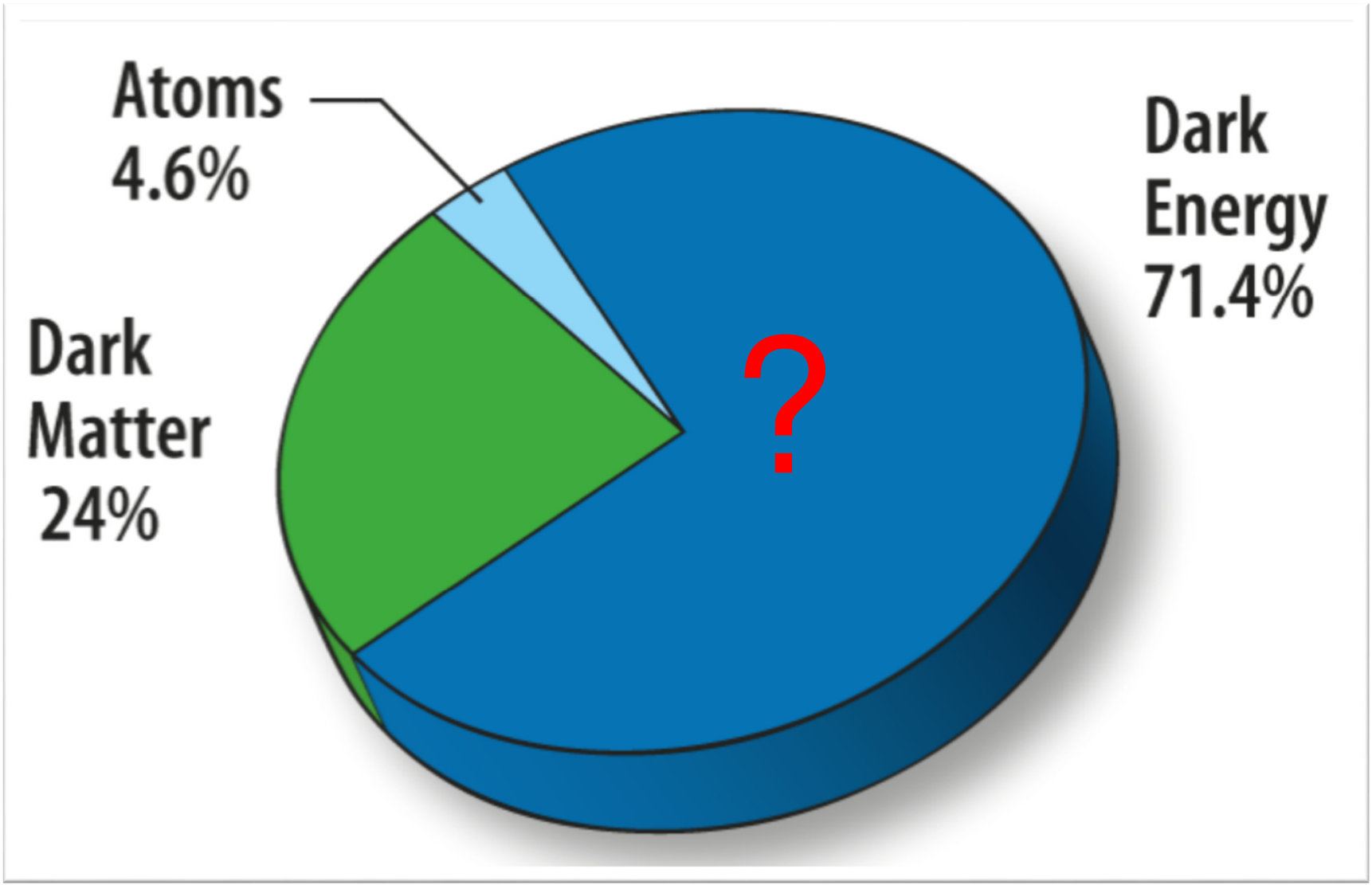
The Dark Energy

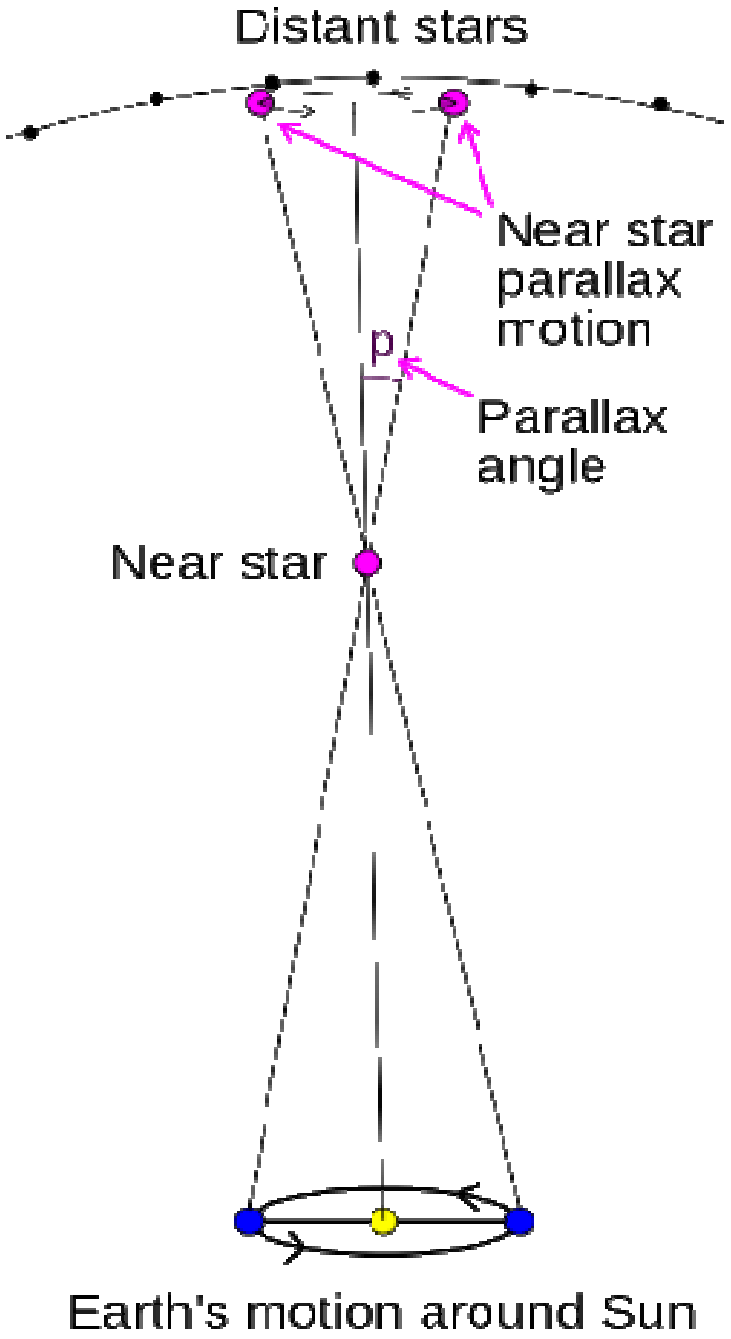


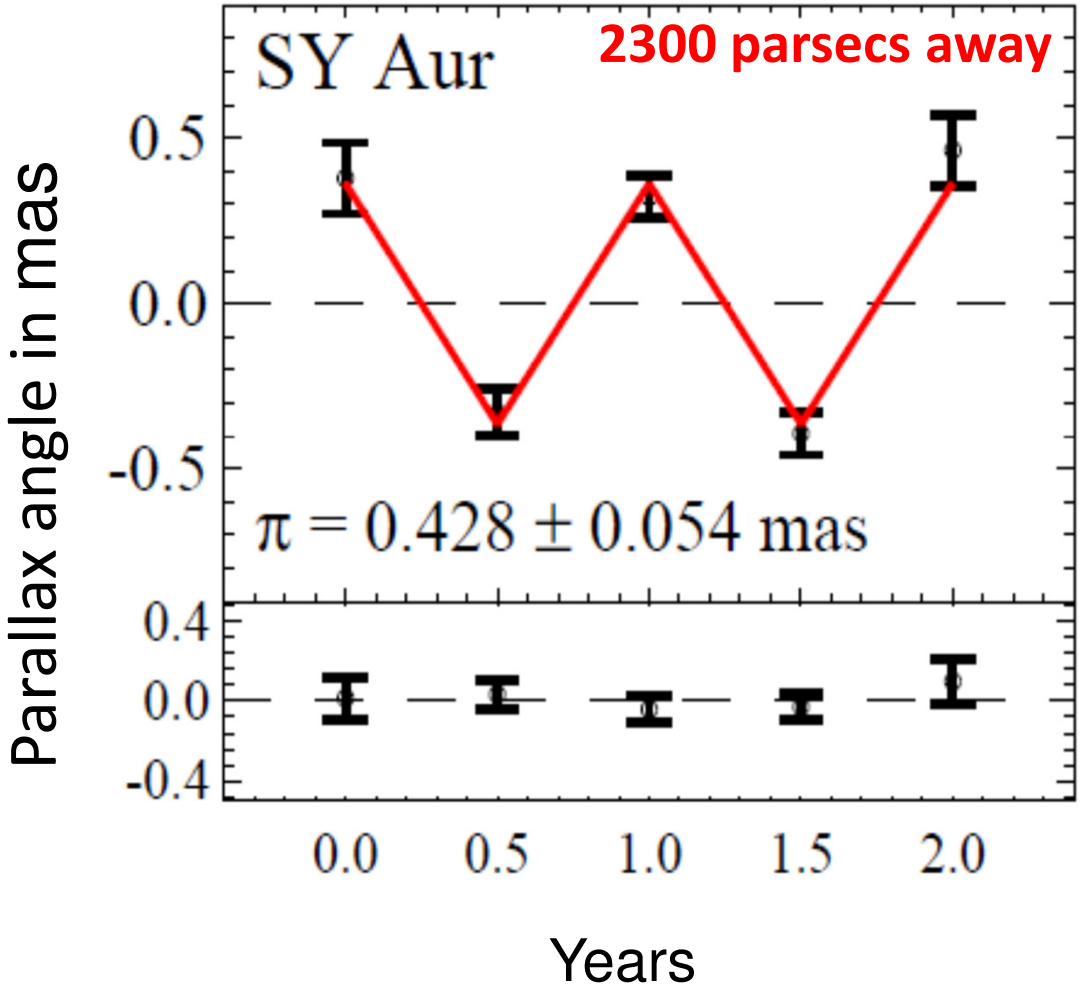
Part 1: The Big Bang and Expanding Universe

1916: The universe of 100 years ago

- Eternal
- Unchanging
- Consisting of a single galaxy
- The galaxy has a few million visible stars

Measuring distances to stars: parallax method



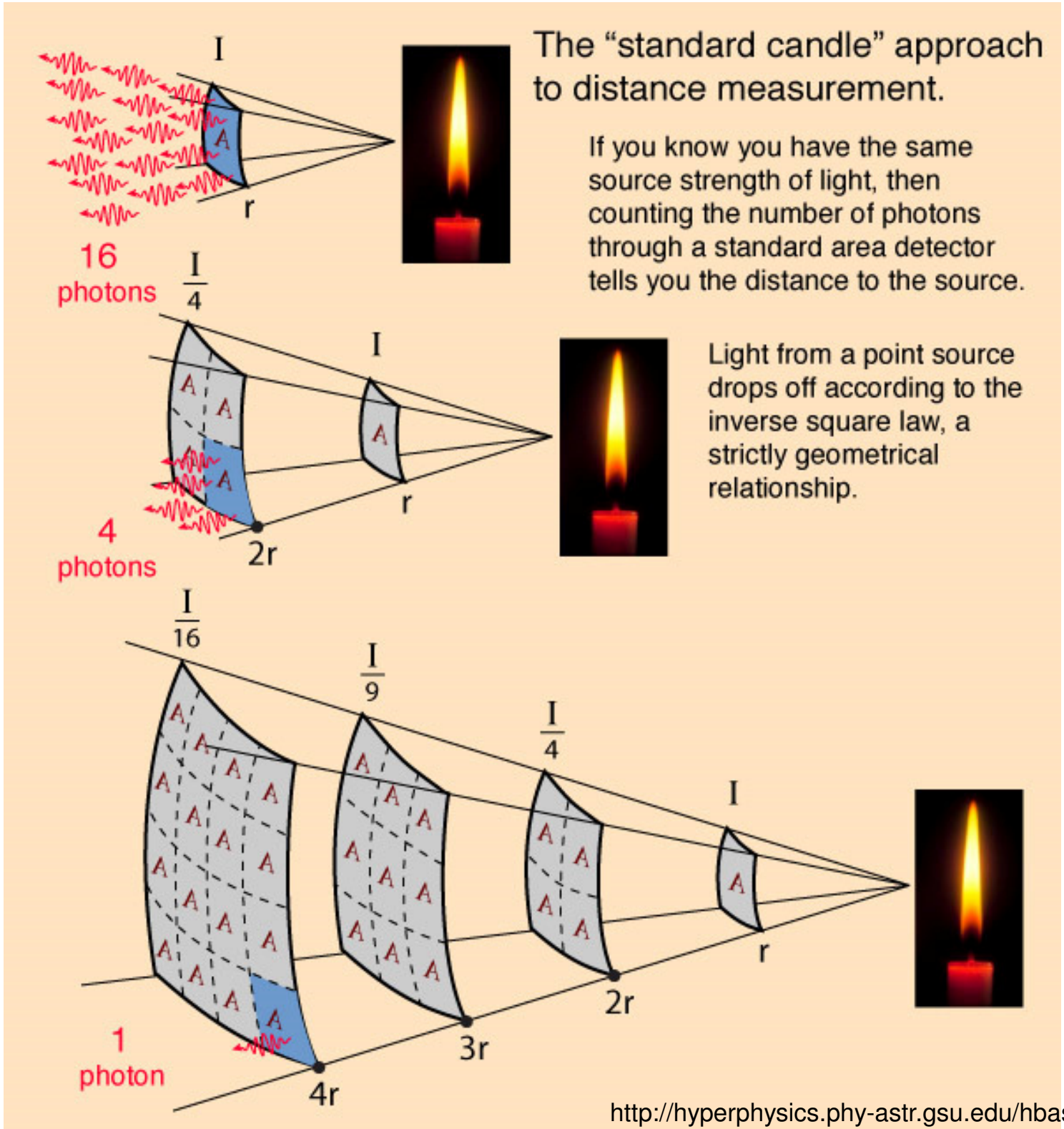


This method works up to about 5000 parsecs even with best modern technologies.

To measure larger distances we need "standard candles"

A **standard candle** is a class of astrophysical objects, such as supernovae or variable stars, which have known luminosity due to some characteristic quality possessed by the entire class of objects.

https://wigglez.swin.edu.au/site/image1.html
http://www.centauri-dreams.org/?p=11322



http://hyperphysics.phy-astr.gsu.edu/hbase/astro/stdcand.html

Standard Candle Distance indicator: Variable Stars

Animation of a variable star:
http://www.spacetelescope.org/videos/heic1323j/

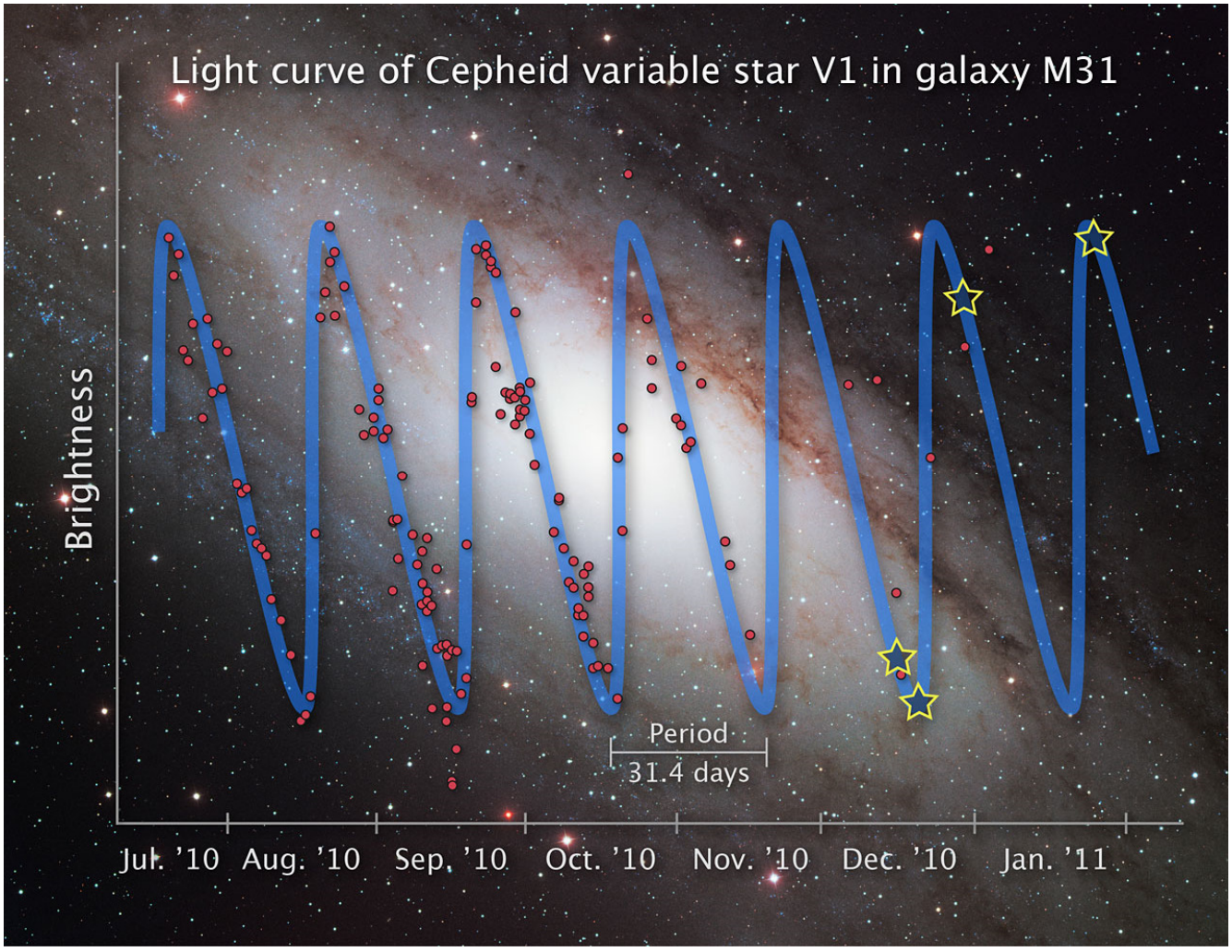
Youtube link (the same video)

https://www.youtube.com/watch?v=sXJBrRmHPj8

Credit:NASA, ESA, M. Kornmesser

Cepheid Variable stars

Cepheid variables are very luminous pulsating stars that brighten and fade in a predictable pattern.



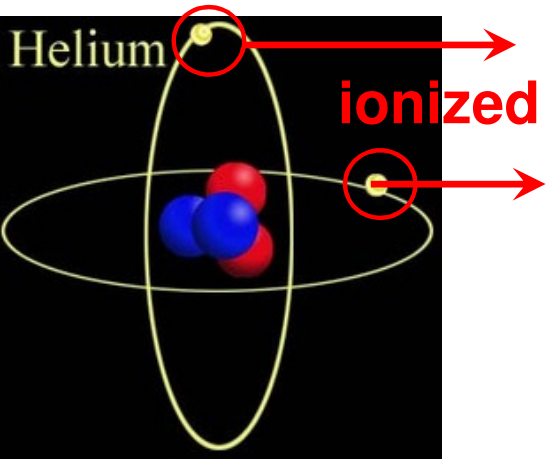
A strong direct relationship between a Cepheid variable's luminosity and pulsation period secures for Cepheids their status as important distance indicators for establishing the galactic and extragalactic distance scales.

Illustration Credit:NASA, ESA and Z. Levay (STScI).
https://www.spacetelescope.org/images/opo1115e/

Why do stars pulsate?

Pulsations arise from variations in the rate at which the radiation can escape from the star. A pulsating star is thus not in equilibrium (gravity vs. pressure) but is always trying to regain it but shooting past the point.

- When a Cepheid is compressed, it becomes opaque.
- Photons are trapped inside, heating the gas and increasing its pressure.
- The high-pressure gas expands, becoming transparent.
- Photons escape, the gas cools, the pressure drops.
- As the pressure drops, the Cepheid is compressed by gravity.



Why do stars pulsate?

Doubly ionized helium (helium whose atoms are missing both electrons) is more opaque than singly ionized helium. The more helium is heated, the more ionized it becomes. The process then repeats.

- **When a Cepheid is compressed, it becomes opaque.**

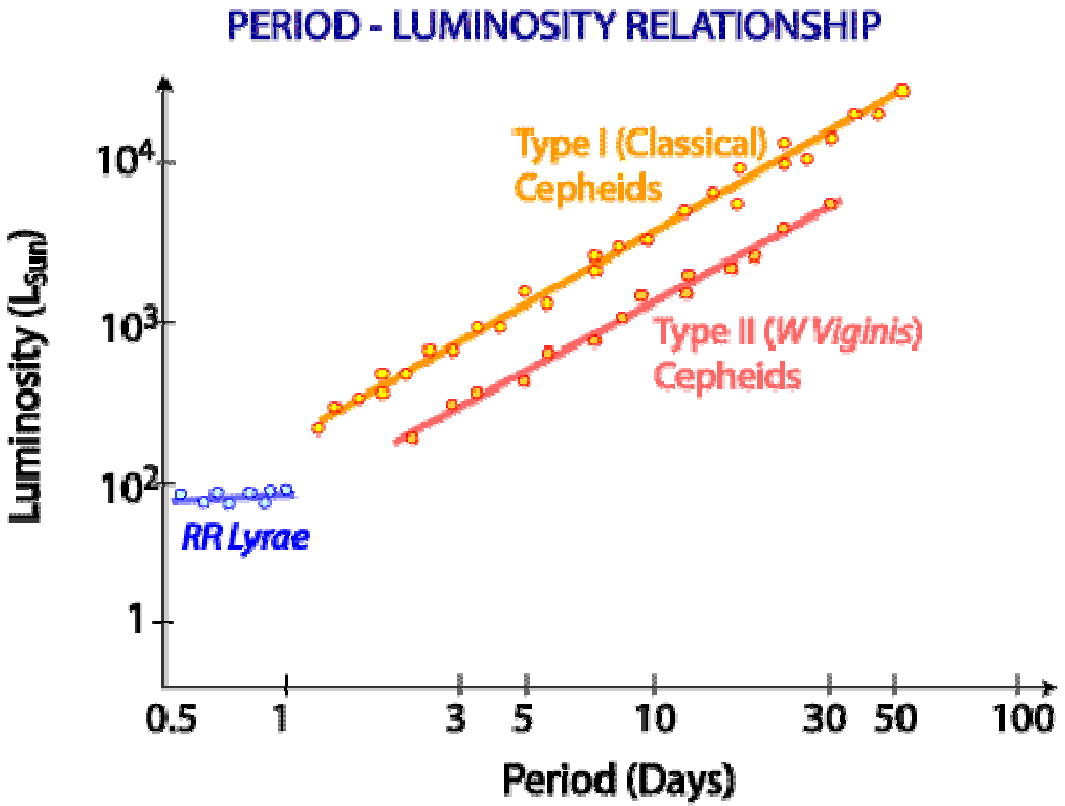
At the dimmest part of a Cepheid's cycle, the ionized gas in the outer layers of the star is opaque.

- **Photons are trapped inside, heating the gas and increasing its pressure.**
- **The high-pressure gas expands. As it expands, it cools**, and so becomes less ionized and therefore more transparent, allowing the radiation to escape.
- **Photons escape, the gas cools, the pressure drops.** Then the expansion stops.
- **As the pressure drops, the Cepheid is compressed by gravity.** The He becomes more ionized again, become opaque, cycle repeats.

Credit: *AAVSO*

Using Cepheid Variable stars to measure distances

Henrietta Leavitt discovered period-luminosity relation for Cepheids in 1900s.



- Measure the period P of a Cepheid variable.
- From the period-luminosity relation, determine the luminosity L.
- Measure the apparent brightness b.
- Compute the distance from the equation: $L = 4 \pi d^2 b$

http://www.atnf.csiro.au/outreach/education/senior/astrophysics/variable_cepheids.html

1920s: Edwin Hubble

Hubble identified Cepheid variable stars in several spiral nebulae, including the Andromeda Nebula and Triangulum.

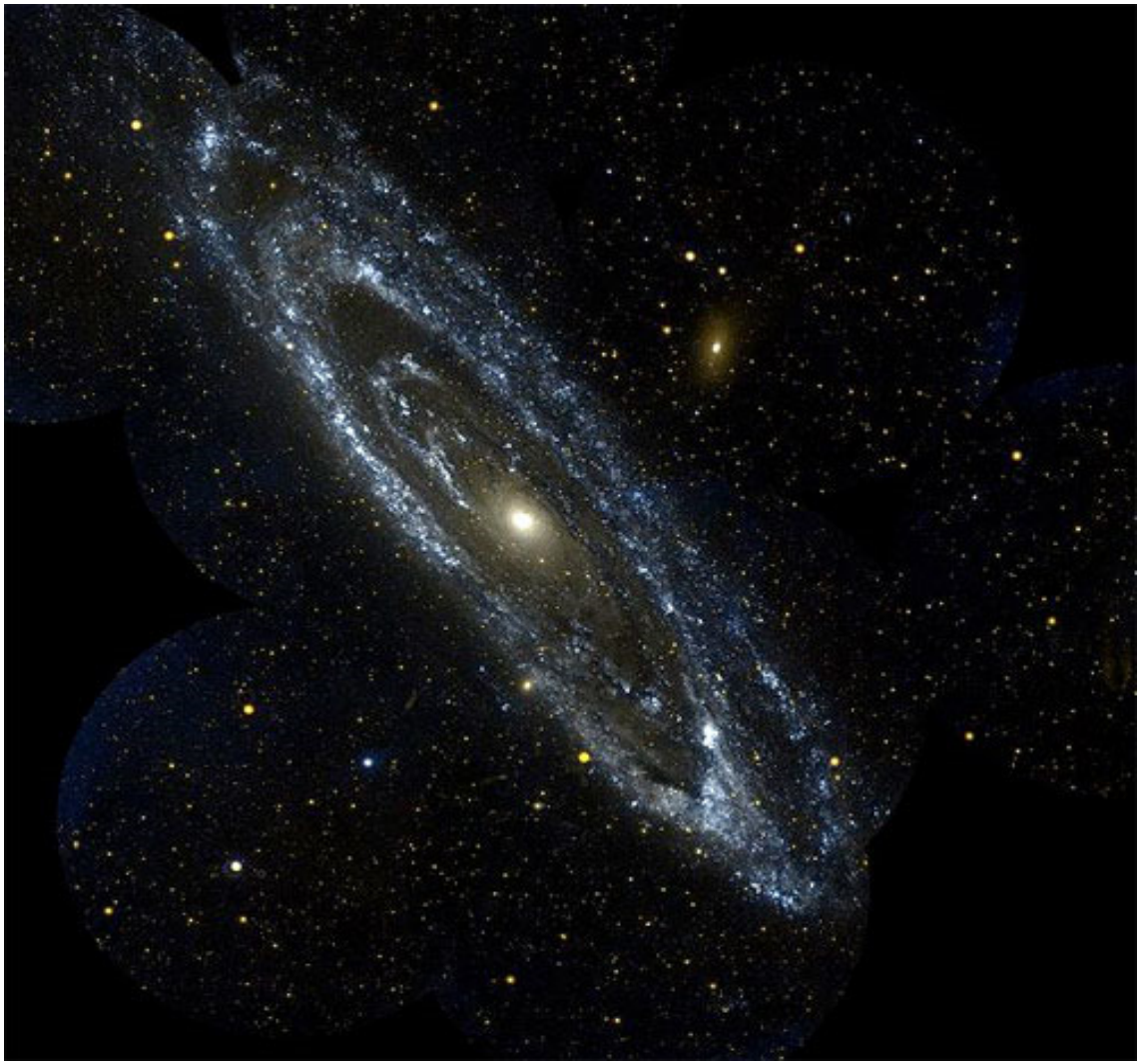
His observations, made in 1922–1923, proved conclusively that these nebulae were much too distant to be part of the Milky Way and were, in fact, entire galaxies outside our own.

https://en.wikipedia.org/wiki/Edwin_Hubble#/media/File:100inchHooker.jpg

1917: 100-inch telescope
Mount Wilson
The world's largest at that time

Dec. 30, 1924: Hubble Reveals We Are Not Alone New York Times

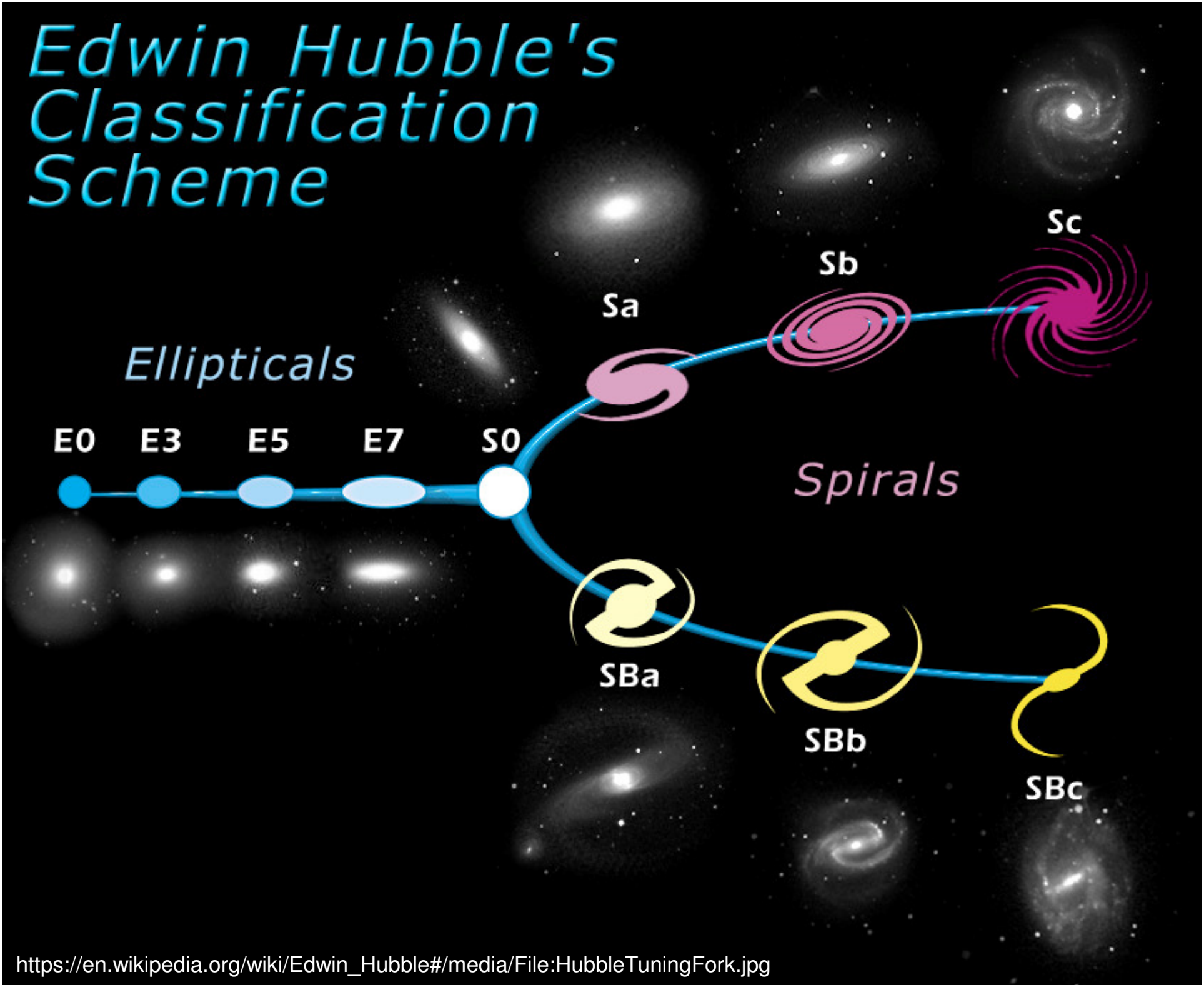
1924: Astronomer Edwin Hubble announces that the spiral nebula Andromeda is actually a galaxy and that the Milky Way is just one of many galaxies in the universe.



These **fuzzy nebulae**, speculated about for several hundred years, were actually **galaxies just like our own** —

and our known Universe become **MUCH larger** – by a factor of 100 billion.

http://www.wired.com/2009/12/1230hubble-first-galaxy-outside-milky-way/



https://en.wikipedia.org/wiki/Edwin_Hubble#/media/File:HubbleTuningFork.jpg

1929: Edwin Hubble

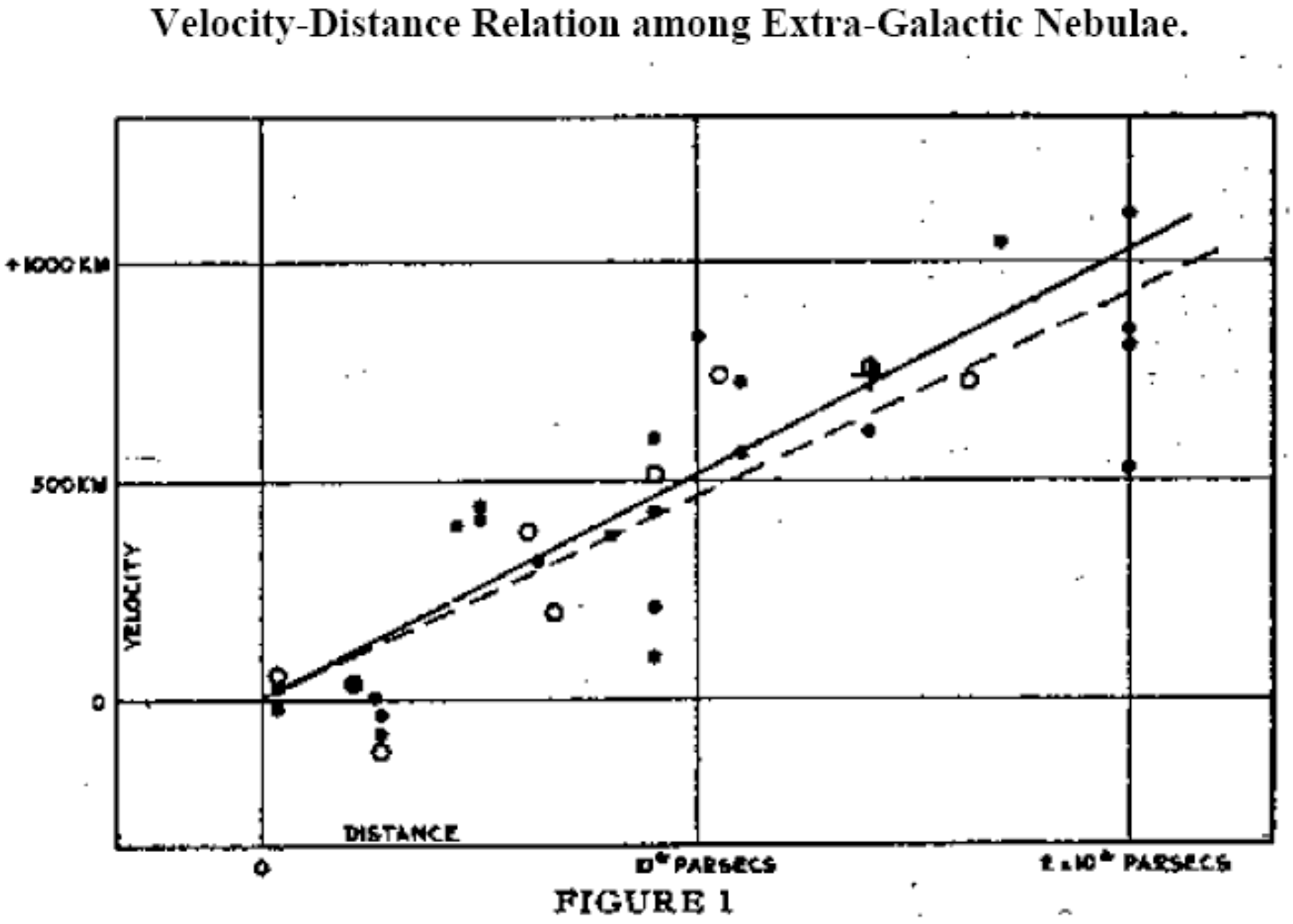
Almost all galaxies are moving AWAY from us!

In 1929, Hubble examined the relation between distance and redshift of galaxies.

He found a rough proportionality of these objects' distances with their redshifts, nowadays termed Hubble's law.

Hubble constant

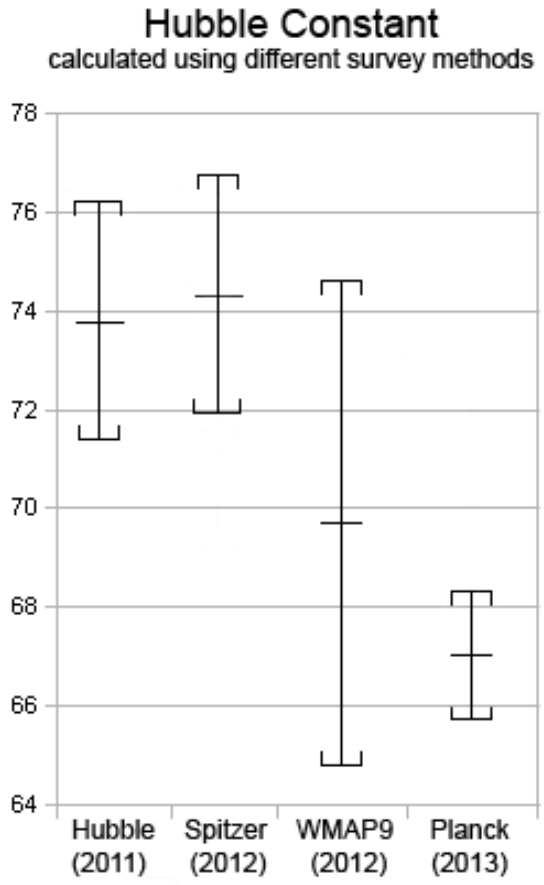
$$v = H_0 D$$

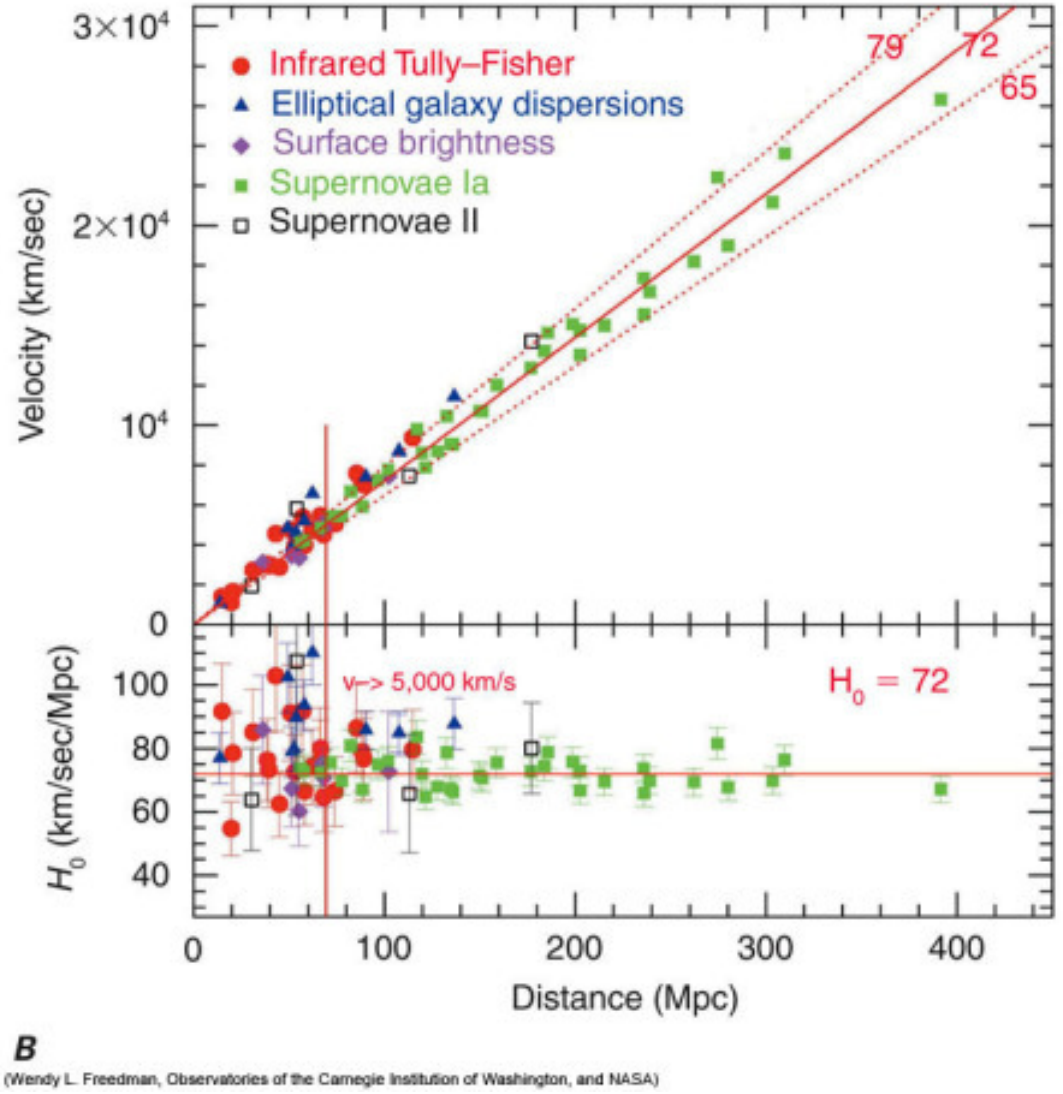


Hubble's Law

$v = H_0 D$

Hubble's law: the galaxies that are farther away are moving faster.





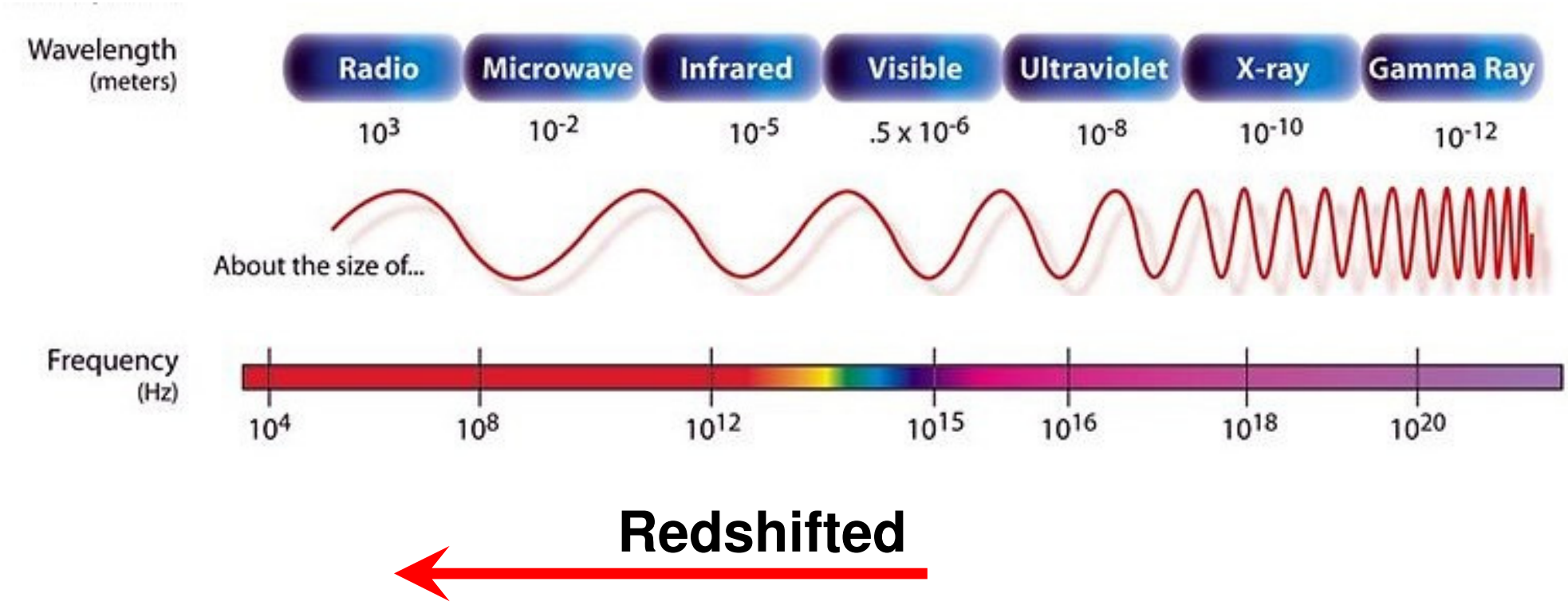
H_0 units: $\dfrac{\text{km/s}}{\text{Mpc } (10^6 \text{ parsecs})}$

https://en.wikipedia.org/wiki/Hubble%27s_law#/media/File:Recent_Hubble%27s_Constant_Values.png

General relativity interpretation of the Hubble's Law:

Space itself is expanding, and galaxies are being carried along for the ride.

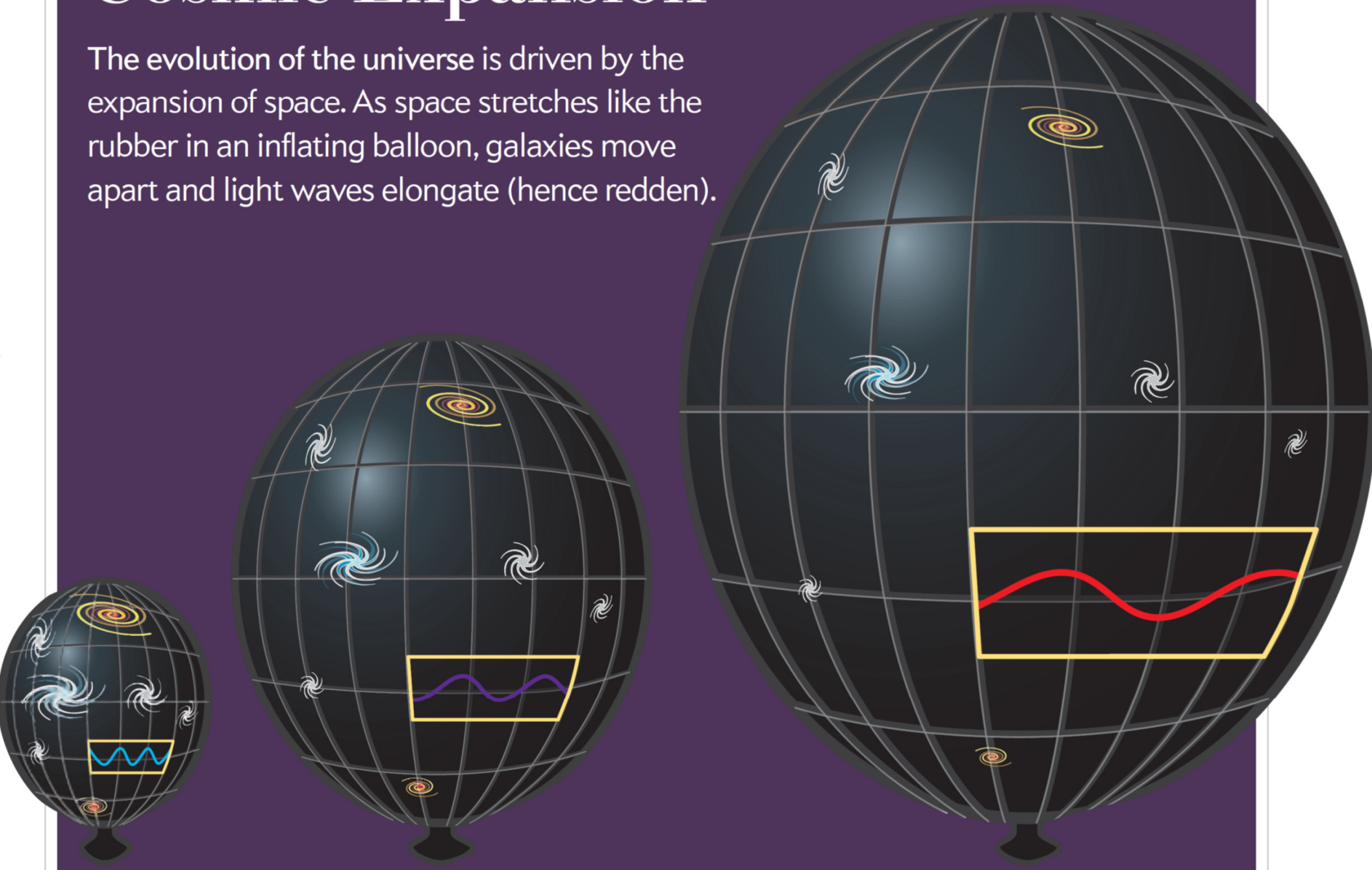
Light, too, is being stretched, i.e. redshifted



Redshifted

Cosmic Expansion

The evolution of the universe is driven by the expansion of space. As space stretches like the rubber in an inflating balloon, galaxies move apart and light waves elongate (hence redden).



Scientific American **22**, 36 (2013)

The expanding Universe

http://www.spacetelescope.org/videos/hubblecast79d/

Let's rewind the clock!

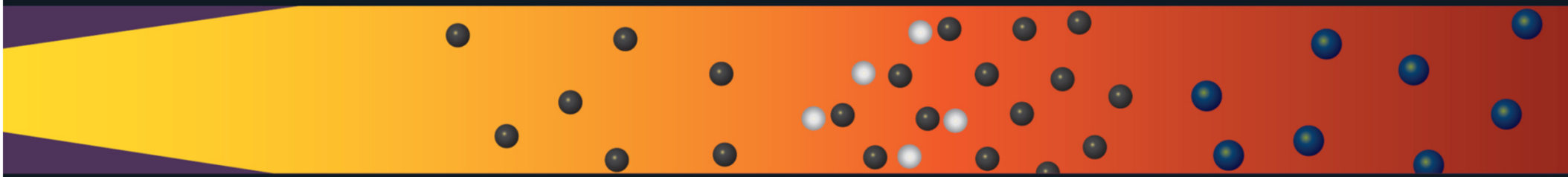
The light from distant galaxies reveals an earlier epoch.

The amount this light has redshifted indicates how much the universe has grown in the intervening years.

Now, let's play it back in time and you get **The Big Bang** 13.7 billion years ago.

Earliest Moments of the Big Bang

The cosmic timeline continues with fairly well-established events leading to the present day.



10^{-35} second
Cosmic inflation creates a large, smooth patch of space filled with lumpy quark soup

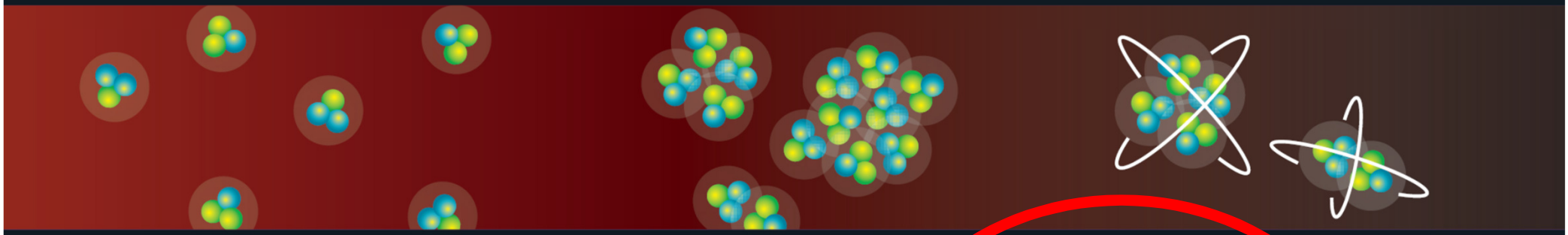
10^{-30} s
One potential type of dark matter (axions) is synthesized

10^{-11} s
Matter gains the upper hand over antimatter

10^{-10} s
A second potential type of dark matter (neutralinos) is synthesized

Scientific American **22**, 36 (2013)

Formation of Atoms



10^{-5} s
Protons and neutrons form from quarks

0.01–300 s
Helium, lithium and heavy hydrogen nuclei form from protons and neutrons

380,000 years
Atoms form from nuclei and electrons, releasing the cosmic microwave background radiation

Scientific American **22**, 36 (2013)

Dark Ages → Modern Era

380,000–
300 million yr
Gravity continues to amplify density differences in the gas that fills space

300 million yr
First stars and galaxies form

600 million yr
Limit of current observations (highest-redshift objects)

Scientific American **22**, 36 (2013)

Modern Era

3 billion yr
Clusters of galaxies form; star formation peaks

9 billion yr
Solar system forms

13.7 billion yr
Today

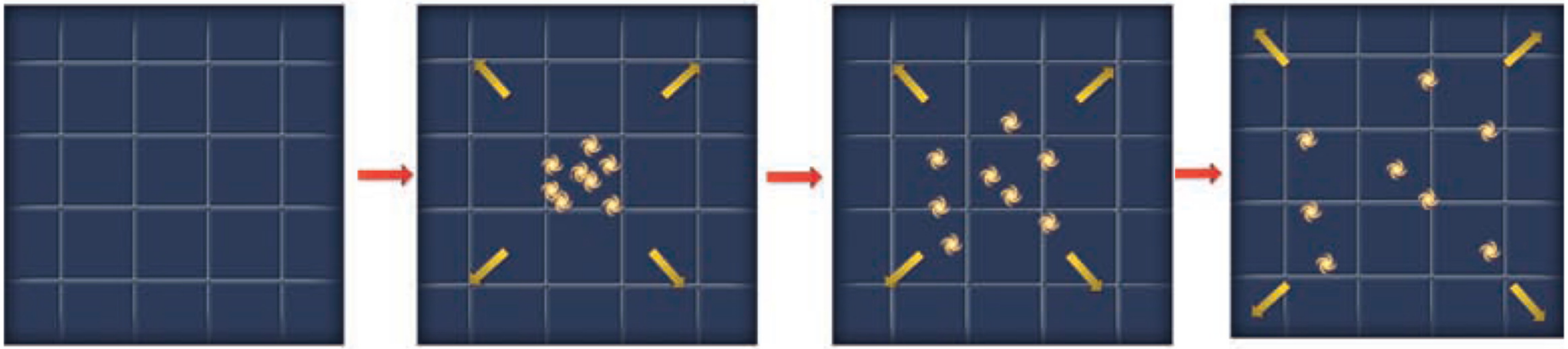
Scientific American **22**, 36 (2013)

A few clarifications about the Big Bang

Do not take “Big Bang” too literately:

It was NOT like a bomb going off at a certain location in previously empty space

Such explosion will look like this:



Scientific American 292, 36 (2005)

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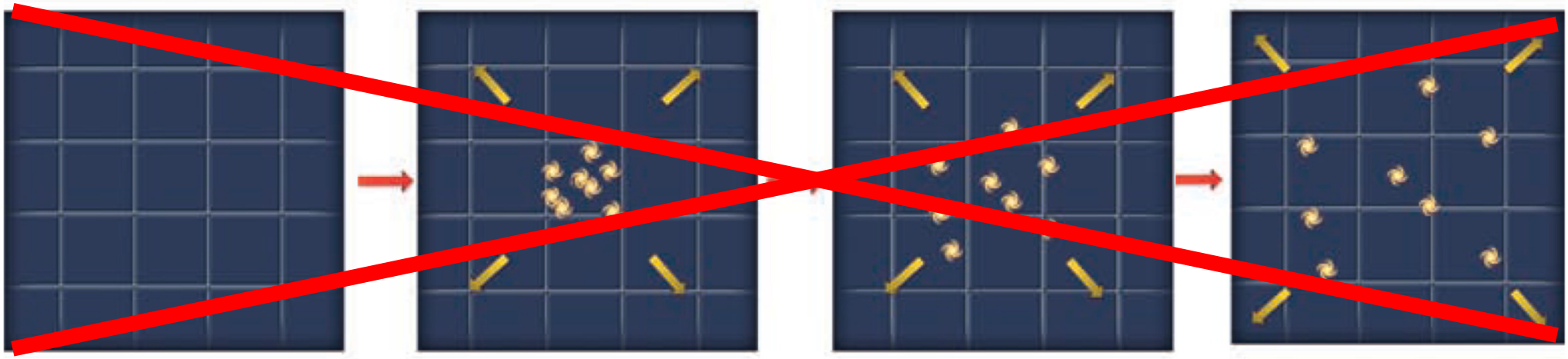

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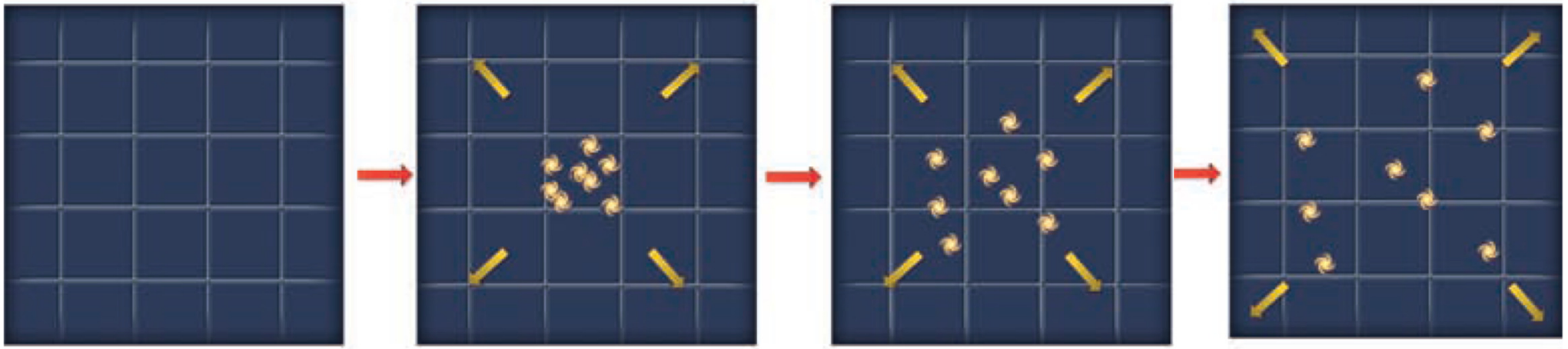
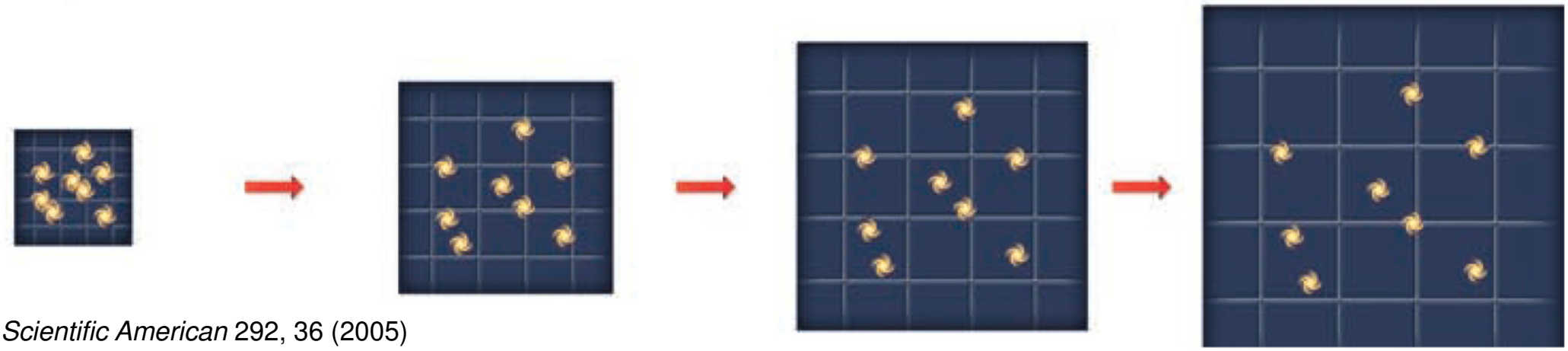


The space we inhabit is itself expanding. There was no center to the Big Bang; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.



Scientific American 292, 36 (2005)

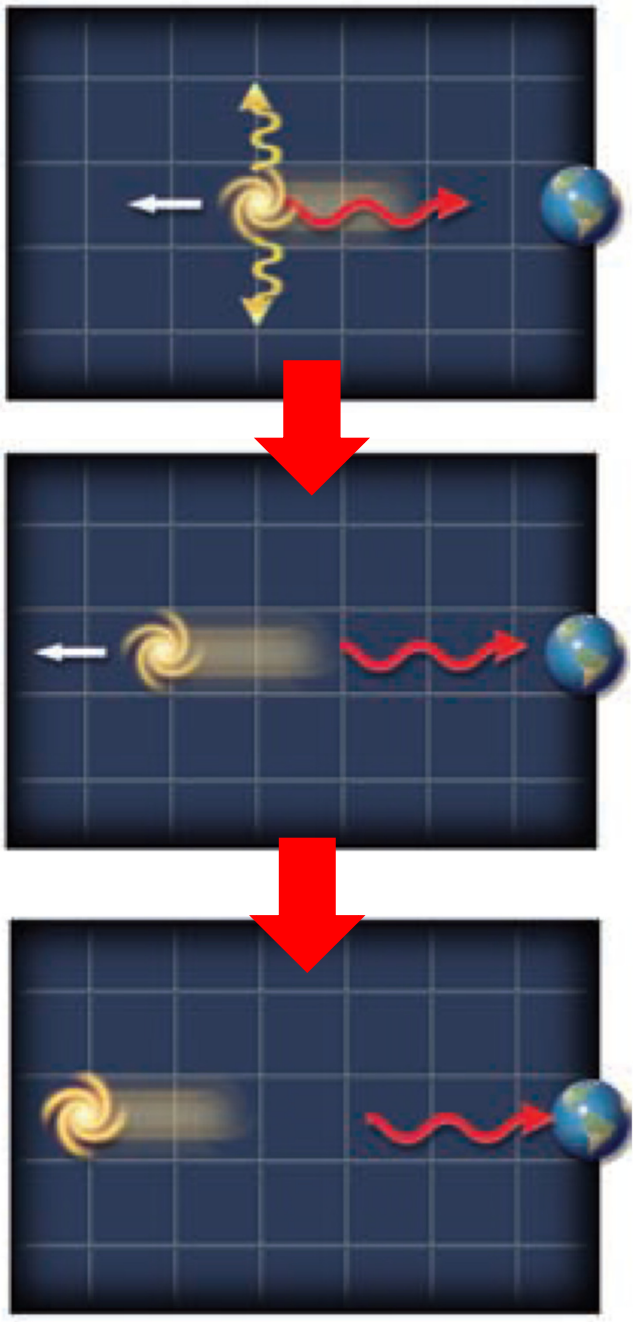
Cosmic redshift is NOT the Doppler shift

The Doppler Effect:

In the Doppler effect, a galaxy's movement away from the observer stretches the light waves, making them redder.

The wavelength of light then stays the same during its journey through space.

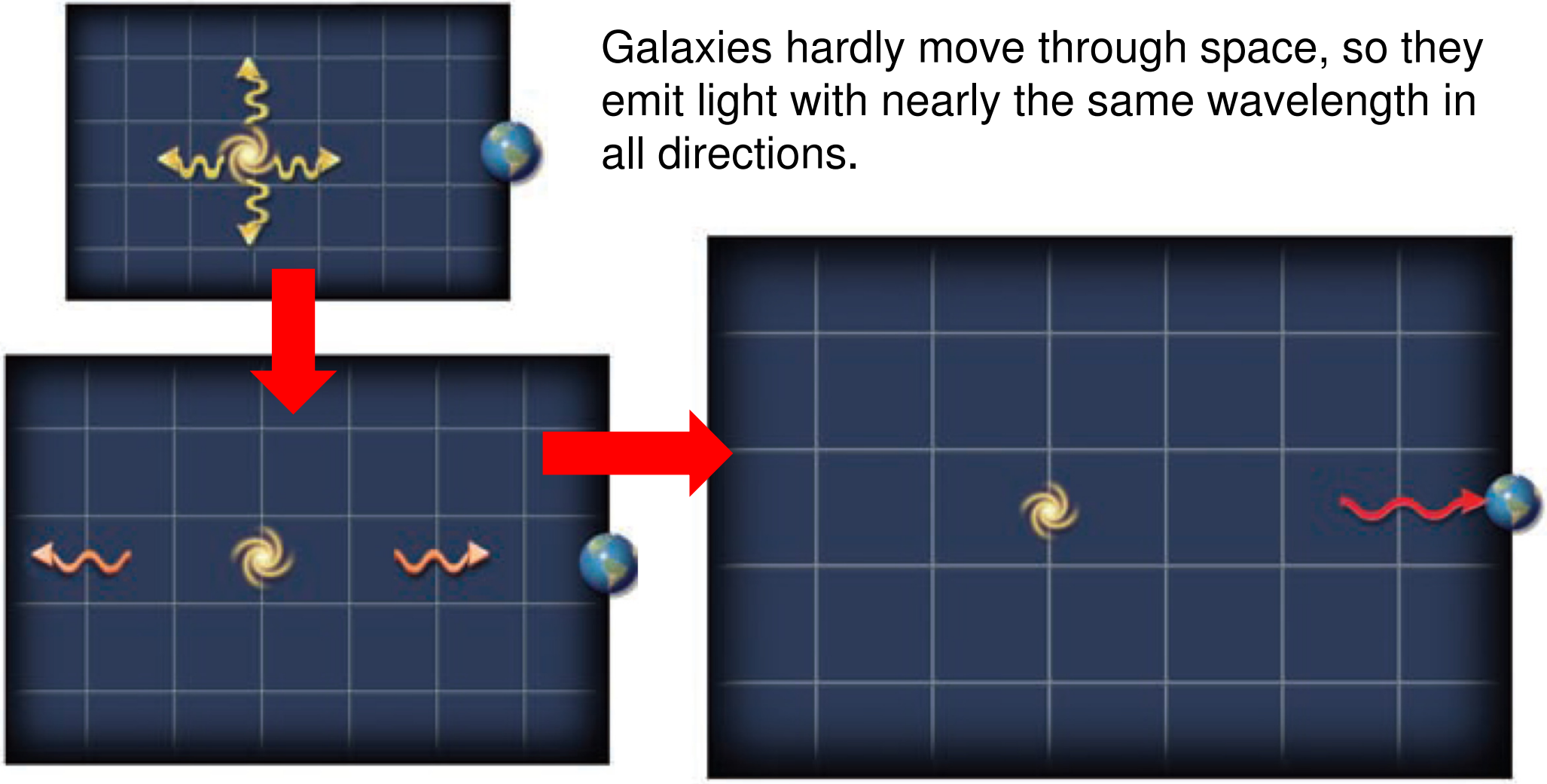
The observer detects the light, measures its Doppler redshift and computes the galaxy velocity



Scientific American 292, 36 (2005)

Scientific American 292, 36 (2005)

Cosmic redshift: expanding space stretches all light waves as they propagate.

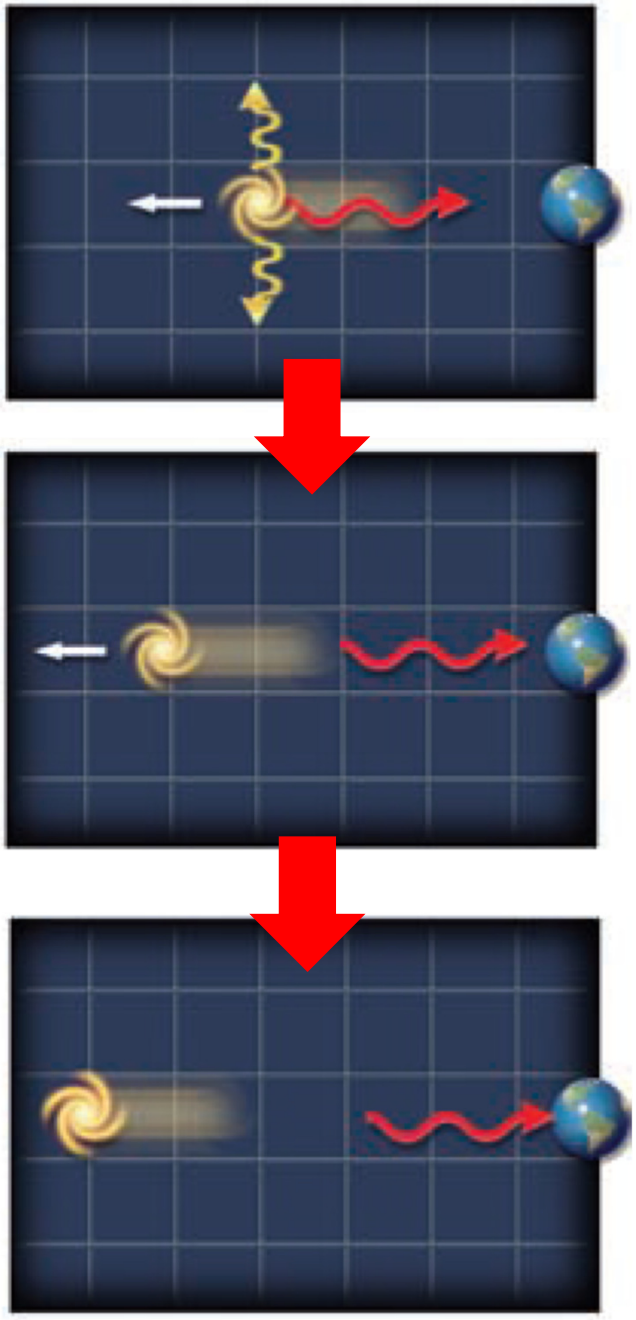


Galaxies hardly move through space, so they emit light with nearly the same wavelength in all directions.

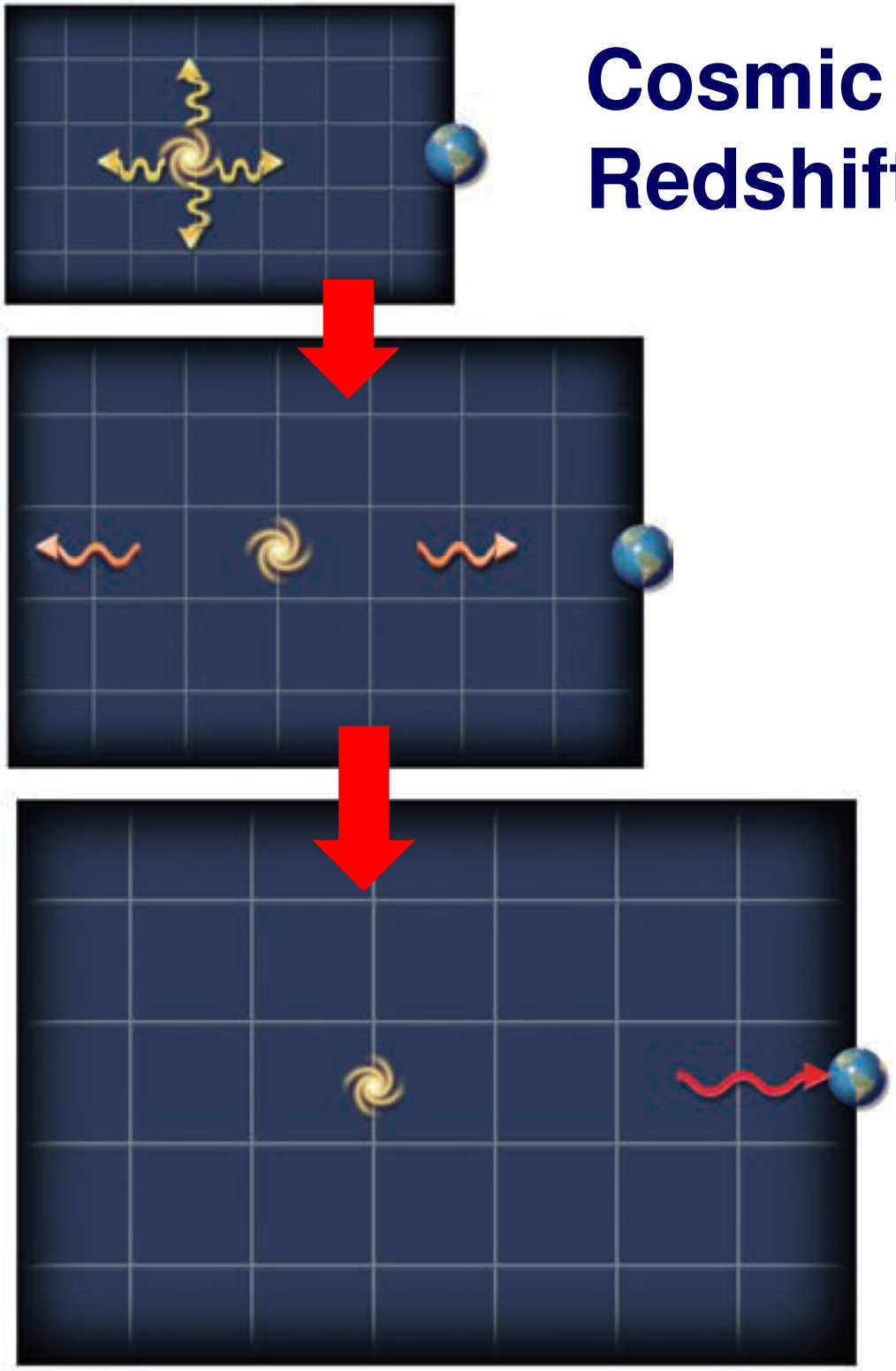
The wavelength gets longer during the journey, because space is expanding. Thus, the light gradually reddens.

The amount of redshift differs from what a Doppler shift would produce.

Doppler Effect



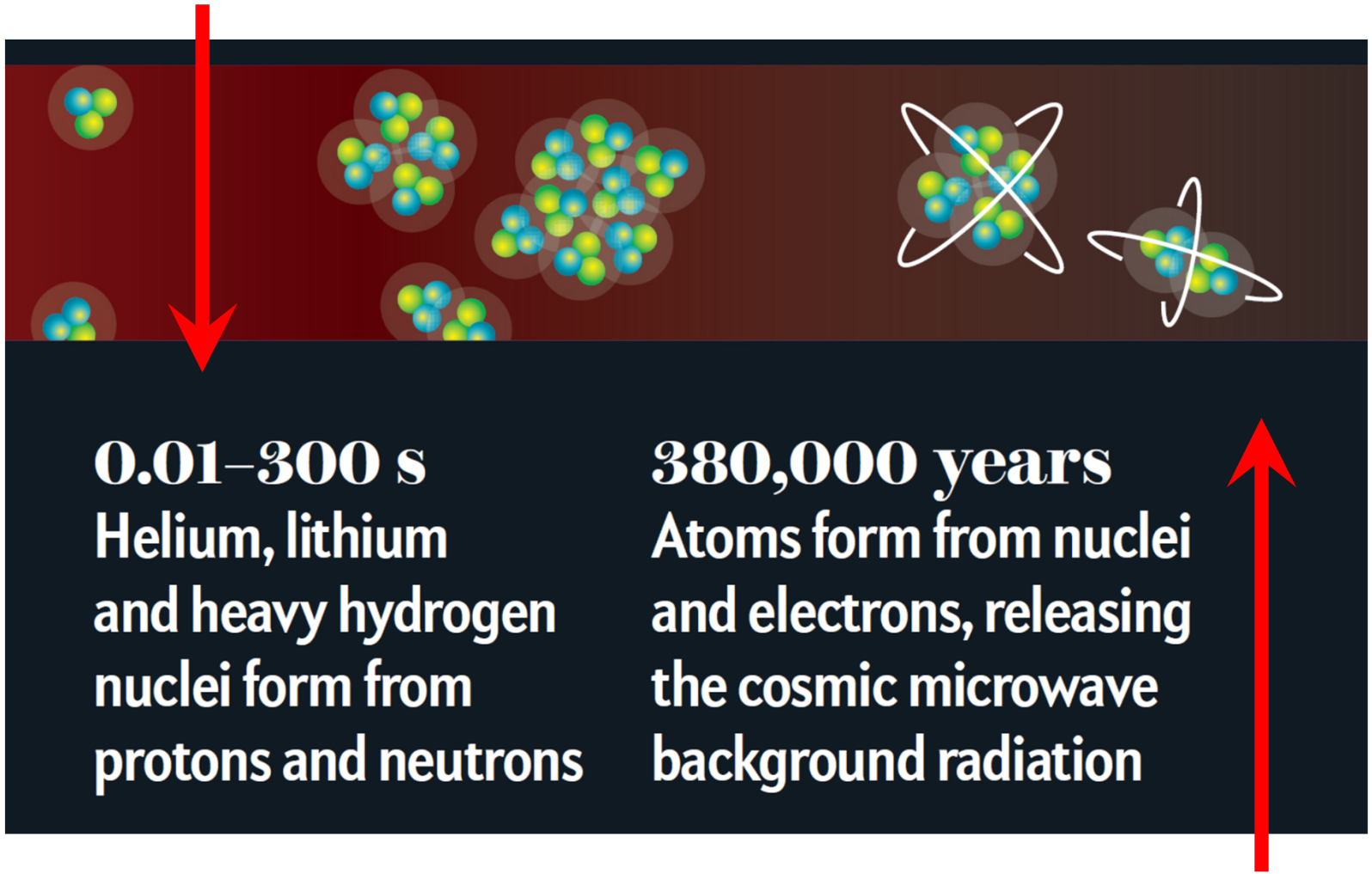
Cosmic Redshift



Scientific American 292, 36 (2005)

The observational evidence for the Big Bang

1. Expansion of the Universe
2. Big Bang Nucleosynthesis



3. Cosmic microwave background (CMB) radiation