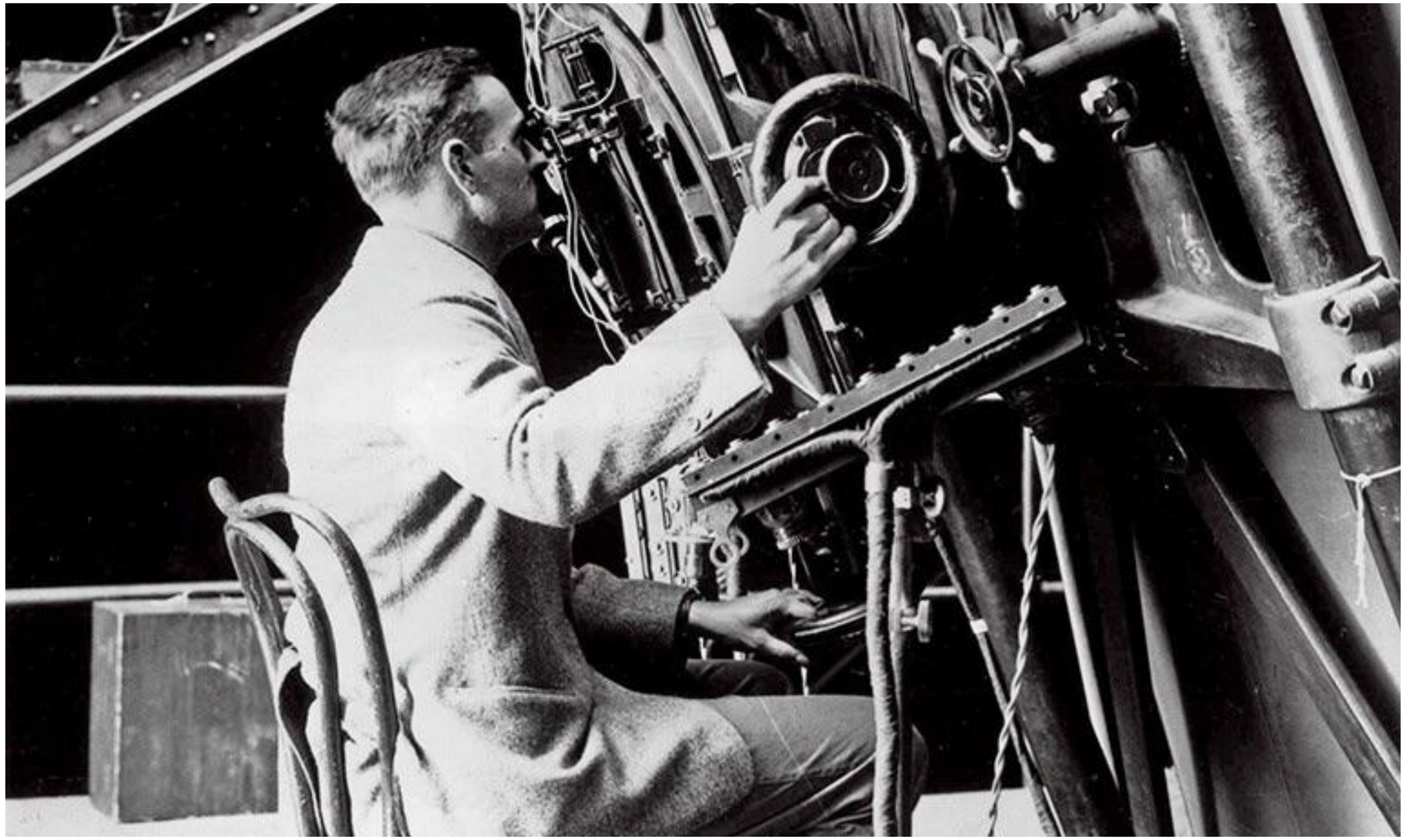
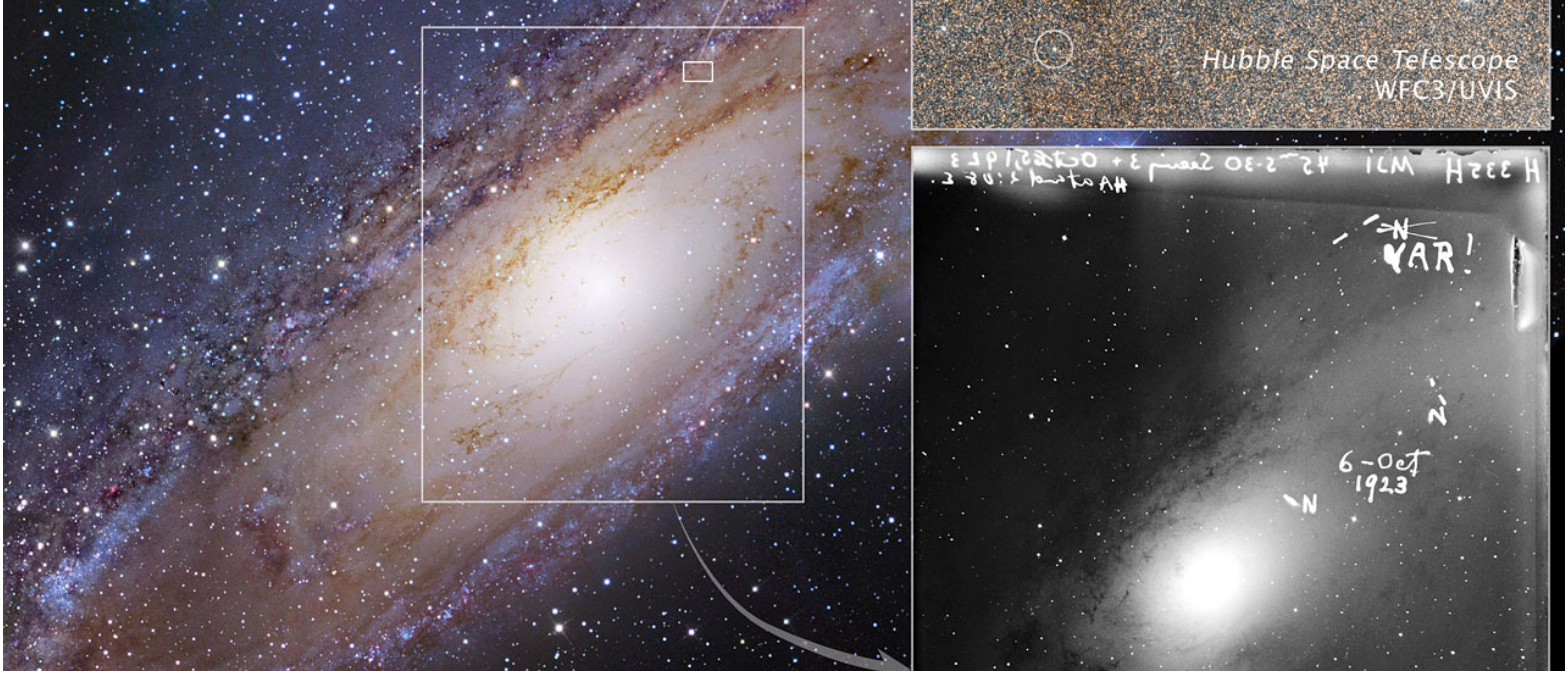
Hubble Trouble



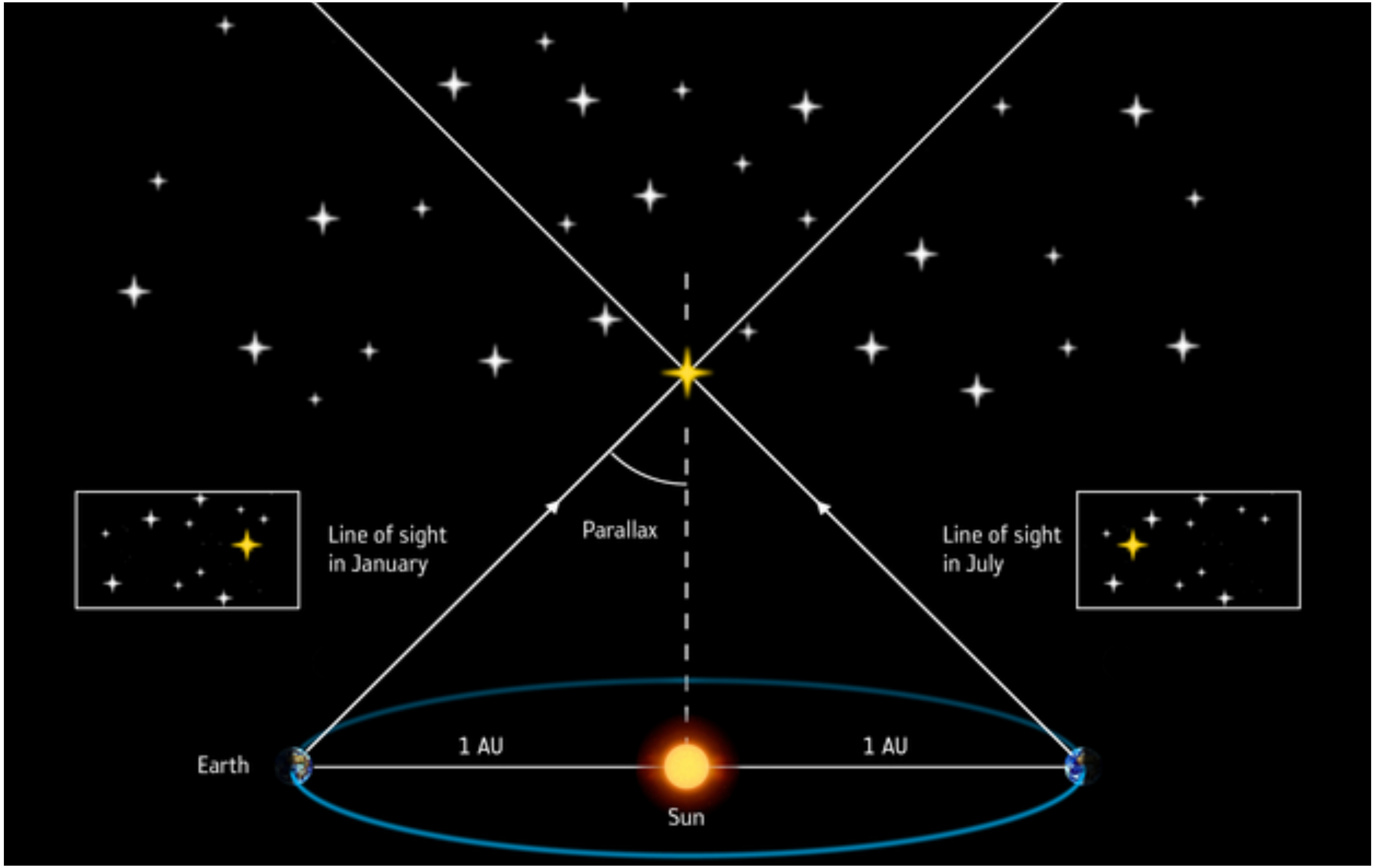
Edwin Hubble in 1922 at the controls of the new 100 inch Mt Wilson Hooker Telescope completed in 1917 and largest telescope until construction of the Hale Telescope on Mt Palomar in 1948



In 1923 Hubble finds a Cepheid Variable star in a nebula called M31 or the Andromeda Galaxy. The Wattage (luminosity) of this star can be found just by measuring its period. The apparent brightness of this Cepheid helped him work out the distance to M31 as 1 MLy, now revised to 2.5 MLy. Not taking dust into consideration, Shapley estimated our own Milky Way galaxy was 300,000 Ly across (now revised to 100 000 Ly). M31 was too far away to be inside our own Milky Way galaxy!

Finding Distances to Nearby Stars

First rung in the Cosmic Ladder (Zero Point) Parallax



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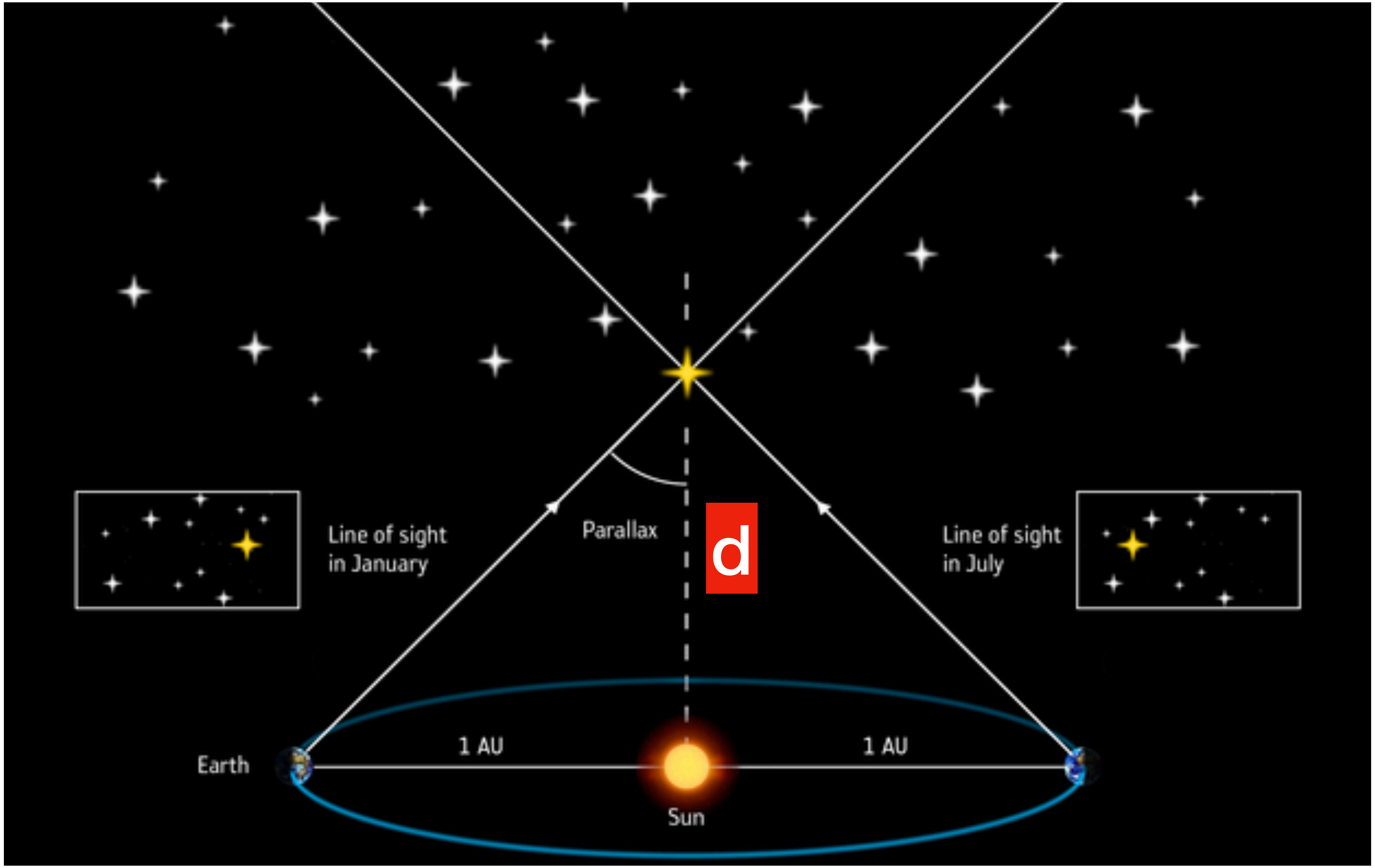
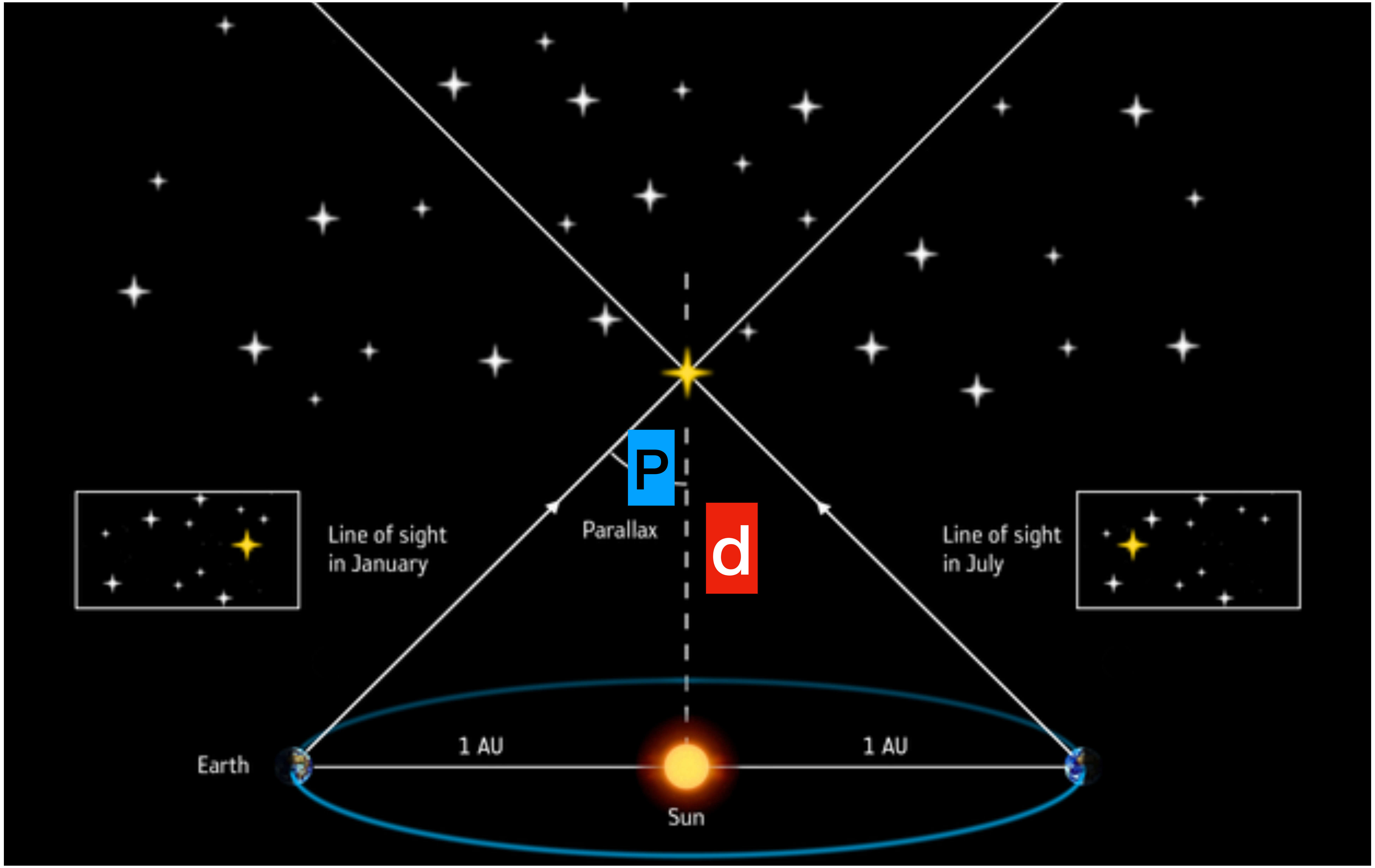


Distance to nearby star is "d"

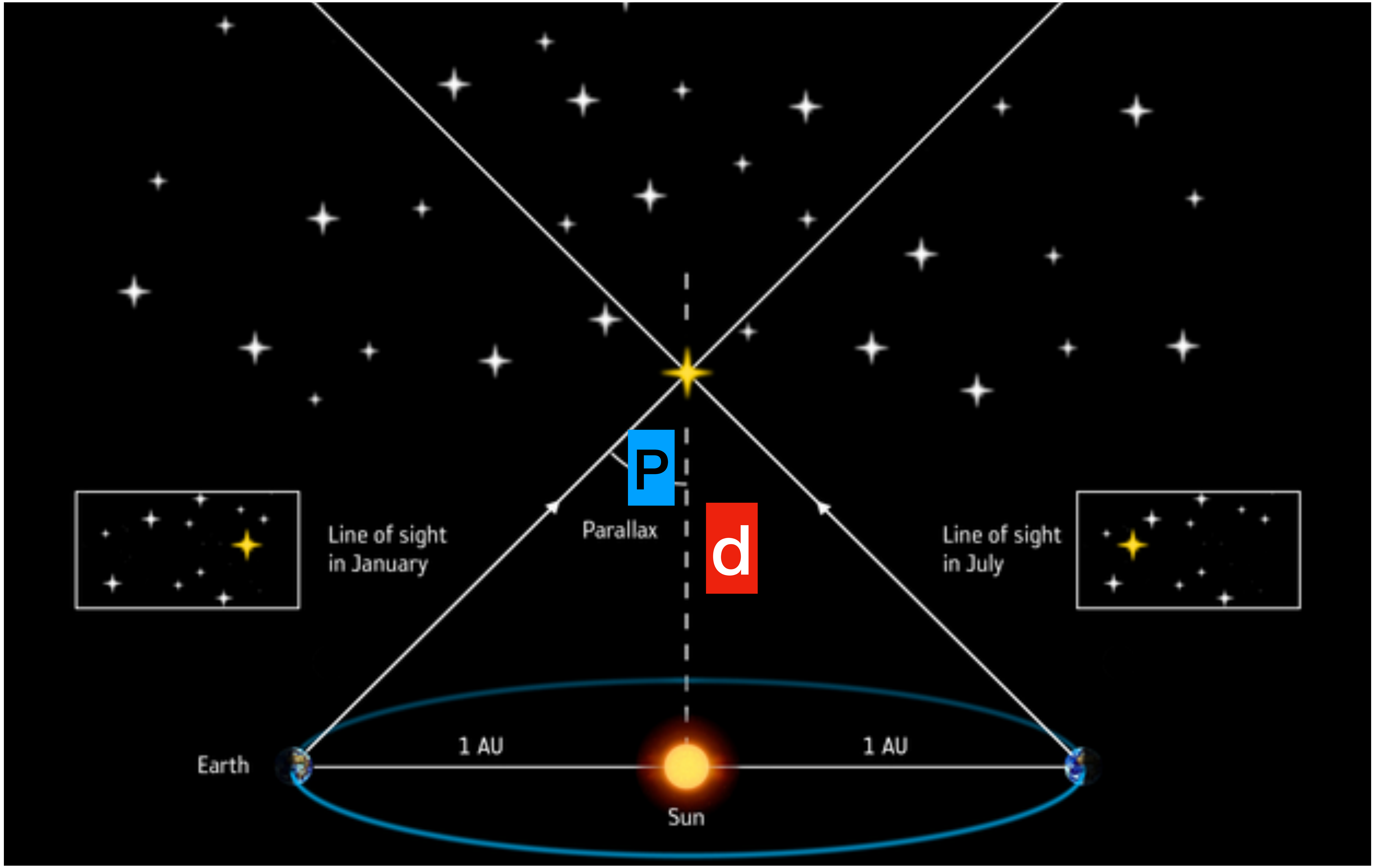
Finding Distances to Nearby Stars
First rung in the Cosmic Ladder (Zero Point) Parallax



Parallax angle is p

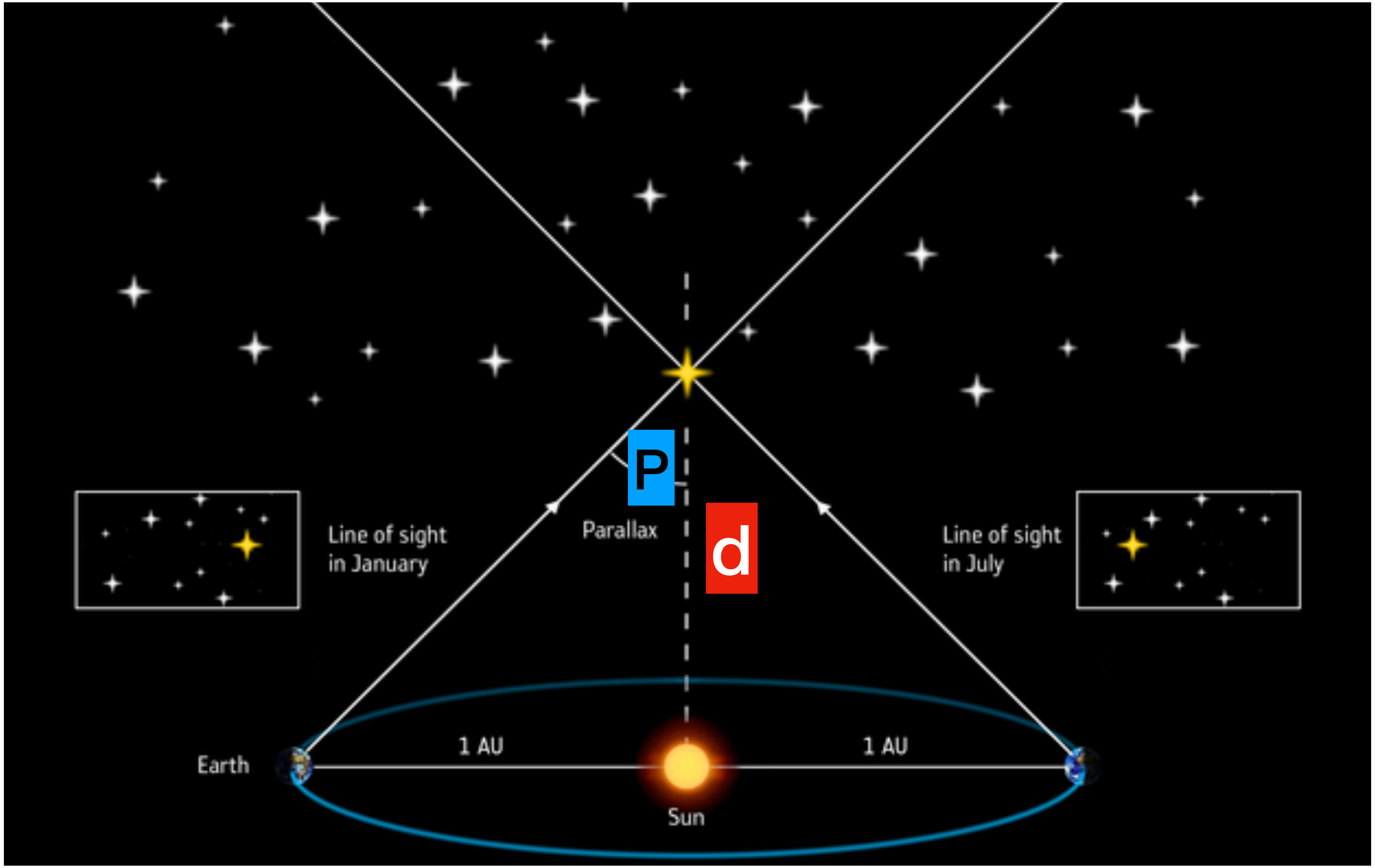
Finding Distances to Nearby Stars

First rung in the Cosmic Ladder (Zero Point) Parallax



Tan p =1A.U/d

Finding Distances to Nearby Stars
First rung in the Cosmic Ladder (Zero Point) Parallax



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For small angles, tan p = p

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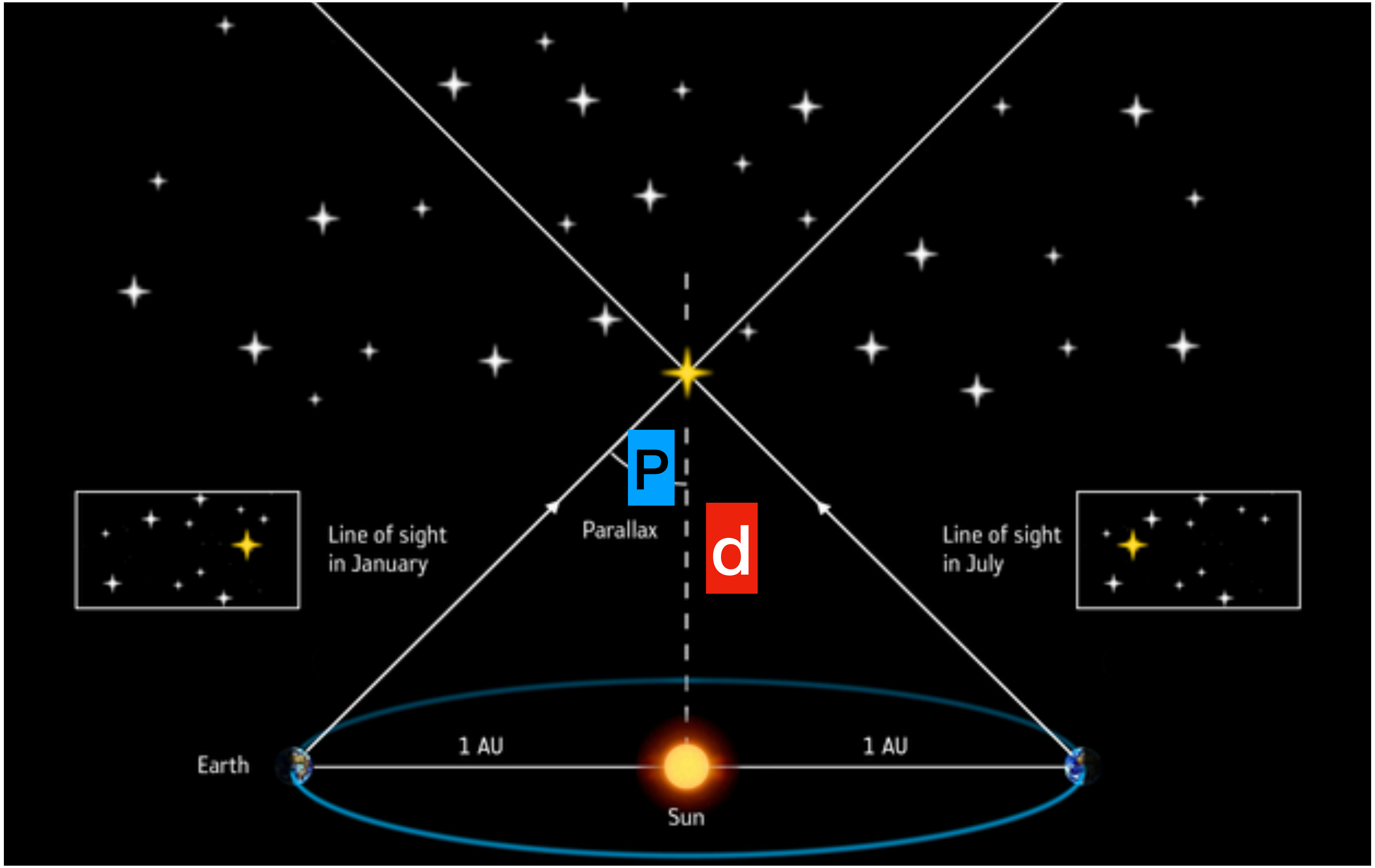

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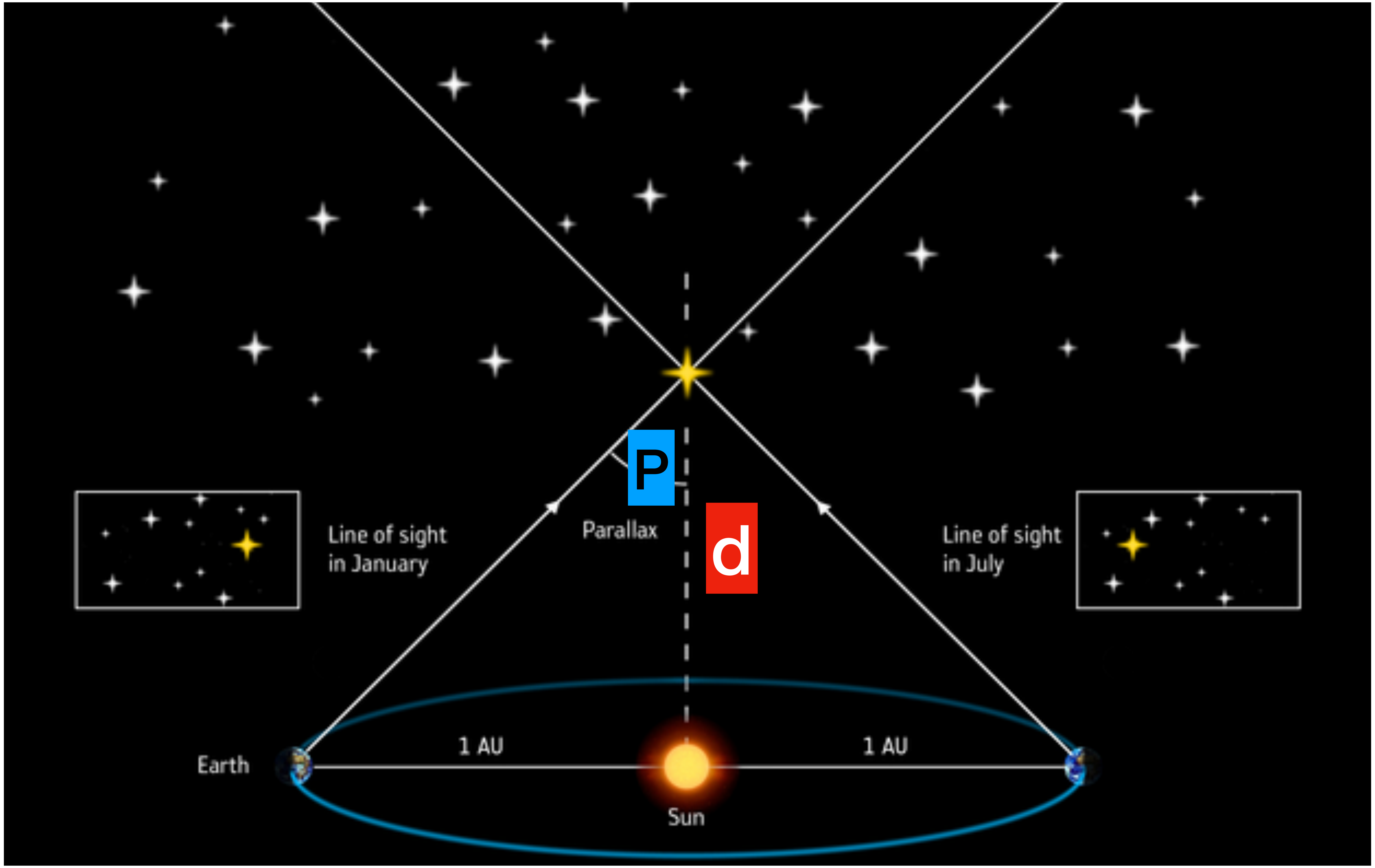

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P = 1 A.U/d

Unit = 1 second
=1/60 X1/60 degree

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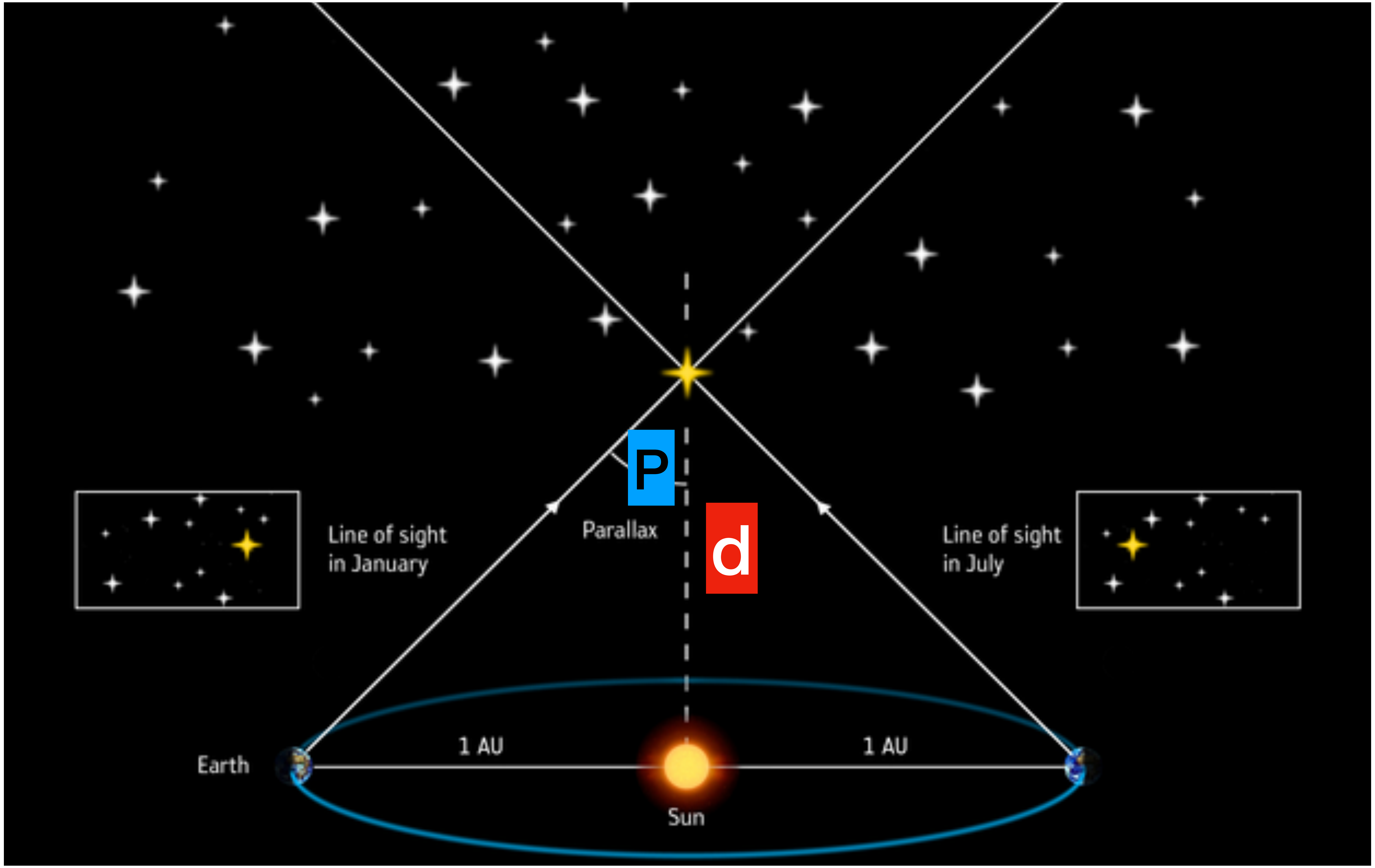


Tan p =1A.U/d

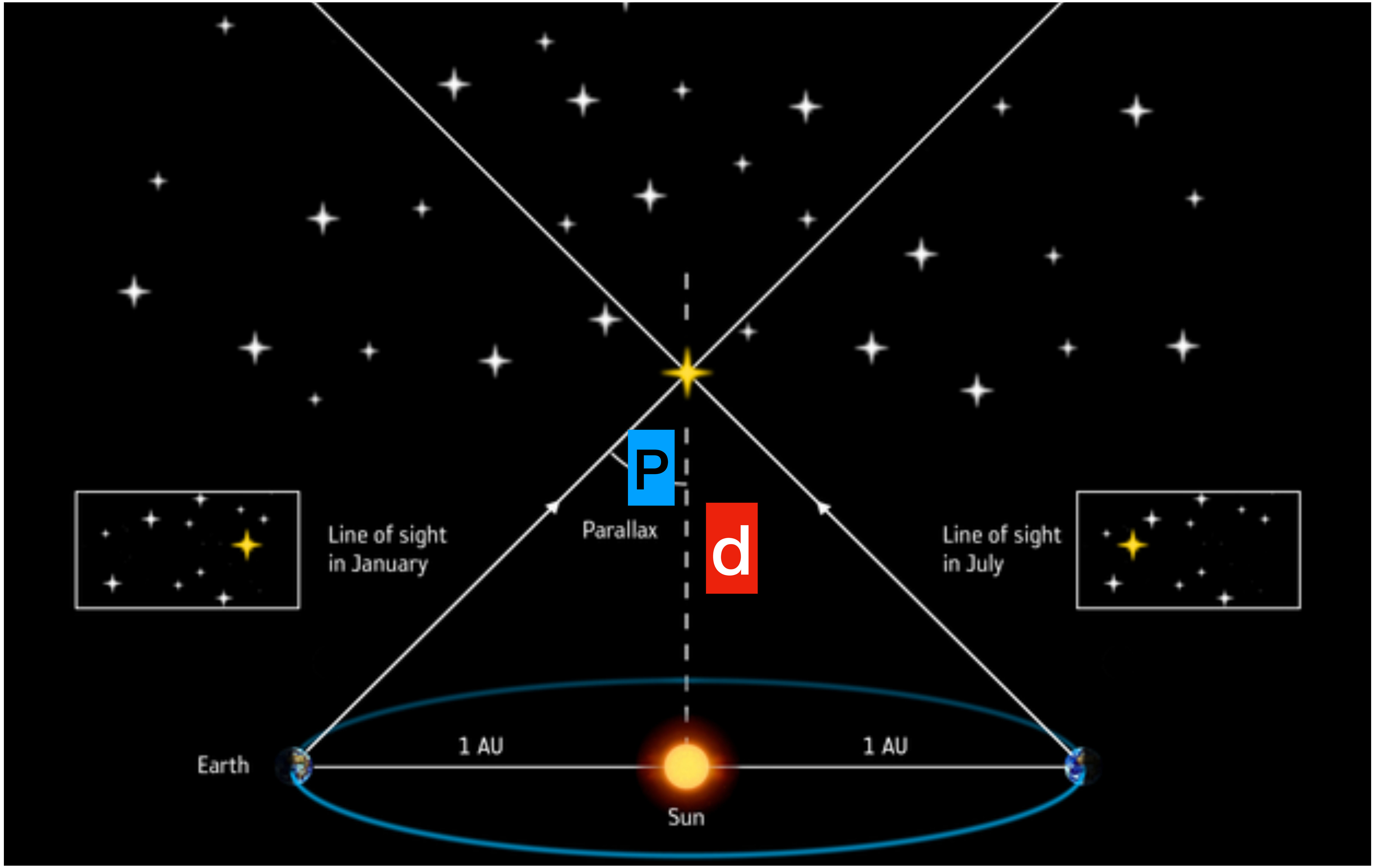
For small angles, tan p = p

P = 1 A.U/d

Unit = 1 second =1/60 X1/60 degree

D = 1 A.U. / p

Finding Distances to Nearby Stars
First rung in the Cosmic Ladder (Zero Point) Parallax



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If p is in seconds of arc D is in units of parsecs or pc

Finding Distances to Nearby Stars

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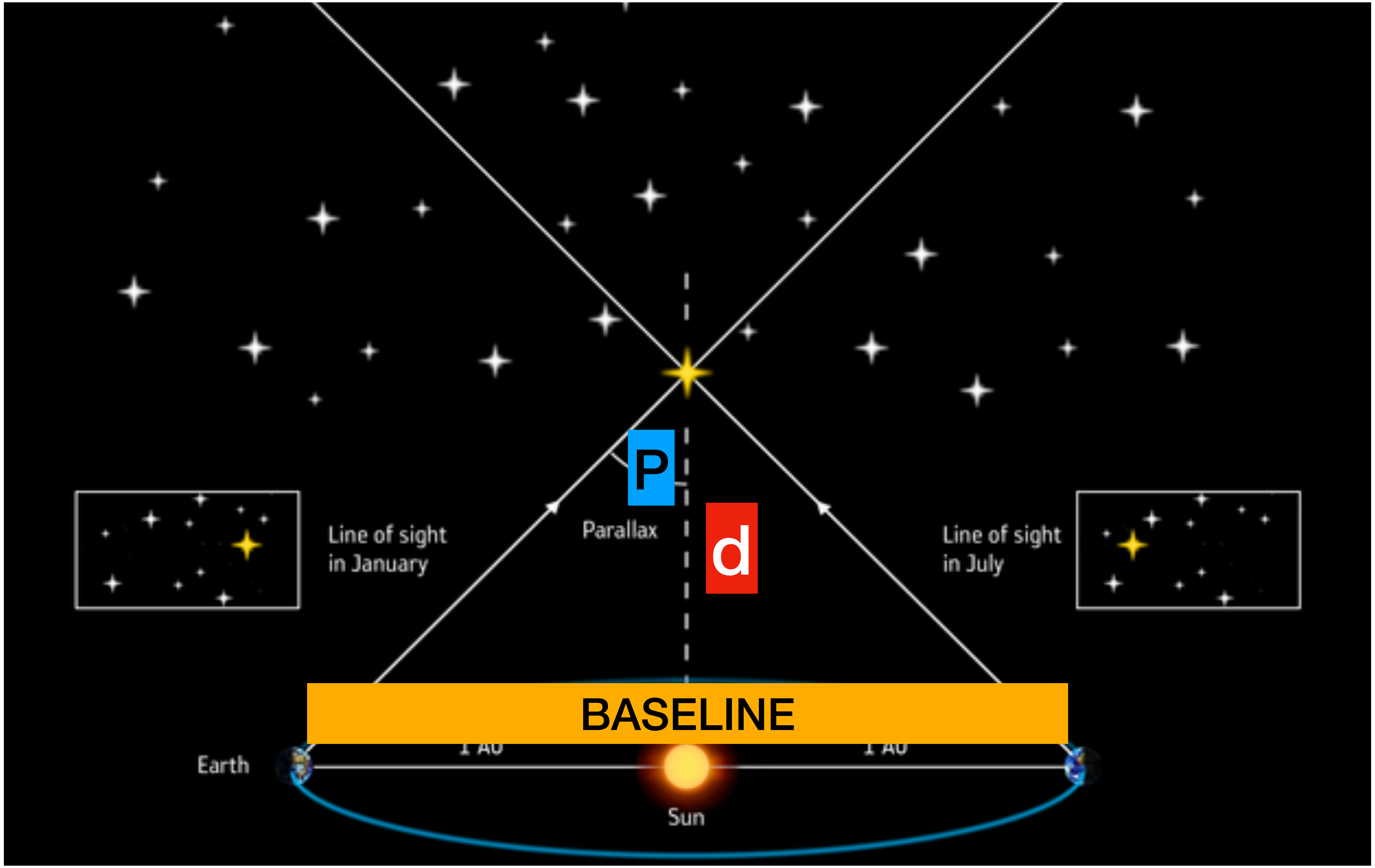

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P = 1 A.U/d

Unit = 1 second =1/60 X1/60 degree

D = 1 A.U. / p

If p is in seconds of arc D is in units of parsecs or pc

Note: Baseline = 2 A.U.

How much is a parsec?

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1 parsec (pc) = 206 265 AU
= 30.9 trillion (10^{12}) km
= 3.26 light years

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Fun Exercise:

Prove the above using d =1 A.U / p

Hint: Change p = 1 sec of arc into degrees and then to radians
Another hint: pi radians = 180 degrees
Your answer is in A.U (earth-sun distance)
Note: 1 A.U. = 150 million km
Speed of light is 3.0 X 10^ 5 km/s

Limitations of Parallax Method of Finding distances

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* Nearby stars also move relative to us, even in a half-year between measurements of the parallax angle: PROPER MOTION

* Nearby stars hard to observe against backdrop of bright distant stars, galaxies and interstellar dust

Parallax Distance Limit: history

Instrument Used	Measured P	D = 1/p	Today's Value: Gaia
Split-lens Refractor 6 inches Built by Fraunhofer	0.314 arc seconds 61 Cygni	3.18 pc 10.4 Ly	3.5 pc 11.4 LY


Friederich Bessel 1838

Maximum Distance Limit: 10 pc or 33 Ly
Small telescope objective, atmospheric blurring
No photographic plate: just eye and micrometer device to measure angles (Heliometer)
Could measure distance to only a dozen stars

Parallax Distance Limit: history

Harlow Shapley 1918
Shapley used parallax and Cepheids to get first reasonable measure of size of Milky Way. He incorrectly conjectured Milky Way galaxy was entire Universe

Instrument Used	Measured P	D = 1/p	Today's Value: Gaia
Much larger Telescopes Up to 100 inch Hooker 1917	0.37 arc seconds Sirius	2.7 pc 8.8 Ly	2.6 pc 8.6 LY

Maximum Distance Limit: 100 pc or 326 Ly
Larger telescopes, atmospheric blurring photographic plates
Could measure distance to only a hundred stars

Parallax Distance Limit: history

Willard Boyle 1970's-80's
Canadian Nobel Physics 2009
His work on CCD's or Charge Coupled Devices ushered in more sensitive astrometry at all wavelengths

Instrument Used	Measured P	D = 1/p	Today's Value: Gaia
Much larger Telescopes 200 inch more CCD photography	0.75 arc seconds Alpha Centauri	1.3 pc 4.3 Ly	1.3 pc 4.3 LY

Maximum Distance Limit: 500 pc or 1630 Ly
Much Larger telescopes , atmospheric blurring
CCD photography replace photographic plates
Could measure distance to eight thousand stars

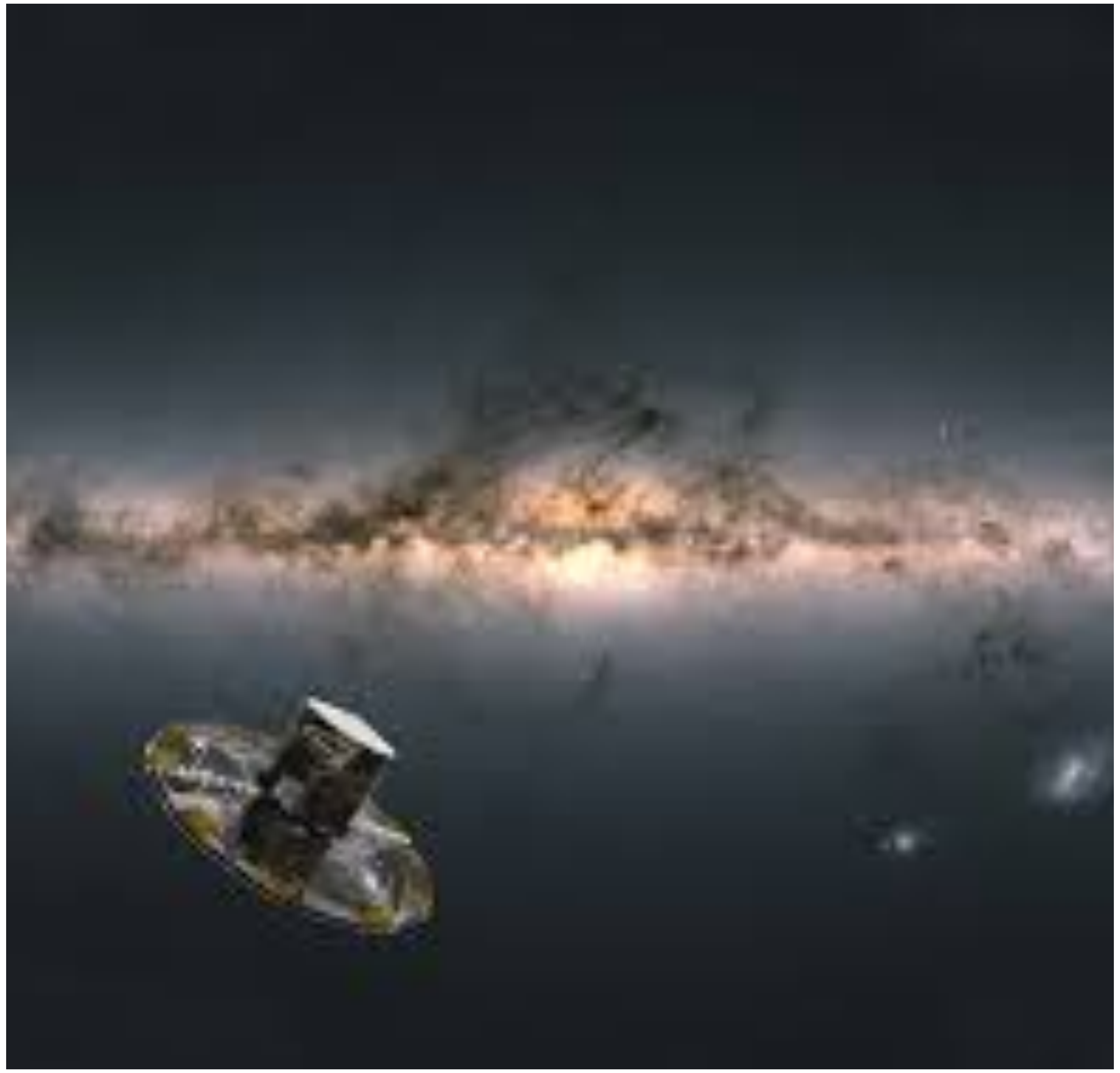
Parallax Distance Limit: history

Hipparcos Space Telescope
1989 -1993 NASA
Designed for parallax distance astrometry

Instrument Used	Measured P	D = 1/p	Today's Value: Gaia
Space-based Telescope 11 inch CCD photography	0.00754 arc seconds Polaris Cepheid	132.6 pc 432.5 Ly	136.9 pc 446.5 LY

Maximum Distance Limit: 1 kpc or 3.26 kLy
No atmospheric blurring
CCD photography replace photographic plates
Could measure distance to 2.5 million stars

Parallax Distance Limit: history



Gaia Astrometry Mission
2014-2025
ESA

Instrument Used	Measured P	D = 1/p	Today's Value: Gaia
Space-based Telescope Two 1.45 m by .5 m Mirrors 10 m sunscreen CCD photography	0.76807 arc seconds Proxima Centauri	1.302 pc 4.246 Ly	1.302 pc 4.246 Ly

Maximum Distance Limit: 10 kpc or 32.6 kLy
No atmospheric blurring, sensitive near IR (infrared wavelengths)
CCD photography replace photographic plates
Could measure distance to 2 billion stars
More to come in data release 4 (DR4)

Key Ideas of Geometric Parallax to find distances to Stars

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* direct measure of distance to stars

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* direct measure of distance to stars

* Even with the accuracy of the Gaia parallax measurements, we can only measure up to about 30 000 Ly, about a third of the distance across the disk our Milky Way galaxy

How can we measure distances beyond the Milky Way?

How can we measure distances beyond the Milky Way?

* Need Very Bright “Standard Candles” with a known Power or Luminosity L (Watts=Joules/second) [Energy per time]

How can we measure distances beyond the Milky Way?

Apparent Brightness or Flux =
Luminosity / (area of sphere at a distance away from the star)

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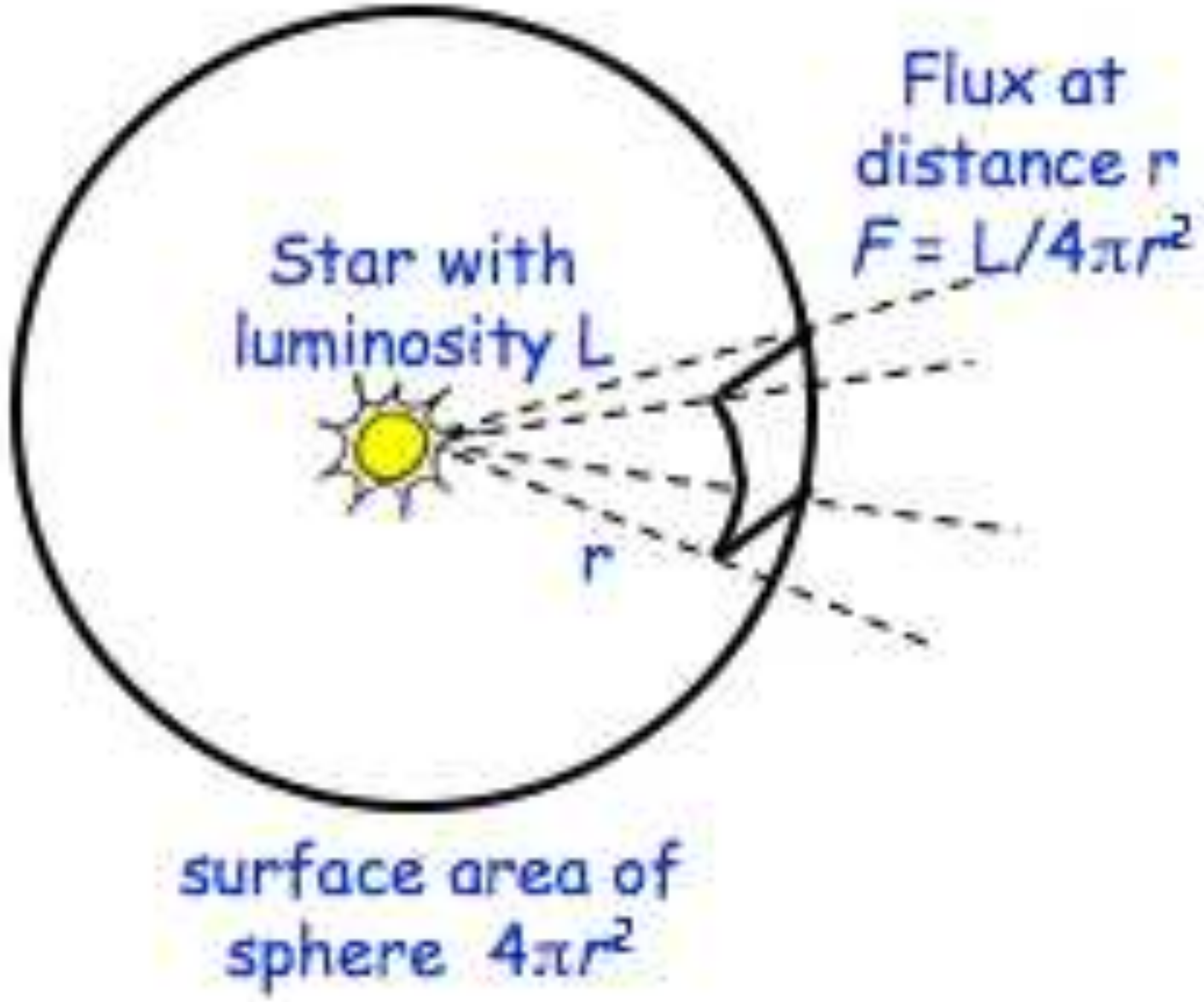
F = L / (4 * pi * D ^ 2)

How can we measure distances beyond the Milky Way?

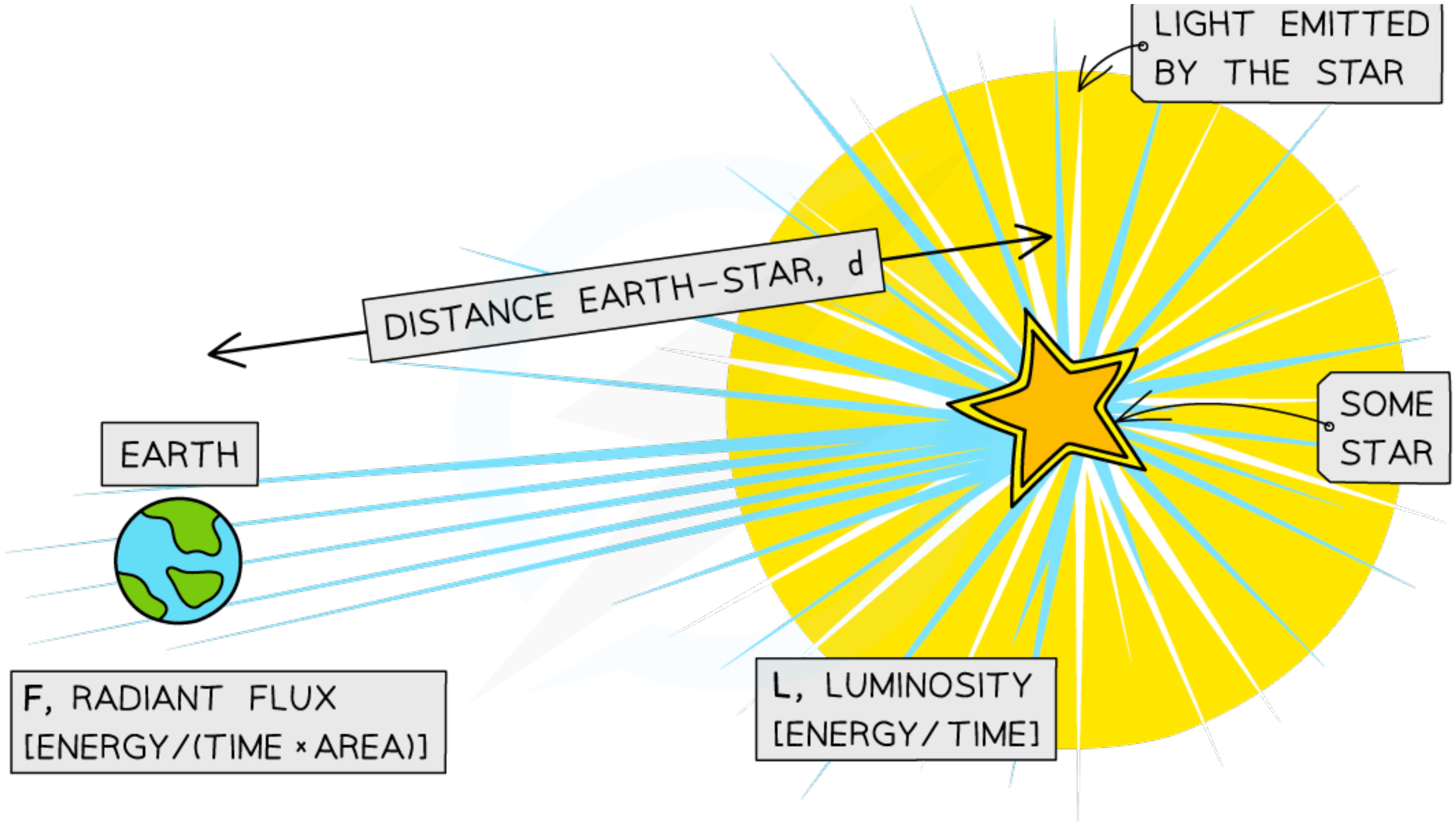
Apparent Brightness or Flux = Luminosity / (area of sphere at a distance away from the star)

$F = L / (4 * pi * D ^ 2)$ [Units = W/m^2]

Brightness follows the Inverse square law



Flux at
distance r
F = L/4πr²
Star with
luminosity L
r
surface area of
sphere 4πr²



Ratio of energy in Joules striking a surface per second per square meter is constant all over the sphere

Calculating the Sun’s distance using flux

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L of the sun = 3.8 X 10 ^ 26 Watts

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Suppose we measure the energy of the sun's light hitting 1 square meter of solar panel each second

Calculating the Sun's distance using flux

L of the sun = 3.8 X 10 ^ 26 Watts

Suppose we measure the energy of the sun's light hitting 1 square meter of solar panel each second

= Flux from sun

= Solar constant

= 1400 W /m^2

Calculating the Sun's distance using flux

F = L / (4 * Pi * d ^ 2)

Calculating the Sun's distance using flux

$$F = L / (4 * \pi * D ^ 2)$$

Solve for D

$$D = \text{square root } (L / 4 * \pi * F)$$

Calculating the Sun's distance using flux

F = L / (4 * pi * D ^ 2)

Solve for D

D = square root (L / 4 * pi *F)

D = square root (3.8 X 10^26 /(4 X pi X 1400)

Calculating the Sun's distance using flux

F = L / (4 * pi * D ^ 2)

Solve for D

D = square root (L / (4 * pi *F))

D = square root (3.8 X 10^26 /(4 X pi X 1400))

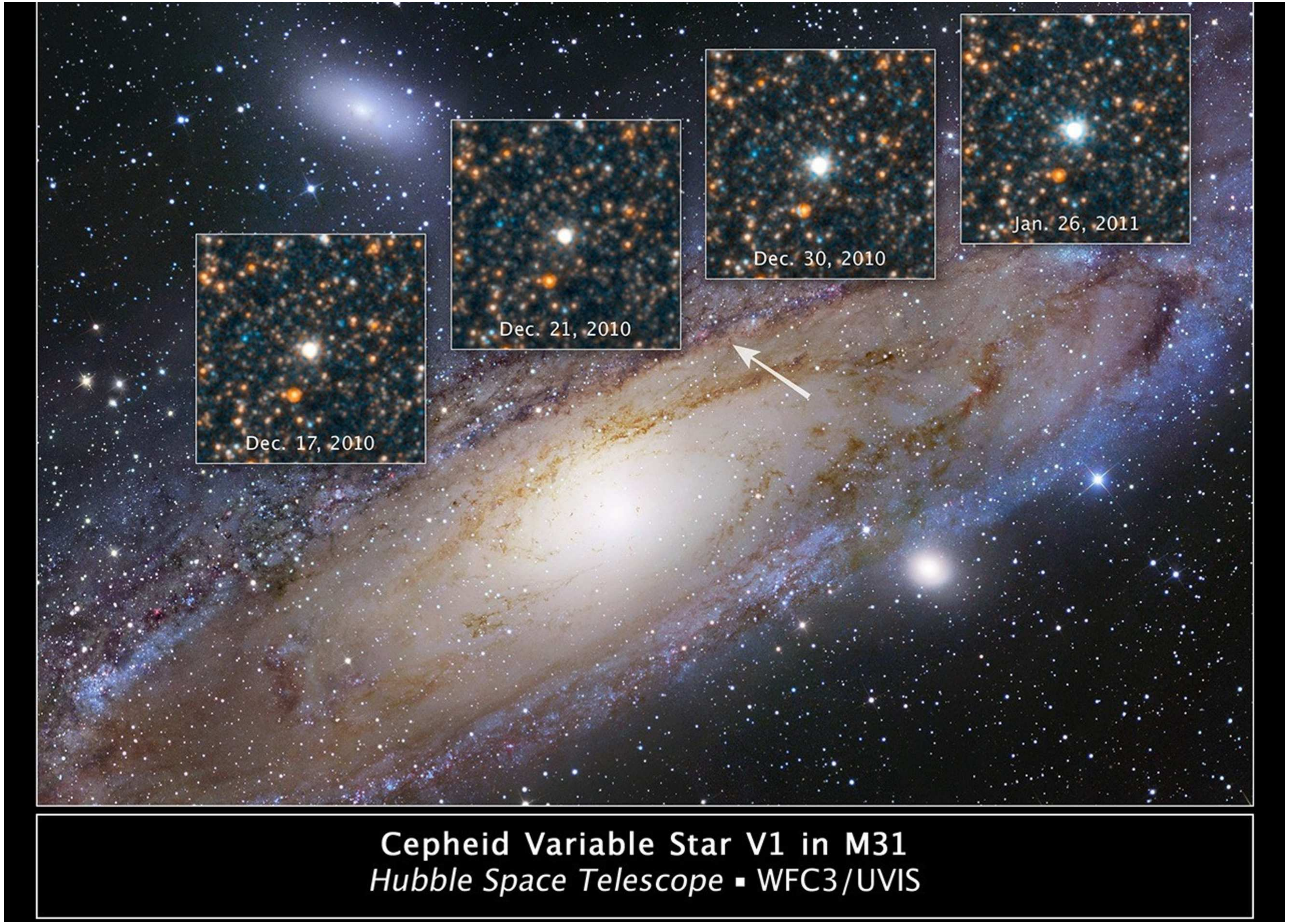
= 1.5 X 10 ^ 11 m or 1 A. U.

How can we measure distances to other galaxies?

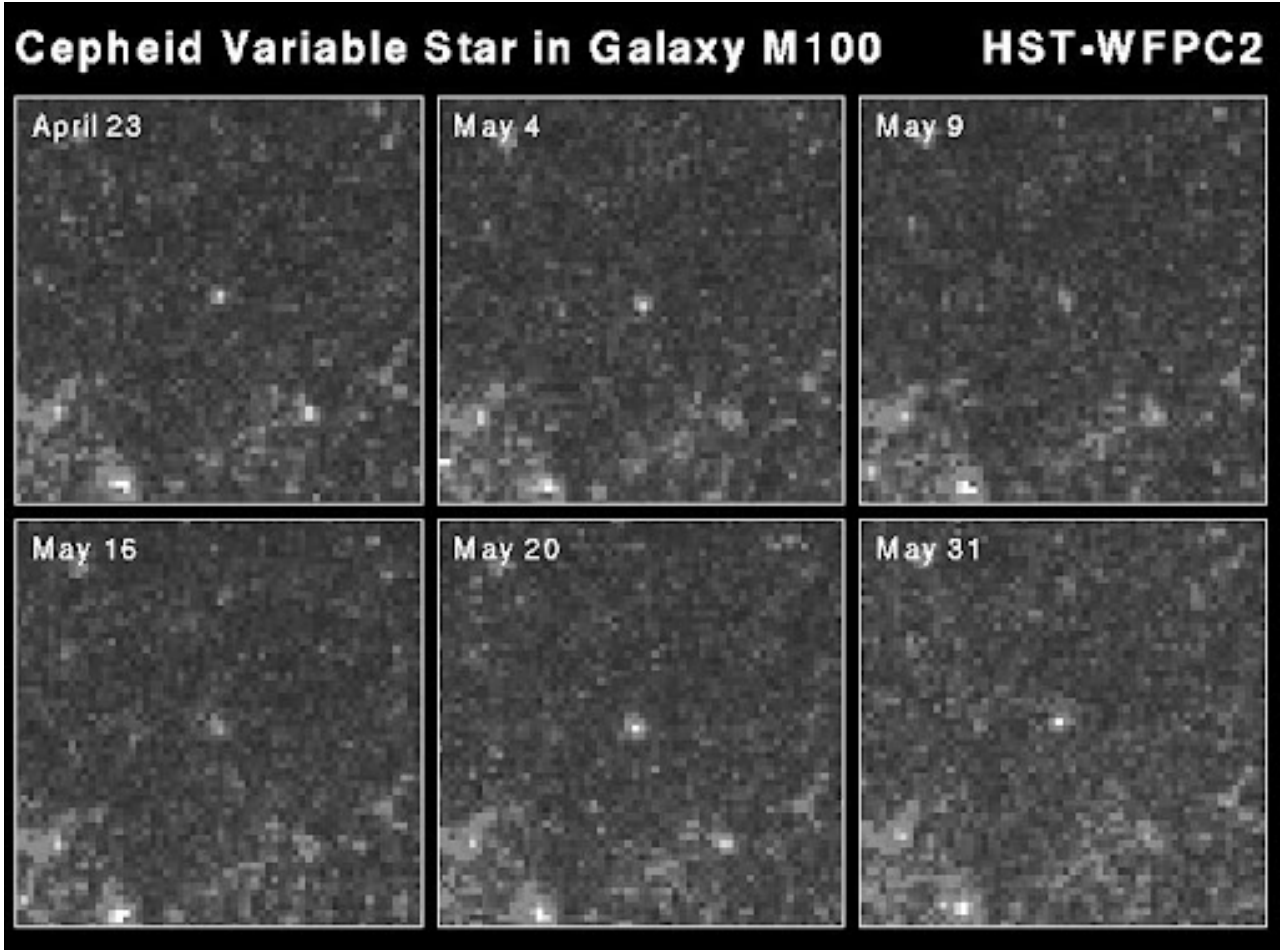
How can we measure distances to other galaxies?

Henrietta Leavitt 1912

As a “computer” of Harvard Observatory, Leavitt examined Cepheid variable stars in a small satellite galaxy of the our own Milky Way Galaxy called the Small Magellanic Cloud (SMC) . These dying stars pulsate both in brightness, diameter, and temperature.



V1, the famous Cepheid star that Hubble used to find the distance to M31.
The universe was bigger than the our Milky Way Galaxy! (1923)



A more recent photo of a Cepheid variable 51 million light years away in M100. Between 1908 and 1912, Henrietta Leavitt was the first to study and realize their importance to determine distances beyond our Galaxy!

How can we measure distances to other galaxies?

Henrietta Leavitt 1912

Leavitt was the first to determine several important attributes of Cepheids

How can we measure distances to other galaxies?

Henrietta Leavitt 1912

Leavitt was the first to determine several important attributes of Cepheids

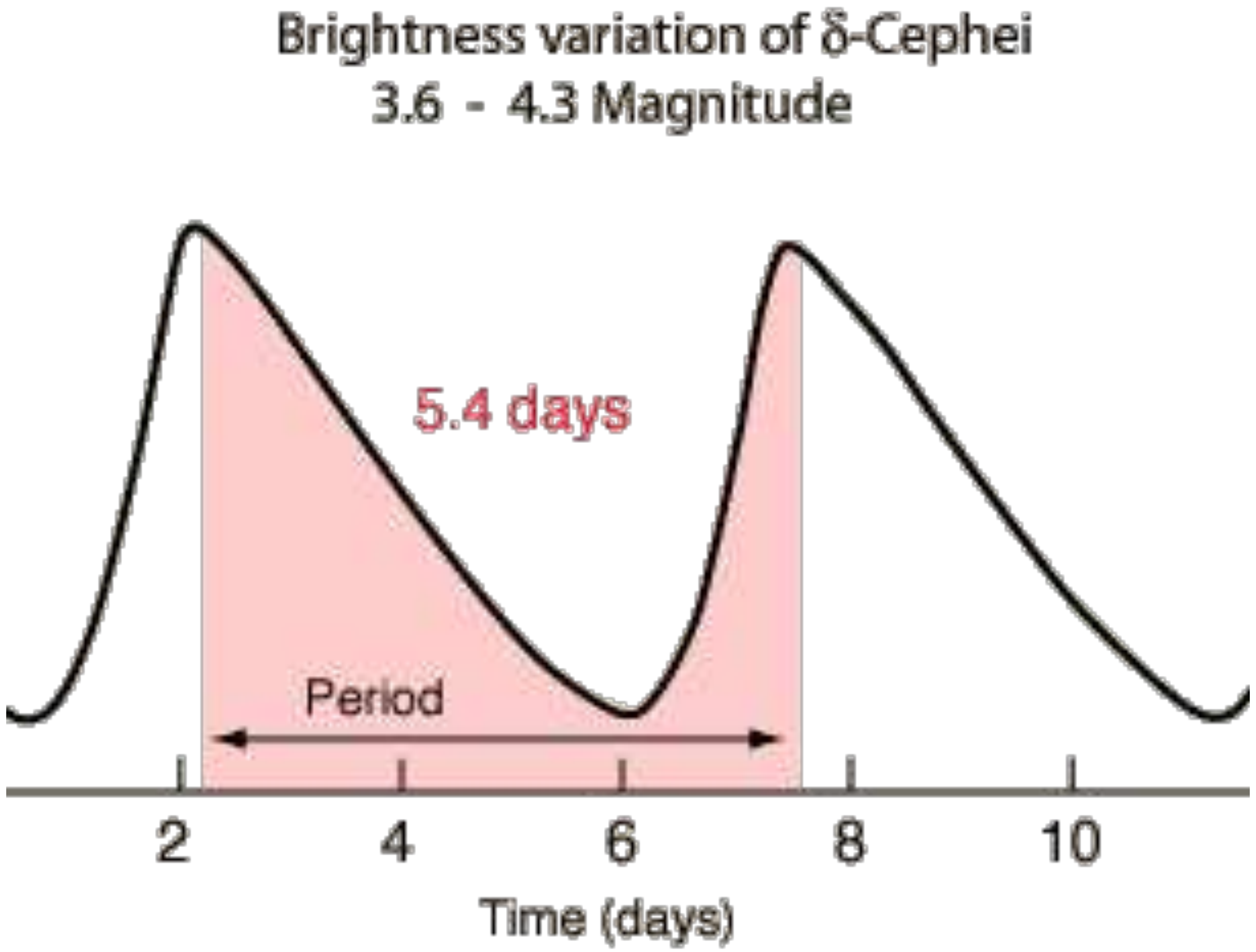
* Cepheids were extremely bright, luminous stars that were found not only in SMC, but in our own galaxy and other "nebula" as well

How can we measure distances to other galaxies?

Henrietta Leavitt 1912

Leavitt was the first to determine several important attributes of Cepheids

* All Cepheids had a definite period of pulsation

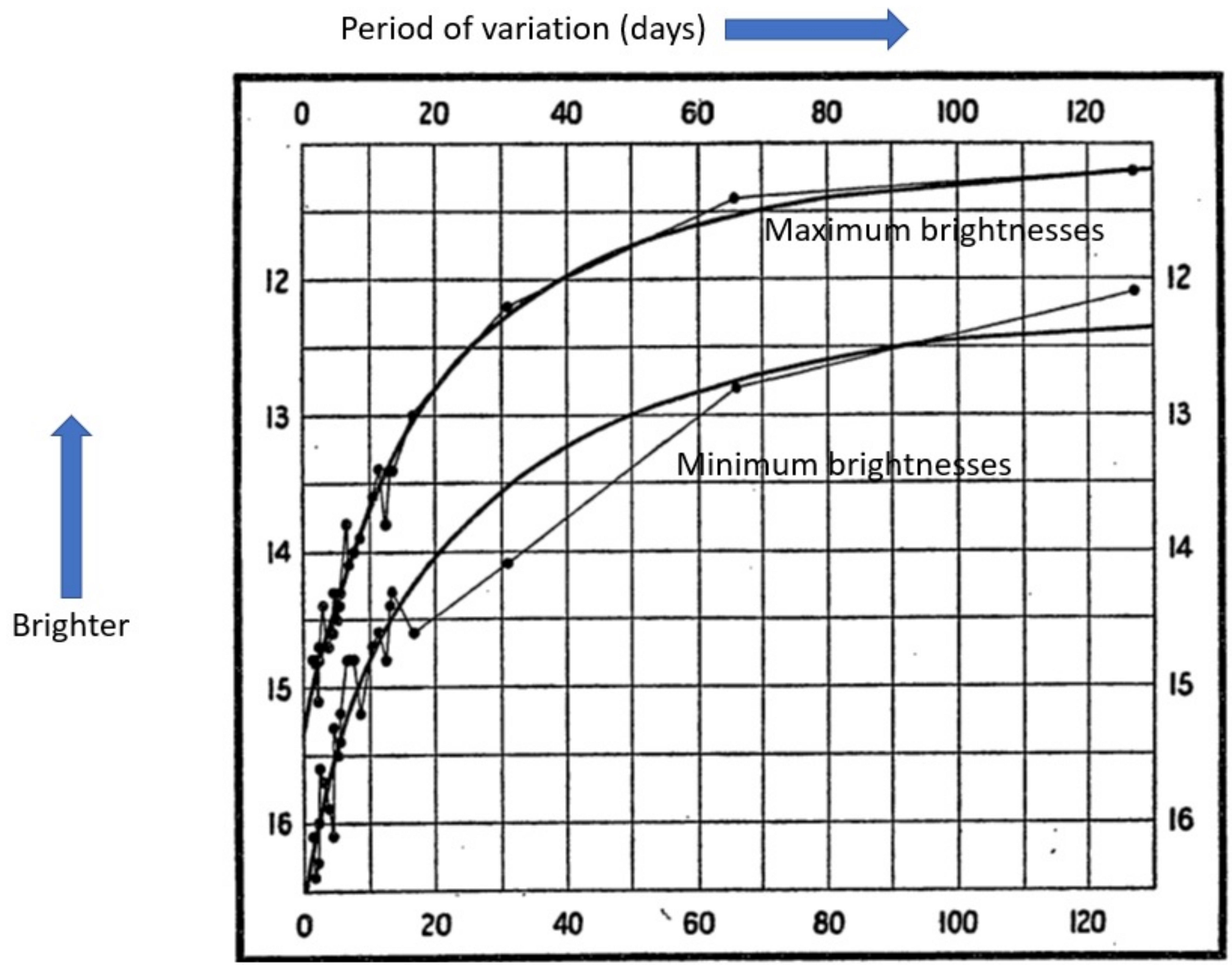


How can we measure distances to other galaxies?

Henrietta Leavitt 1912

Leavitt was the first to determine several important attributes of Cepheids

* As the period of the Cepheid increased, the apparent brightness or "flux" increased in a very predictable mathematical way as well



1912 graph by Leavitt of Cepheid stars “Flux” or “Apparent Brightness” in SMC vs period

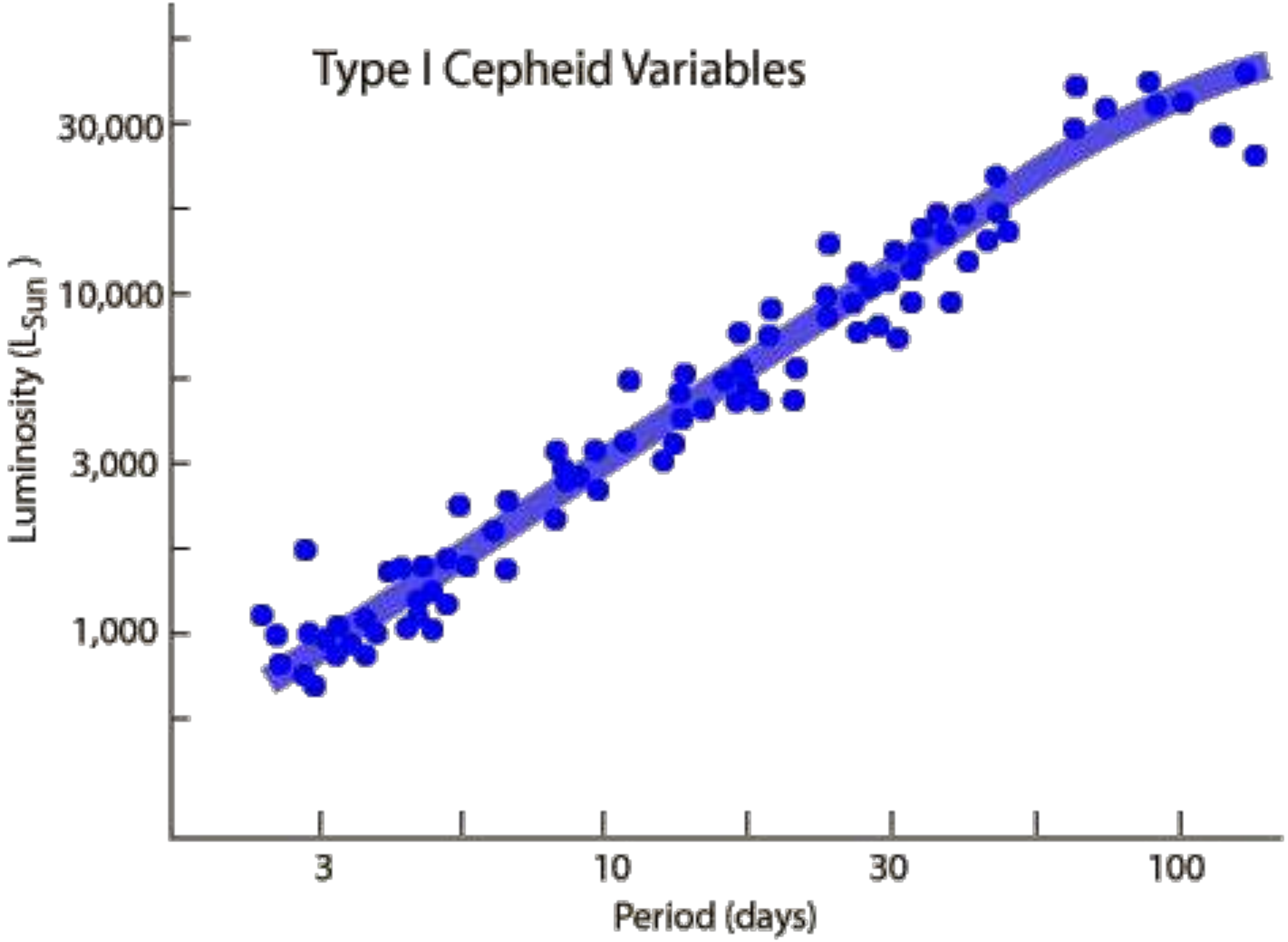
How can we measure distances to other galaxies?

Henrietta Leavitt 1912

Leavitt was the first to determine several important attributes of Cepheids

* Since all the Cepheids in the SMC were the same distance away, Leavitt concluded that their flux or brightness was directly proportional to each star's Luminosity by F = L / (4 * pi *d ^ 2)

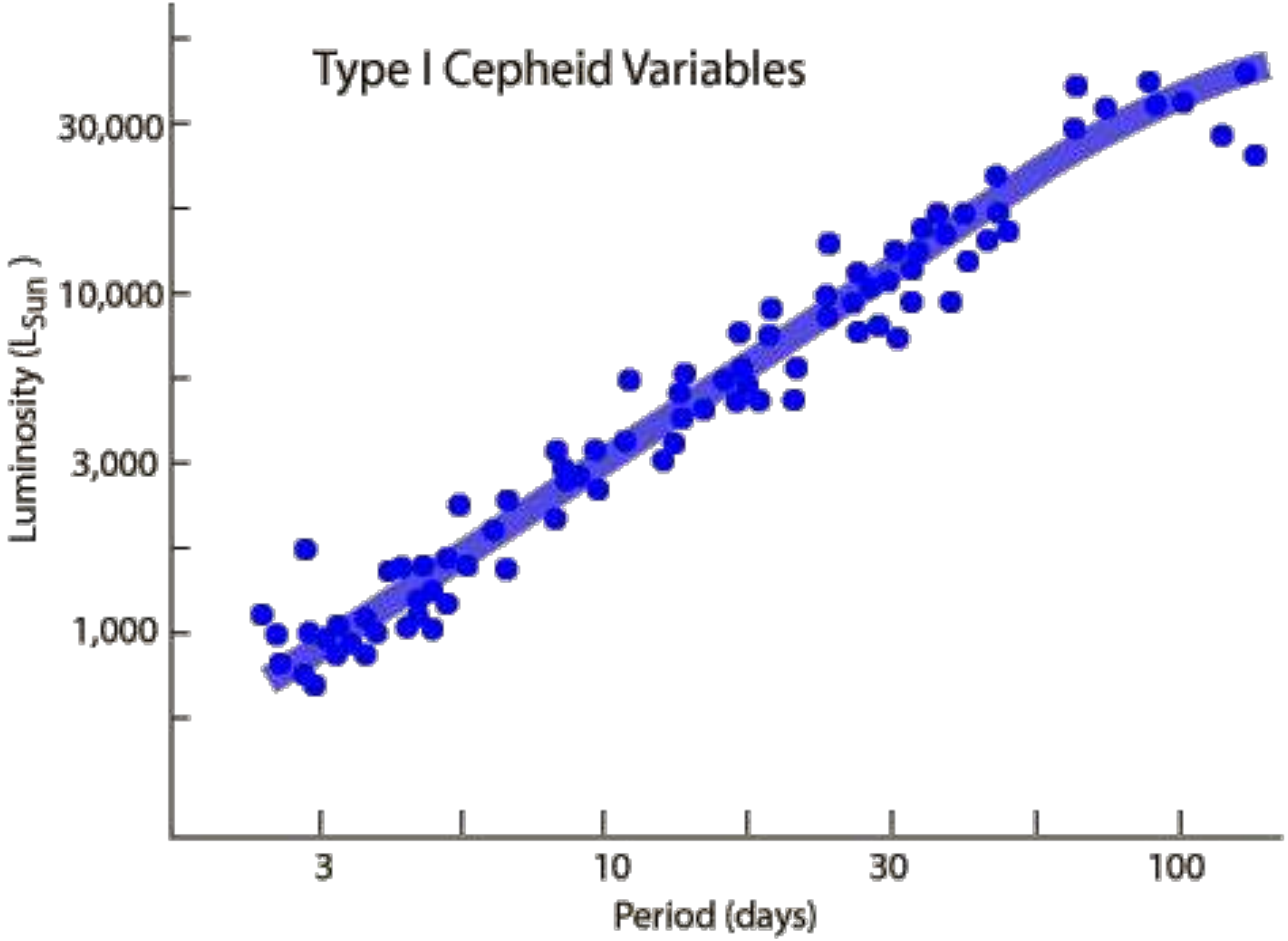
Leavitt asserted the apparent brightness or "flux" on the vertical axis could be replaced with the actual luminosity of the Cepheid.



"Leavitt" Period - Luminosity Relation for Cepheids

This was done by measuring distances to nearby Cepheid stars like Polaris and delta Cephei in our own Galaxy by parallax. Using the inverse square formula, luminosity can be easily calculated.

F = L / (4 * pi * d ^ 2)

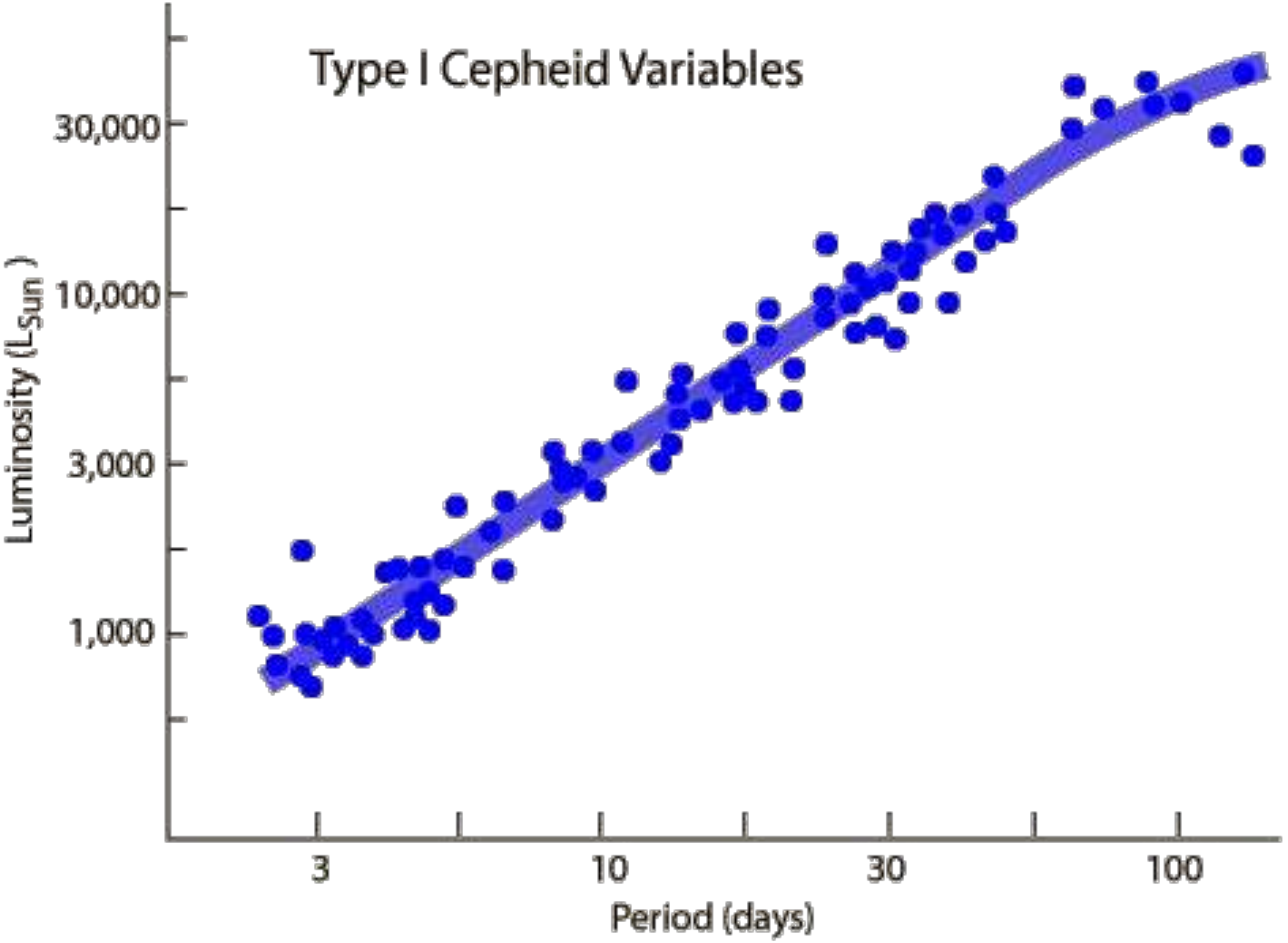


"Leavitt" **Period - Luminosity Relation** for Cepheids

Inverse square law

$F = L / (4 * pi * d ^ 2)$

This is called "calibrating" the Cepheids to a luminosity.
Harlow did this to help make a graph similar to the one seen.
Hubble measured the period of his famous "V" star. He then just read the luminosity from the graph, plugged it in to the inverse square law along with the flux (brightness), and determined the distance to M31!



"Leavitt" **Period - Luminosity Relation** for Cepheids

Key notes about Leavitt’s Law of Cepheids

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Cepheids are thousands of times more luminous than our sun, so they can be seen in galaxies up to 100 million light years away!

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Because each Cepheid has a measurable period, its luminosity can be determined by Leavitt's period - luminosity law. From the luminosity, its distance and the distance to the galaxy it is in can be determined from the inverse square formula shown!

Key notes about Leavitt's Law of Cepheids

Because each Cepheid has a constant max/min/average Luminosity, they are called STANDARD CANDLES in astronomy. Distances determined in this way are called LUMINOSITY DISTANCES! Nearby Cepheids distance are calculated using the first rung in the cosmic distance ladder, PARALLAX, as a calibration. CEPHEIDS are the second rung in the ladder to determine greater distances.

More Notes on luminosity distances

More Notes on luminosity distances

There are actually two populations of Cepheids. "Classical" or Type One Cepheids are more massive metal rich stars, typically 4 to 20 times the mass of the sun, but they are in their death throes of pulsation. Type Two Cepheids are older metal-poor stars sometimes found in globular clusters with masses at about one-half a solar mass. Both types are very luminous, but have a different period-luminosity relationship.

More Notes on luminosity distances

Walter Baade circa 1940's

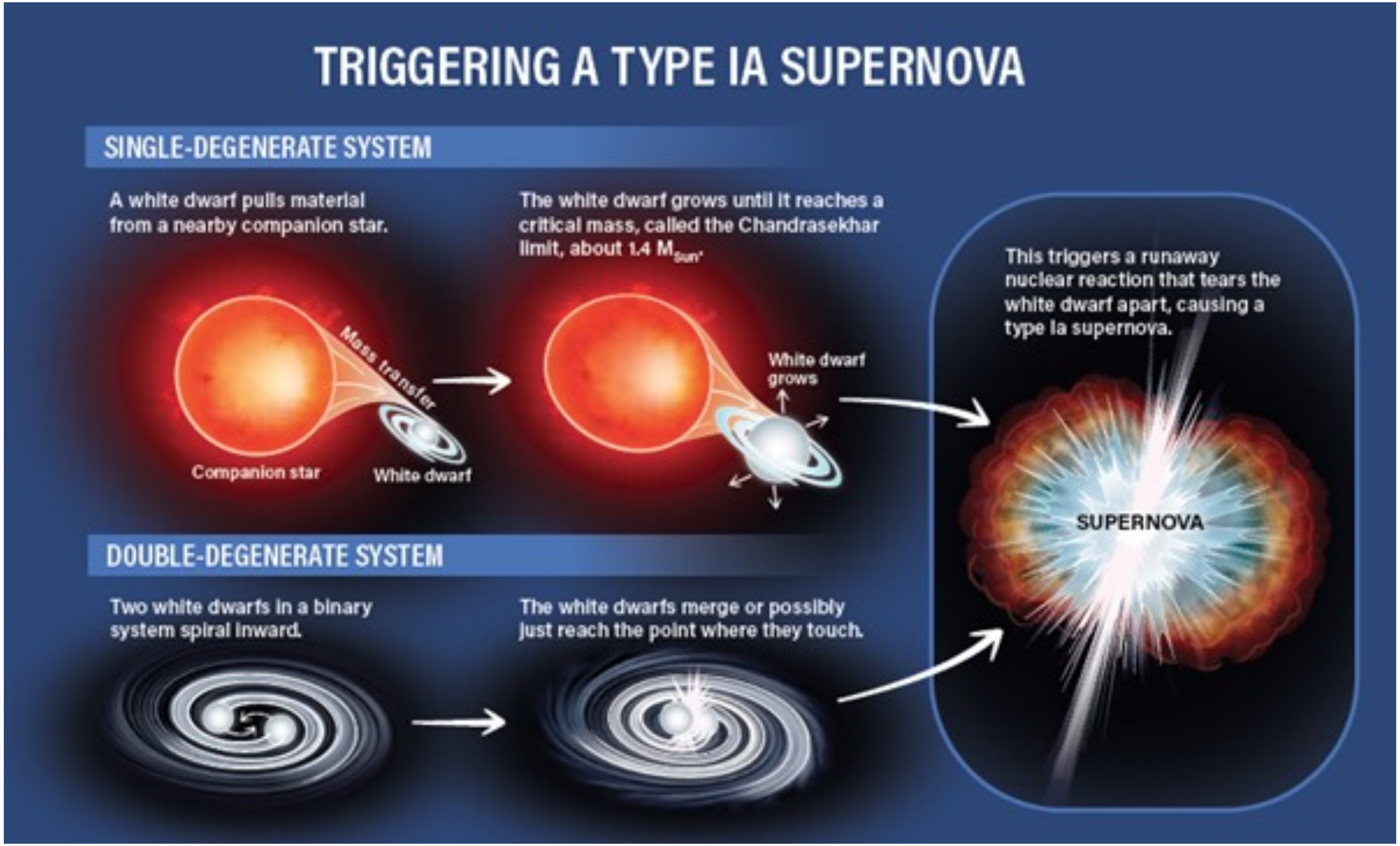
Before the late 1940's and the discovery of the types of Cepheids by Walter Baade, all Cepheids were thought of as being the same type. This caused Harlow, Hubble, and other astronomers to make errors of scale on distance and measurements of the "Hubble constant". However, their methods had a sound scientific basis.

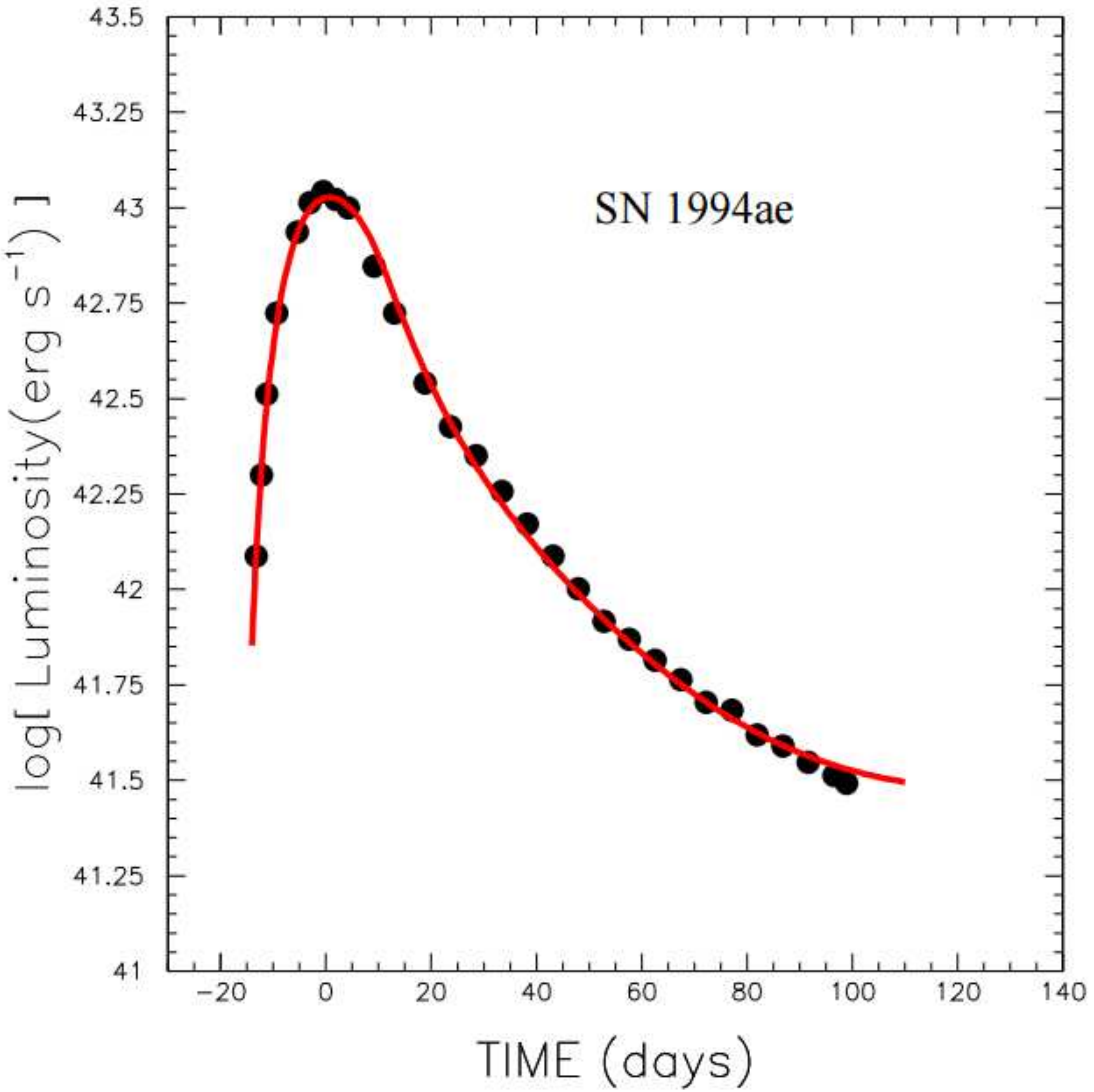
Luminosity distances from 1a Supernovas

A Type 1a supernova explodes in the pinwheel galaxy! These supernovae explode the same mass every time (1.4 X solar mass) and have an easily calculable luminosity. From the apparent brightness of the supernova, the distance to the galaxy can be determined!

Type 1a supernova are even brighter standard candles to find luminosity distances. They are 250 000 times more luminous than Cepheids and equal to 5 billion suns at their peak! Unlike core-collapse supernovas, they completely obliterate the white dwarf in a runaway nuclear reaction.

Luminosity distances from 1a Supernovas





All type 1a supernova are due to 1.4 solar Masses exploding, so the peak luminosity is fairly constant at about 5 billion suns (Hipparchus absolute magnitude =-19.3)

There are variations in the peak but astronomers know how to correct any changes in the peak luminosity by looking at the shape of the curve: Phillips Relation

Luminosity distances from 1a Supernovas

Adam Riess
Nobel Prize 2011
In 1998 Riess used 1a supernovas to determine luminosity distances of up to 12 GLy away! These supernovas were 10 - 15 % fainter than expected in a strictly matter dominated universe. An expanding universe that switched from slowing down to speeding up about 5 billion years ago due to "dark" energy "explained" the results! (Lambda-CDM Model)

Type 1a supernova are the third rung in the cosmic distance ladder. Distances to 1a supernova are "calibrated" with Cepheids at luminosity distances from 60 to 250 MLy. In 2021, Adam Riess and his SH0ES team used 1a supernova in measuring luminosity distances from 30 MLy to 300 MLy to find Hubble's constant now.

$H_0 = (da/dt) / a$ (fractional expansion rate)

Recession Speed of Galaxies and “Redshift”

Recession Speed of Galaxies and "Redshift"

In 1929, Hubble produced evidence for an expanding universe, and ever since then astrophysicists have been trying to find how the size of the observable universe changes over time by finding H(t), the Hubble-Lemaitre Parameter. In order to find H_0 the Hubble-Lemaitre parameter now, astronomers needed to find the distance to far-away galaxies and how fast they were moving away from "us". (Centre of Milky Way Galaxy)

Recession Speed of Galaxies and "Redshift"

Hubble's observations in 1929 offered an equation to find H_0

$$H_0 = V_R / D_P$$

Recession Speed of Galaxies and "Redshift"

$H_0 = V_R / D_P$

Hubble's Law

Recession Speed of Galaxies and "Redshift"

$$H_0 = V_R / D_P$$

Hubble's Law

D_P = the tape measure distance or the distance to the galaxy now, called proper distance in Mpc (3.26 MLy)

This distance is measured from the centre of the Milky Way as our frame of reference.

Recession Speed of Galaxies and "Redshift"

$H_0 = V_R / D_P$

D_P = the tape measure distance or the distance to the galaxy now called proper distance in Mpc (3.26 MLy)

Note: For luminosity distances less than 300 MLy, proper distance and luminosity distance are within 3%

Recession Speed of Galaxies and "Redshift"

$H_0 = V_R / D_P$

V_R = relative speed away from the centre of the Milky Way due to the expansion of space/scale factor in km/s

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NOT

V_P or the local Peculiar Velocity of a galaxy through space due to local gravitational effects

Recession Speed of Galaxies and "Redshift"

$H_0 = V_R / D_P$

For example, Andromeda Galaxy M31 has a <u>peculiar speed</u> through space at V_P = 165 km/s toward "us" but space is expanding at V_R = <u>recession speed</u> of 55 km/s away from "us" (Milky Way centre)

So…

M31 is still moving toward us at 110 km/s

Recession Speed of Galaxies and "Redshift"

$$H_0 = V_R / D_P$$

A D_P gets bigger, V_R must get bigger too to keep H_0 constant. This means V_R can get even larger than the speed of light c for far away galaxies. V_P of galaxies through space due to gravitational effects stay less than 1000 km/s no matter what. At large scales and distances, for D_P greater than 300 MLy, all galaxies are moving away from us.

Recession Speed of Galaxies and "Redshift"

$$H_0 = V_R / D_P$$

We know how distances are measured, but what about recession speeds V_R ?

Vesto Slipher, Recession Speeds and "Redshift"

Vesto Slipher (1875 -1969)

Vesto Slipher, Recession Speeds and “Redshift”


Vesto Slipher (1875 -1969)

Worked at Lowell Observatory in Flagstaff Arizona from 1901 until 1954

Vesto Slipher, Recession Speeds and "Redshift"

Vesto Slipher (1875 -1969)

First to measure the radial velocities of spiral nebulae and galaxies using a spectrograph attached to a 24 inch refractor

Vesto Slipher, Recession Speeds and "Redshift"

Vesto Slipher (1875 -1969)

In 1912, first to measure the radial velocity of M31, the Andromeda Galaxy at 300 km/s towards us relative to the sun and 110 km/s relative to the centre of the Milky Way)

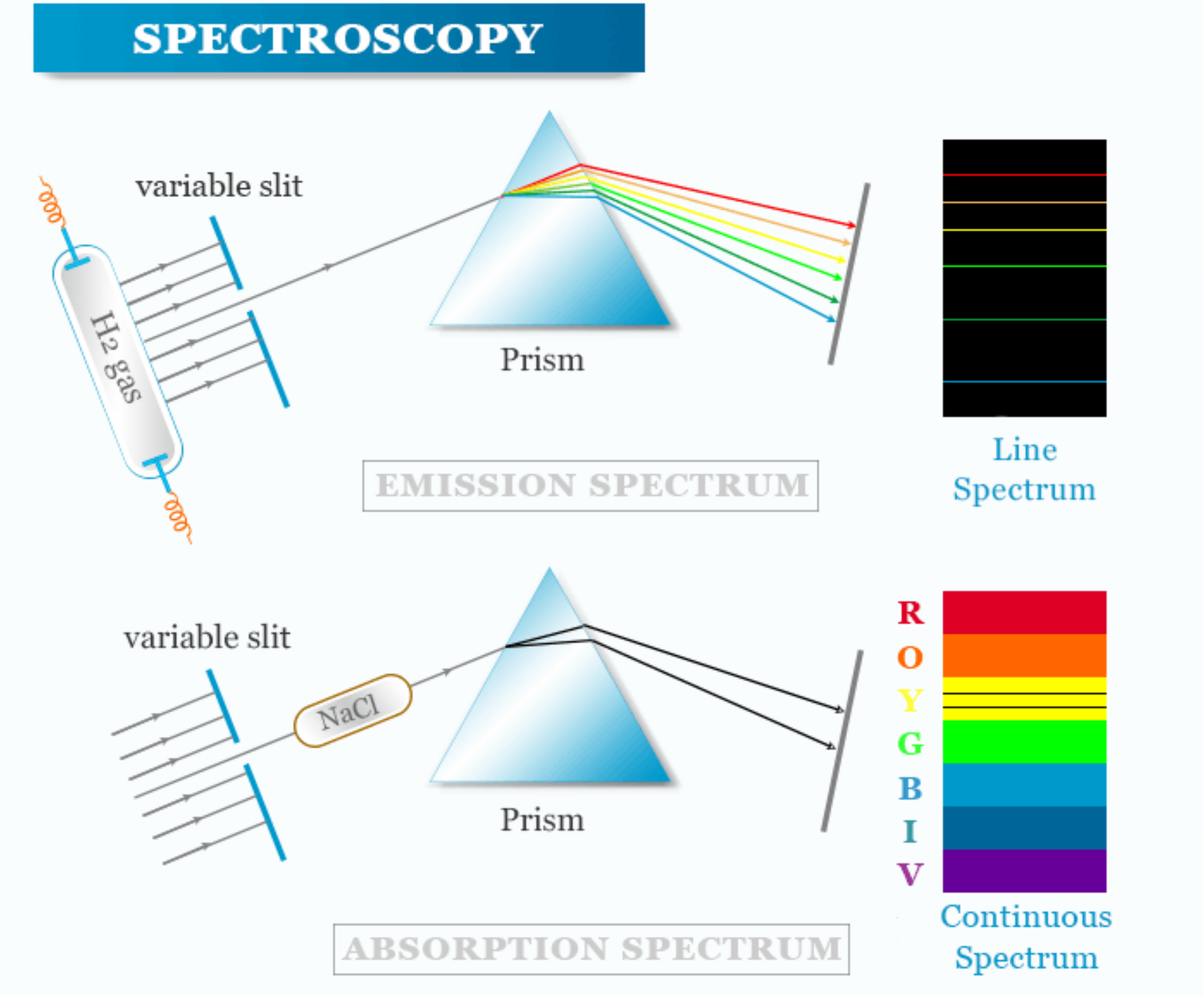
Vesto Slipher, Recession Speeds and "Redshift"

Vesto Slipher (1875 -1969)

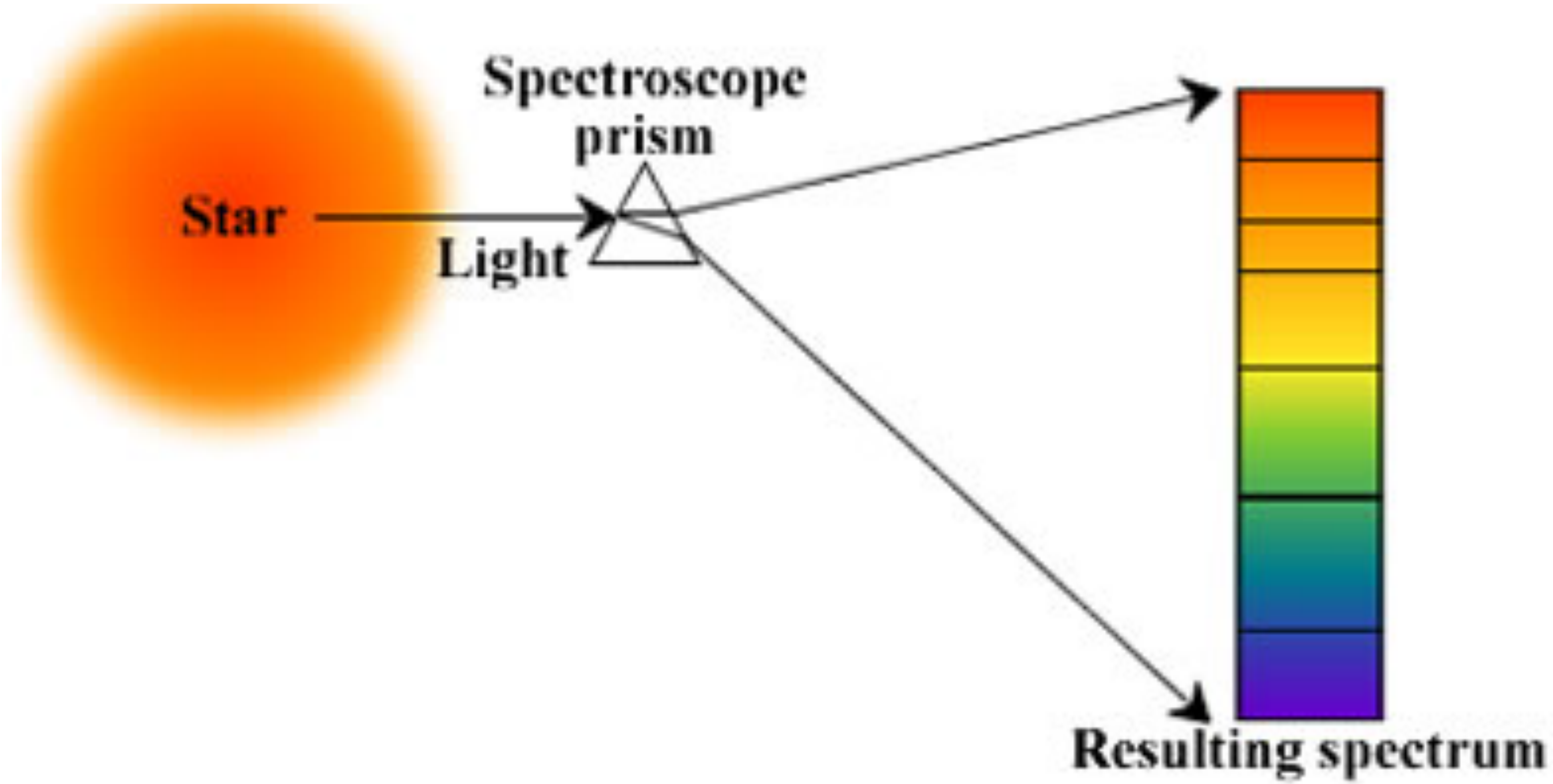
In 1917, Slipher found that 21 out of 25 spiral galaxies had radial velocities away from "us" ! His data helped Lemaitre and Hubble assert Hubble's Expansion Law (1927 & 1929)

$H_0 = V_R / D_P$

How did Slipher find the radial velocities of galaxies?



Three types of spectra



Applying Spectroscopy to Astronomy: Slipher looked at absorption lines in starlight

Two Ways Absorption Lines “Shift” position

Two Ways Absorption Lines “Shift” position

A line on a star at rest to “us” will have a definite wavelength λ in nm (billionth of a meter) called λ_e (emitted wavelength) and can be measured on a spectrometer or spectrograph.

Two Ways Absorption Lines "Shift" position

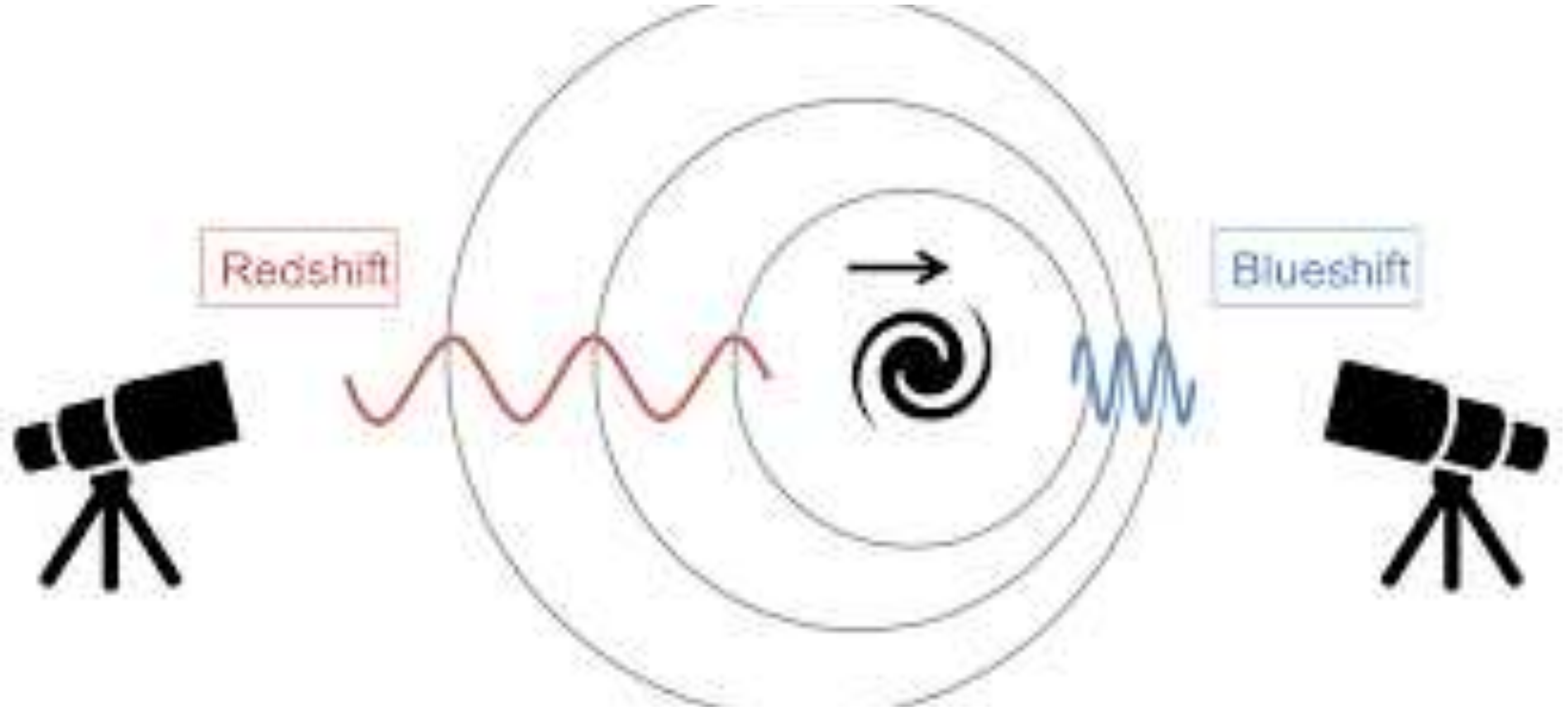
If the star is moving away from "us", the light's wavelength gets longer and is observed by us as λ_o (observed wavelength)   The line shifts position on the spectrum toward the longer wavelengths like red and is said to be "redshifted". The wavelength does not necessarily correspond to a "red" colour! In fact, the line could correspond to a wavelength so long it is "infrared" and no longer visible to us, but its position on the spectrum and its wavelength can still be measured.

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

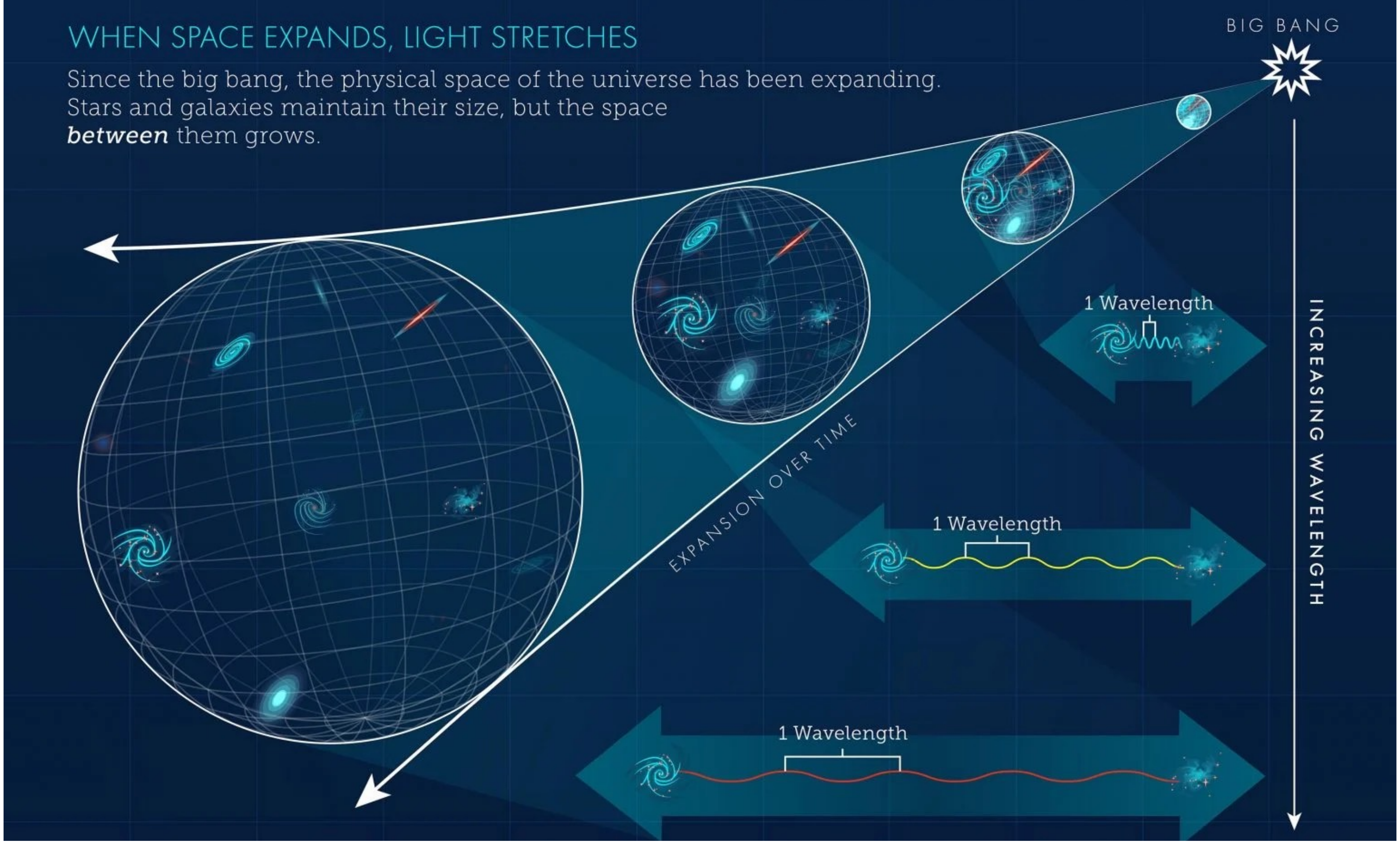
Redshift Defined: It is much easier to measure redshift of starlight off a spectrometer or spectrograph than to measure distances. The symbol for redshift is **Z**

Two Ways Absorption Lines "Shift" position

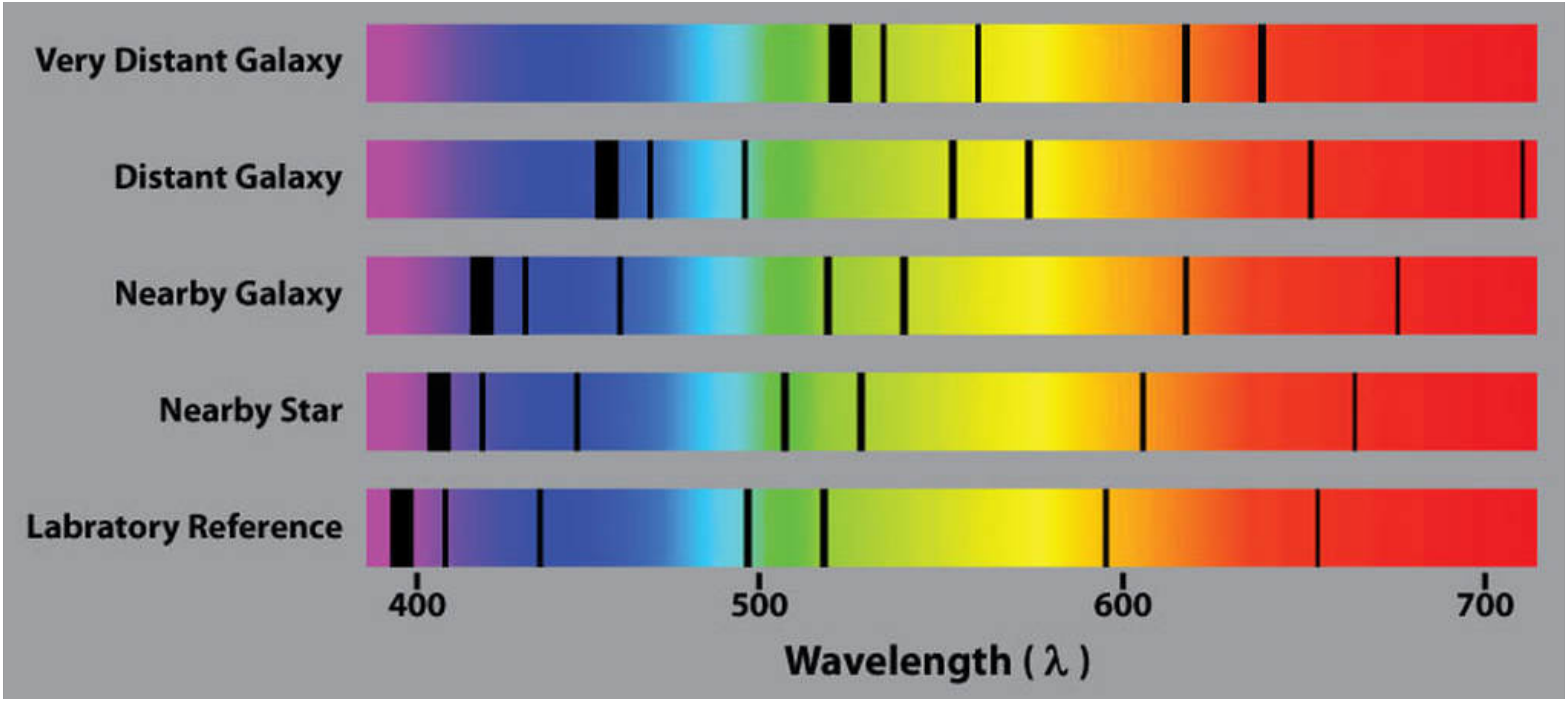
If the star is moving toward "us", the light's wavelength gets shorter and is observed by us as λ_o (observed wavelength) The line shifts position on the spectrum toward the shorter wavelengths like blue and is said to be "blueshifted". The wavelength does not necessarily correspond to a "blue" colour! In fact, the line could correspond to a wavelength so short it is "ultraviolet" and no longer visible to us, but its position on the spectrum and its wavelength can still be measured. Z will be negative!



When a galaxy moves through space due to local gravitational effects it is "Doppler-shifted". The wavelength of the light can get longer or shorter! This kind of effect corresponds to peculiar velocity and cannot exceed the speed of light C.



When galaxies are carried along with expanding space, the wavelength stretches longer and never gets shorter. This is not the same as the Doppler Effect due to galaxy motion through space. Galaxy motion with expanding space or the "Hubble Flow" is called Cosmological redshift. According to General Relativity, recession speed of space can exceed light speed.



Measuring redshift: Fifth line from left-very distant galaxy

Z = (635 nm - 520 nm) / 520 nm

Z = 0.221

How do we get recession speed from redshift?

How do we get recession speed from redshift?

EQ#1 $V_R = c\,(\,da(t)/dt\,) \int dz \,/\, H\,(\,z\,)$

(Davis)

Flat Homogeneous Isotropic universe

Expansion of space/scale factor

(dark energy) $\Omega_\Lambda = .7$ (matter) $\Omega_m = .3$

large scales > 300 MLy

General Relativity FLRW metric

"no speed limit"

How do we get recession speed from redshift?

EQ#2 $$V_P = c \frac{((1+z)^2 - 1)}{((1+z)^2 + 1)}$$

Peculiar Velocities within / near galaxy clusters
Due to local gravitational effects

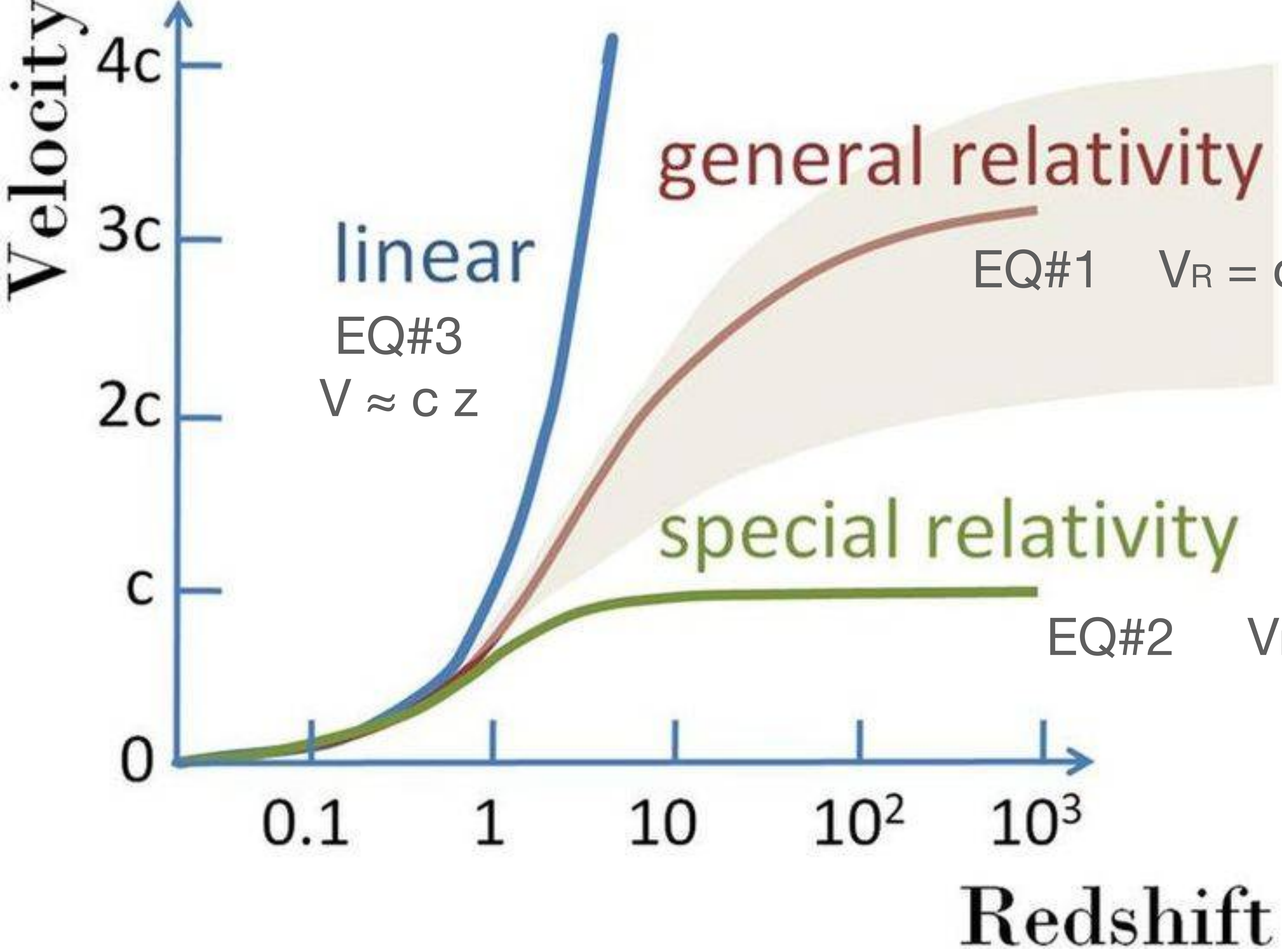
Governed by Special Relativity $V_P < c$

How do we get recession speed from redshift?

EQ#3 $V \approx c\,z$

for $z \leq 0.05$ within 5%

Used by Slipher and Hubble
1920’s 1930’s



EQ#1 $V_R = c \, (da(t)/dt) \int dz / H(z)$

EQ#2 $V_P = c \dfrac{((1+z)^2 - 1)}{((1+z)^2 + 1)}$

EQ # 1 expansion of space ΛCDM homogeneous isotropic FLRW metric —
EQ # 2 peculiar velocities of galaxies through space —
EQ # 3 approximate radial velocity good for $z \leq 0.1$ —

1929
Edwin Hubble's Great Discovery

Edwin Hubble:
Observational Evidence for an Expanding Universe 1929

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Slipher + Leavitt = Hubble's Law

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Used 21 radial velocities of spiral nebula determined by Vesto Slipher plus 4 of his own

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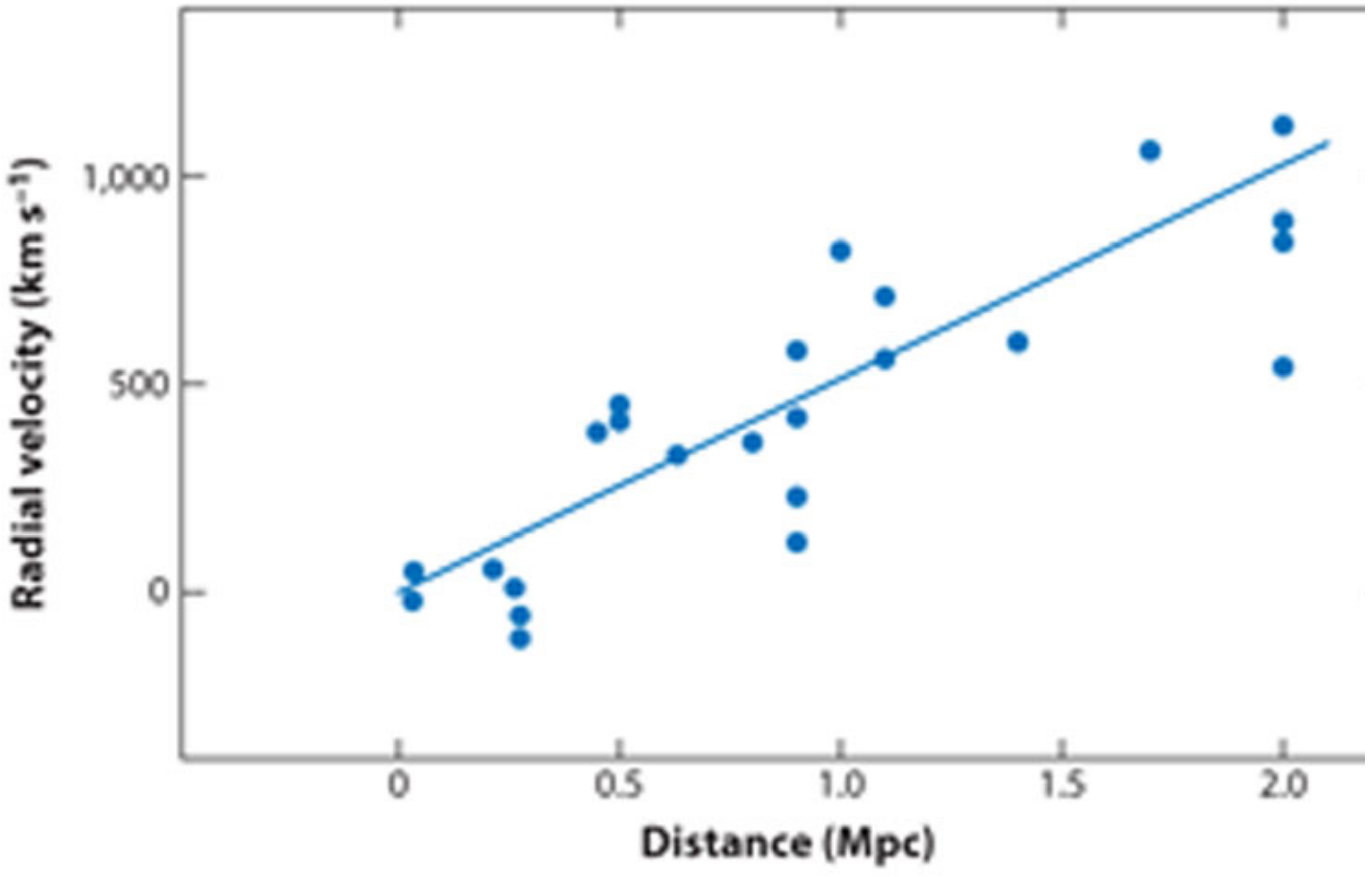
1929: Edwin Hubble's Great Discovery



Hubble's Great Insight:

Connect radial velocity and distance

V α D

V = H X D

H is the slope = 500 km/s/ Mpc

At 1 Mpc, recession is 500 km/s

At 2 Mpc, recession is 1000 km/s

Slipher + Leavitt = Hubble's Law

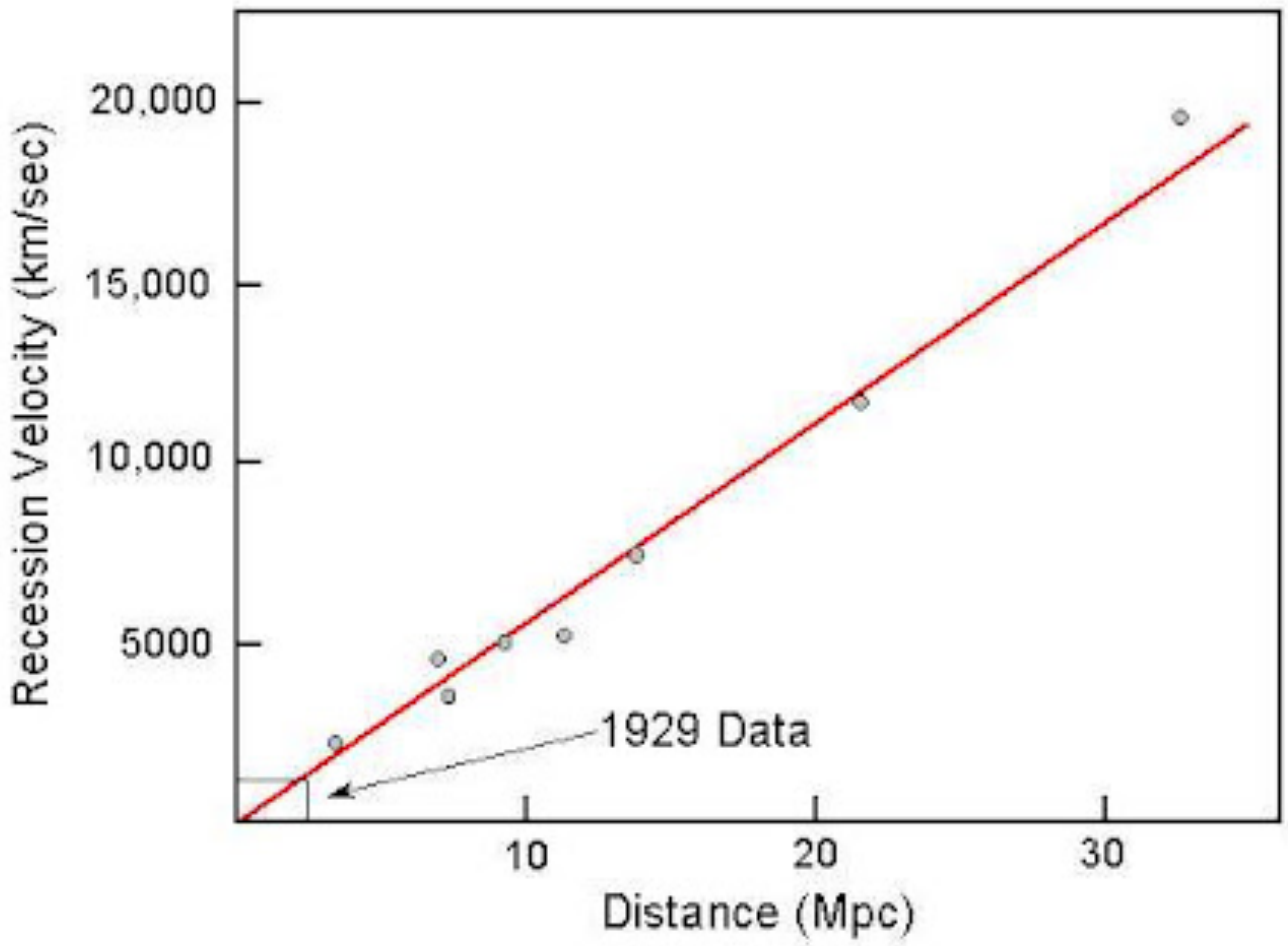
V α D

V = H X D

Used 21 radial velocities of spiral nebula determined by Vesto Slipher plus 4 of his own

Used Henrietta Leavitt's Cepheid "Period - Luminosity" Law to find distances to the 25 spiral galaxies he knew radial velocities for

Hubble & Humason (1931)



Hubble's Law holds for much larger distance values in 1931

Hubble's Great Insight:

Connect radial velocity and distance

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Hubble's Great Insight:

Connect radial velocity and distance

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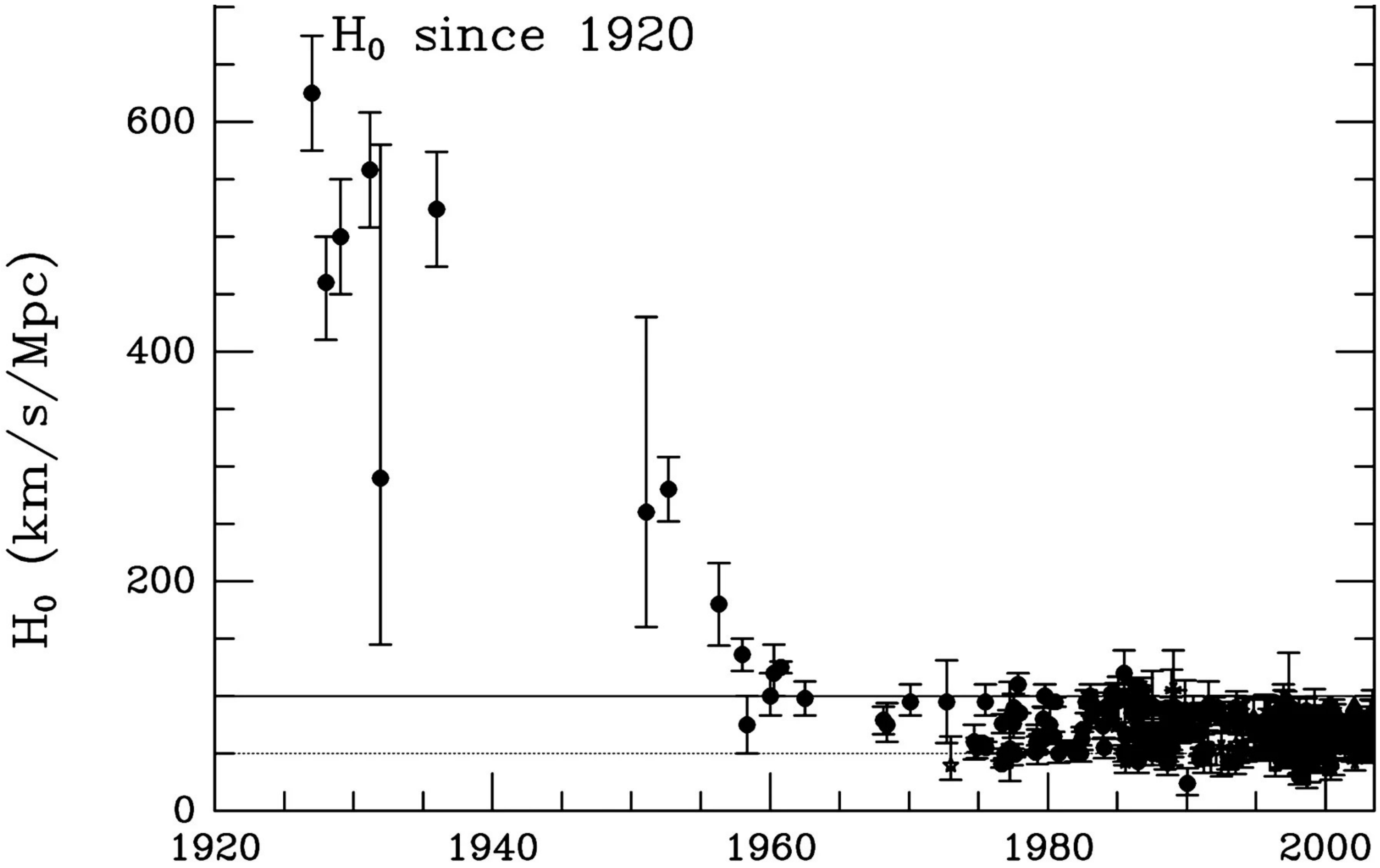
Hubble did not know there were two types of Cepheids. As a result his value for the "Hubble constant now" H_0 was about seven times too big. However, his work was strong evidence for a universe that was not static as once believed, but expanding in scale!



With better technology, space telescopes, and better models, measurement of “Hubble’s constant H_0 now” is now about 70 km/s/Mpc

What does 70 km/s/Mpc mean?

What does 70 km/s/Mpc mean?

#1) A galaxy 100 Mpc from us now is moving at

______________ km/s

What does 70 km/s/Mpc mean?

#1) A galaxy 100 Mpc from us now is moving at

7000 km/s

What does 70 km/s/Mpc mean?

#2) A galaxy 200 Mpc from us now is moving at

________________ km/s

What does 70 km/s/Mpc mean?

#2) A galaxy 200 Mpc from us now is moving at

14000 km/s

What does 70 km/s/Mpc mean?

#2) A galaxy 5000 Mpc or 5 Gps from us now is moving at

________________km/s

What does 70 km/s/Mpc mean?

#2) A galaxy 5000 Mpc or 5 Gpc from us now is moving at

350 000 km/s

What does 70 km/s/Mpc mean?

#2) A galaxy 5000 Mpc or 5 Gpc from us now is moving at 350 000 km/s

Note:

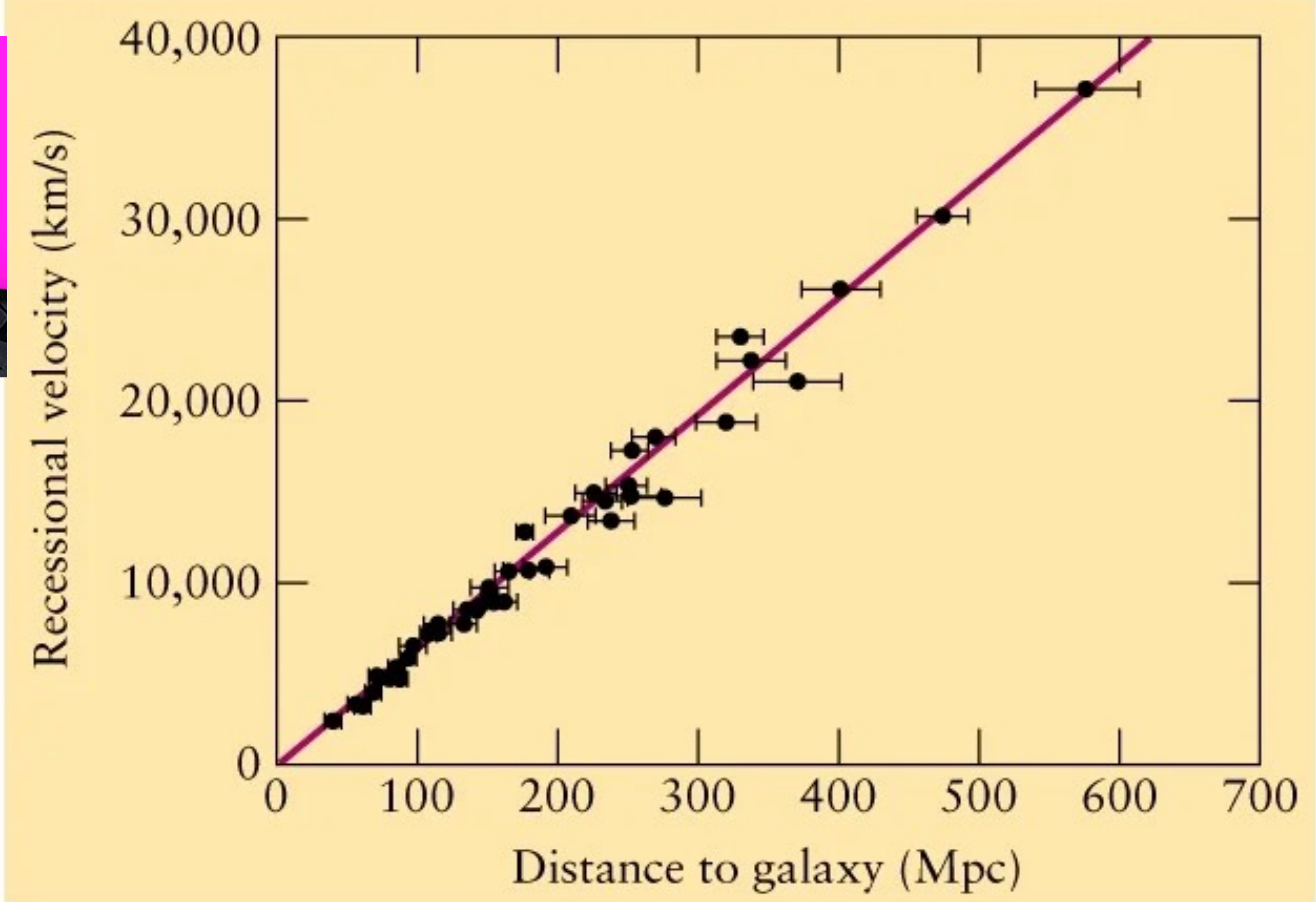
When we use H_0 this way, we think of the galaxy moving away from us because it is being carried away with expanding space!

According to General Relativity, space has no speed limit when it expands and it can expand faster than “c” the speed of light

Velocities of galaxies through space are called peculiar velocities due to local gravitational effects. Peculiar velocities are subject to Special Relativity and cannot exceed light speed “c”

Hubble’s law becomes more valid as proper distance (the distance now) between our Milky Way and other galaxies become large, say, greater than 100 Mpc.
At distances less than 5 Mpc, peculiar velocity is comparable to the speed of expanding space and Hubble’s Law is less valid. Our Andromeda galaxy is 0.77 Mpc away and is actually moving toward the centre of our Milky Way

Let's find H_0 ?



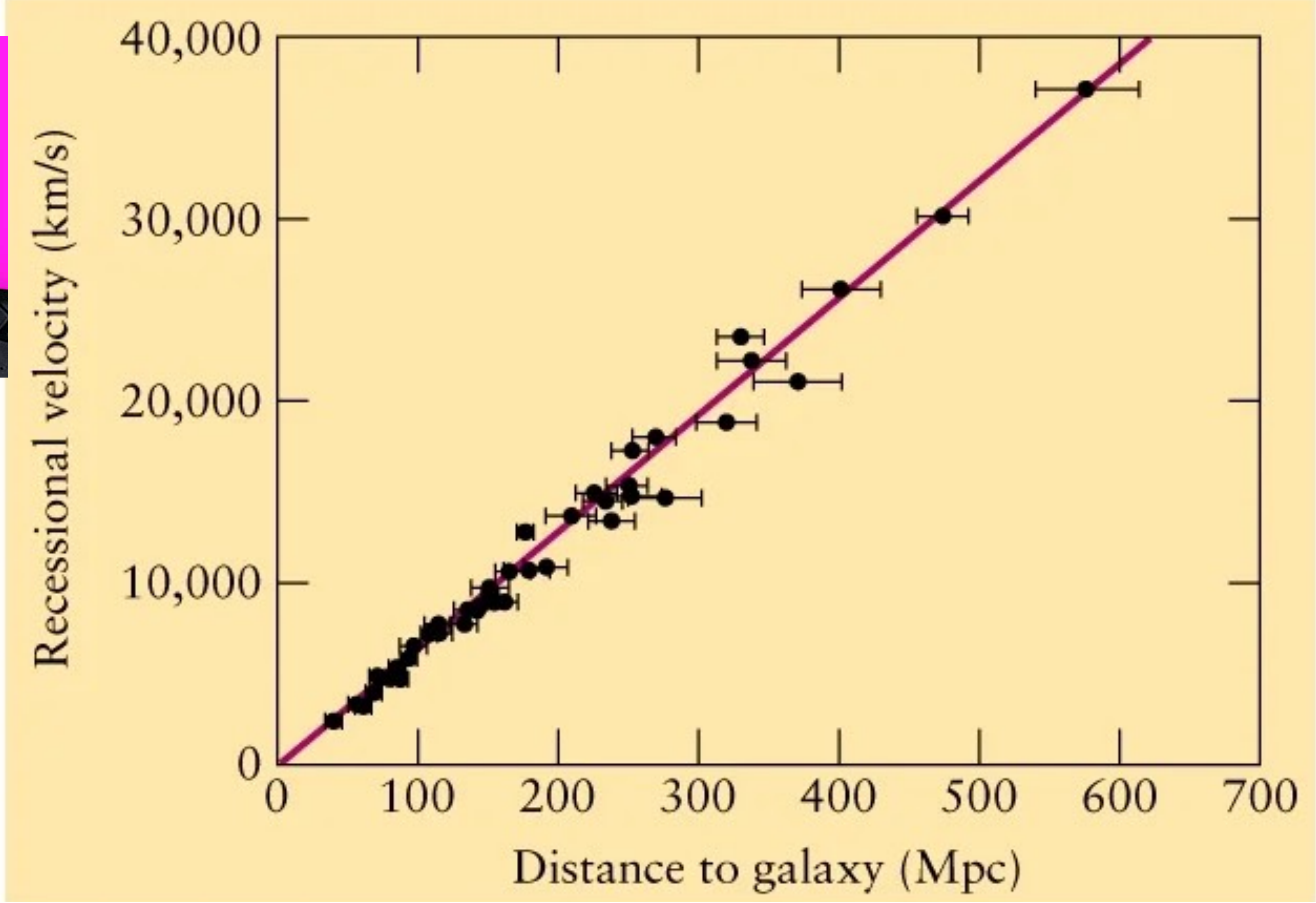
Adam Riess

Hubble constant graph

John Hopkins University SHoES project 2021

Let's find H_0 ?

H_0 = slope



Adam Riess

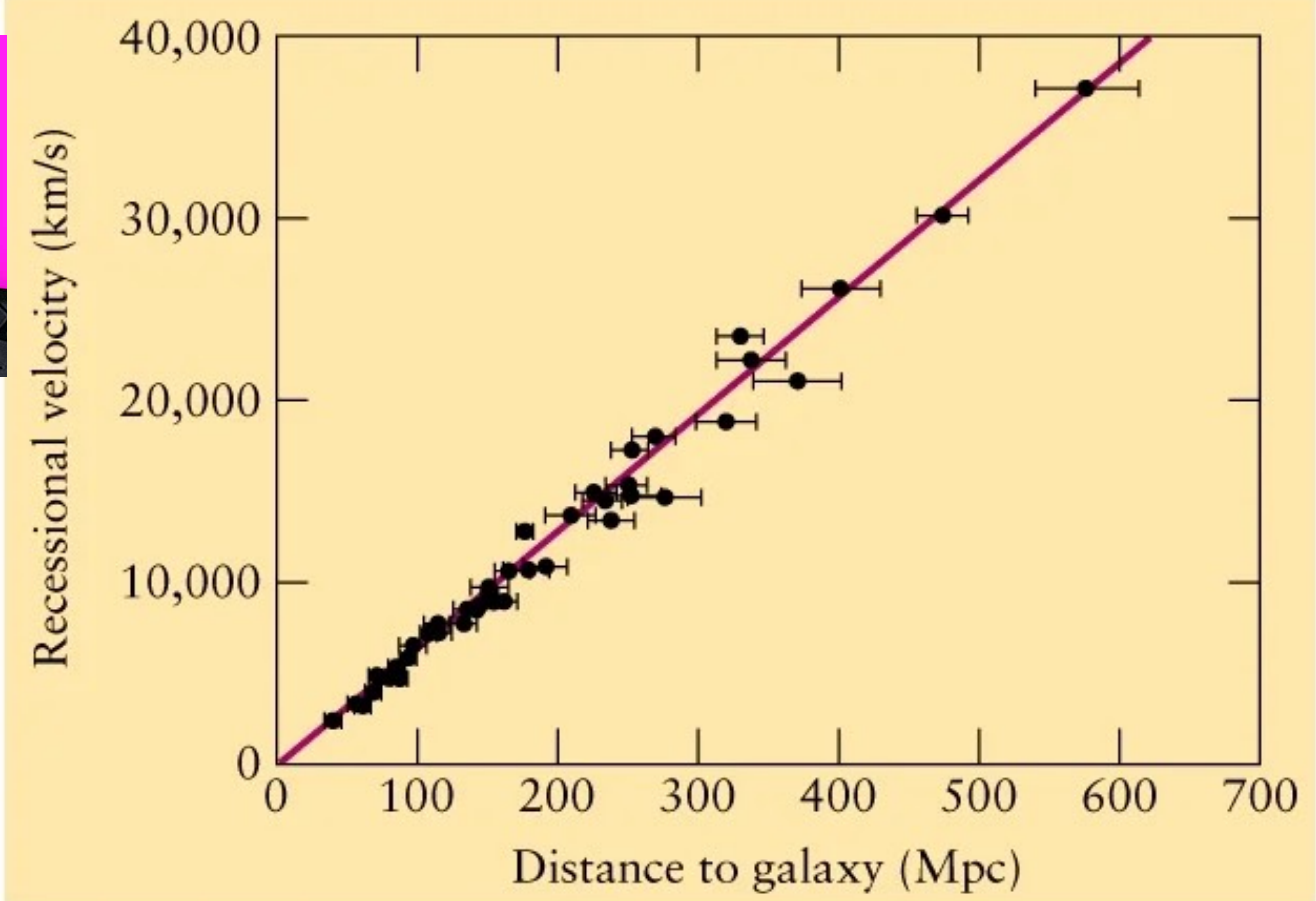
Hubble constant graph

John Hopkins University SHoES project 2021

Let's find H_0 ?

H_0 = slope

$= \frac{40\ 000\ km/s}{620\ Mpc}$



Adam Riess

Hubble constant graph

John Hopkins University SHoES project 2021

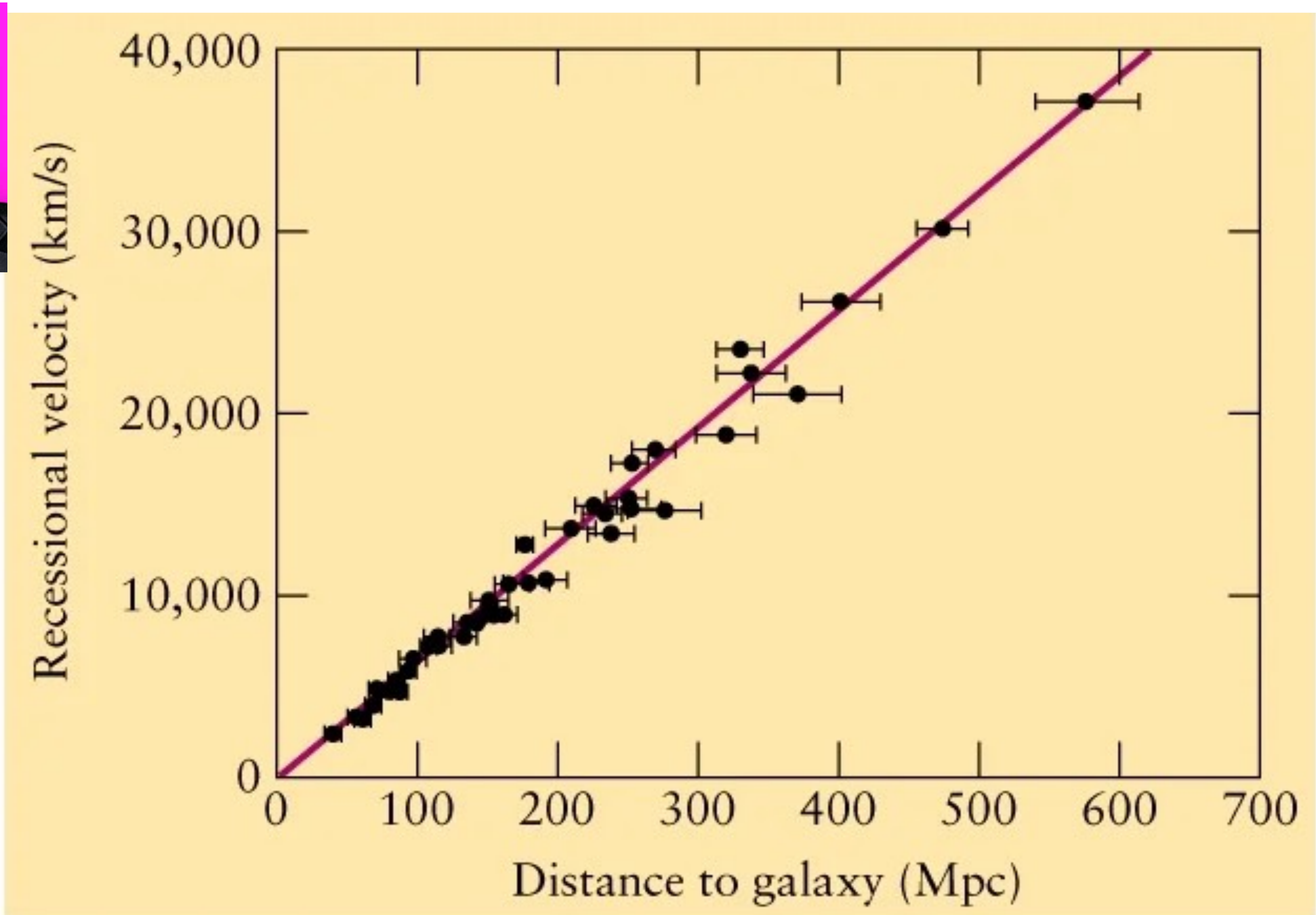
Let's find H_0 ?

H_0 = slope

= $\frac{40\,000 \text{ km/s}}{620 \text{ Mpc}}$

But 620 Mpc is a luminosity distance assuming a static universe

We want a proper distance! (Expanding universe)



Adam Riess

Hubble constant graph

John Hopkins University SHoES project 2021

As light waves lengthen they lose energy …

Light arriving to us appears less bright and things look farther away than they actually are …

So astrophysicists use a formula to calculate actual proper distance from luminosity distance

Proper distance

=

luminosity distance / (1 + redshift or z)

Proper distance
= luminosity distance / (1 + redshift or z)

= 620 Mpc (1 + 0.132)
assuming 70% dark energy and 30% matter

Proper distance
= luminosity distance / (1 + redshift or z)

= 620 Mpc (1 + 0.132)
assuming 70% dark energy and 30% matter

= 547.7 Mpc

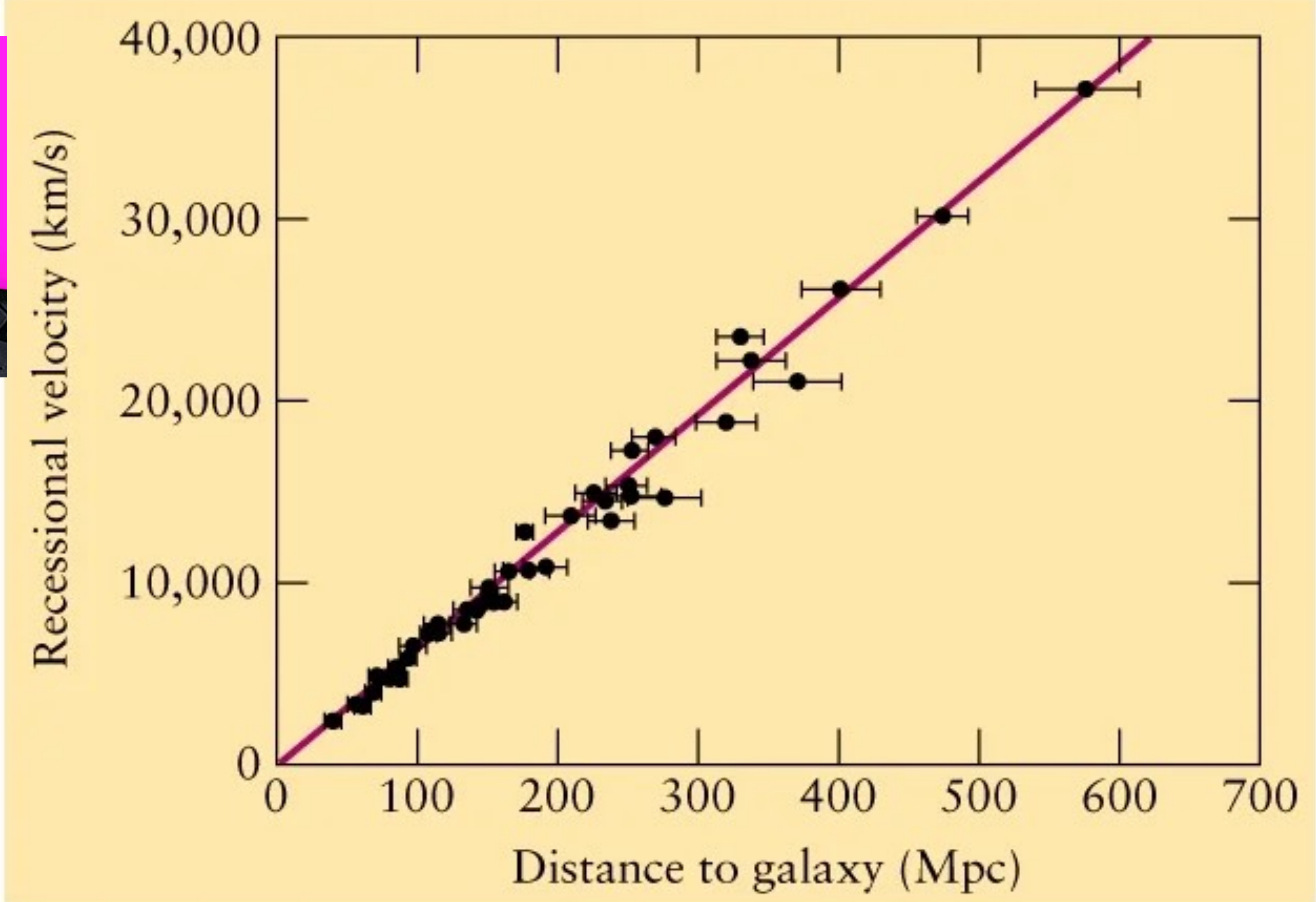
Let's find H_0 ?

H_0 = slope

$= \frac{40\,000 \text{ km/s}}{620 \text{ Mpc}}$

$= \frac{40\,000 \text{ km/s}}{547.7 \text{ Mpc}}$

Corrected for expansion



Adam Riess

Hubble constant graph

John Hopkins University SHoES project 2021

Let's find H_0 ?

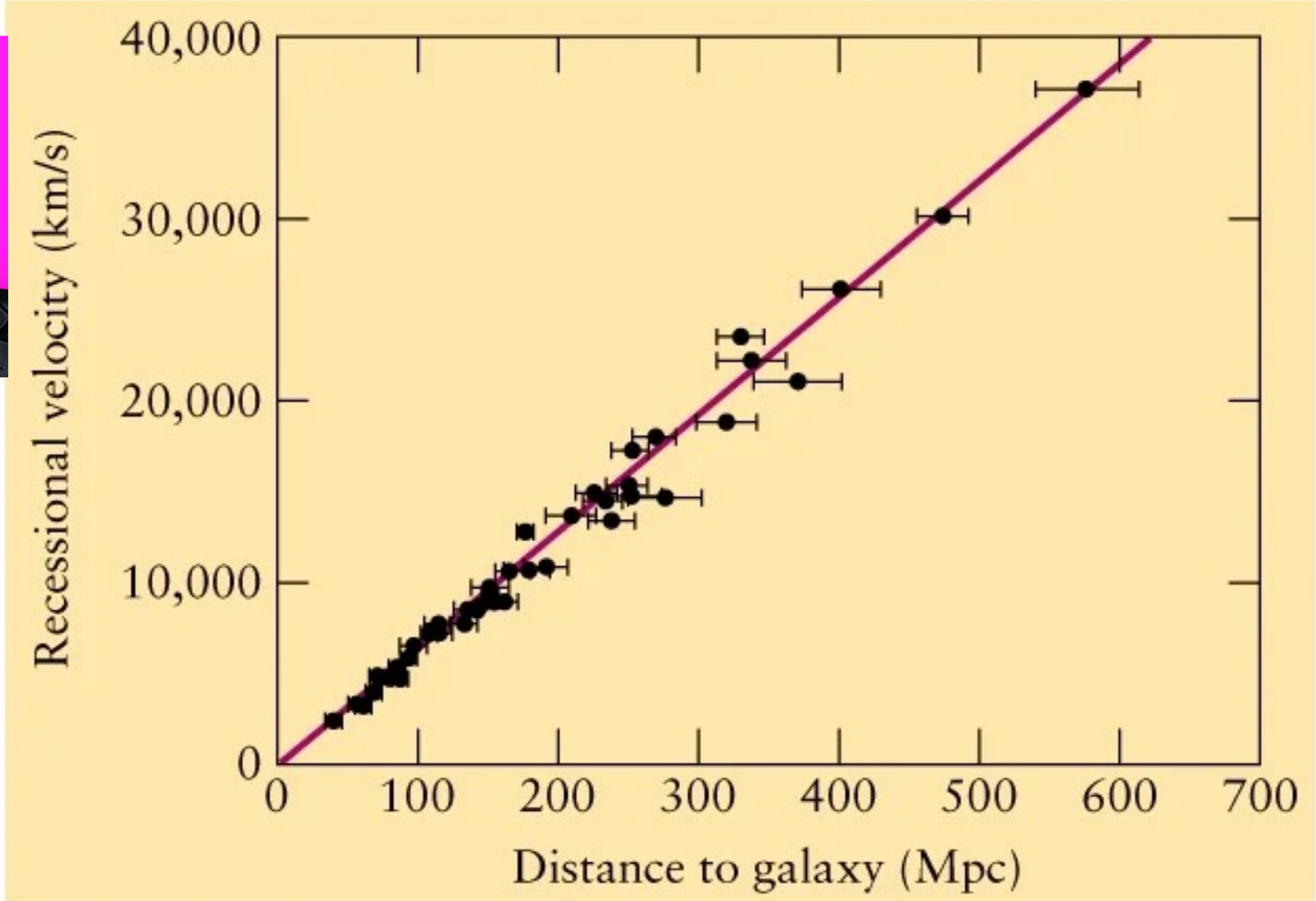
H_0 = slope

$= \frac{40\,000 \text{ km/s}}{620 \text{ Mpc}}$

$= \frac{40\,000 \text{ km/s}}{547.7 \text{ Mpc}}$

Corrected for expansion

= 73.0 km/s/Mpc



Adam Riess

Hubble constant graph

John Hopkins University SHoES project 2021

H_0 = 73.0 km/s/Mpc
+/- 1.0
Used Cepheids and
type 1a supernova
as standard candles
John Hopkins
SHoES
2021

H_0 = 73.0 km/s/Mpc +/- 1.0

Used Cepheids and type 1a supernova as standard candles

John Hopkins

SHoES

2021

Wendy Freedman

Carnegie Chicago Hubble Program 2025

H_0 = 70.4 km/s/Mpc +/- 1.9

Used Tip of Red Giant Branch (see Hertzsprung-Russel diagrams for more info)

and type 1a supernovas as standard candles

Measuring H_0 using the CMB

Measuring H_0 using the CMB

What is the CMB?

Measuring H_0 using the CMB

What is the CMB?

Oldest light in the universe

Light has been **stretched** for 13.8 GLy

Was visible/infrared but is **now microwave**

Detected **everywhere** in the sky

Very **Uniform** with 1 in 10^5 density variation

(COLD and HOT spots)

Cosmic Microwave Background

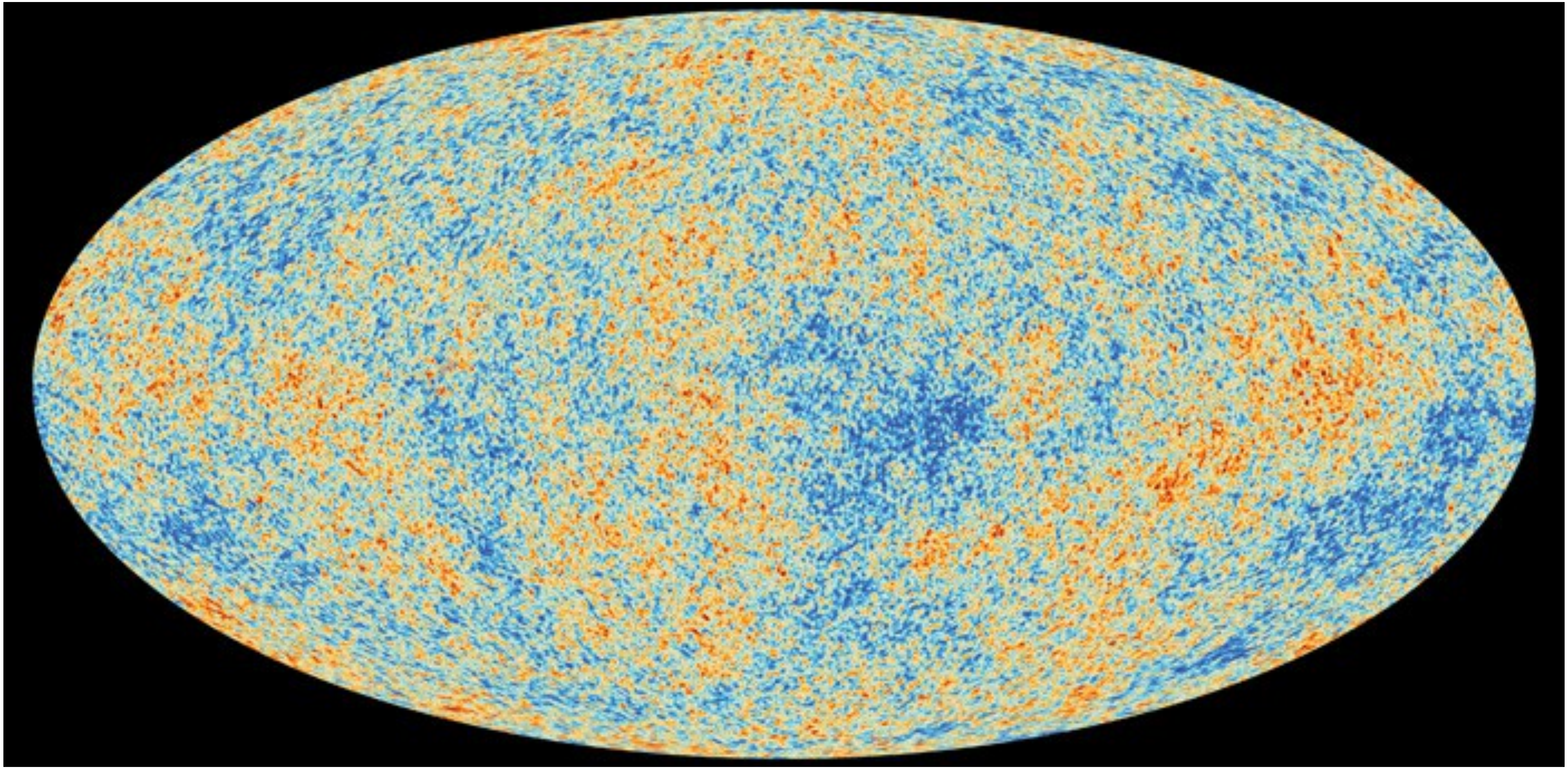
When and how did the CMB form?

When and how did the CMB form?

Light released 380 000 years after the big bang

Plasma of protons and electrons expanded and cooled enough to allow them to come together to form neutral atoms 3000 K
Era of Recombination

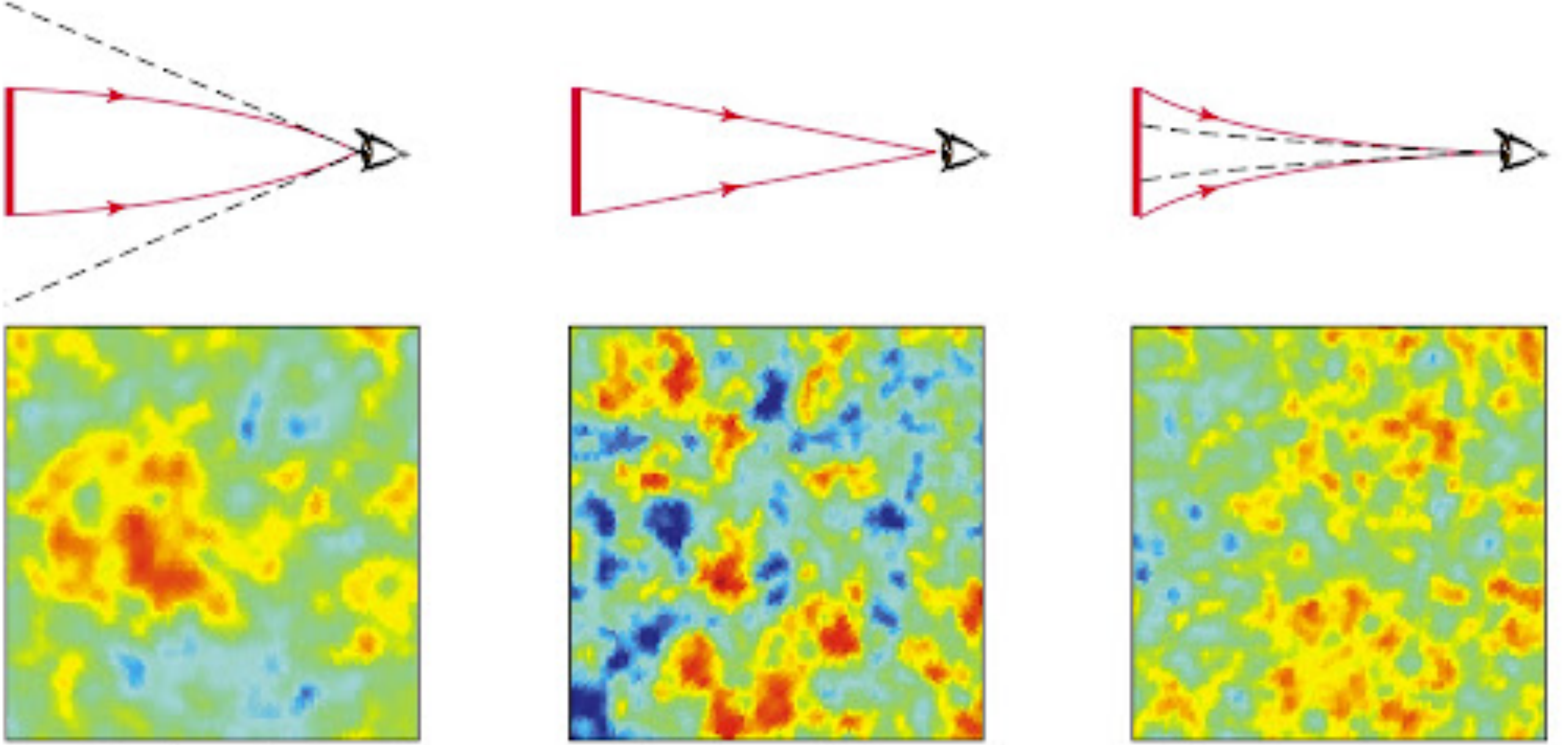
Made space transparent to light



Planck Satellite Microwave Map: ESA

By studying the size and relative frequency of the more common spots H_0 and curvature can be determined

Measuring the Cold and dark spots of the CMB helps determine the geometry of the universe and Hubble's constant then and now



a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

"Hot spots" are areas of more mass and greater density that **later form galaxies** and galaxy clusters

The **Planck satellite** found that most spots appeared **actual size** of about 1 degree, indicating a flat universe with no curvature

What were the results of the Planck Satellite CMB mapping?

What were the results of the Planck Satellite CMB mapping?

Strong evidence of a flat universe by looking at the size of density fluctuations, as they were the same size as predicted by sound standing waves in a plasma

Observations of the relative frequency and size of hot spots in the CMB matched the Λ-CDM model of the universe

Ω (critical density) = $\Omega_m + \Omega_\Lambda = 1$ (flat)

Approximately $\Omega_m = 0.3$ (normal and dark matter)

Approximately $\Omega_\Lambda = 0.7$ (dark energy)

Using the data from the Planck CMB mapping and how it matched the above Λ-CDM model,

the value of the Hubble-Lemaitre parameter was calculated 380 000 years After the Big Bang and extrapolated to the present as

H_0 =67.4 km/s/Mpc. +/- 0.5

Unresolved Definite Disagreement for H_0 : "Hubble Trouble" or "Tension"

H_0 = 73.0 km/s/Mpc +/- 1.0

Used Cepheids and type 1a supernova as standard candles

John Hopkins SHoES 2021

Wendy Freedman

Carnegie Chicago Hubble Program 2025

H_0 = 70.4 km/s/Mpc +/- 1.9

Used Tip of Red Giant Branch (see Hertzsprung-Russel diagrams for more info)
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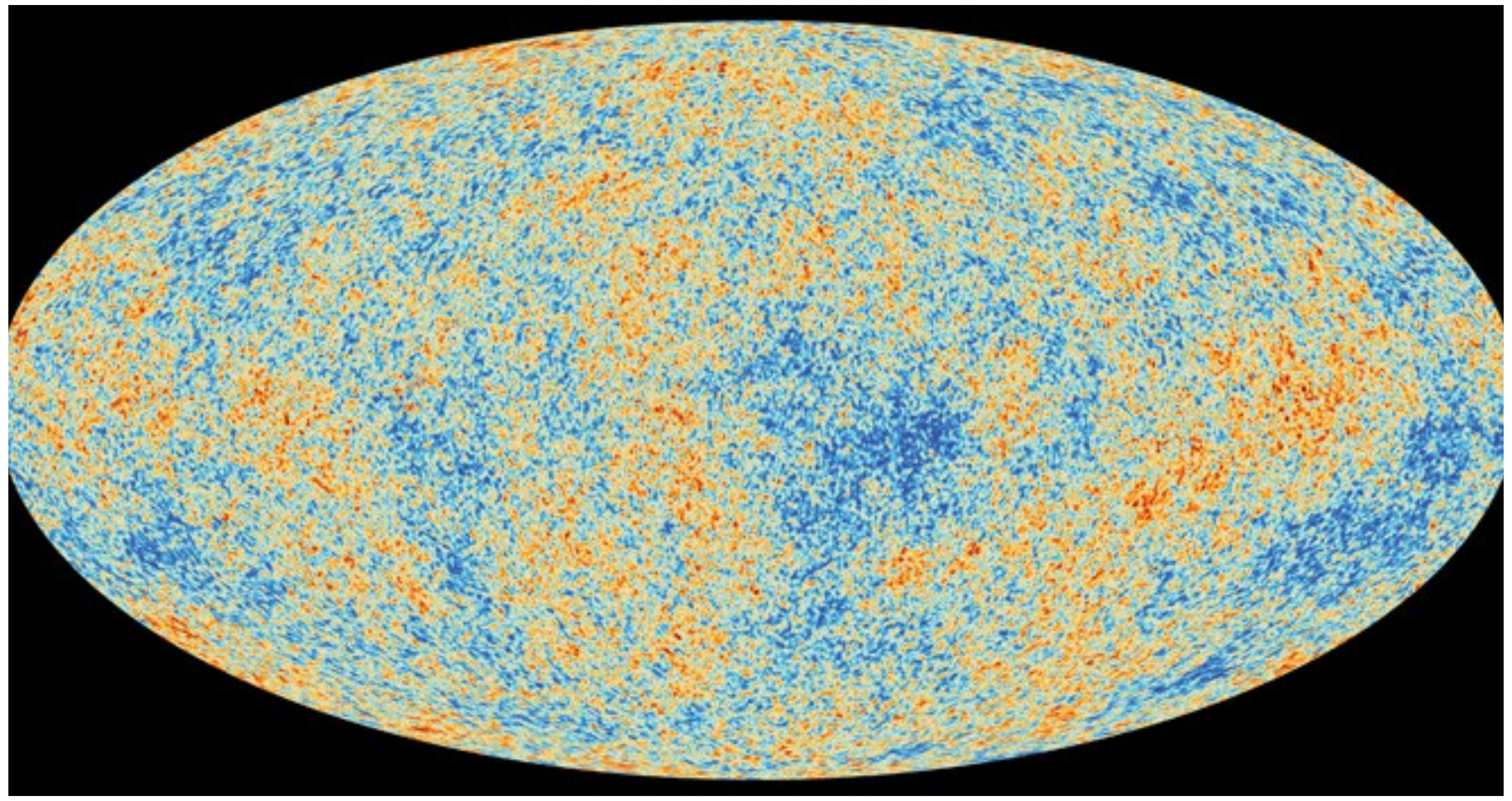


Planck Collaboration 2018

Used the ESA Planck satellite to measure relative frequency and size of hot spots in the CMB to find the best fit match with Λ-CDM model

H_0 = 67.4 km/s/Mpc +/- 0.5

How are “Hubble’s Law” and the “expansion rate” related?

How are “Hubble’s Law” and the “expansion rate” related?

$H_0 = V_R / D_P$

Hubble’s law from observations

↕

$H(t) = \frac{da(t) / dt}{a(t)}$

Defining equation ?

How are “Hubble’s Law” and the “expansion rate” related?

$H_{(t)} = V_{R(t)} / D_{P(t)}$

Hubble’s law from observations

↕

$$H(t) = \frac{da(t) / dt}{a(t)}$$

Defining equation ?

$$H(t) = \frac{da(t) / dt}{a(t)}$$

Note: H(t) is actually a **fractional expansion rate**

Hubble's Constant

$$H(t) = \frac{da(t) / dt}{a(t)}$$

Hubble's
Constant

$$H(t) = \frac{da(t) / dt}{a(t)}$$

Hubble-Lemaitre
Parameter

Hubble's Constant

$$H(t) = \frac{da(t) / dt}{a(t)}$$

Hubble-Lemaitre Parameter

(t) means "depends on time"

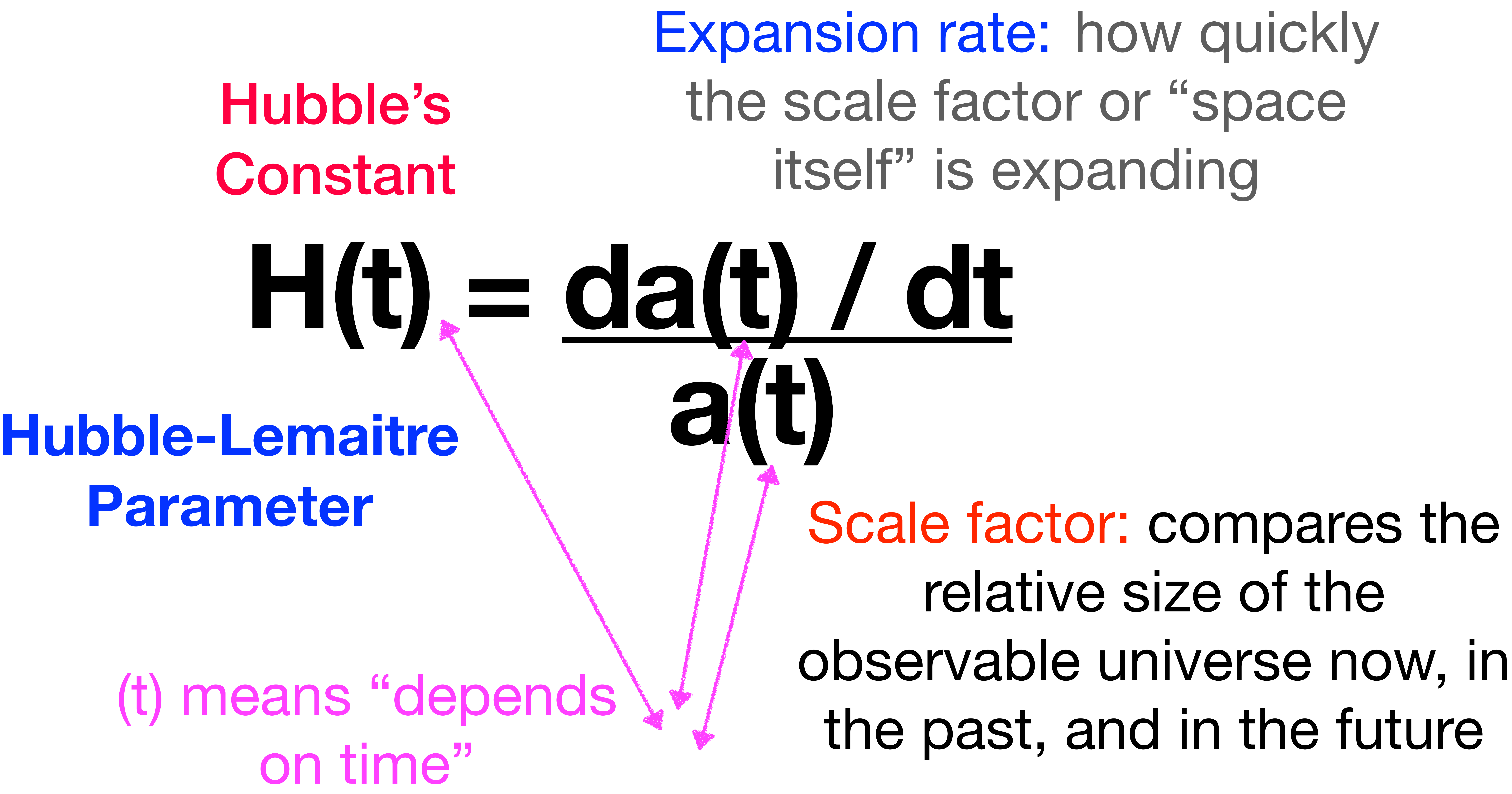
Hubble's Constant

$$H(t) = \frac{da(t) / dt}{a(t)}$$

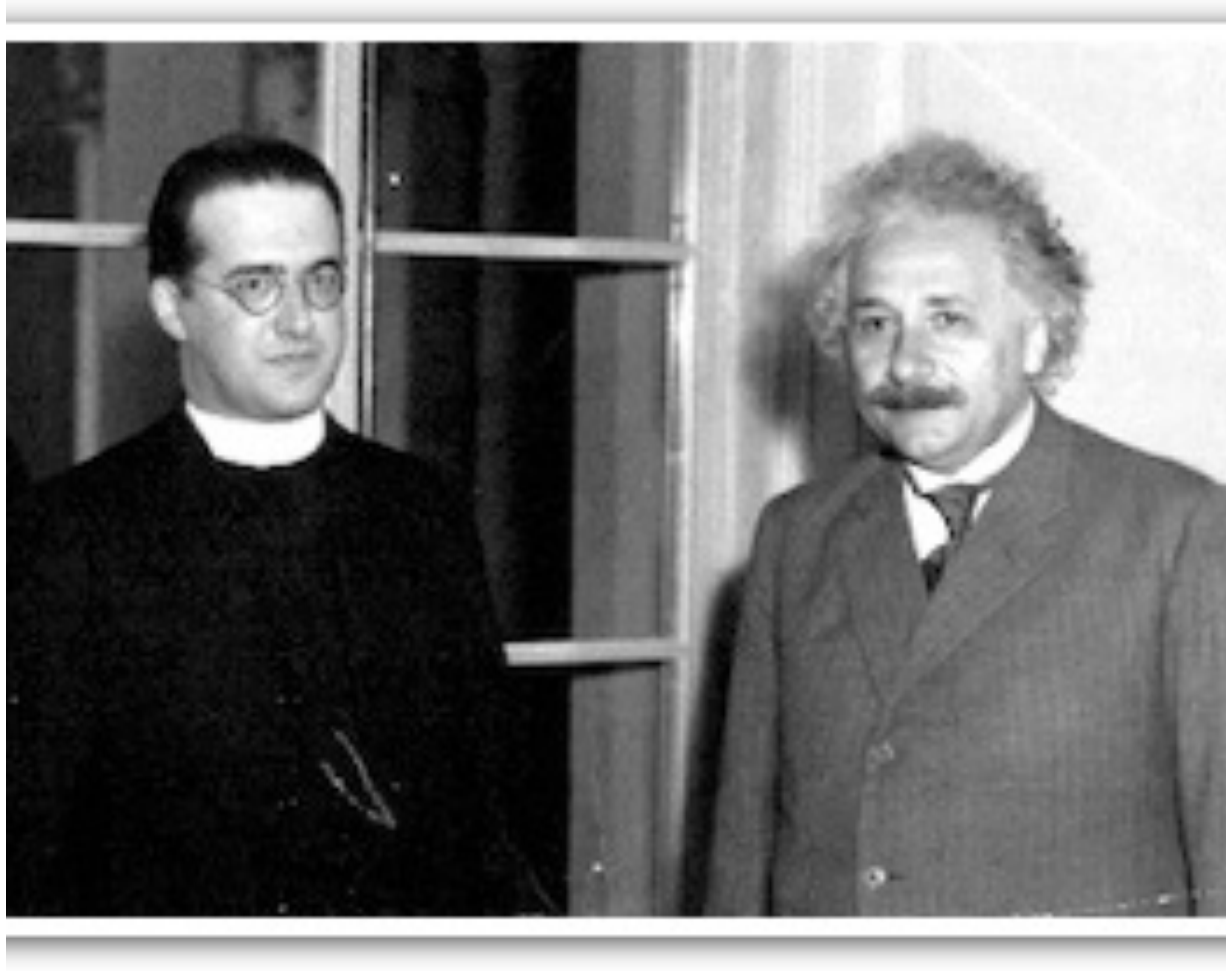
Hubble-Lemaitre Parameter

(t) means "depends on time"

Scale factor: compares the relative size of the observable universe now, in the past, and in the future


Expansion rate: how quickly the scale factor or “space itself” is expanding
Hubble’s Constant
H(t) = da(t) / dt
a(t)
Hubble-Lemaitre Parameter
Scale factor: compares the relative size of the observable universe now, in the past, and in the future
(t) means “depends on time”

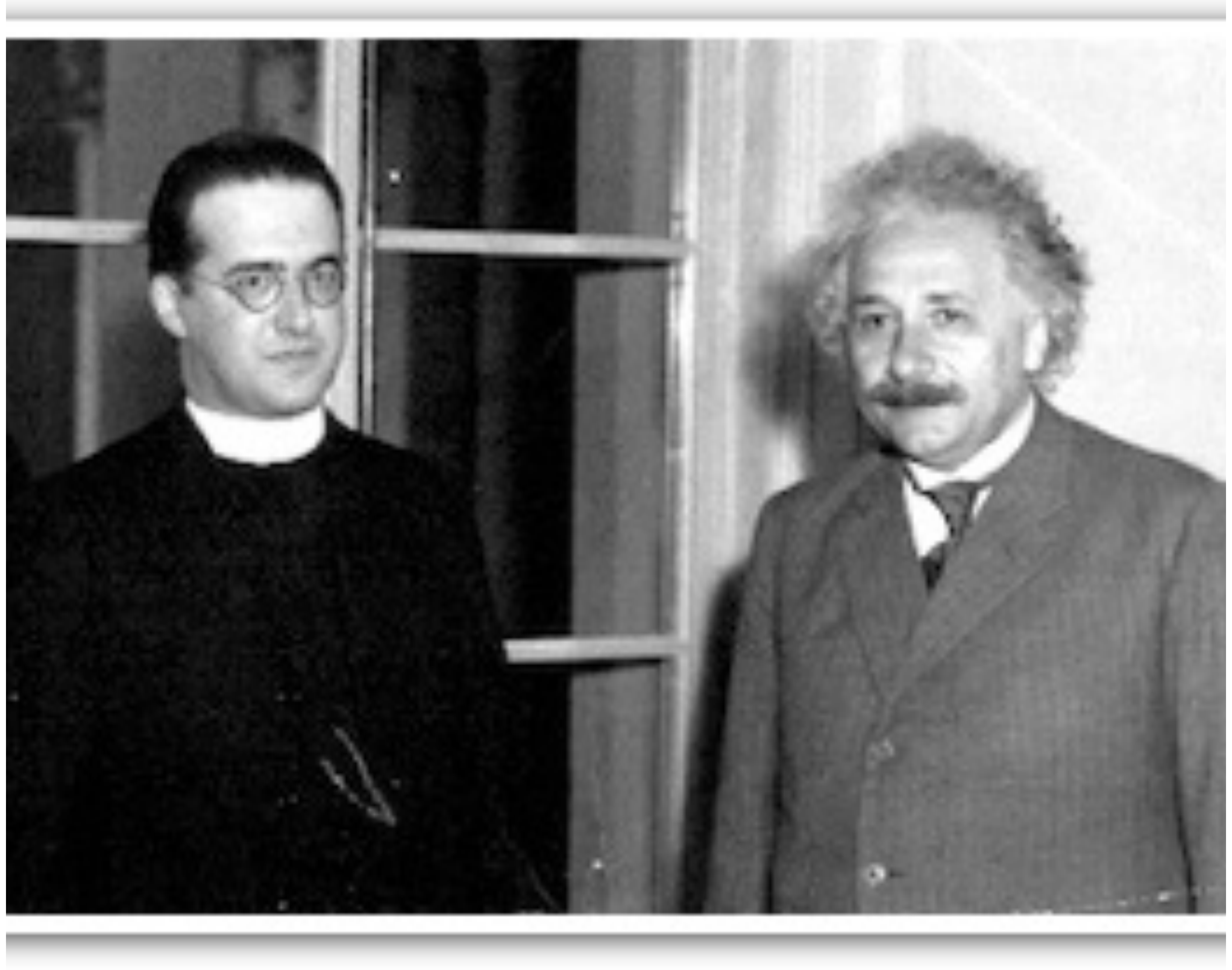
How are "Hubble's Law" and the "expansion rate" related?



George Lemaitre and Einstein

George Lemaitre to the rescue!

How are “Hubble’s Law” and the “expansion rate” related?



George Lemaitre and Einstein

George Lemaitre to the rescue!

In 1927, George Lemaitre, a Belgian priest and astrophysicist, theoretically derived Hubble’s Law and its connection to how quickly the scale factor of the universe is increasing! He did this two years before Edwin Hubble discovered his Famous Law through observation and analysis!

$V = H \times D$

George Lemaitre 1927

George Lemaitre late 1920's

Interpreted Slipher's 21 out of 25 spiral nebula receding away from us as the physical expansion of space itself

George Lemaitre 1927

Suggested the universe was **not static** as Einstein had thought

George Lemaitre late 1920's

George Lemaitre 1927

Used Einstein's Field Equations to derive equations for the expansion of the universe theoretically

George Lemaitre late 1920's

George Lemaitre 1927

Assumptions

George Lemaitre late 1920's

George Lemaitre 1927

Assumptions

For large scales, say 300 MLy…

George Lemaitre late 1920's

George Lemaitre 1927

Assumptions

For large scales, say 300 MLy…

1. **Universe was filled with matter**

George Lemaitre late 1920's

George Lemaitre 1927

Assumptions

For large scales, say 300 MLy…

1.Universe was filled with matter

2. Looks the same no matter where you are… Homogeneous or spatially symmetric

George Lemaitre late 1920's

Assumptions

For large scales, say 300 MLy…

1.Universe was filled with matter

2. Looks the same no matter where you are… Homogeneous or spatially symmetric

3. Looks the same no matter which direction you look… Isotropic or rotationally symmetric

George Lemaitre late 1920's

Assumptions

For large scales, say 300 MLy…

1. Universe was filled with matter

2. Looks the same no matter where you are… Homogeneous or spatially symmetric

3. Looks the same no matter which direction you look… Isotropic or rotationally symmetric

4. The peculiar motion of galaxies through space was negligible compared to the expansion of space carrying the galaxies with them.

George Lemaitre late 1920's

Assumptions: Cosmological Principle

For large scales, say 300 MLy…

1. Universe was filled with matter

2. Looks the same no matter where you are… Homogeneous or spatially symmetric

George Lemaitre late 1920’s

3. Looks the same no matter which direction you look… Isotropic or rotationally symmetric

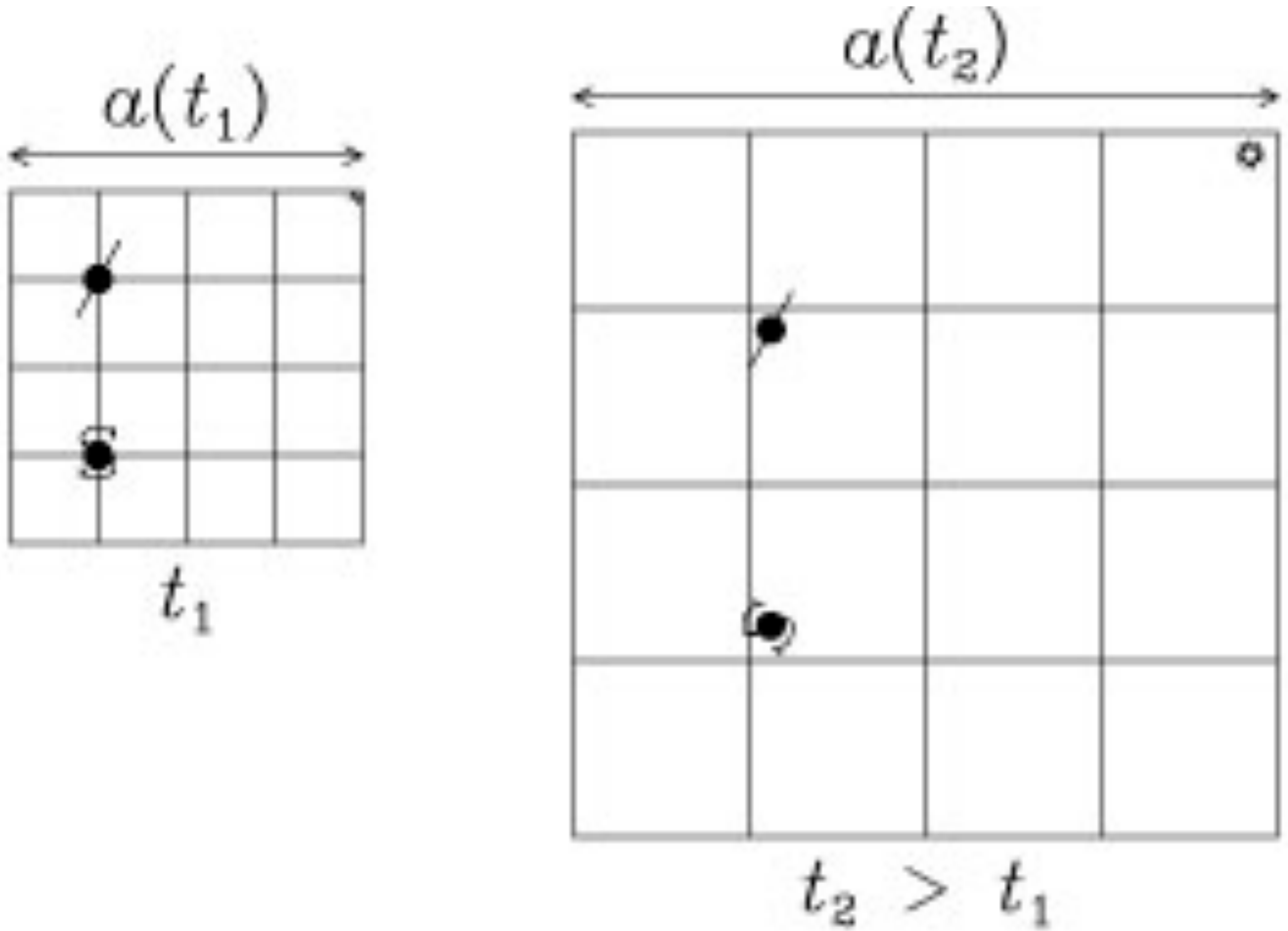
4. The peculiar motion of galaxies through space was negligible compared to the expansion of space carrying the galaxies with them.

Theoretical framework?

For large scales, say 300 MLy…

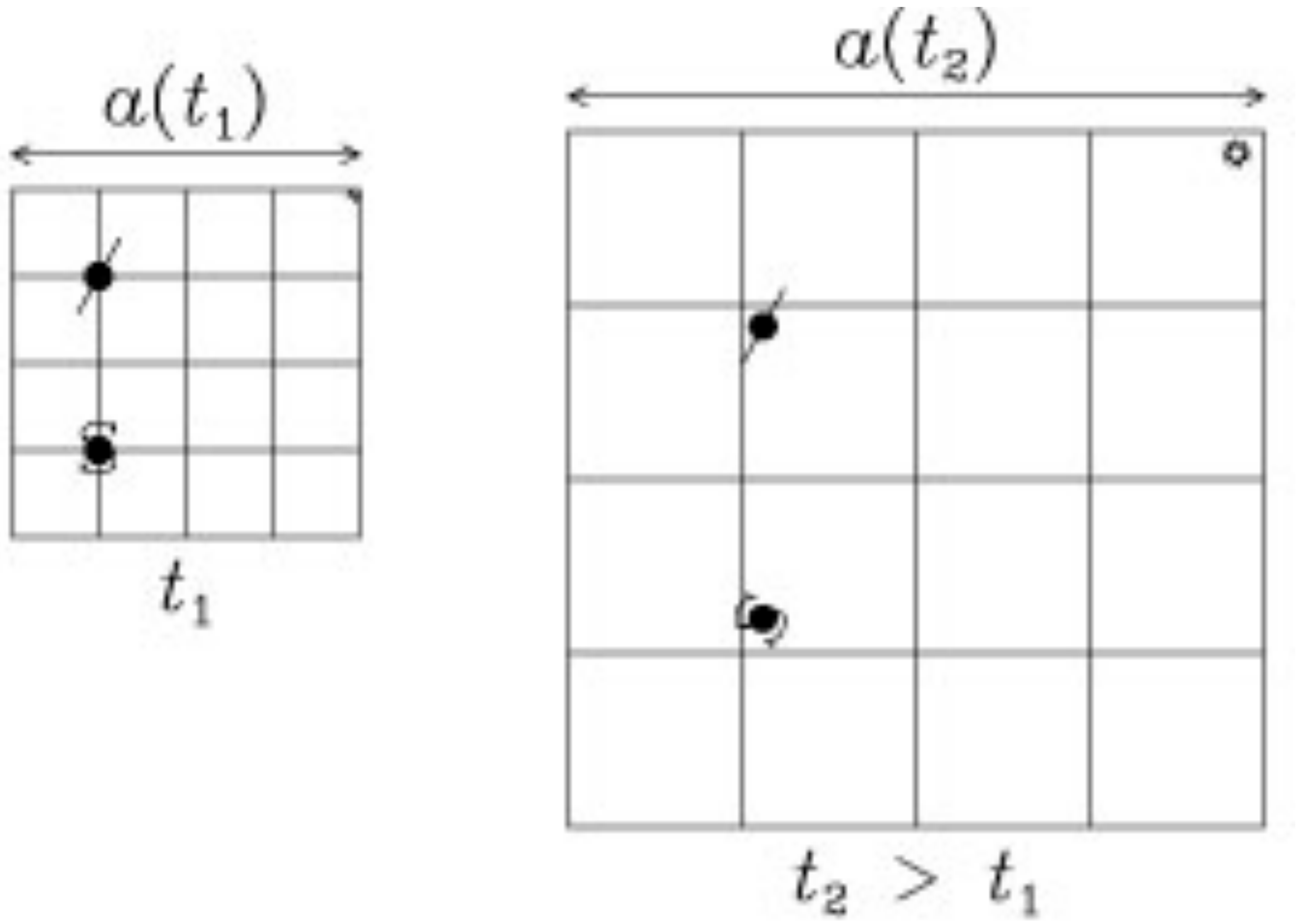
He was first to set up the idea of scale factor a(t) which depended on time and introduced comoving coordinates

George Lemaitre late 1920's



Comoving coordinates and Scale Factor a(t)

The comoving coordinates expand with the universe

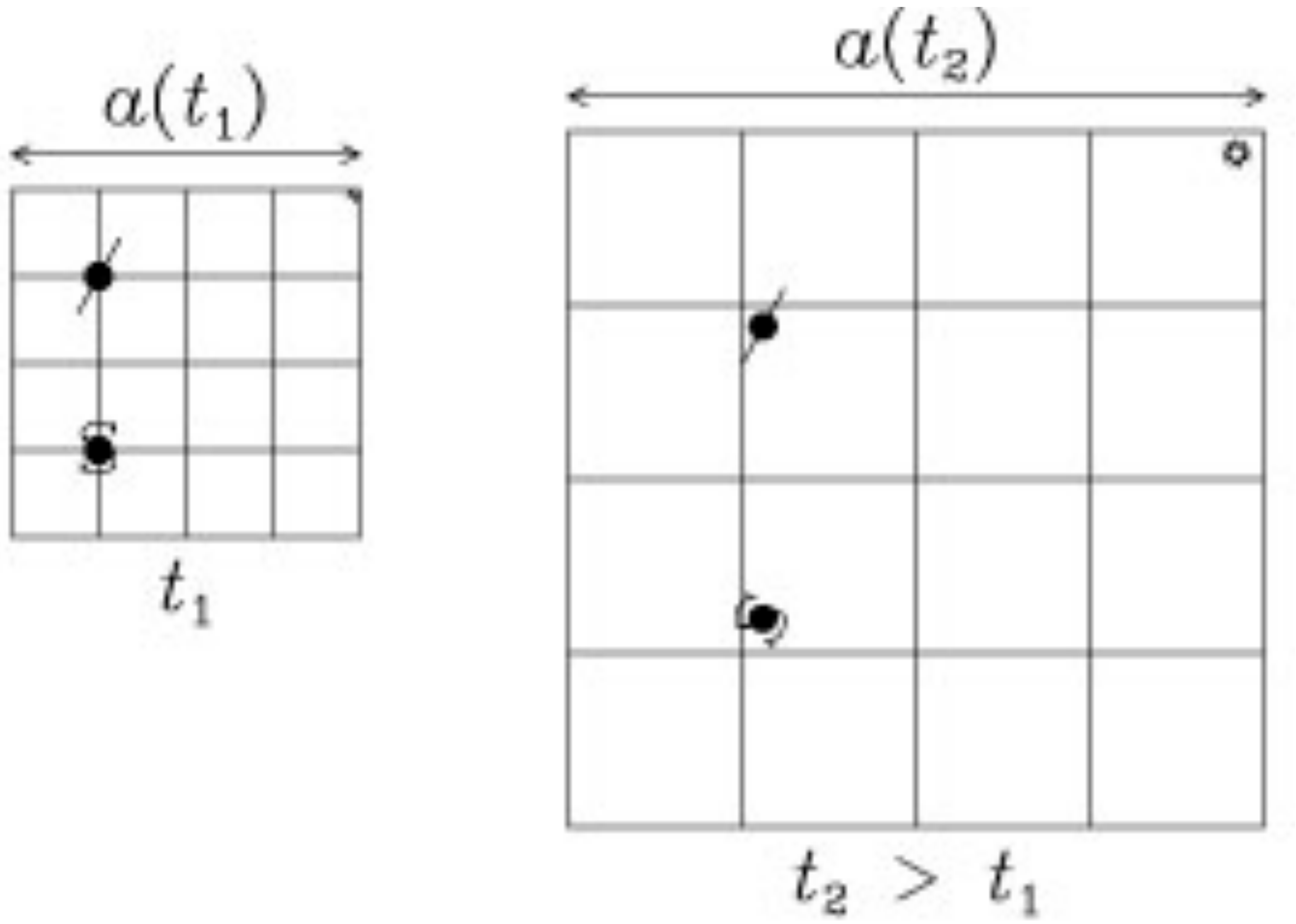


The comoving distance X between galaxies stays constant.

Here, the comoving distance between galaxies stays constant at X = 2 MLy (arbitrary unit).

Comoving coordinates and Scale Factor a(t)

The comoving coordinates expand with the universe



The comoving distance X between galaxies stays constant.

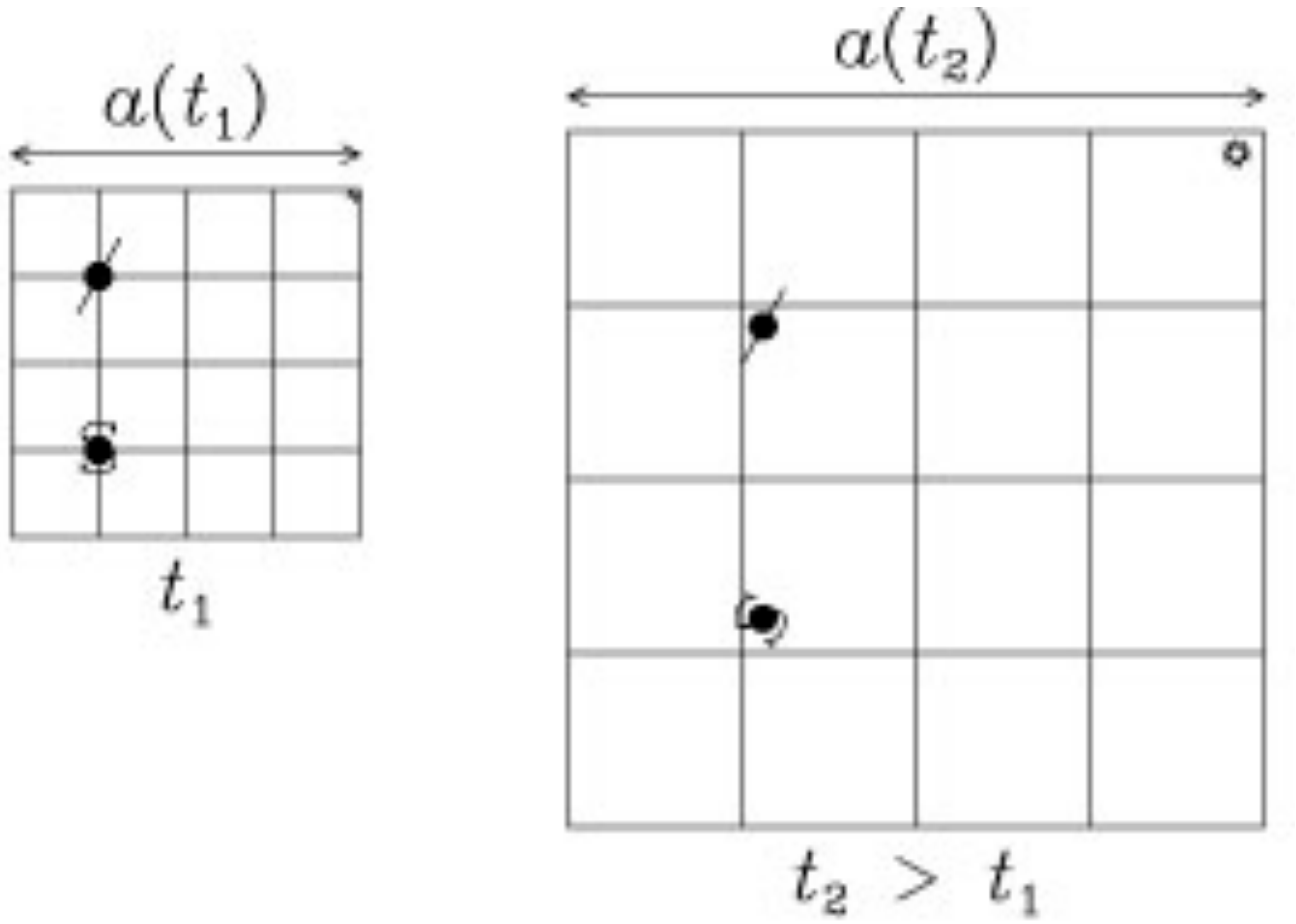
Here, the comoving distance between galaxies stays constant at X = 2 MLy (arbitrary unit).

The **proper distance** or actual tape measure distance at any one time does change

At any given time $D_P = a X$

Comoving coordinates and Scale Factor a(t)

The comoving coordinates expand with the universe



Comoving coordinates and **Scale Factor a(t)**

The comoving coordinates expand with the universe

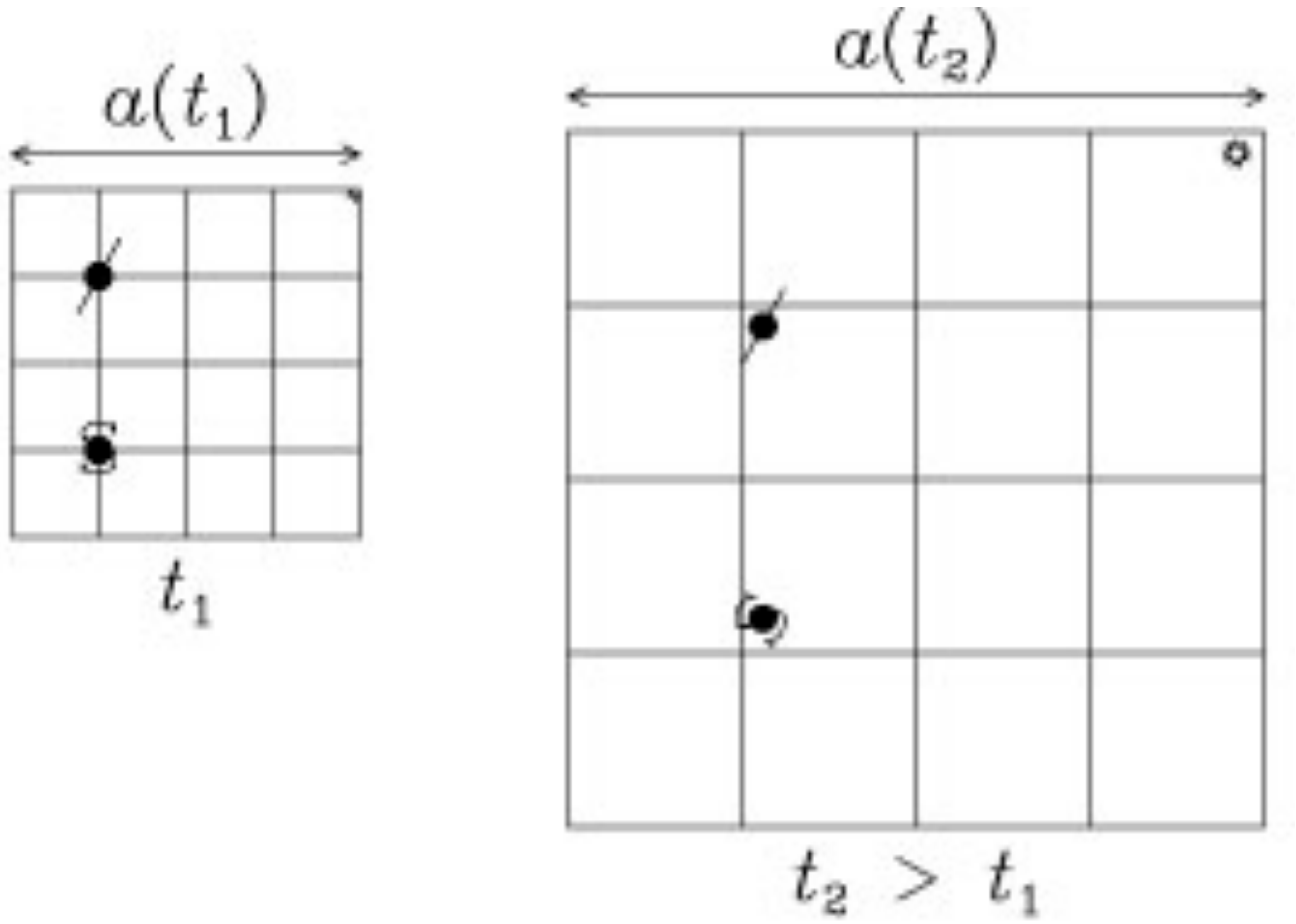
If at one cosmic time t_2 ,
$a(t_2) = 5$

And X = 2 MLy

The proper distance at t_2

$D_P = a\,X$

$D_P = 5\ (2\ \text{MLY})$
$= 10\ \text{MLY}$



If at one cosmic time t_1 ,
$a(t_1) = 3$

And X = 2 MLy

The proper distance at t_1

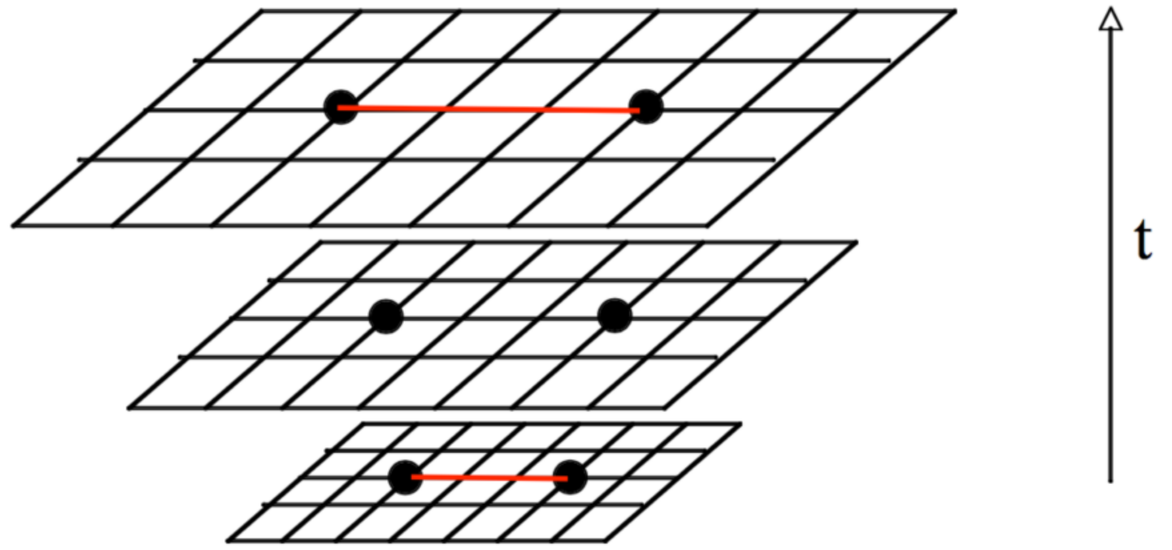
$D_P = a X$

$D_P = 3 (2 \text{ MLY})$
$= 6 \text{ MLY}$

Comoving coordinates and Scale Factor a(t)

The comoving coordinates expand with the universe

Distances:
co-moving, physical, scale factor

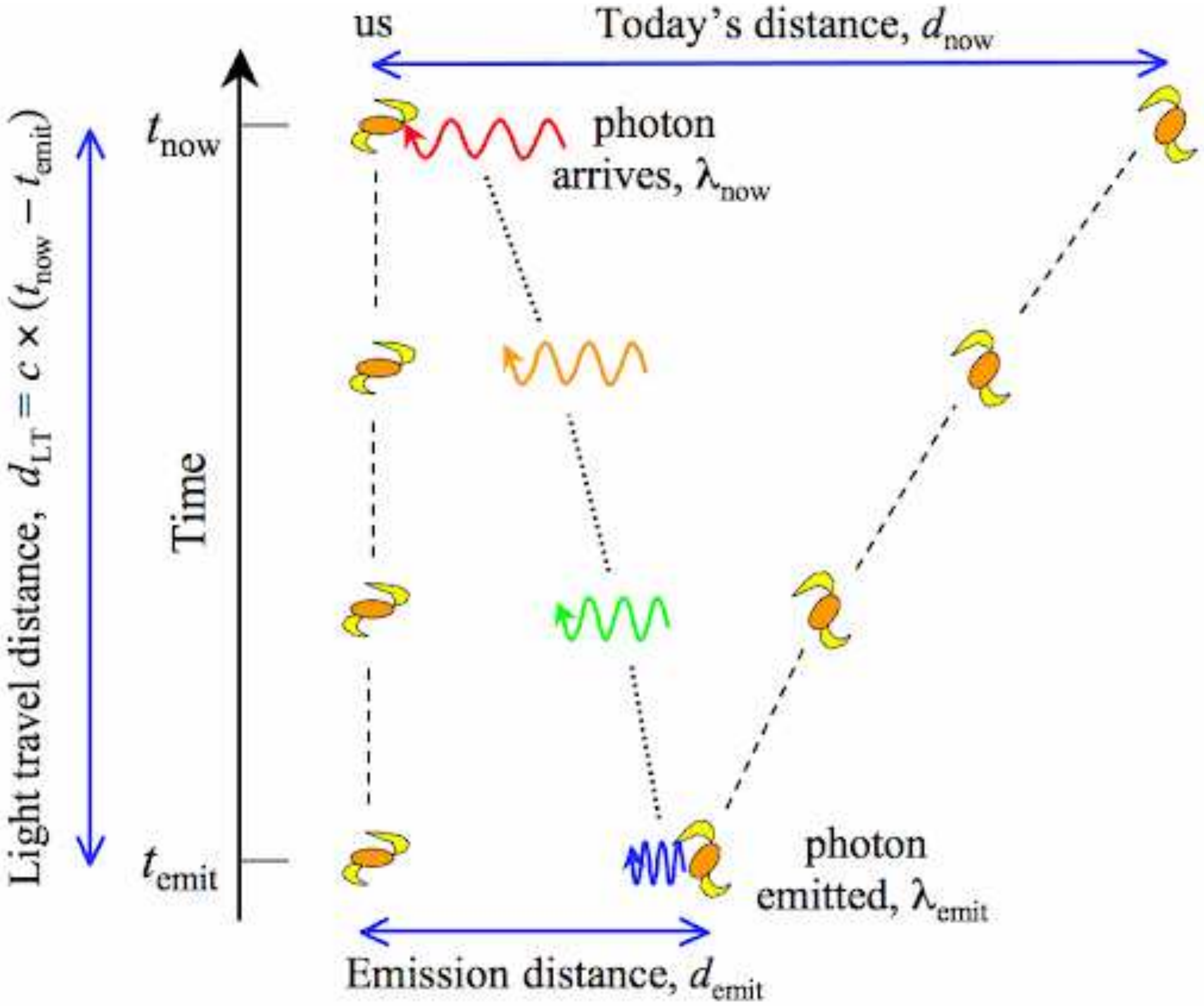


physical distance

$$r(t) = a(t)x$$

co-moving distance x: distance measured on the grid (always 3 units in this example)

scale factor a(t): size of the grid (varies with time as universe expands)



Another way of looking at proper distance or DNOW

Lemaitre’s Derivation

Lemaitre’s Derivation

$$r = a(t)\, X$$

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Proper distance

Comoving distance

$$r = a(t)\, X$$

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Proper distance

Comoving distance

$$r = a(t)\,X$$

Divide both sides by very small t value

Lemaitre's Derivation

Proper distance ↔ $r = a(t)\,X$ ↔ Comoving distance

Divide both sides by very small t value

$$\frac{dr}{dt} = \frac{da(t)}{dt} X$$

Lemaitre's Derivation

Proper distance

Comoving distance

Recession speed

$$r = a(t)\,X$$

$$V = \frac{dr}{dt} = \frac{da(t)}{dt}\,X$$

Lemaitre's Derivation

Proper distance ↔ $r = a(t)\,X$ ↔ Comoving distance

Recession speed ↔ $V = \dfrac{da(t)\,X}{dt}\,\dfrac{a(t)}{a(t)}$

Multiply top and bottom by the scale factor a(t)

Lemaitre’s Derivation

Proper distance

Comoving distance

$$r = a(t)\, X$$

But what is X a(t) ?

Recession speed

$$V = \frac{da(t)\; X\; a(t)}{dt\;\; a(t)}$$

Lemaitre's Derivation

Proper distance ↔ $r = a(t)\, X$ ↔ Comoving distance

Recession speed ↔ $V = \frac{da(t)}{dt}\frac{r}{a(t)}$

It is just proper distance r

Lemaitre's Derivation

Proper distance

Comoving distance

$$r = a(t)\,X$$

Lets rewrite the red in a neater way!

Recession speed

$$V = \frac{da(t)\;r}{dt\;a(t)}$$

Lemaitre's Derivation

Proper distance ↔ $r = a(t)\,X$ ↔ Comoving distance

Recession speed ↔ $V = \frac{da(t)/dt}{a(t)}\, r$

Lets rewrite the red in a neater way!

Lemaitre's Derivation

Proper distance ↔ $r = a(t)\,X$ ↔ Comoving distance

Recession speed ↔ $$V = \frac{da(t)/dt}{a(t)}\, r$$

Lets rewrite the red in a neater way!

For an expanding universe following Einstein's Field equations and his cosmological principle, Lemaitre also knew theoretically that V α D i.e. Hubble's law ↔ $V = H(t)\, r$

Lemaitre's Derivation

Proper distance

Comoving distance

$$r = a(t)\,X$$

Recession speed

$$V = \frac{da(t)/dt}{a(t)}\,r$$

Compare the two bottom equations. What is H(t)?

For an expanding universe following Einstein's Field equations and his cosmological principle, Lemaitre also knew theoretically that V α D i.e. Hubble's law

$$V = H(t)\,r$$

$$H(t) = \frac{da(t) / dt}{a(t)}$$

This defines what the Hubble -Lemaitre parameter is all about!

Redshift and Scale Factor

The scale factor and redshift are related in a simple equation. Let’s reason it out!

Redshift and Scale Factor

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

Redshift and Scale Factor

$$Z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

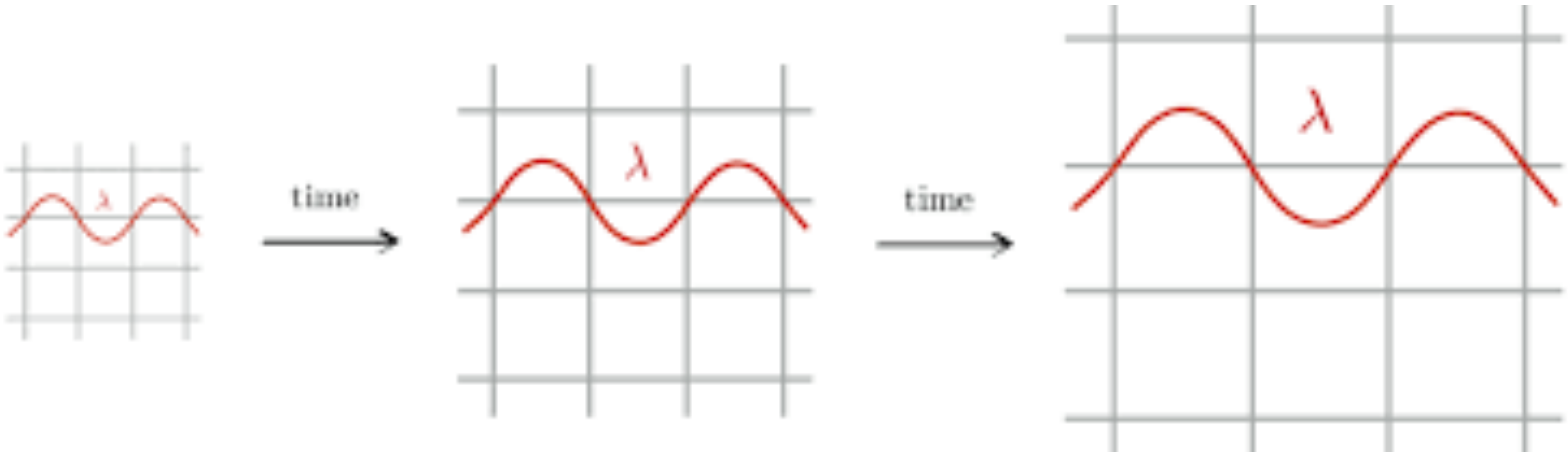
$$Z = \lambda_{obs}/\lambda_{em} \; - 1$$

Redshift and Scale Factor

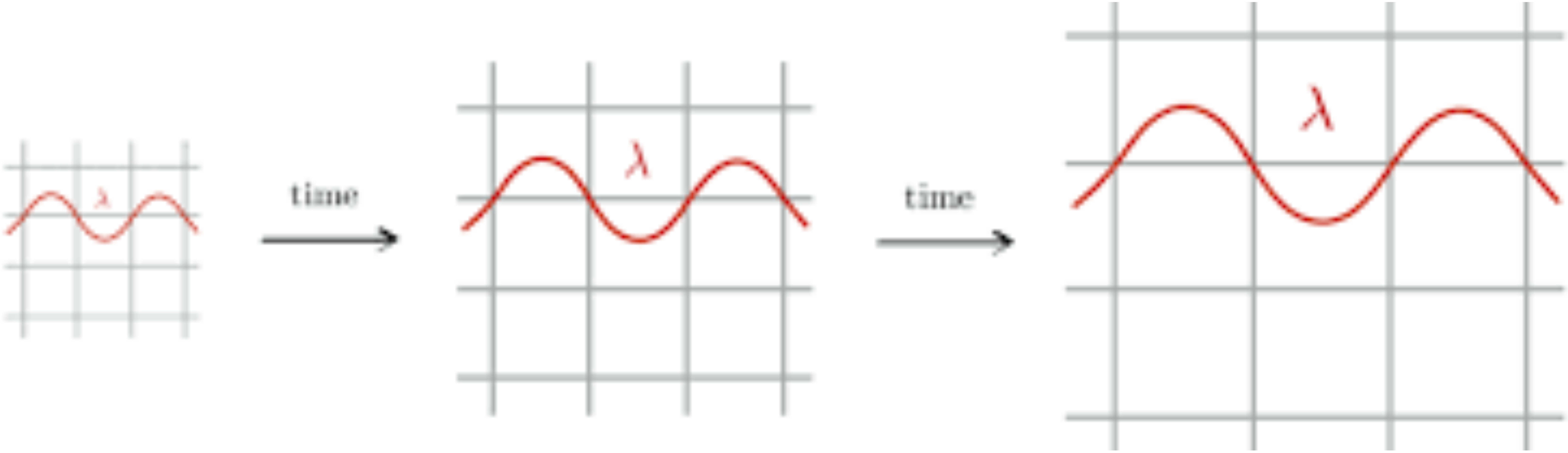
$$Z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

$$Z = \lambda_{obs}/\lambda_{em} - 1$$

$$Z + 1 = \lambda_{obs}/\lambda_{em}$$

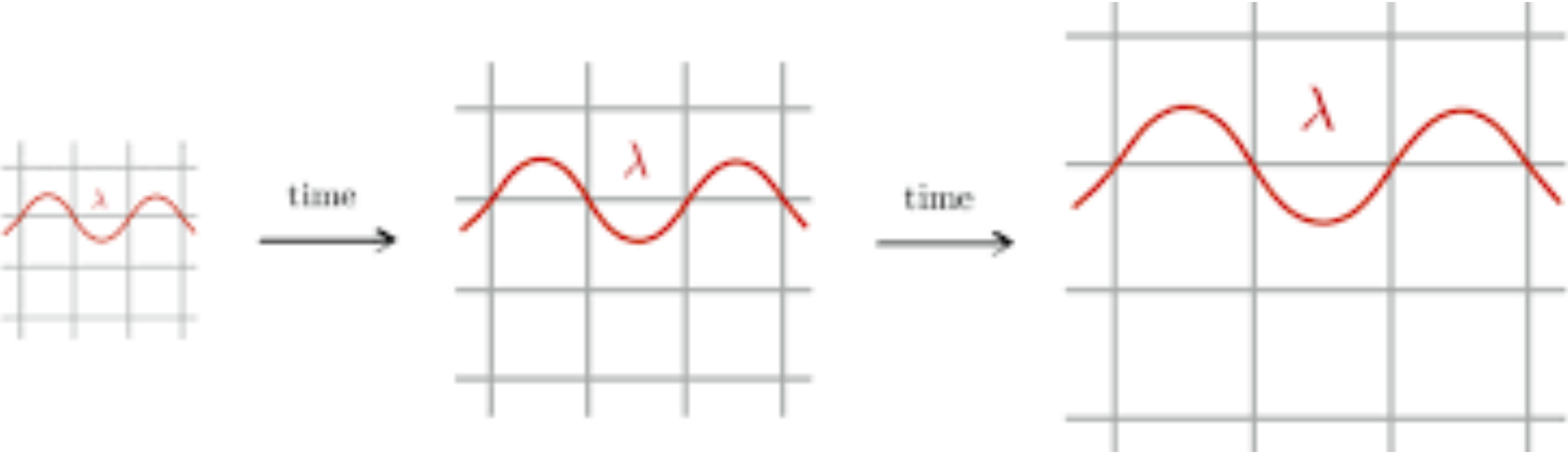


Light gets stretched by expanding space!



Light gets stretched by expanding space!

So a “ is proportional to ” λ



Light gets stretched by expanding space!

So a " is proportional to " λ

Which means... $a(t_{obs}) / a(t_{em}) = \lambda_{obs} / \lambda_{em}$

Redshift and Scale Factor

$$Z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

$$Z = \lambda_{obs}/\lambda_{em} - 1$$

$Z + 1 = \lambda_{obs}/\lambda_{em}$ **red symbols can replace with**

$a(t_{obs}) / a(t_{em})$

Redshift and Scale Factor

$$Z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

$$Z = \lambda_{obs}/\lambda_{em} - 1$$

$$Z + 1 = a(t_{obs}) / a(t_{em})$$

Redshift and Scale Factor

Common Formula in Astrophysics

$$Z + 1 = a(t_{obs}) / a(t_{em})$$

Redshift and Scale Factor

Common Formulas in Astrophysics

$$Z + 1 = a(t_{obs}) / a(t_{em})$$

By convention, $a(t_{obs}) = 1$

Therefore $Z + 1 = 1 / a(t_{em})$

Redshift and Scale Factor

Common Formulas in Astrophysics

$$Z + 1 = a(t_{obs}) / a(t_{em})$$

By convention, $a(t_{obs}) = 1$

Therefore $Z + 1 = 1 / a(t_{em})$

Knowing redshift can get us the scale factor in the past!