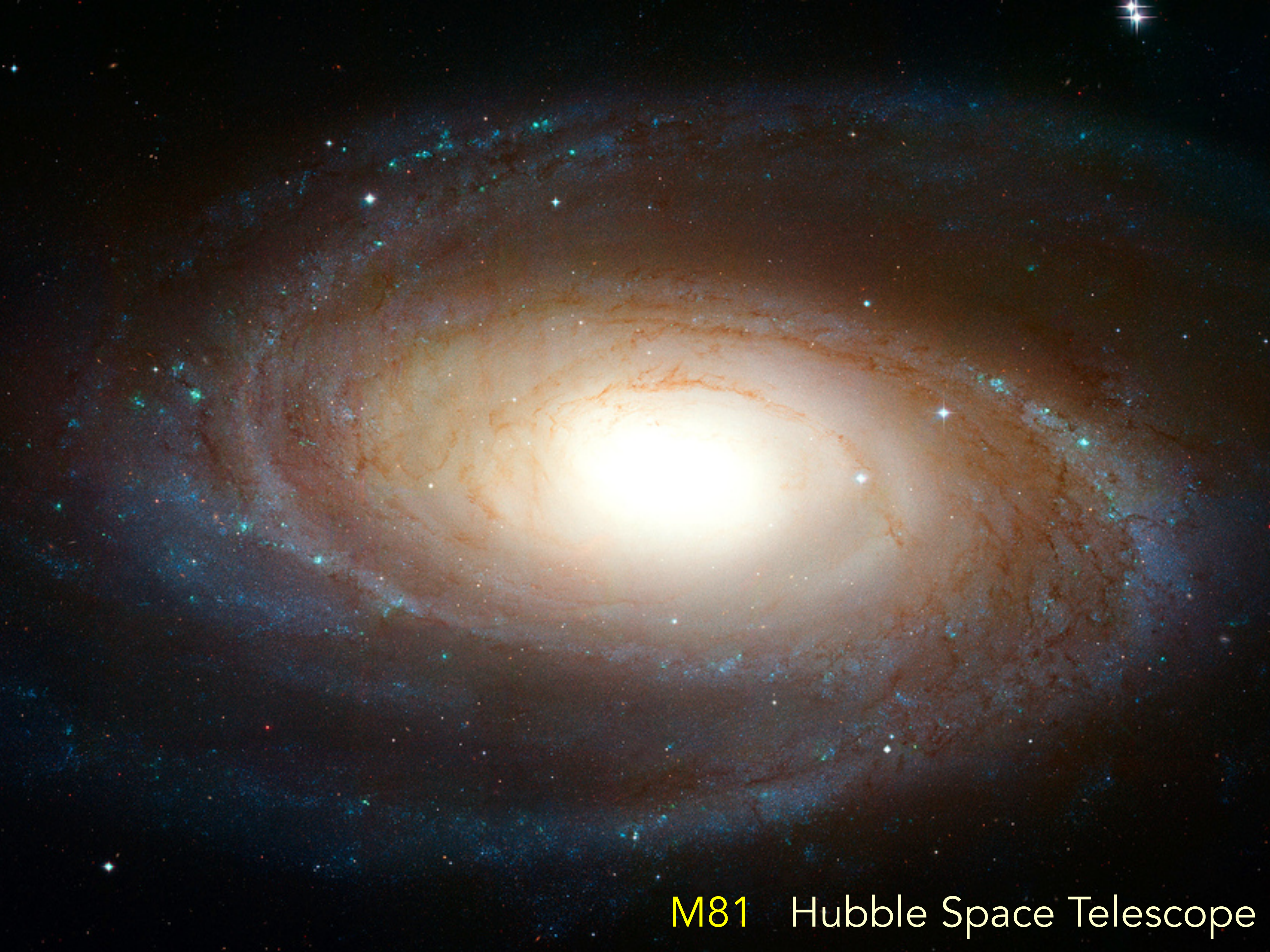
Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA


M33

DARK ENERGY SURVEY

M42 Orion nebula

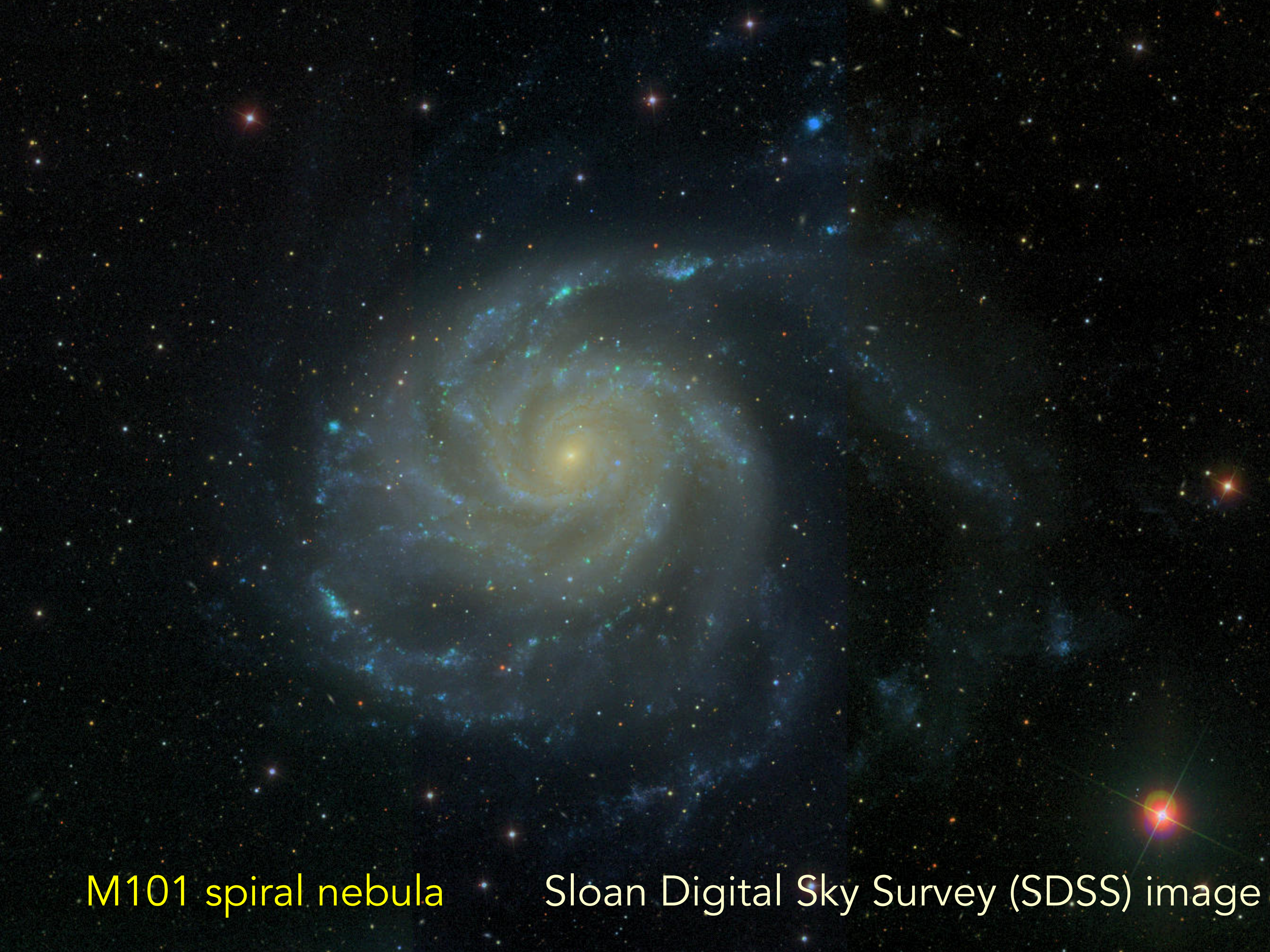


M81 Hubble Space Telescope

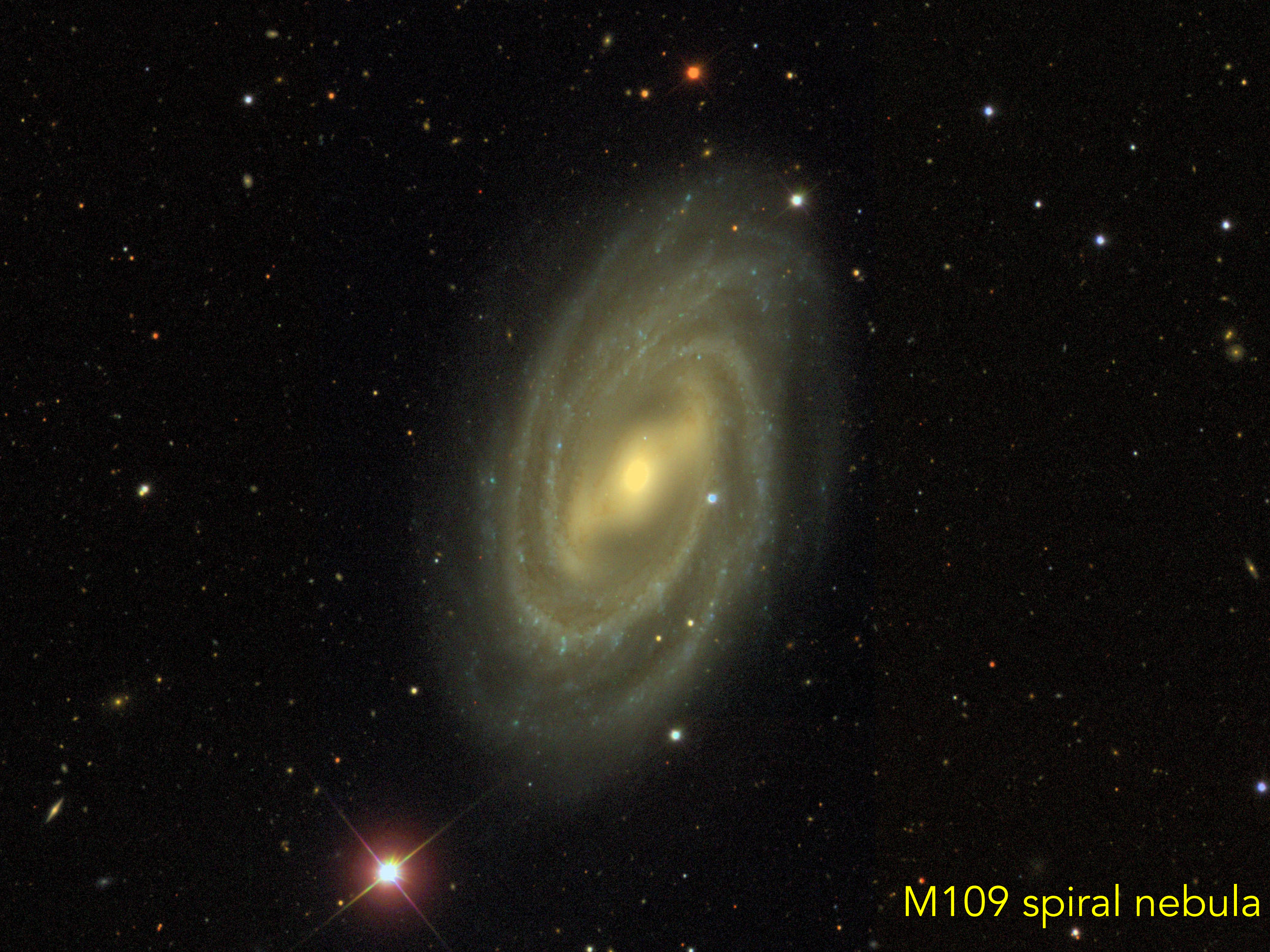
M82

M87

M100


M101 spiral nebula

Sloan Digital Sky Survey (SDSS) image



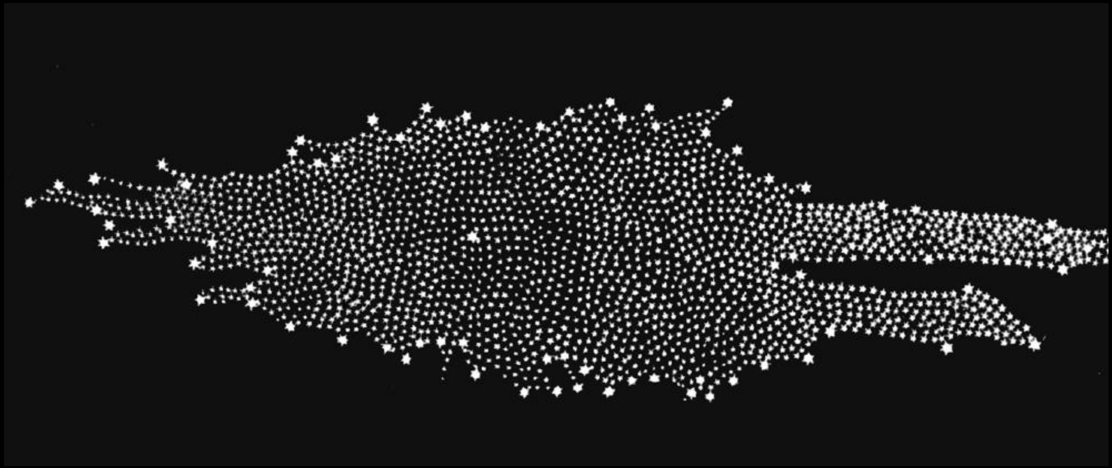
M109 spiral nebula

DARK ENERGY SURVEY

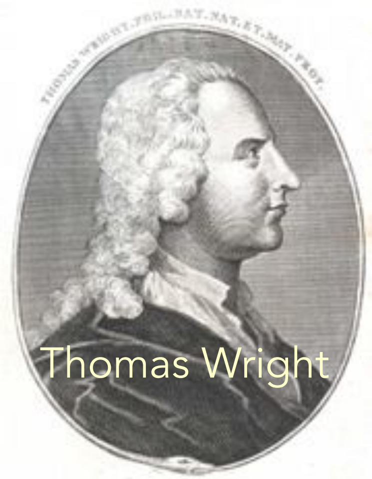
NGC 1365 in Fornax spiral nebula

What is the nature of the nebulae?

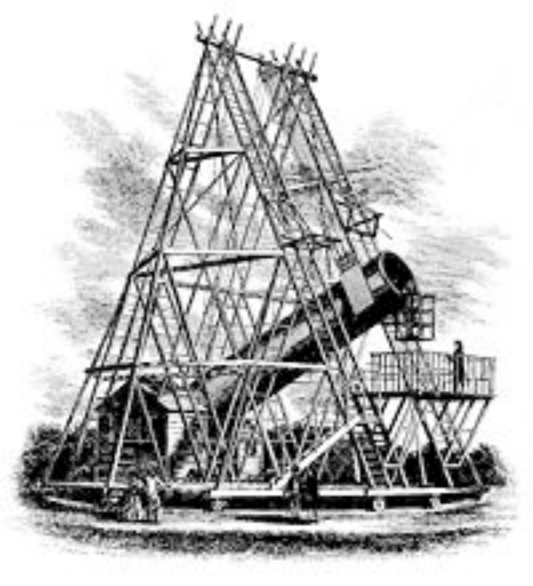
- And how are they related to the distribution of stars on the sky?
- Thomas Wright (1750): visible stars are distributed in a flat slab, the Milky Way
- William Herschel (1785): mapped distribution of stars
- Immanuel Kant (1750s): suggested that (some) nebulae are “island universes”, or galaxies like our own
- Lord Rosse (1845): observed that some nebulae have a disky shape, suggesting they could be Kant’s island universes, similar to Milky Way



Herschel’s map of the Milky Way



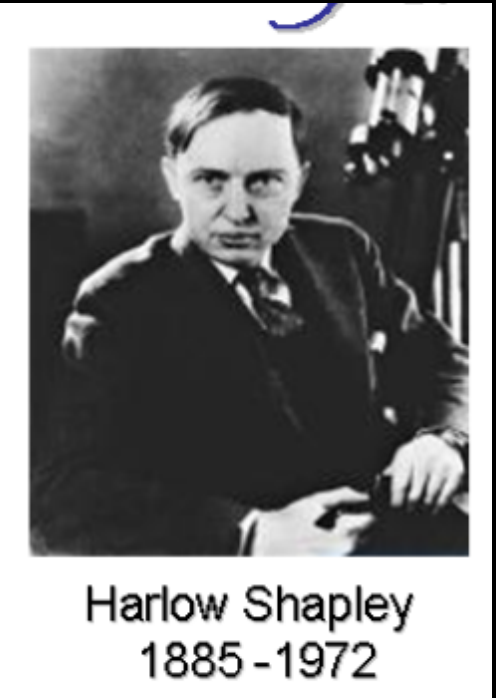
Thomas Wright



William Herschel

Caroline Herschel

Immanuel Kant



Harlow Shapley
1885 - 1972

Heber Curtis

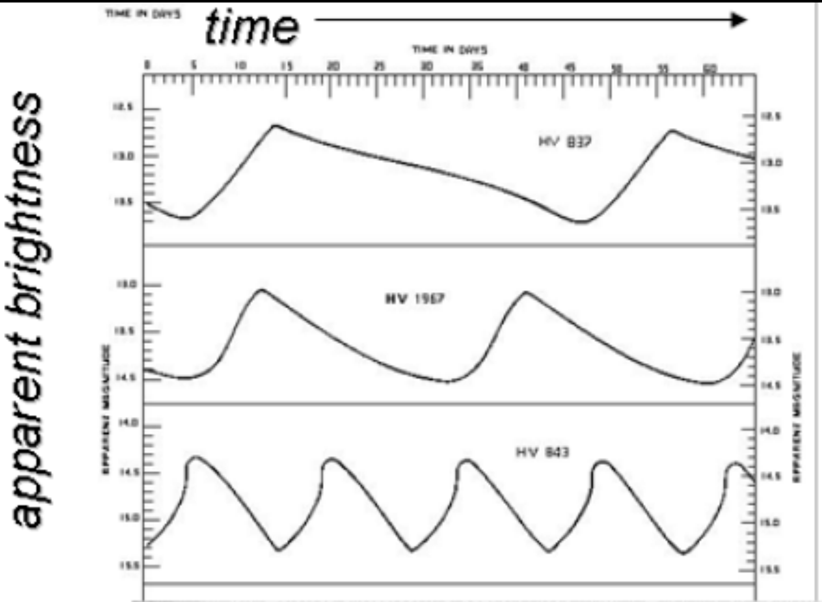
The Great Debate

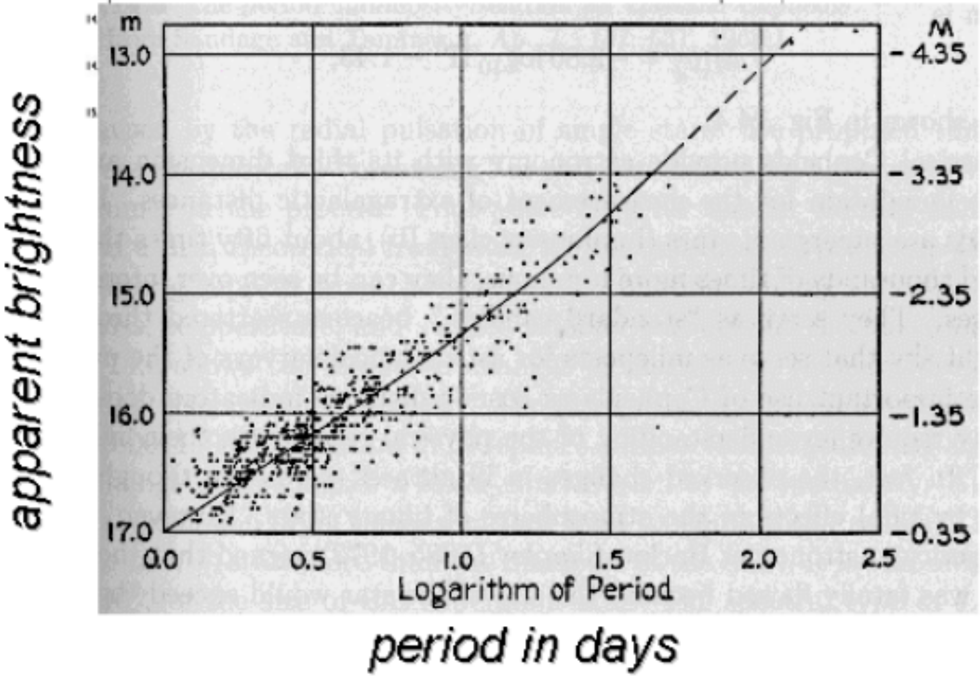
- Without distance measurements to the spiral nebulae, their nature remained elusive: are they within the Milky Way or separate island universes beyond it?
- 1920: Heber Curtis and Harlow Shapley debate at National Academy of Sciences
  - Curtis: spirals are distant galaxies
  - Shapley: spirals are systems within the Milky Way

Cepheid Variable Stars

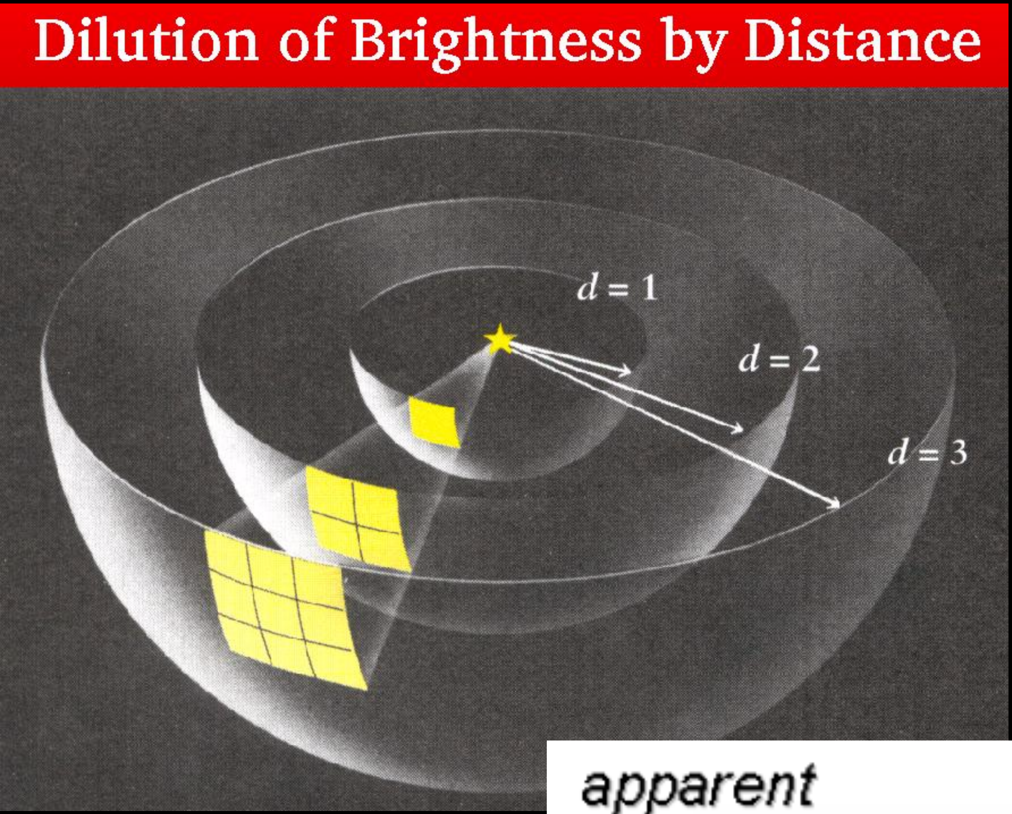
- Very luminous stars that regularly pulsate:
  - Smaller, hotter, brighter → larger, cooler, fainter
  - ~30,000 times brighter than the Sun
  - Relation between the intrinsic luminosity of Cepheids and their pulsation periods discovered by Henrietta Leavitt

Henrietta Leavitt
1868-1921
discovered relation
between intrinsic
luminosity and period of
variable Cepheid stars:
the period-luminosity relation





Brightness and Distance



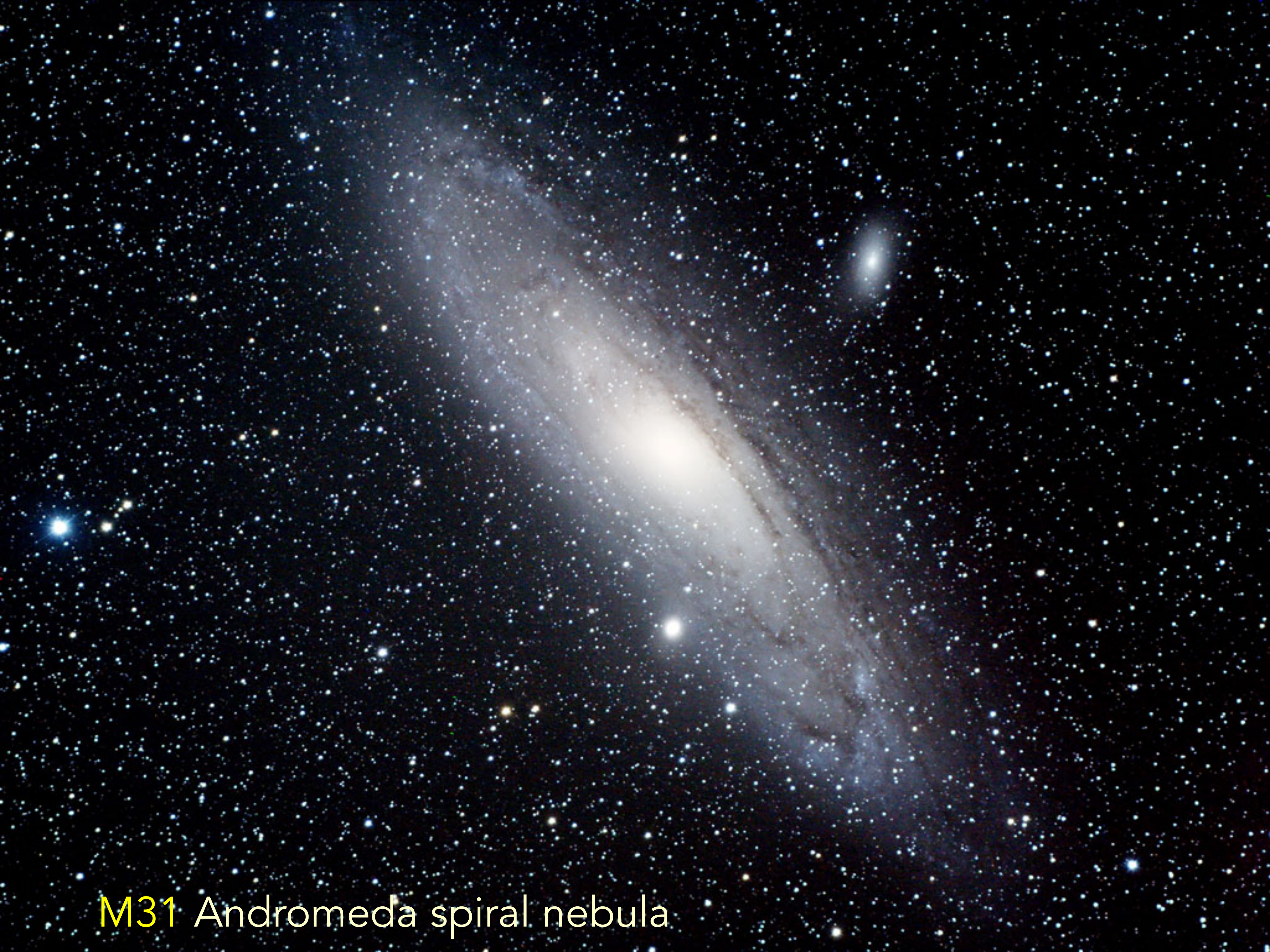
Dilution of Brightness by Distance

apparent brightness

luminosity

distance

$$B = \frac{L}{4\pi d^2} \Rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$$



M31 Andromeda spiral nebula

Edwin Hubble

(1889-1953)

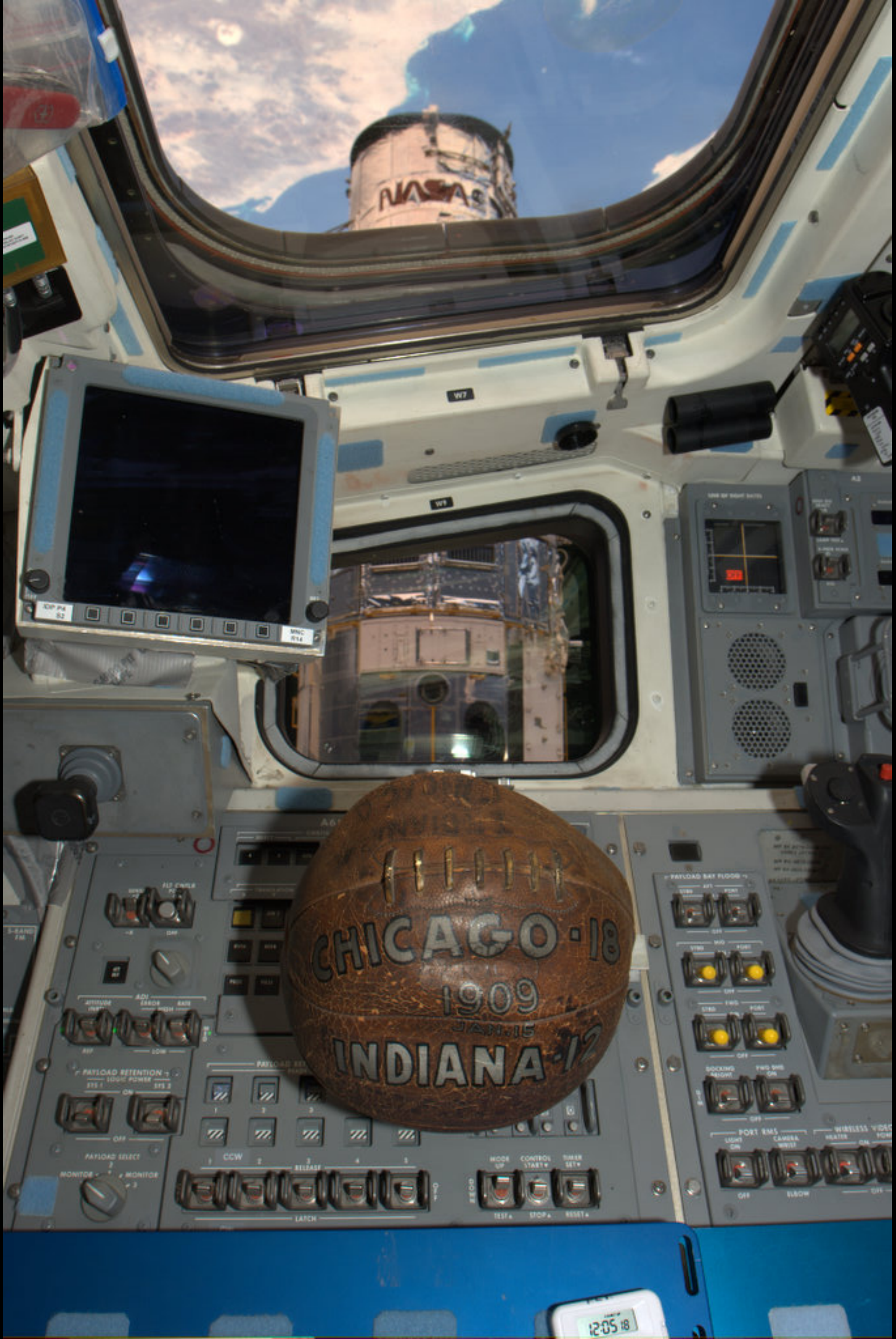
U of C graduate, Lawyer, Boxer, Astronomer

1924: Discovered 12 Cepheids in Andromeda spiral nebula, measured their periods, used Leavitt's relation to determine luminosity and thus distance: d_{And}= 2 Million light-years, far beyond Milky Way

Palomar 48-inch Telescope

Hubble's U. Chicago National Championship Basketball on board the
Space Shuttle

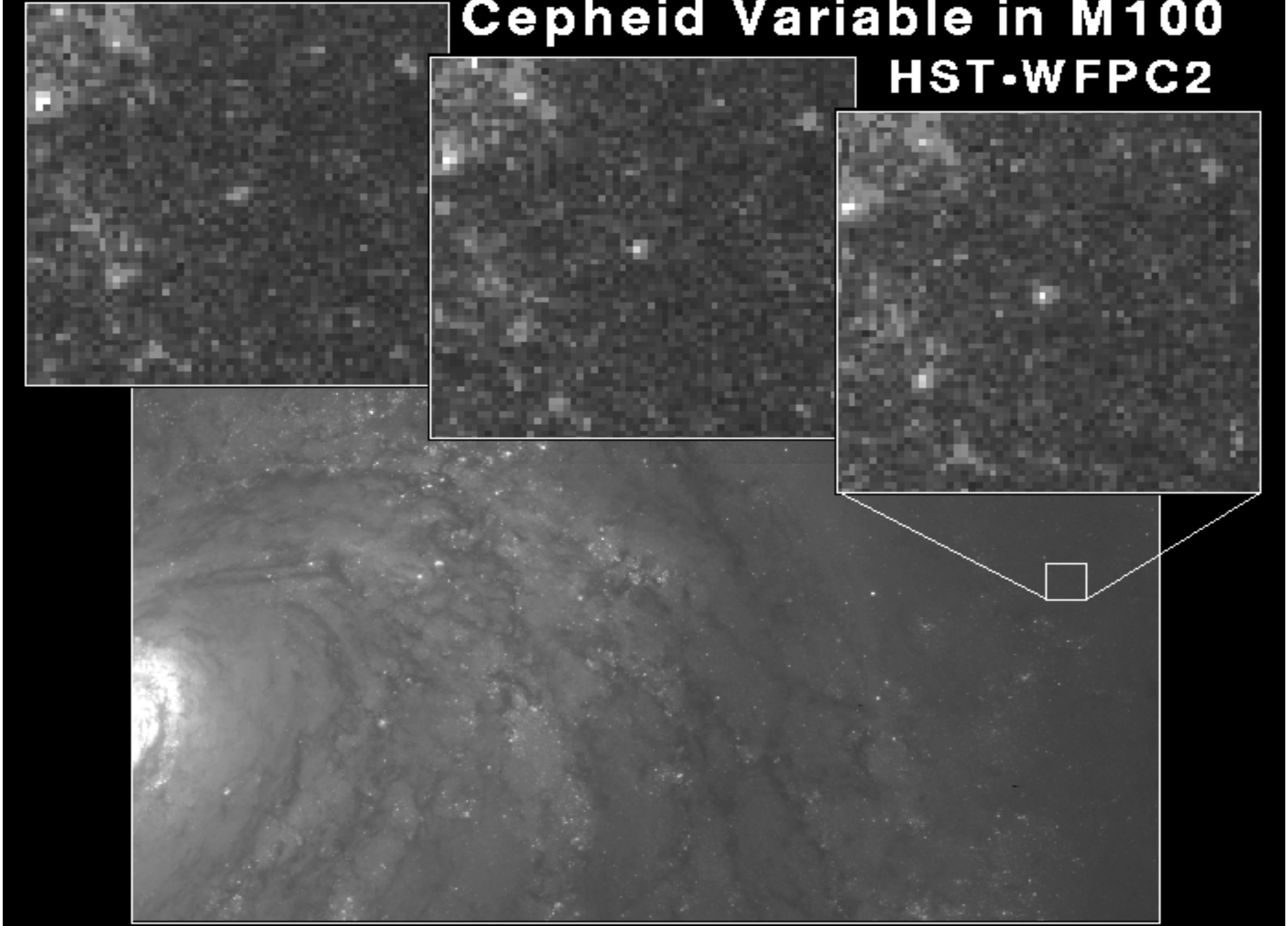
Hubble Space Telescope in background



Hubble Space Telescope
refurbishment, May 2009

Cepheid Variable in M100

HST•WFPC2



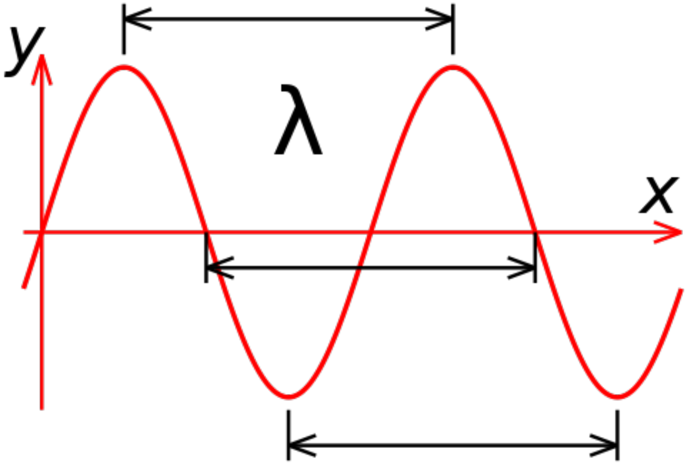
The Extragalactic Universe

- Hubble (1920's): measured distances to 29 galaxies using Cepheids and other techniques, using 100-inch telescope at Mt. Wilson (CA)

- Vesto Slipher (1912): measured spectrum of light from a number of spiral nebulae, using telescope at Lowell Observatory (Arizona).

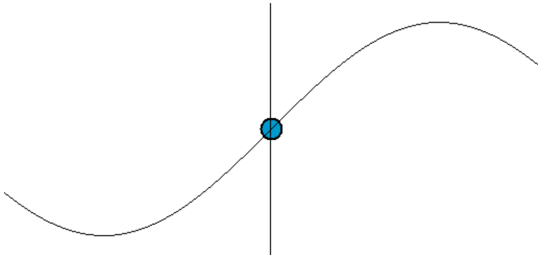
Spectrum of Light

Light is an Electromagnetic Wave



λ – wavelength –
distance between wavecrests

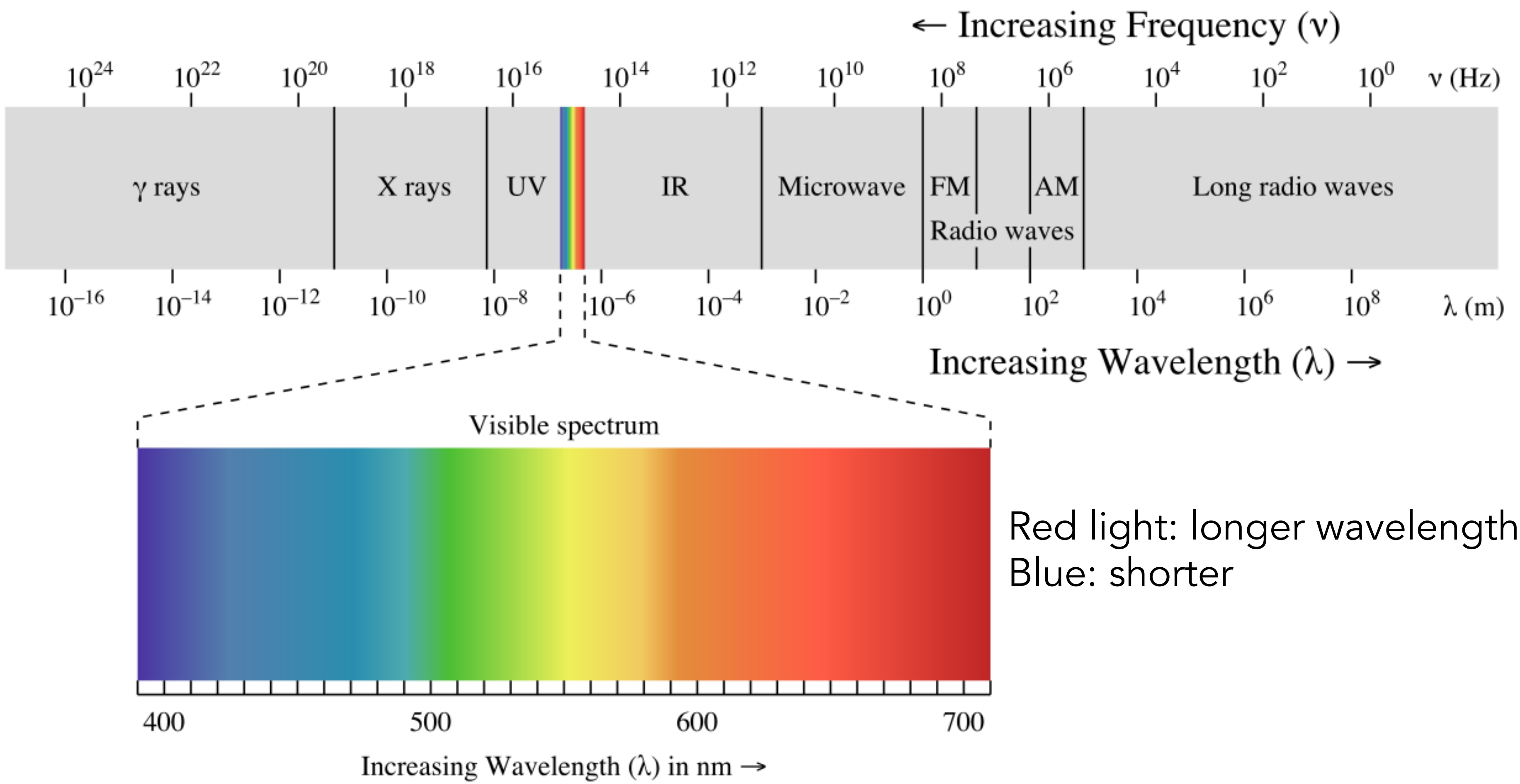
ν – frequency
ν= 1/Δt
1/period (time between wavecrests)
Unit: Hz = 1/second



λν=c
(speed of light)

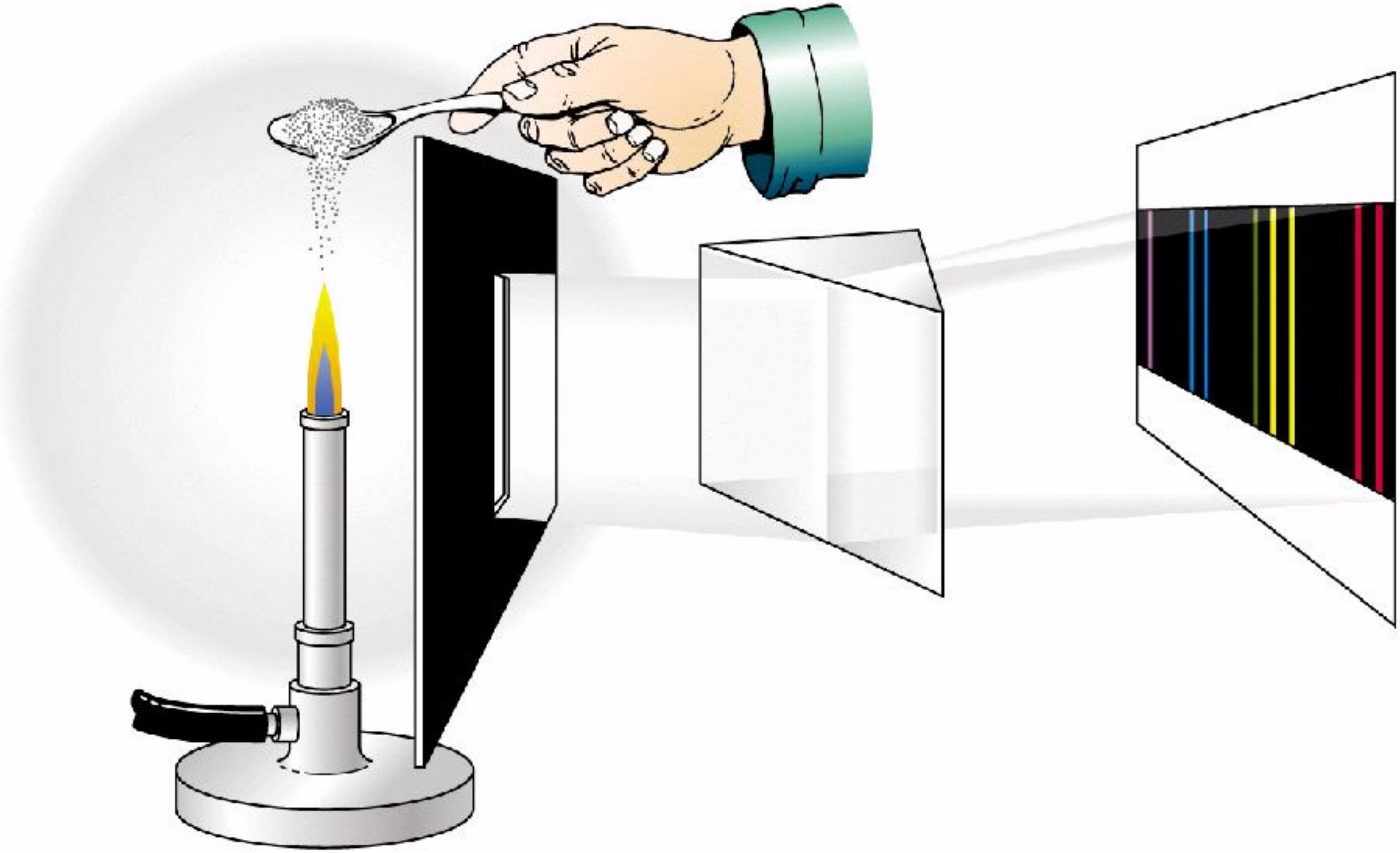
Wikipedia - waves

Electromagnetic Spectrum

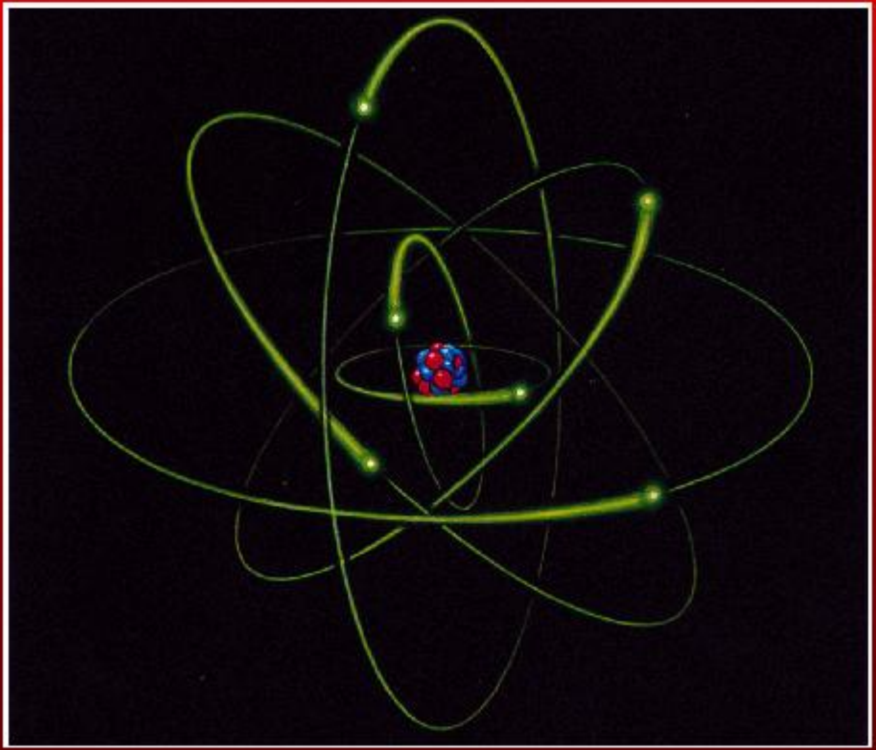


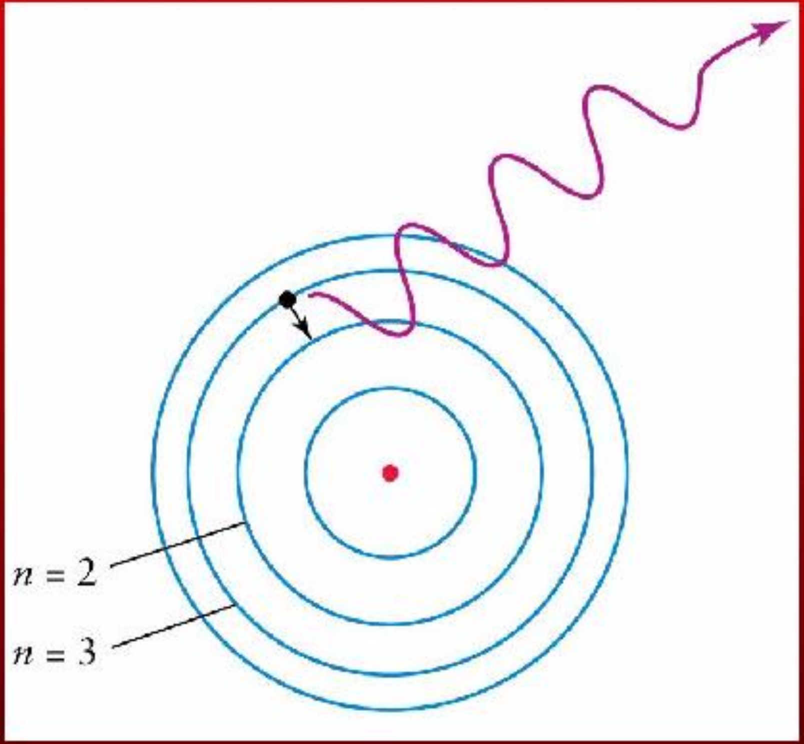
Red light: longer wavelength
Blue: shorter

Each Element has a Unique "Fingerprint"



Rutherford Atomic Model

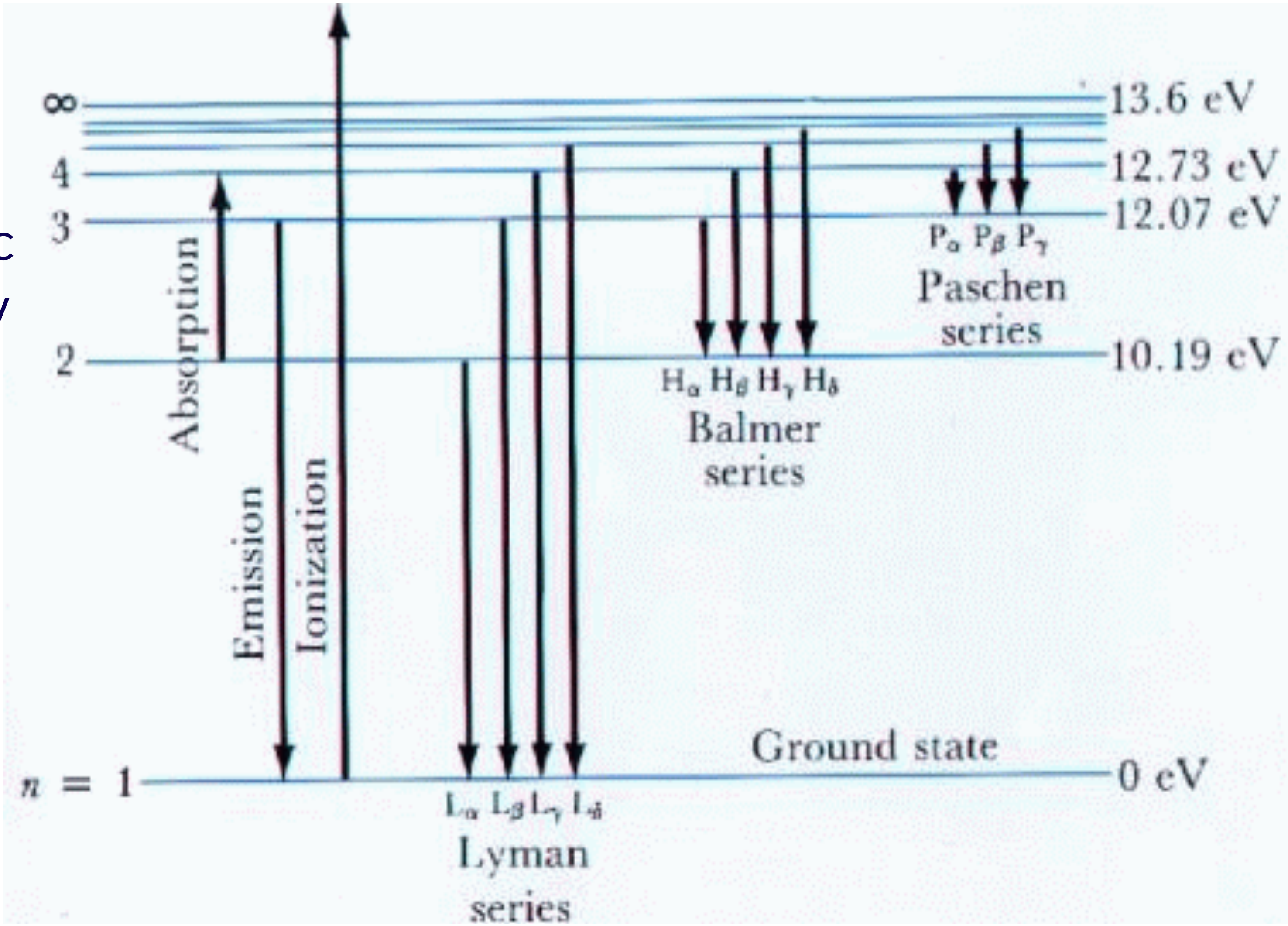




- Electrons orbit a Nucleus.
- Each element has fixed set of possible electron orbits.
- Each transition of an electron from a higher to a lower orbit gives a "packet" of light (photon) with a specific color.

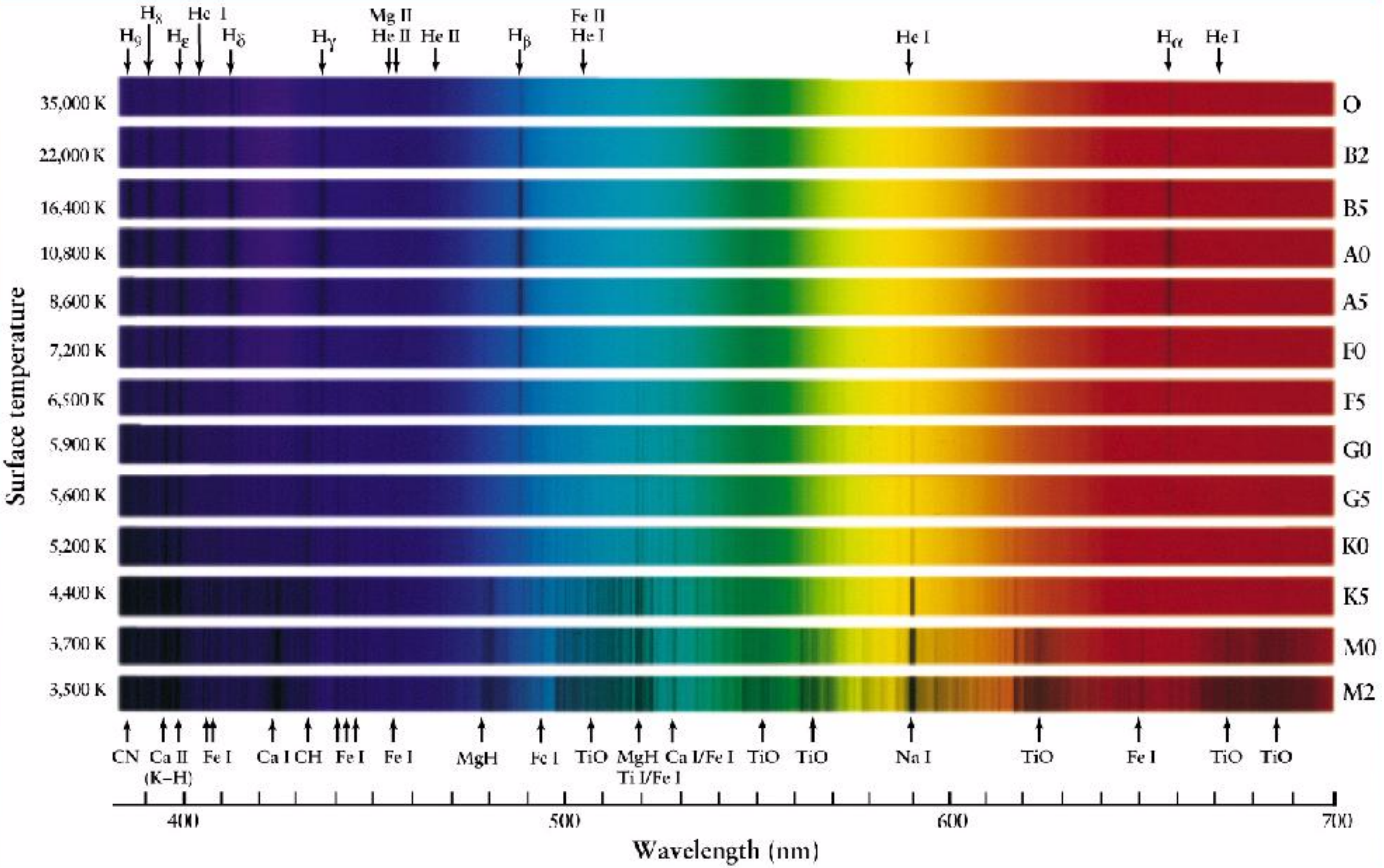
Hydrogen emission and absorption lines

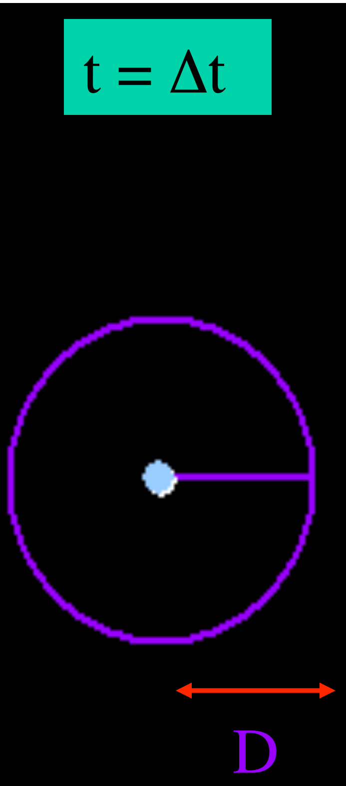
Atomic Energy Levels



Downward (upward) transition between two energy levels of an atom accompanied by emission (absorption) of light: ΔE = energy difference between the levels; it determines wavelength of emitted or absorbed light

Stellar Spectra





c = velocity of wave

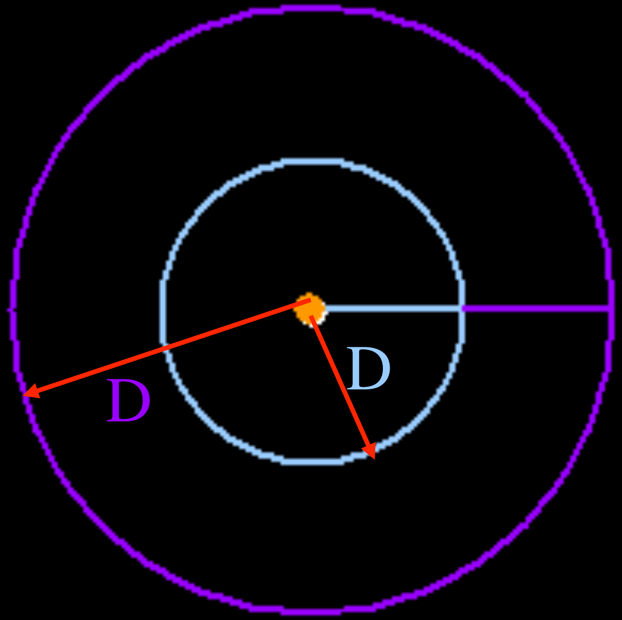
Δt time difference

D = distance traveled by light wave in time Δt

$D = c \Delta t$

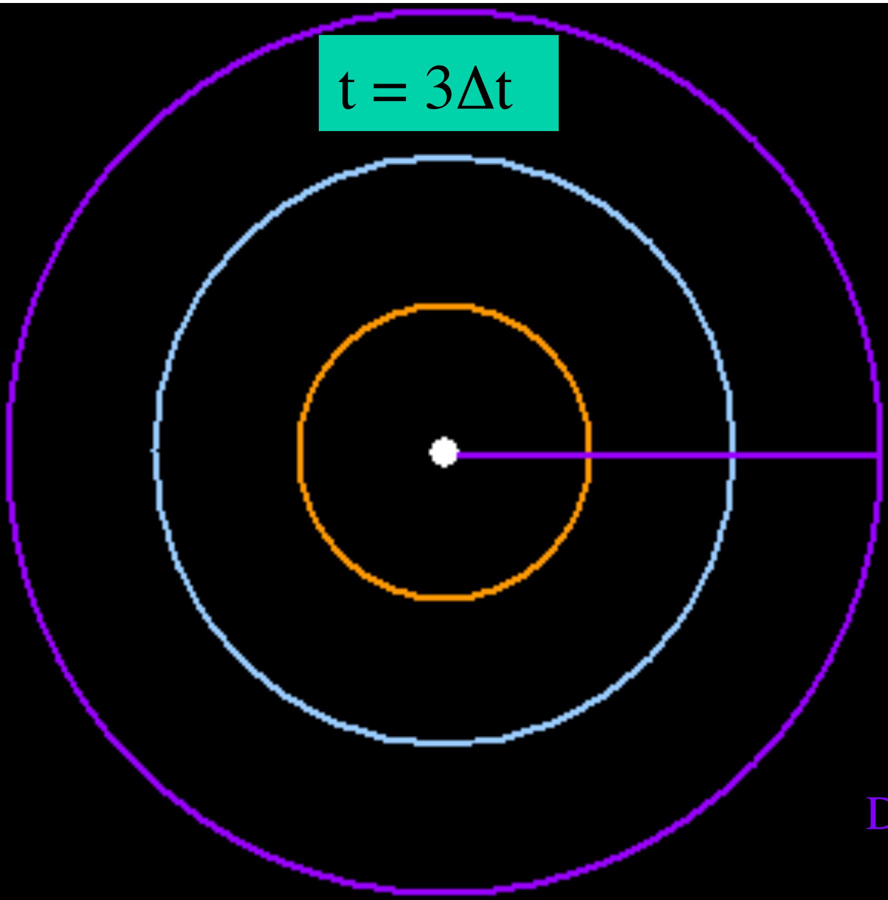
Stationary Source emitting light waves at intervals (Δt)

$t = 2\Delta t$



$D = c\ 2\ \Delta t$

$D = c\ \Delta t$



$t = 3\Delta t$

$\lambda = c\ \Delta t$

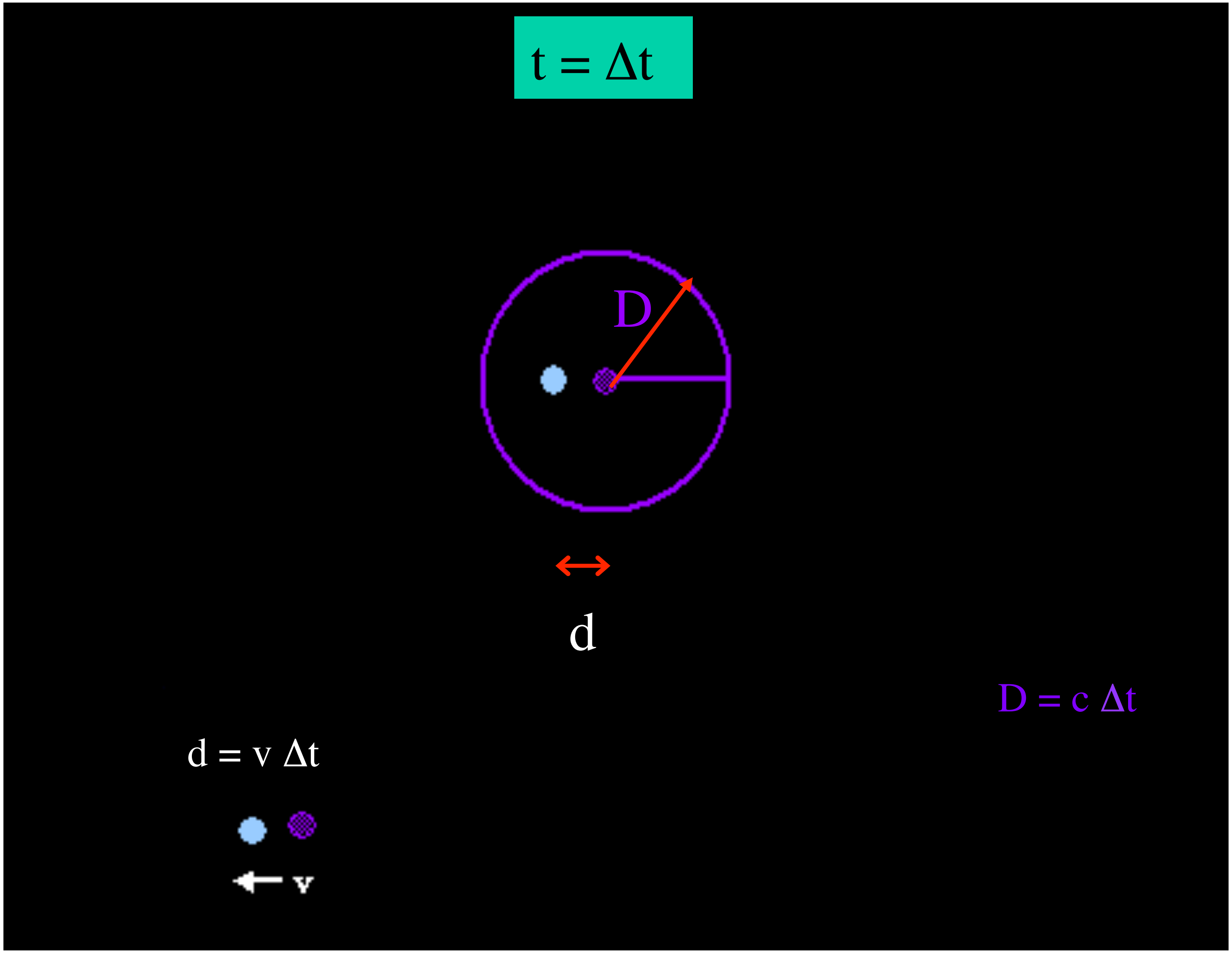
$D = c\ 3\ \Delta t$

$D = c\ 2\ \Delta t$

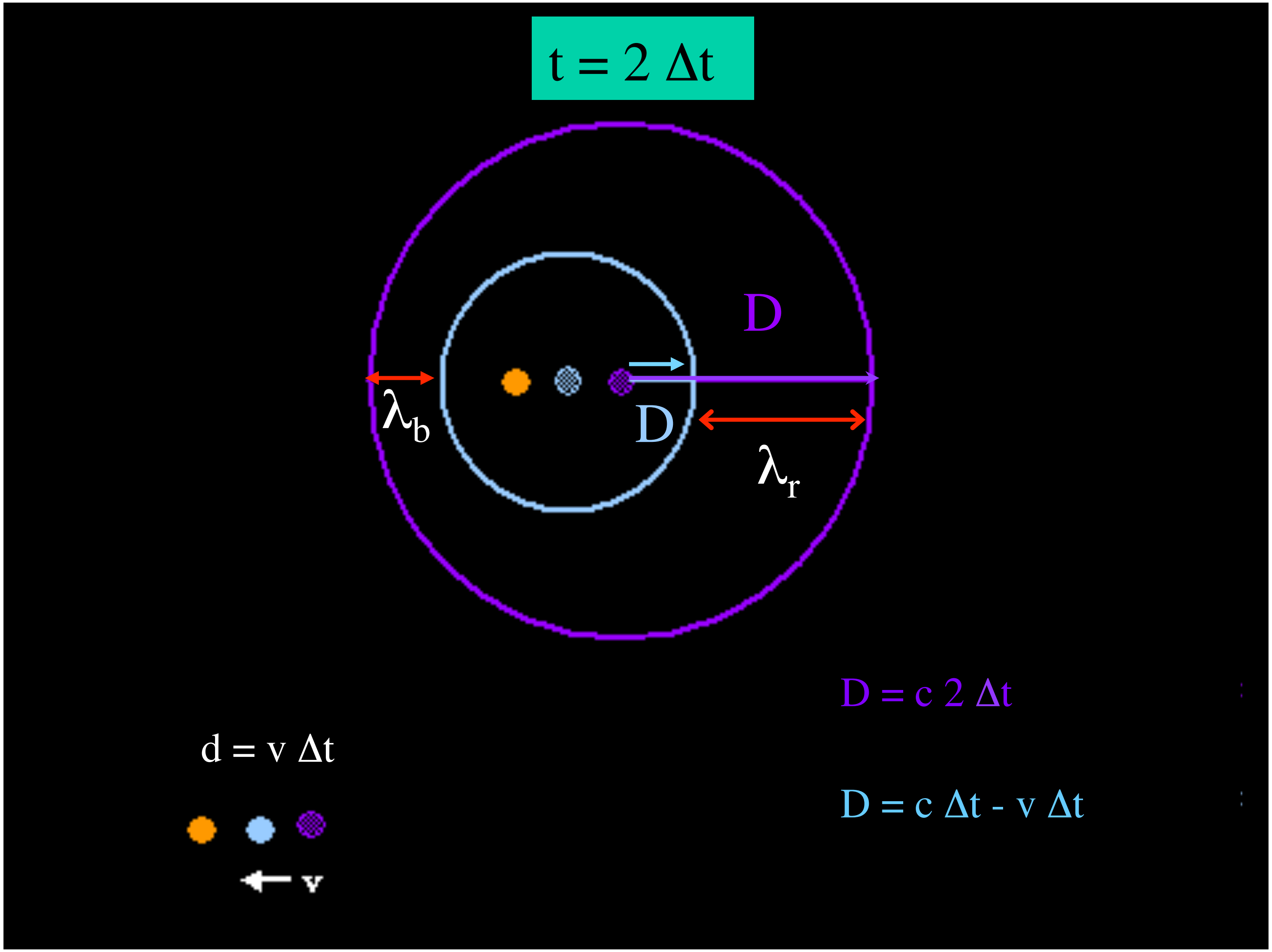
$D = c\ \Delta t$

$\lambda =$ distance between

successive wavecrests

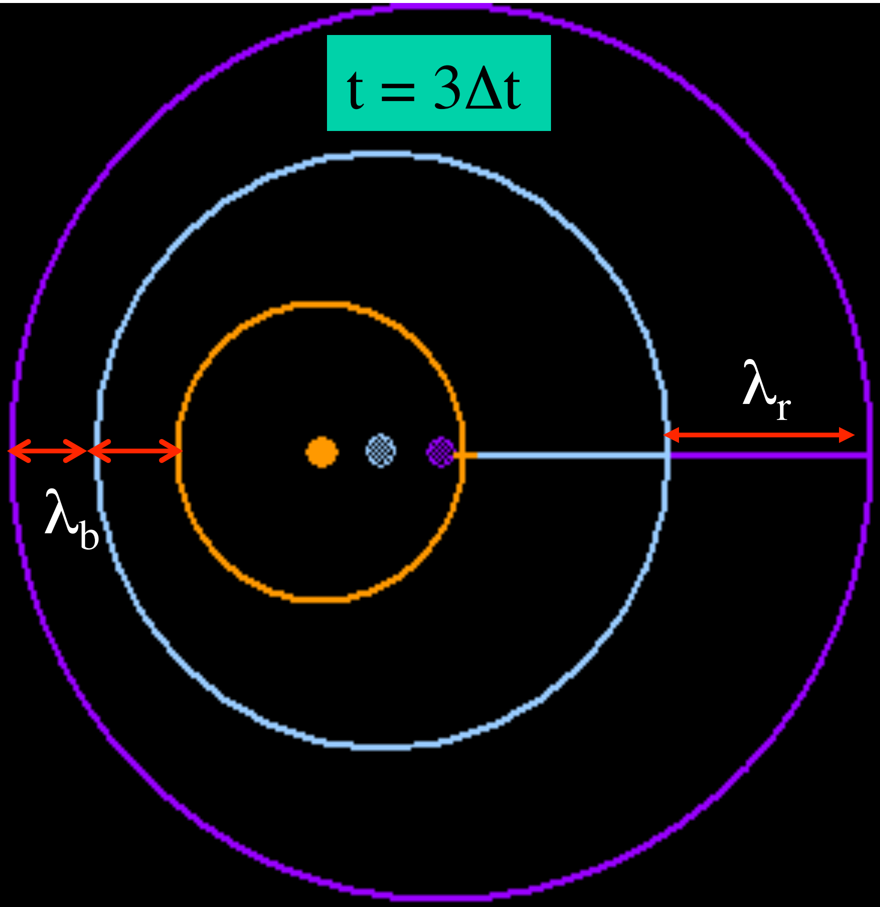


Moving source emitting light waves
at intervals Δt



λ_r = distance between successive wavecrests towards right

$= D - D = c\,2(\Delta t) - c\,(\Delta t) + v\,(\Delta t) = (c+v)(\Delta t)$



$t = 3\Delta t$

$\lambda_b = c\,\Delta t$
$-v\,\Delta t$

$\lambda = c\,\Delta t$
$+\,v\,\Delta t$

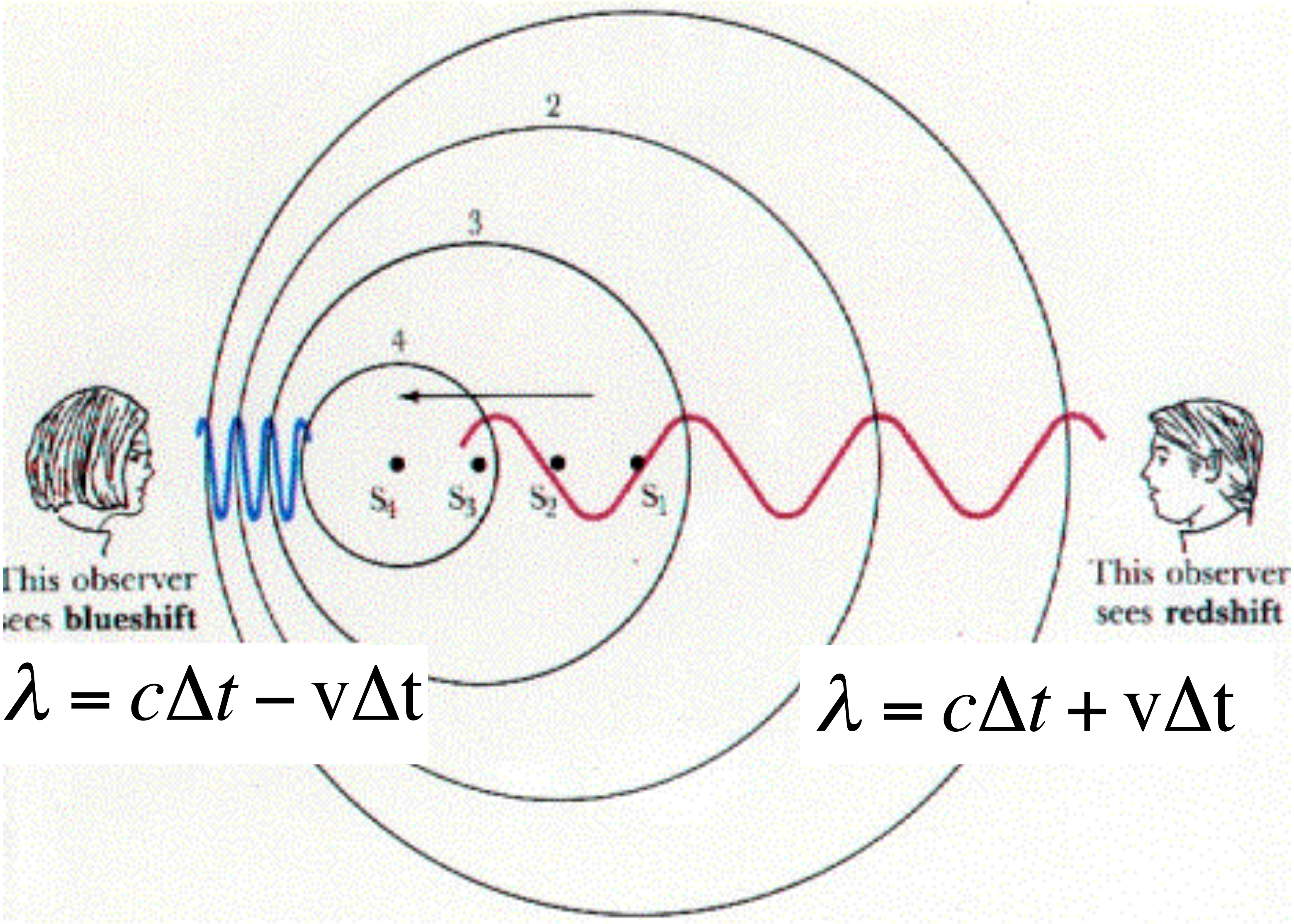
$D = c\,3\,\Delta t$

$D = c\,2\,\Delta t - v\,\Delta t$

$D = c\,\Delta t - 2\,v\,\Delta t$

λ = distance between
successive wavecrests

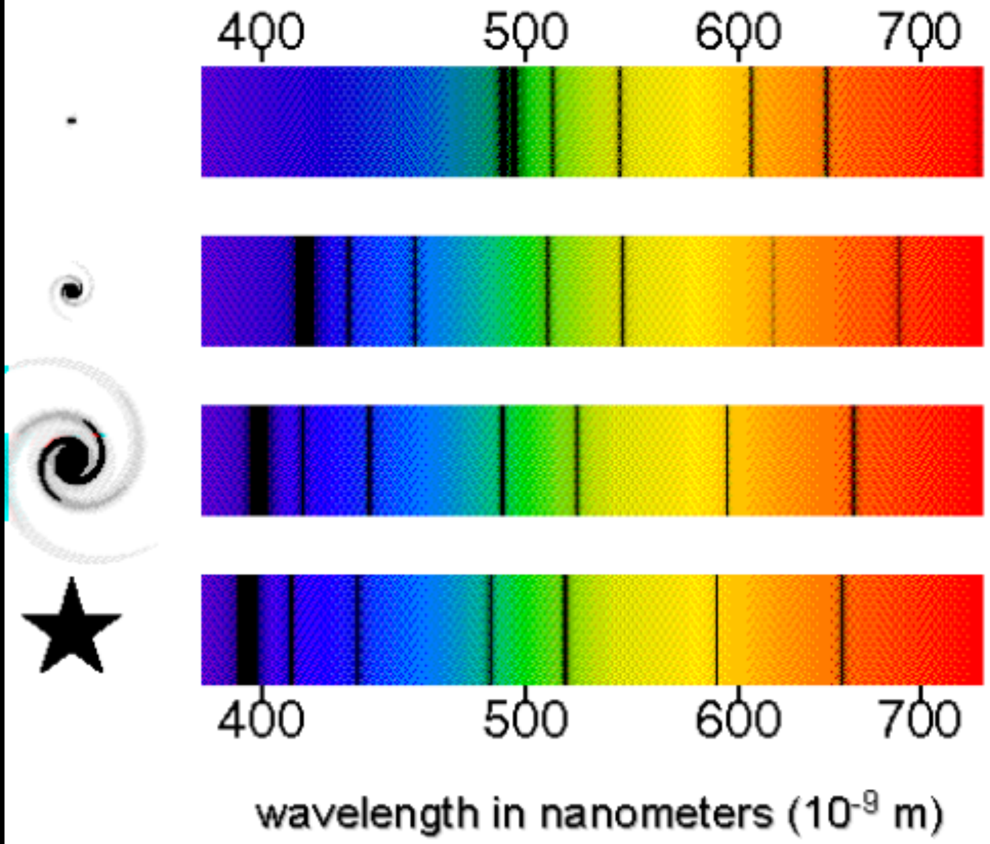
Doppler Shift of Light wavelength



$$\lambda = c\Delta t - \mathrm{v}\Delta \mathrm{t}$$

$$\lambda = c\Delta t + \mathrm{v}\Delta \mathrm{t}$$

Redshift & Blueshift



$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}},$$

$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{f_{\text{emitted}}}{f_{\text{observed}}}.$$

z can be measured from an observed spectrum if we know what the lines are and which wavelength they should correspond to *at rest*

Doppler Shift of Light Wavelength

Wavelength λ = distance between successive crests

$$\lambda = c\,\Delta t \pm \mathrm{v}\,\Delta t$$

$$c\,\Delta t = \lambda_0 \quad \Rightarrow \quad \lambda = \lambda_0 \pm \mathrm{v}\,\Delta t$$

$$\Delta t = \frac{\lambda_0}{c} \quad \Rightarrow \quad \lambda = \lambda_0 \pm \frac{\mathrm{v}}{c}\lambda_0$$

Redshift z

$$\boxed{\frac{\lambda}{\lambda_0} = 1 \pm \frac{\mathrm{v}}{c}}$$

(for v<<c)

Recession velocity v

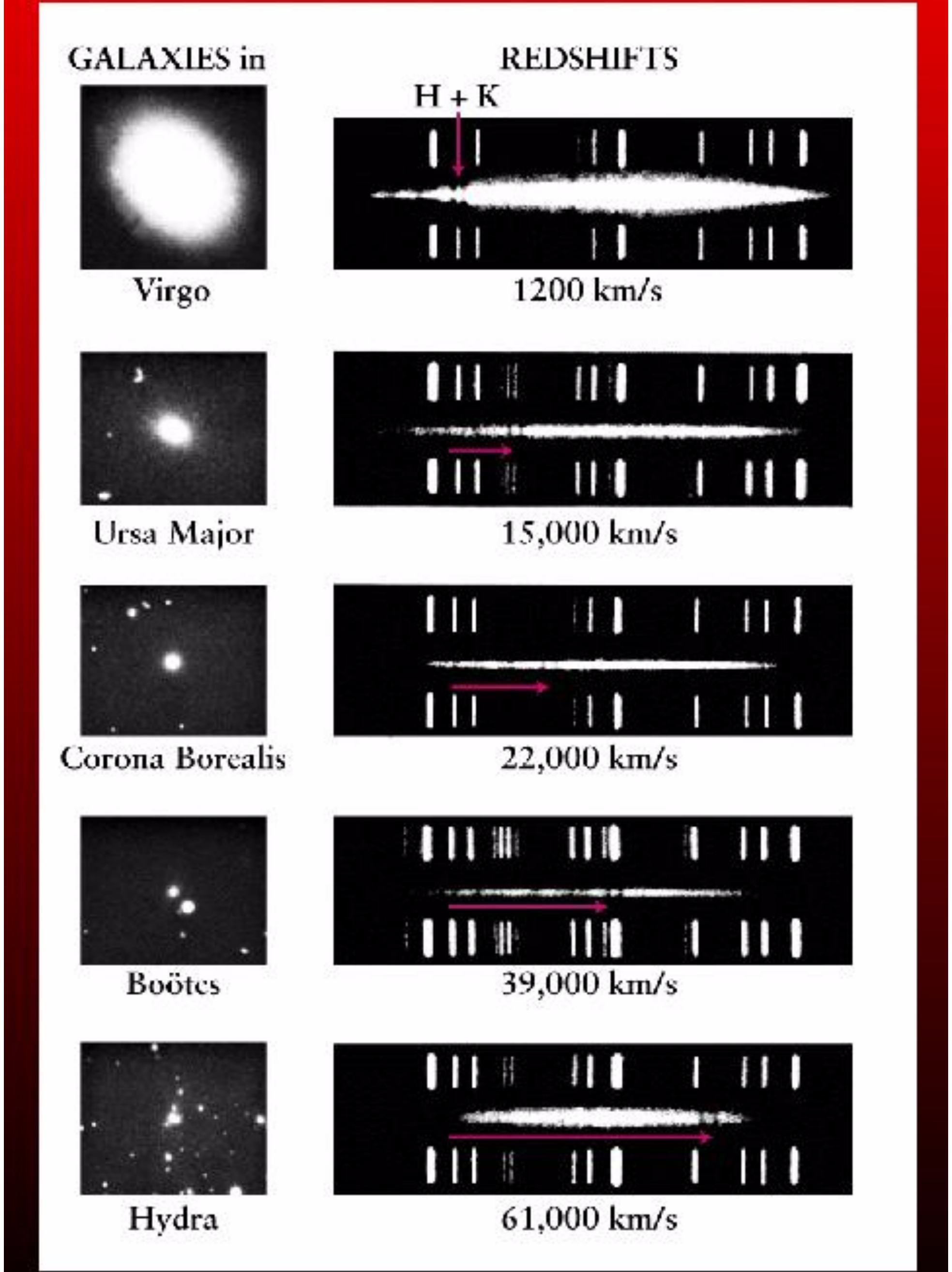
Speed of light c

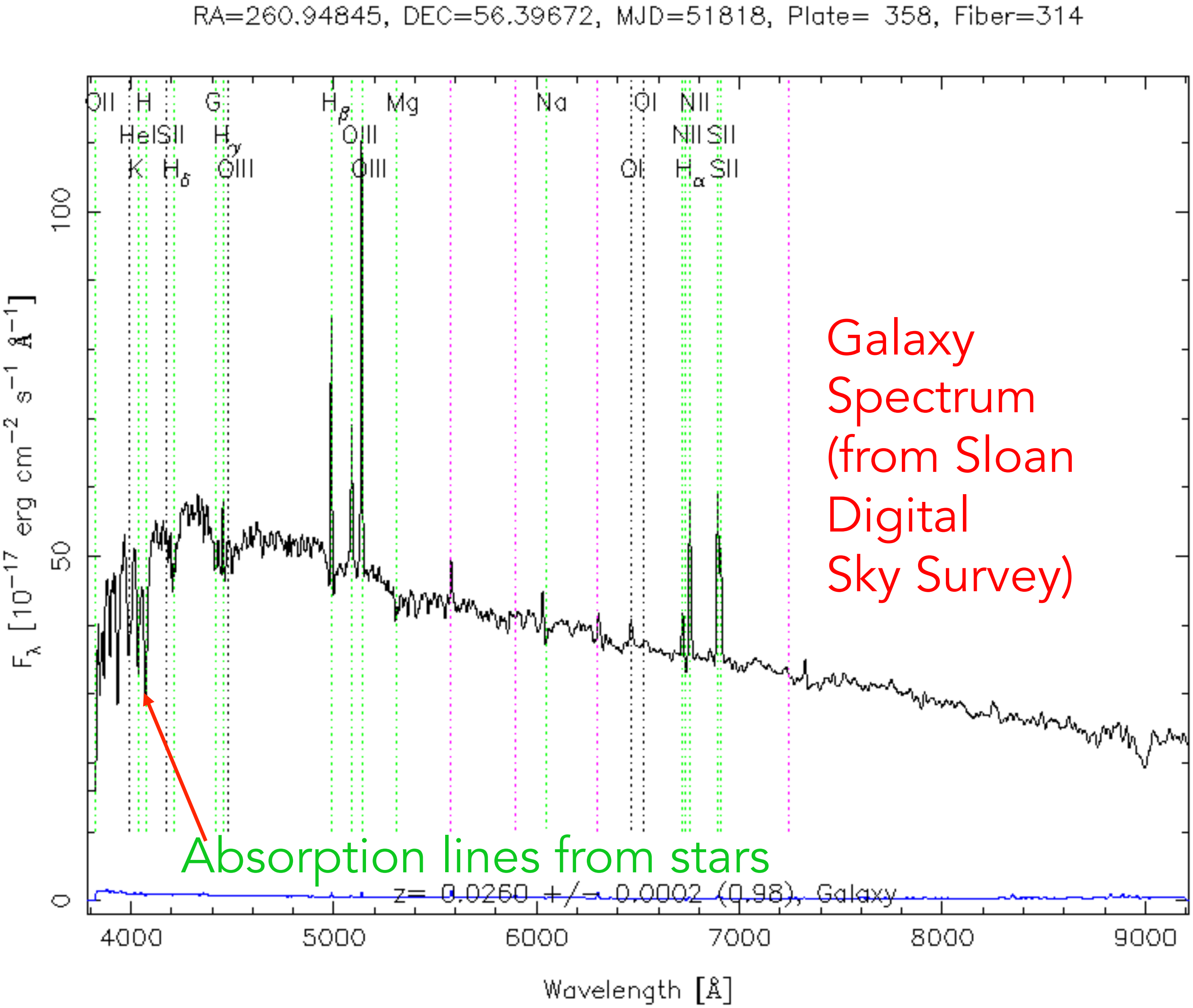
Observed wavelength λ

`Rest' wavelength λ_0

Wavelength of light (or sound) emitted by moving object is shortened if it is approaching you, lengthened if recedes from you

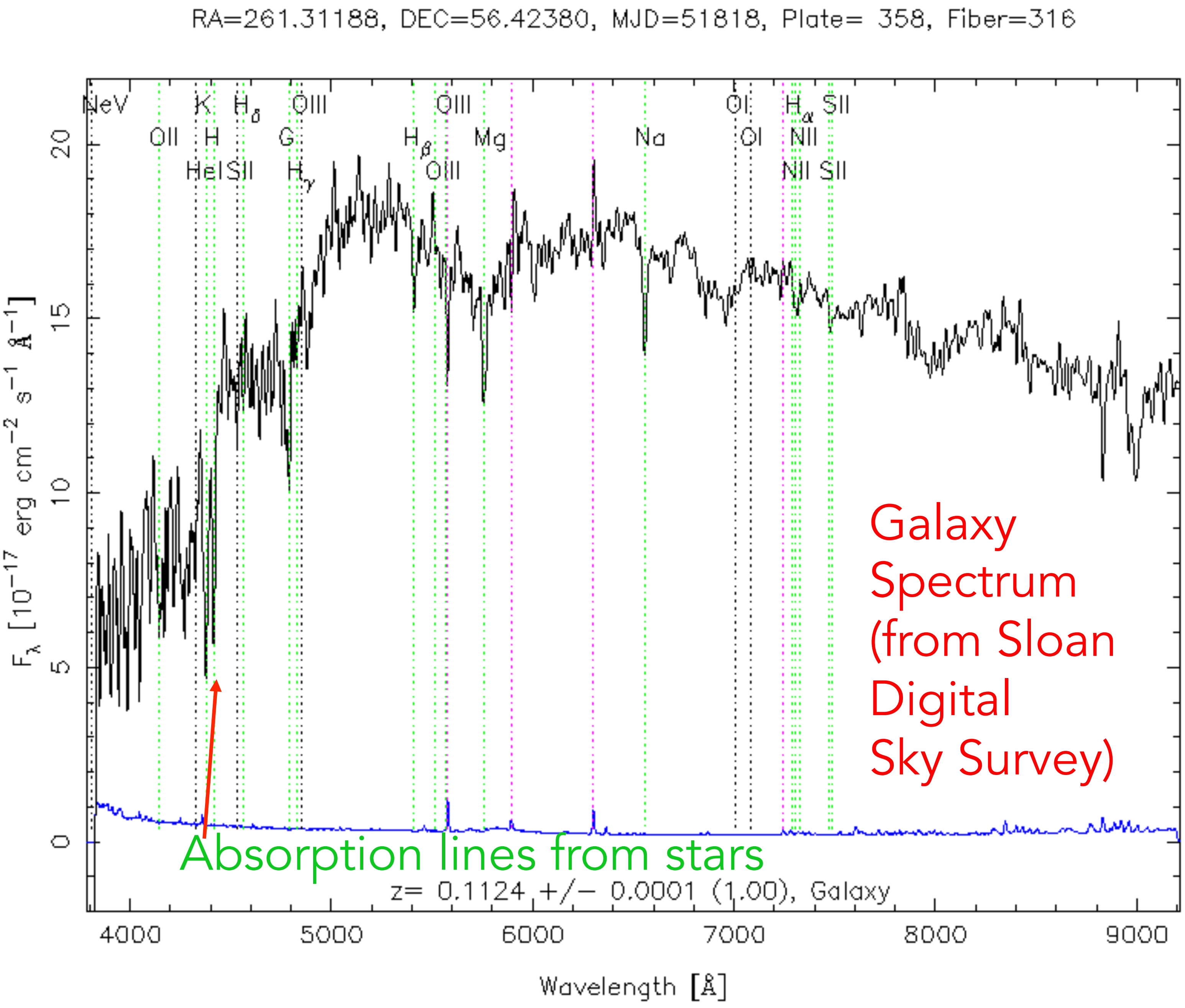
Galactic Redshifts





Galaxy Spectrum (from Sloan Digital Sky Survey)

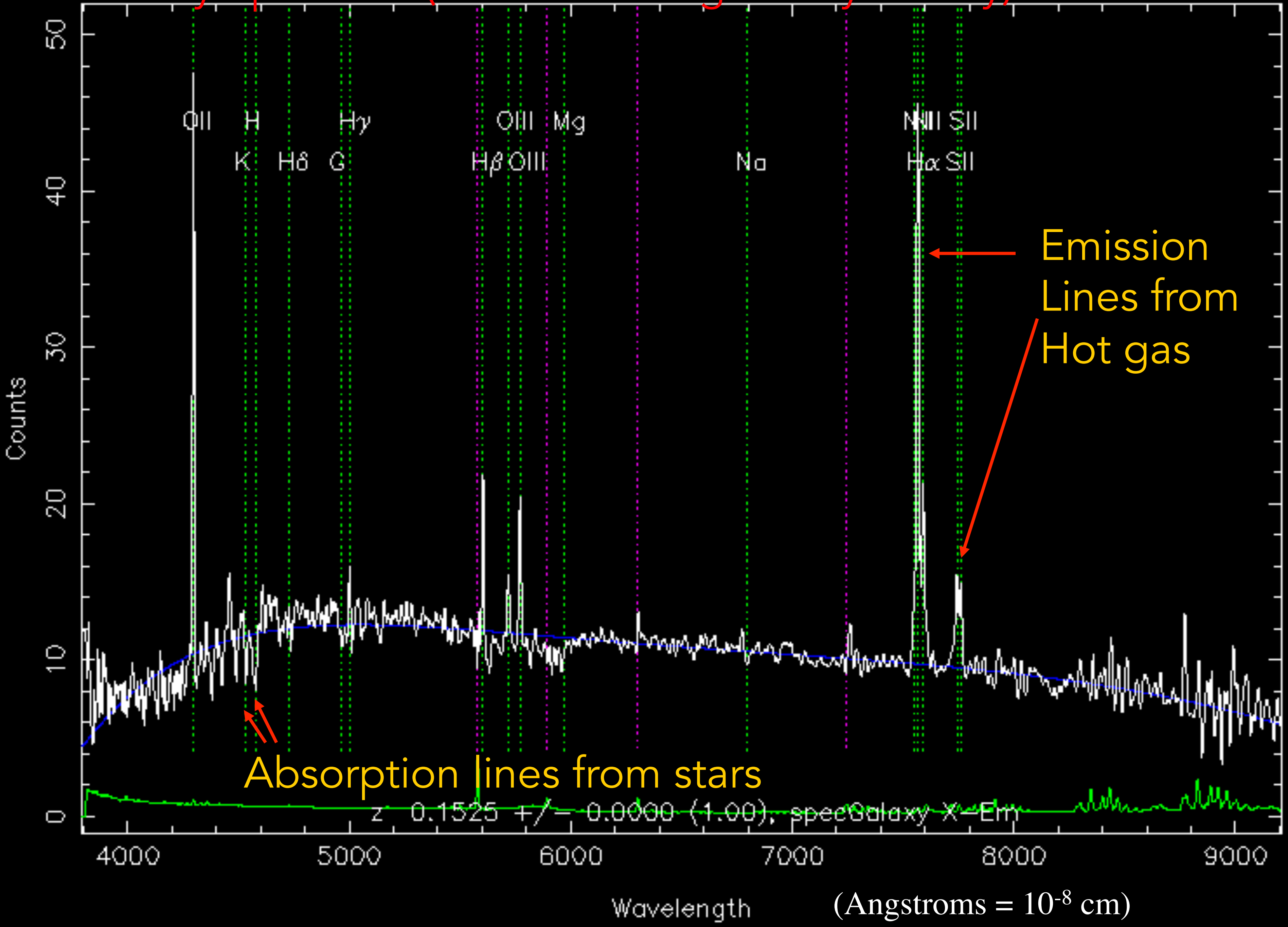
Absorption lines from stars



Galaxy Spectrum (from Sloan Digital Sky Survey)

Absorption lines from stars

Galaxy Spectrum (from Sloan Digital Sky Survey) z = 0.1525



Emission Lines from Hot gas

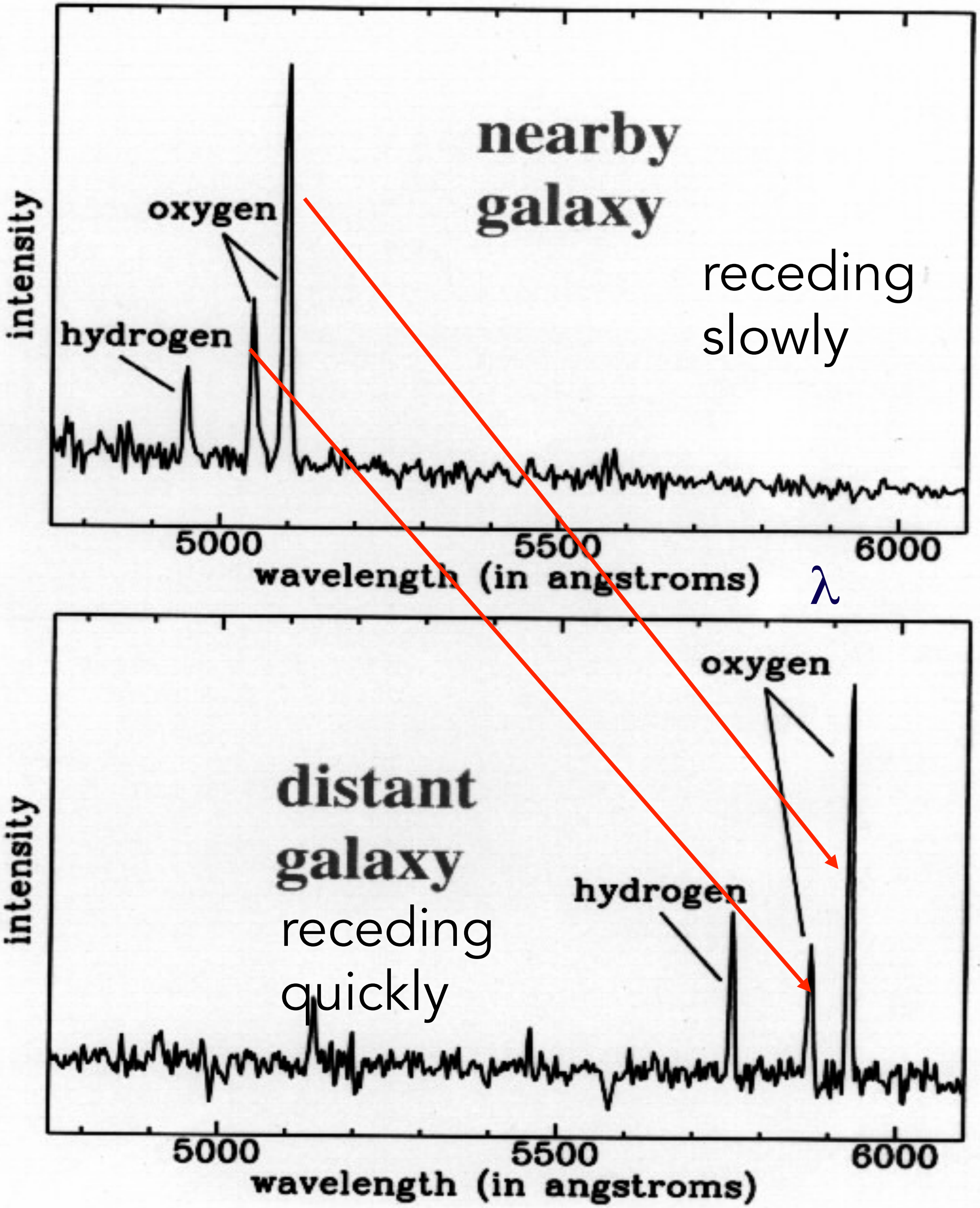
Absorption lines from stars

(Angstroms = 10^{-8} cm)

Redshifting of Galaxy Emission and Absorption Lines

$v/c \approx z = \Delta\lambda/\lambda_0$

(approximation for objects moving with $v/c << 1$)



receding slowly

λ

receding quickly

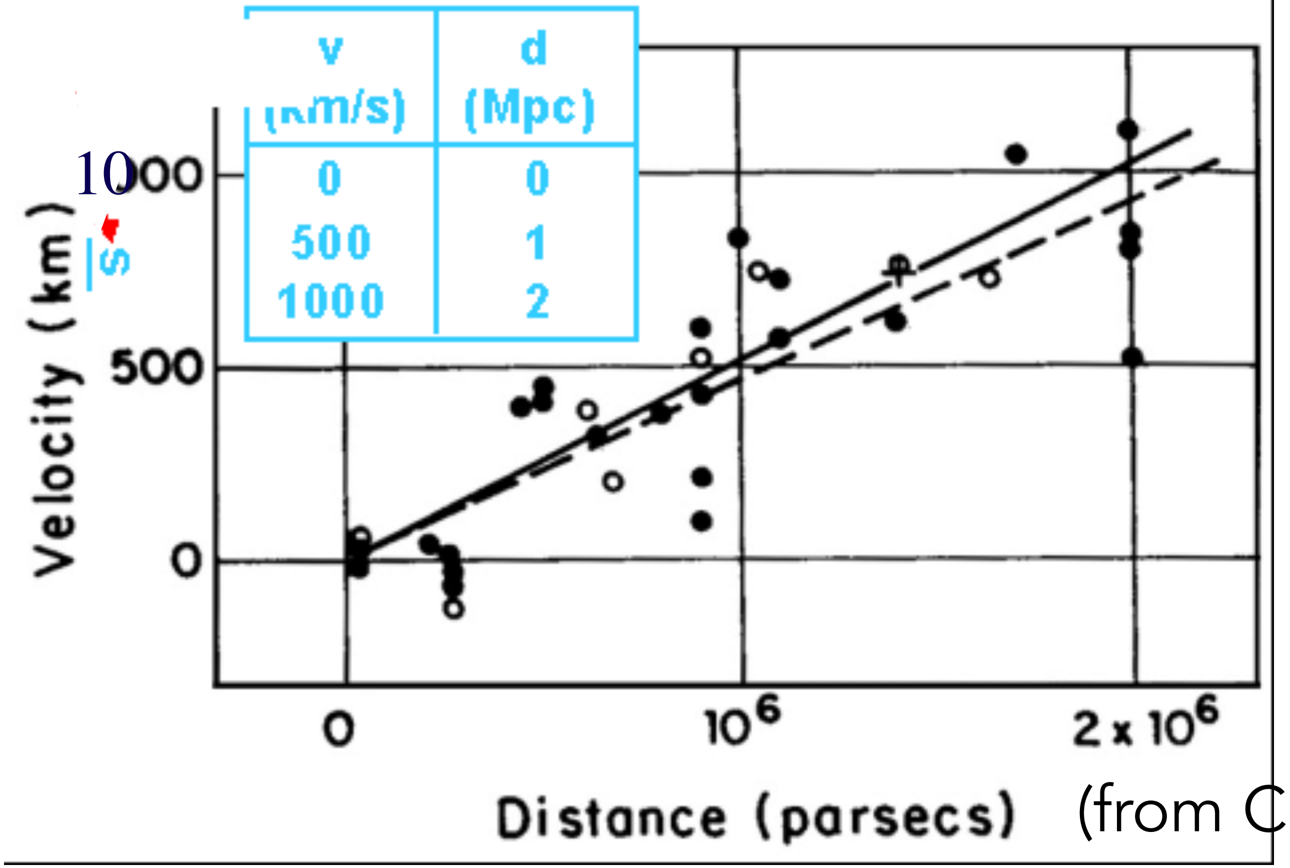
The Extragalactic Universe

- Hubble (1920's): measured distances to 29 galaxies using Cepheids and other techniques, using 100-inch telescope at Mt. Wilson (CA)

- Vesto Slipher (1912): measured spectrum of light from a number of spiral nebulae, using telescope at Lowell Observatory (Arizona). Found that spectral lines of almost all spiral nebulae are shifted to the red, and have recession speeds much larger than Milky Way stars (although Andromeda is blueshifted).

Hubble (1929): plotted his distances vs Slipher's velocities

From
redshifts
(spectra)



v (km/s)	d (Mpc)
0	0
500	1
1000	2

(from Cepheids)

Hubble: slope of line: H_0= v/d = 550 km/sec/Megaparsec

(1 parsec = 3.26 light year = 3 x 10^{18} cm)

Hubble’s Law

More distant galaxies appear redder.
They are moving away from us, with:

speed (redshift) $\propto$ distance

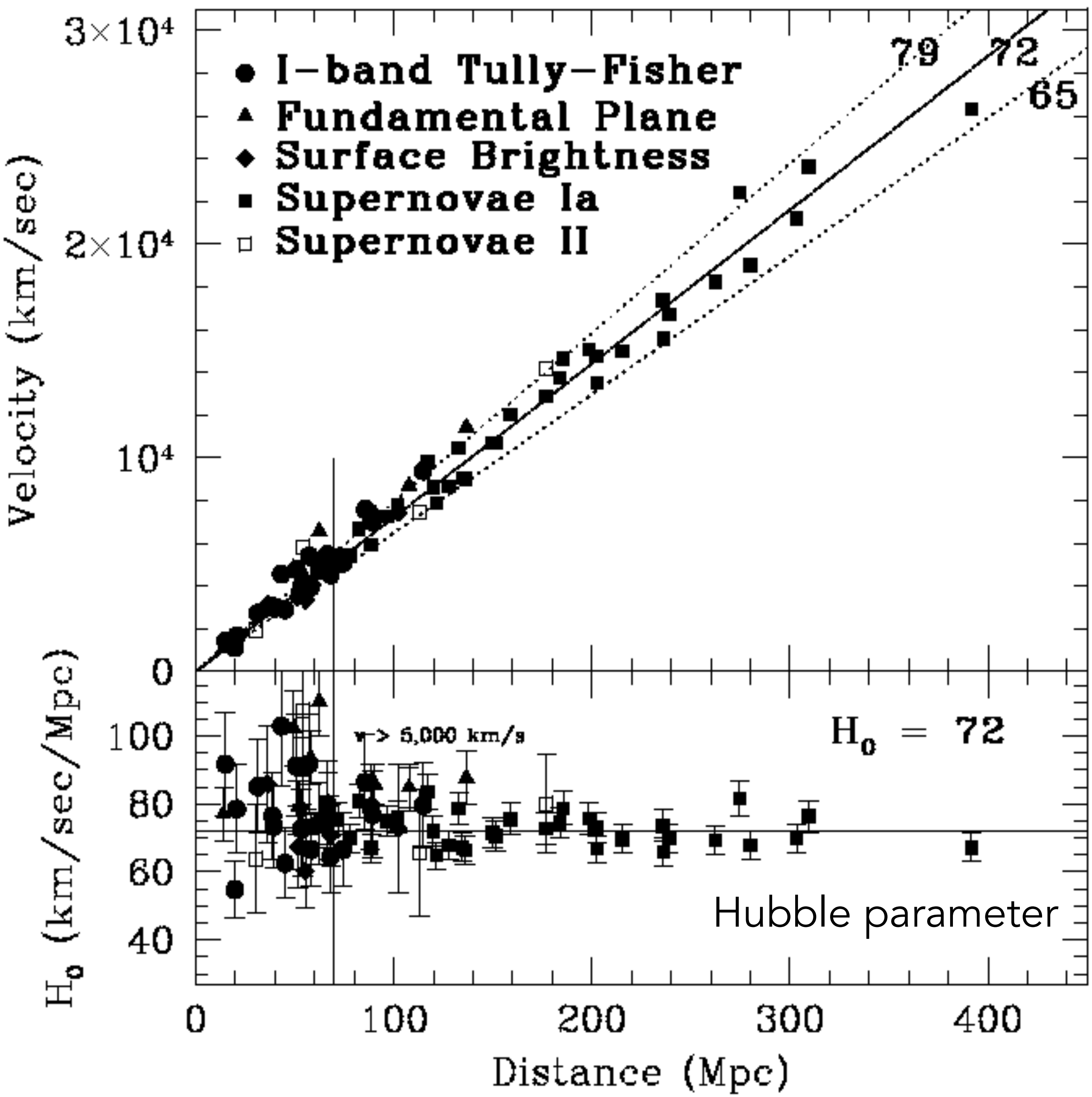
$$v=H_0d$$

A galaxy 100 Million light years away is receding from us at 2000 miles per second.
Modern value: H_0=70 km/sec/Mpc

Modern Hubble Diagram

Hubble Space Telescope Key Project

Freedman etal



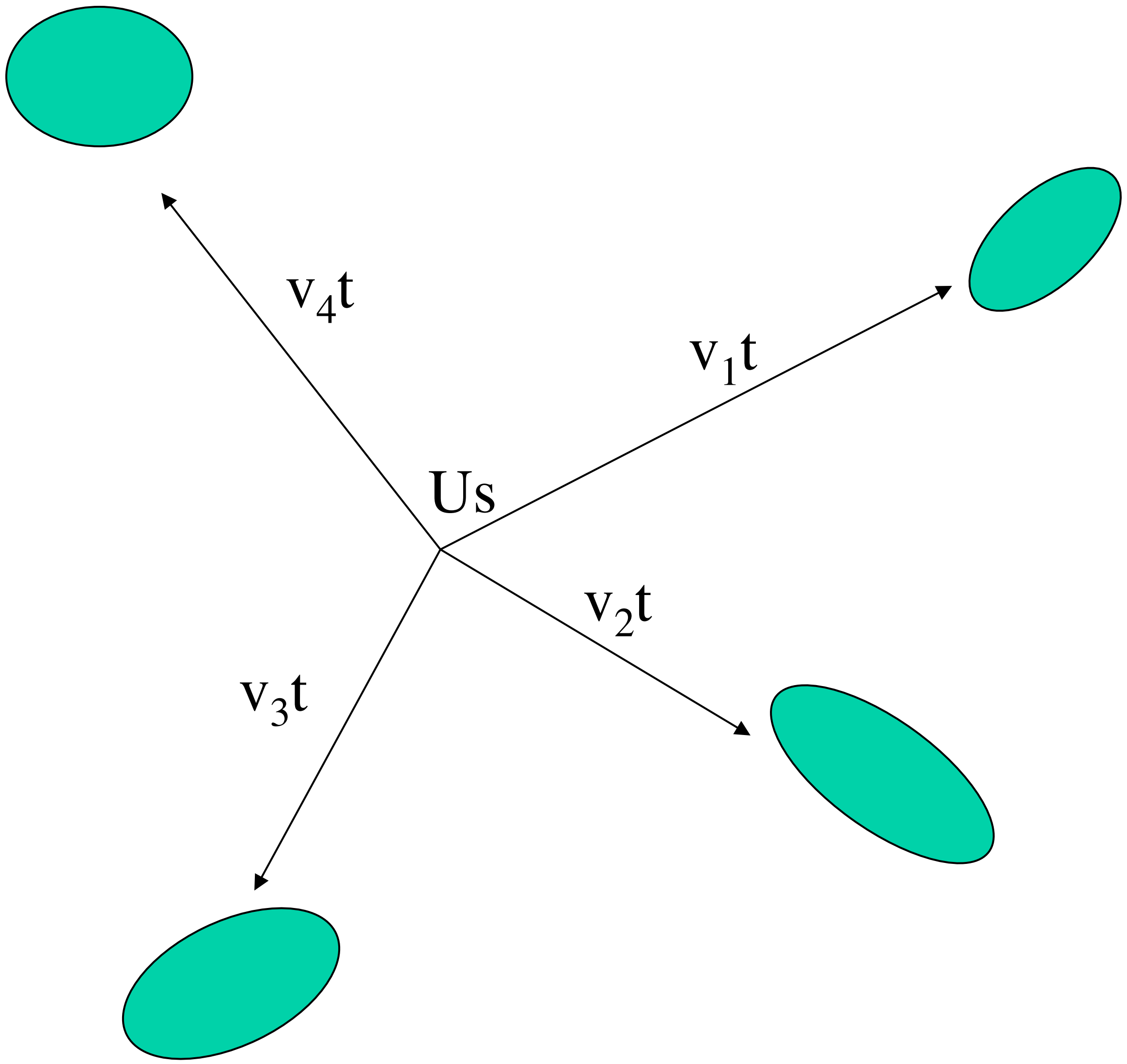
Hubble parameter

Interpretations of Hubble's Law

- Naïve (pre-Copernican) interpretation:
  - We see galaxies distributed around us and receding from us with speeds $v=H_0d$ in all directions. Hence, we live at the Center of the Universe. Tracing their motions backward, we infer an explosion occurred at our location a time t ago:

  - A galaxy moving at (assumed) constant velocity v has travelled a distance $d=vt$, i.e., $v=d/t$. This agrees with Hubble's law $v=H_0d$, if the age of the Universe (since explosion) is

$$t_H = 1/H_0 \qquad \text{(known as the Hubble time)}$$


v_4t
v_1t
Us
v_2t
v_3t

Hubble Time

Hubble (1929):

H_0 = 550 km/sec/Mpc = 170 km/sec/Million-light year

Now

1 M-lightyear = 10^6 light year

= 3×10^5 km/sec x 10^6 yr = 3×10^{11} (km/sec) x yr

Thus

$$t_H = 1/H_0 = \frac{3\text{x}10^{11}\ (\text{km/sec})\ \text{x yr}}{170\ \text{km/sec}} = 1.8 \text{ x } 10^9 \text{ years}$$

But the age of the Earth is about 4.5×10^9 years!

Current value: H_0 = 72 km/sec/Mpc, which implies

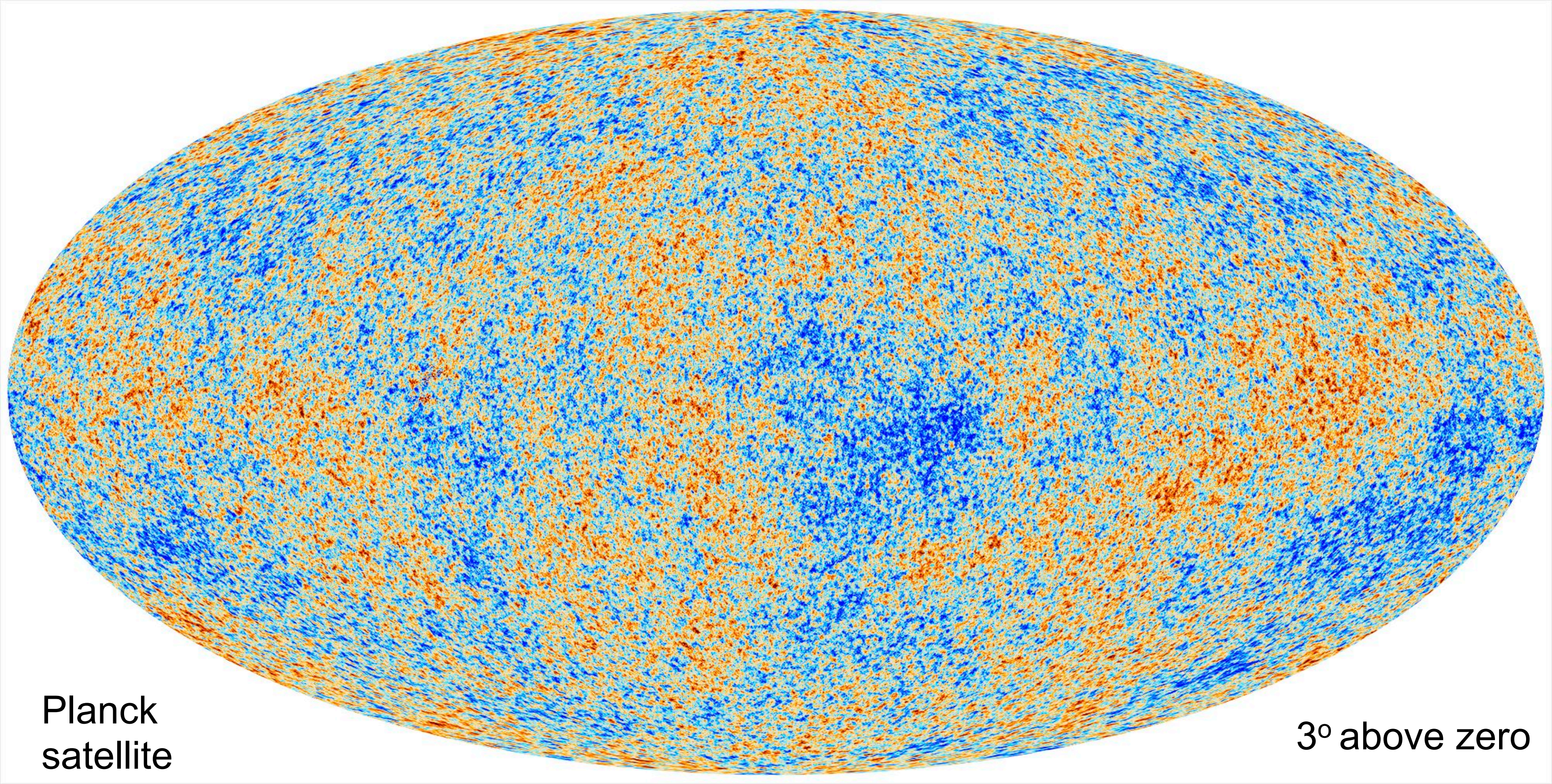
t_H = 14 billion years

(comfortably older than the Earth, consistent with oldest stars)

The Cosmological Principle

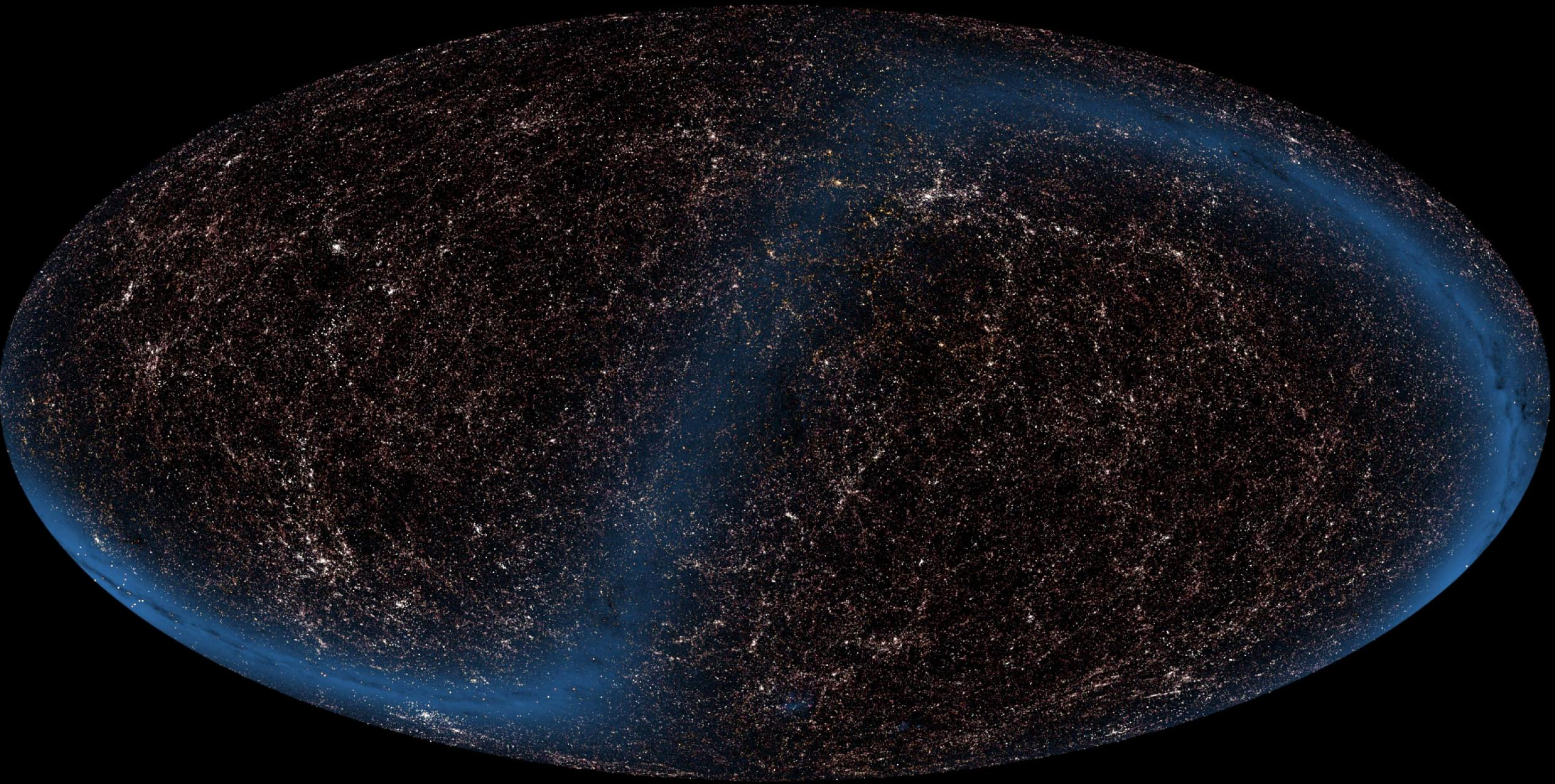
- On large scales, the Universe appears *isotropic* around us: looks on average the same in every direction on the sky.
  - Temperature of the Universe (as measured from the Cosmic Microwave Background) is about 2.7 degrees, within +/- 10^{-5} deg, in all directions
- Let's assume we are not privileged observers: our Galaxy looks much like the others.
- Then the Universe should appear isotropic to *all* observers. In that case, one can show it must be *homogeneous:* have the same properties at every location. In particular, it has no center.

Cosmic Microwave Background Radiation



Snapshot of the Universe when it was only 400,000 years old
Temperature varies by only 0.00001 deg across the sky.

Large-scale Map of Galaxies Today



2MASS Infrared Sky Survey: Universe much lumpier now, but it looks homogenous on large scales.

New Interpretation of Hubble Law

- Instead of us being at the Center, there is no Center: all (comoving) observers will measure the Hubble law, i.e., will see galaxies receding from them with speed proportional to distance.

- The Universe is Expanding.

Expanding Universe

- How can every galaxy appear to be moving away from everyone else, instead of moving away from some galaxies and toward others?

- It only works if recession speed is linearly proportional to distance: $v \sim d$ (not, e.g., $v \sim d^2$)

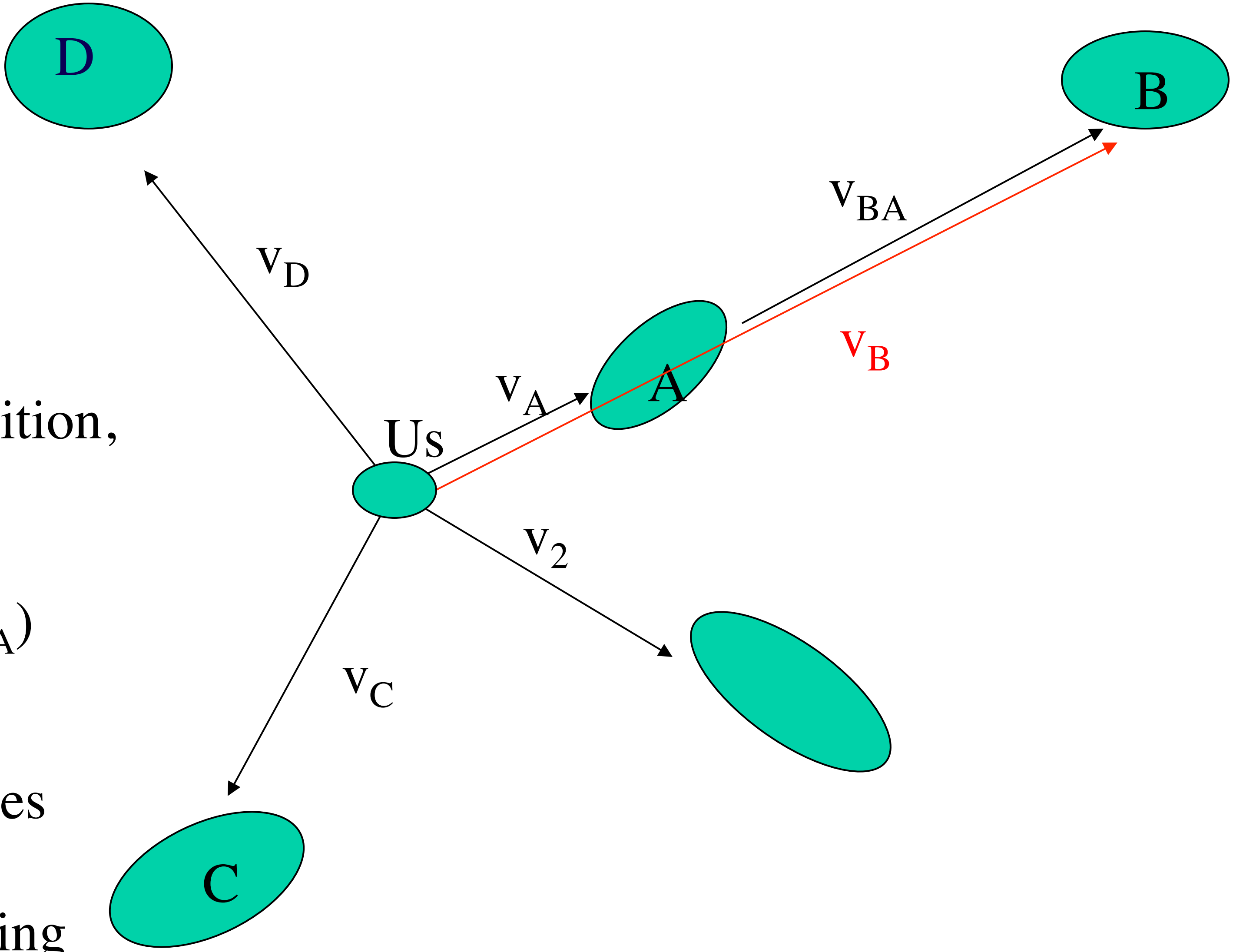
- The Expansion of the Universe preserves homogeneity and isotropy.

We observe Hubble law:

$v_B = Hd_B$
$v_A = Hd_A$

By vector addition,

$$v_{BA} = v_B - v_A$$
$$= H(d_B - d_A)$$
$$= Hd_{BA}$$



Observer A sees Galaxy B recede according to the Hubble Law as well: Hubble's Law is Universal

The Expanding Universe

No reason to assume we are at the Center: observers in all galaxies can see Hubble law

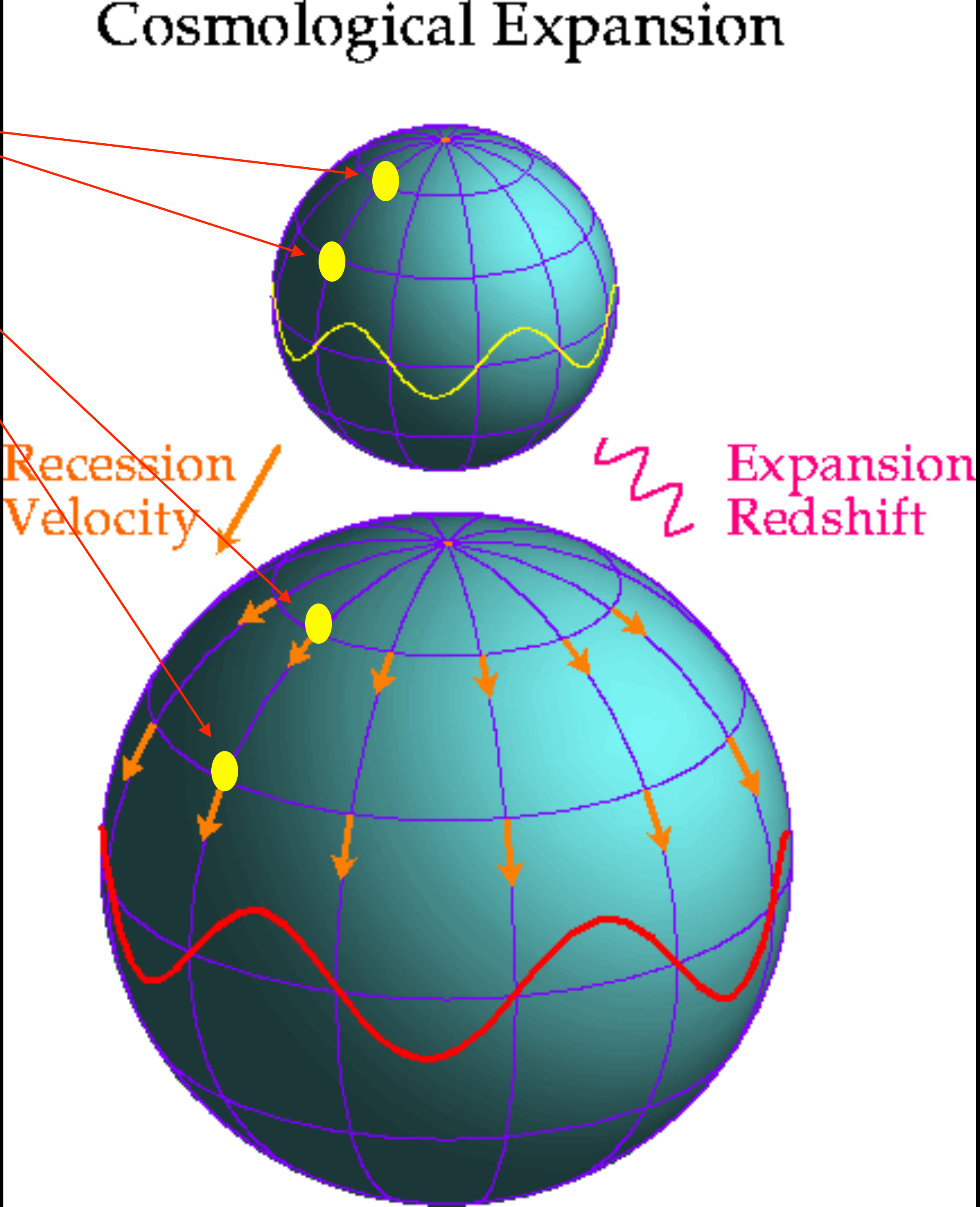
The Expanding Universe

Run it backward: expansion started in a Big Bang 13.8 billion years ago

The distance *between* galaxies increases with time

A galaxy 100 Million light years away is moving away from us at 2000 miles per second.

Galaxies are not expanding: they are bound together by the gravity of dark matter.



On average, galaxies are <u>at rest</u> in these expanding (comoving) coordinates.

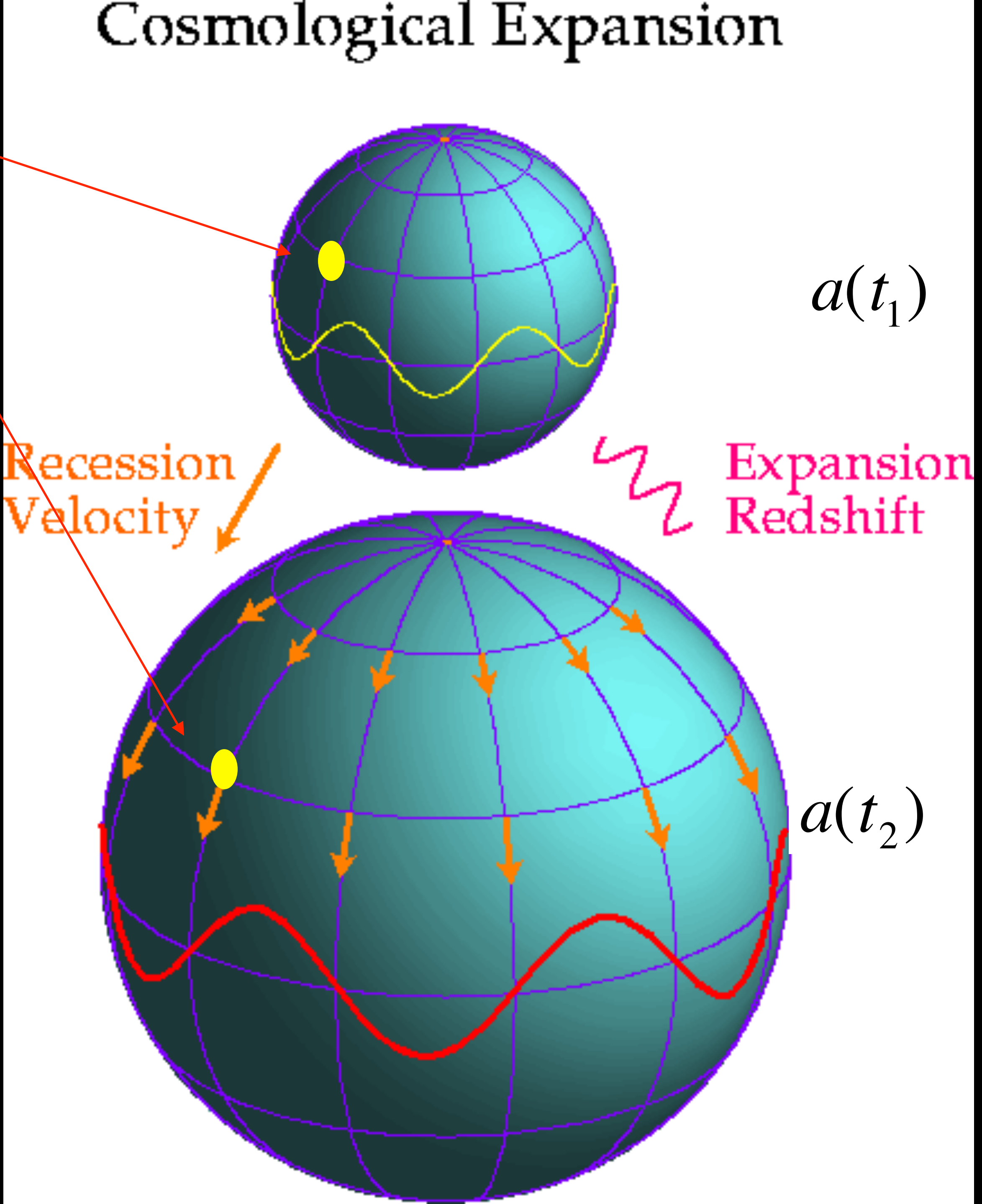
Wavelength of radiation scales with scale factor:

$$\lambda \sim a(t)$$

Redshift of light:

$$1+z=\frac{\lambda(t_2)}{\lambda(t_1)}=\frac{a(t_2)}{a(t_1)}$$

emitted at t_1, observed at t_2



Expansion of the Universe

- The Universe has no center and no edge (that we can see): it looks the same everywhere.
- The expansion is happening everywhere: the Universe is not exploding into empty space.

3D Model

- Think of the Universe as an infinite, yeast-filled raisin cake with some heat source. Each raisin represents a galaxy. As the cake expands due to the heat, the raisins recede away from each other, with a relative speed proportional to their distance from each other.
- Since the cake is infinite, it is not expanding into empty space: the raisin cake IS the Universe.