Cosmology

Lecture #1

Paul Woodward

Getting a Feel for the Scale of the Cosmos:

Work our way out from the Sun.

1. Use parallax to measure distances to the nearest stars.
   a) Parallax of nearest star is only 1 second of arc, so hard to measure accurately.
   b) Accuracy also rests on knowledge of size of earth's orbit.
   c) No further assumptions enter, so these distances are solid.
2. Main sequence fitting.
   a) Plot H-R diagram for stars with distances from parallax.
   b) Plot H-R diagram for a distant star cluster.
   c) All cluster stars at same distance.
   d) Apparent brightness decreases as inverse square of distance for star of given luminosity.
   e) Fit main sequence of cluster to that of nearby stars by adjusting the distance to the cluster so that measured brightness values correspond to correct luminosities.

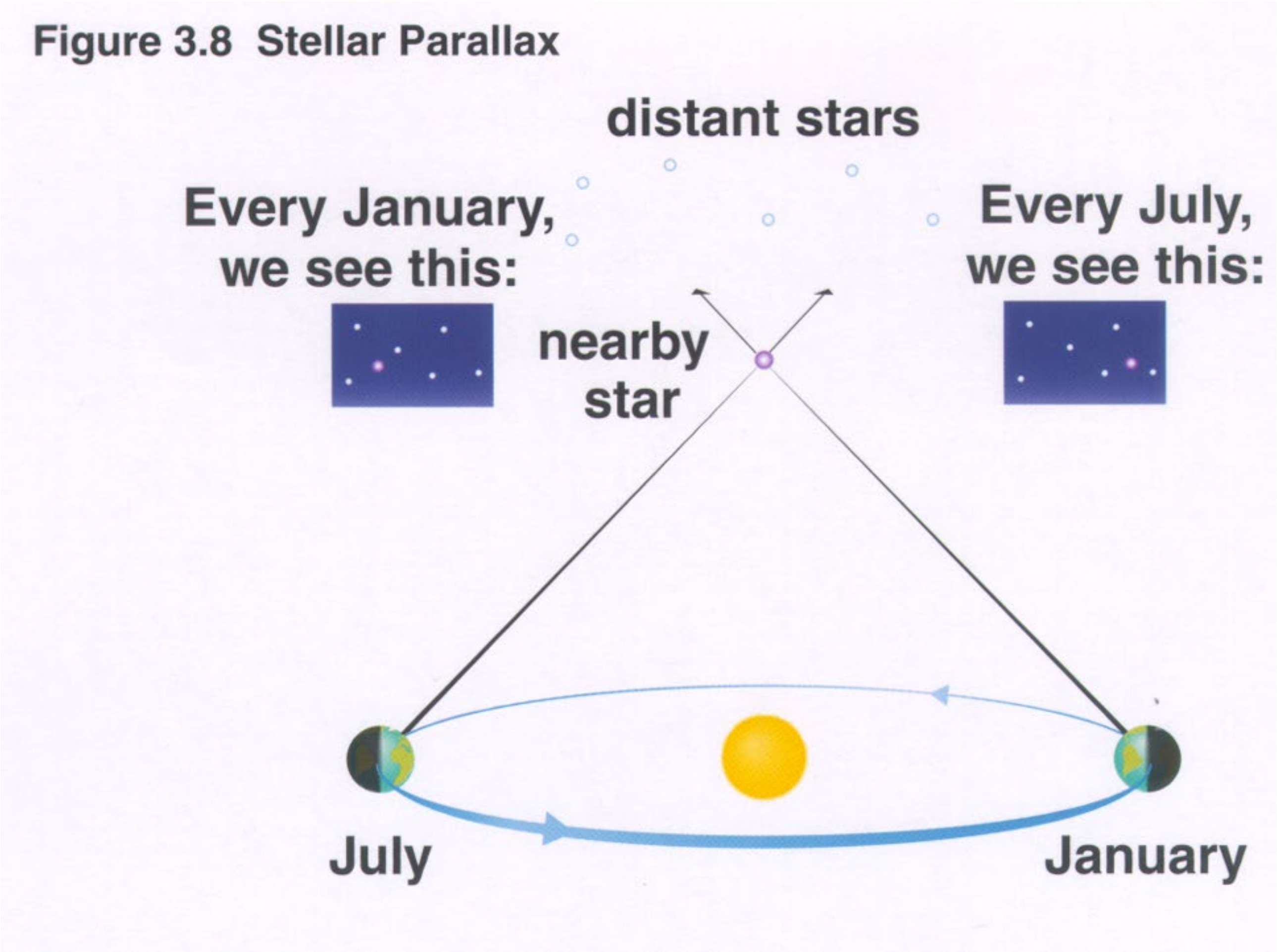
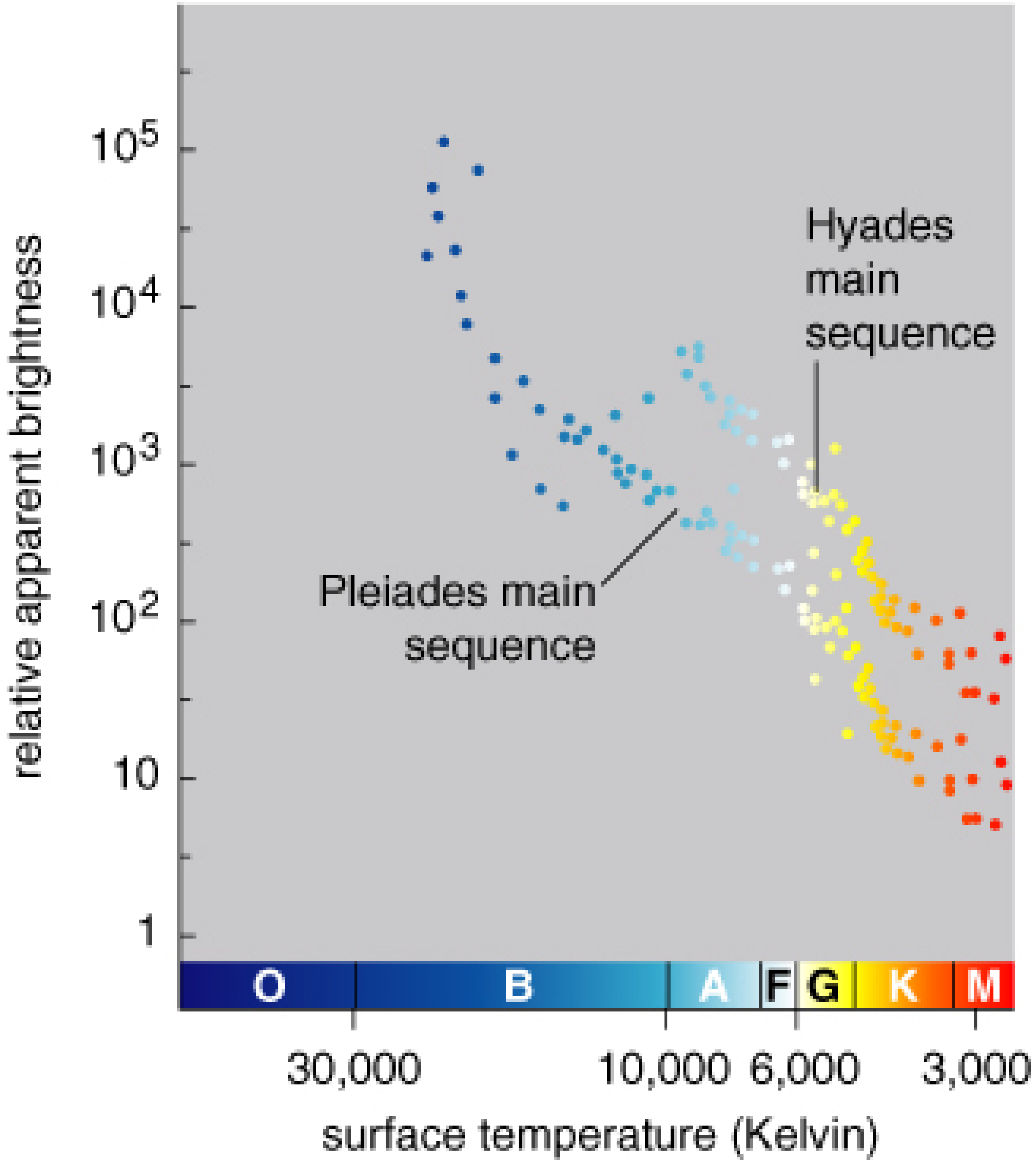
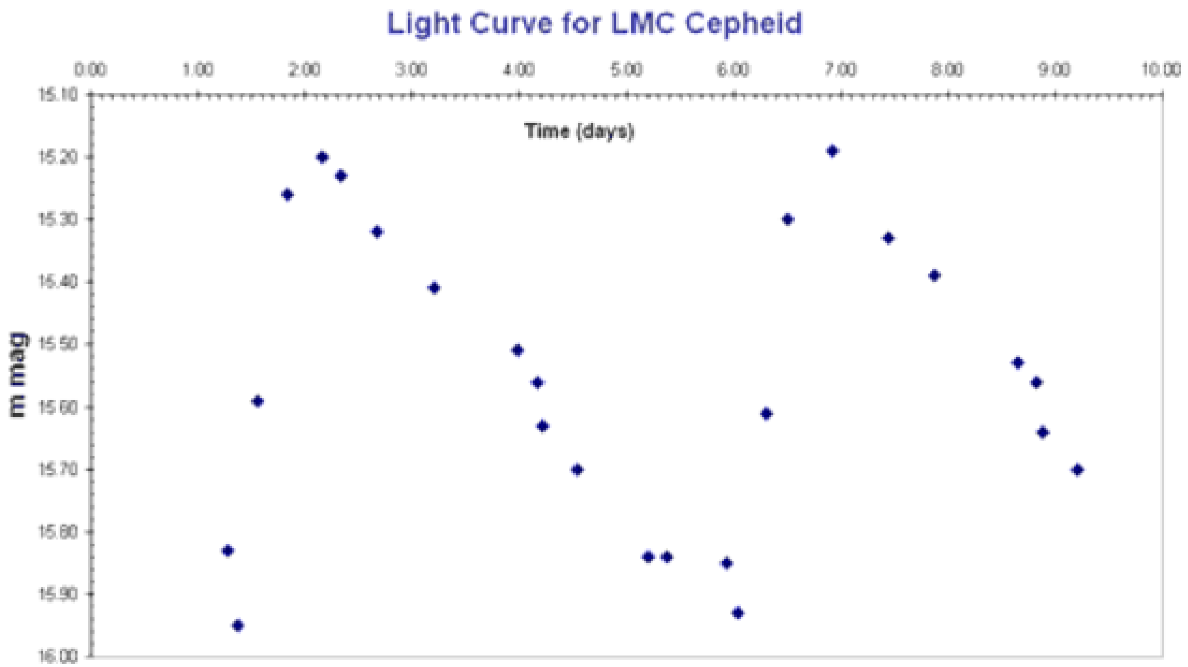


Figure 3.8 Stellar Parallax
distant stars
Every January, we see this:
Every July, we see this:
nearby star
July
January


relative apparent brightness
10^5
10^4
10^3
10^2
10
1
Hyades main sequence
Pleiades main sequence
O B A F G K M
30,000
10,000 6,000
3,000
surface temperature (Kelvin)

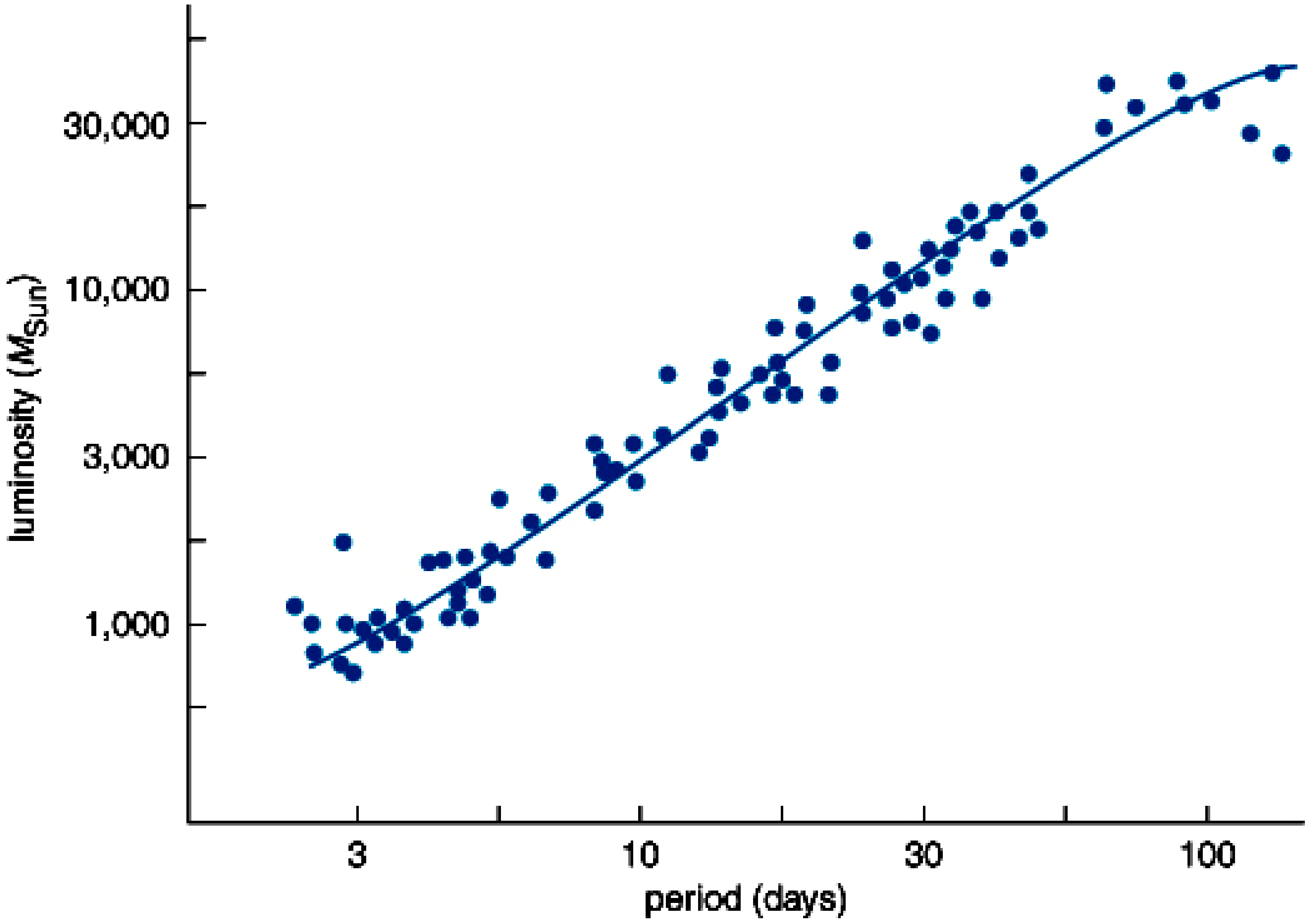
$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

3. Cepheid variable stars.
   a) Pulsational period (easily measured) directly related to luminosity.
   b) Relation depends upon composition (amount of heavy elements).
   c) Giant stars, so are very bright.
   d) Used to get distances to Magellanic Clouds and Andromeda Galaxy, proving that these star systems are not in our Galaxy.
   e) Used to determine spatial distribution of globular clusters.
   f) Hubble telescope resolves these stars out to M100 galaxy, 300 million light years away!



3. From the light curve and the photometric data, two values can be determined; the average apparent magnitude, *m*, of the star and its period in days. In the example above the Cepheid has a mean apparent magnitude of 15.56 and a period of 4.76 days.
4. Knowing the period of the Cepheid we can now determine its mean absolute magnitude, *M*, by interpolating on the period-luminosity plot. The one shown below is based on Cepheids within the Milky Way. The vertical axis shows absolute magnitude whilst period is displayed as a log value on the horizontal axes.

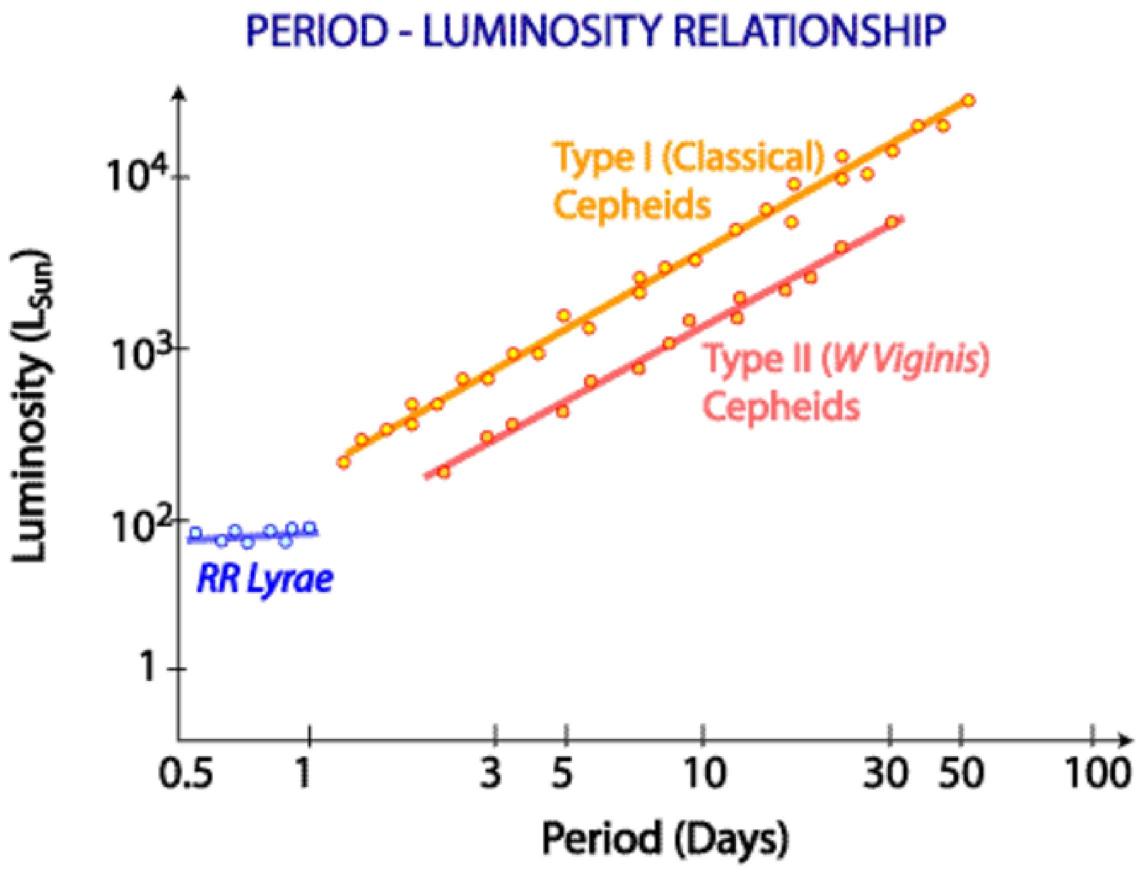
Using the Cepheid period luminosity relation.



Cepheid period luminosity relation.

Calculating Distances Using Cepheids

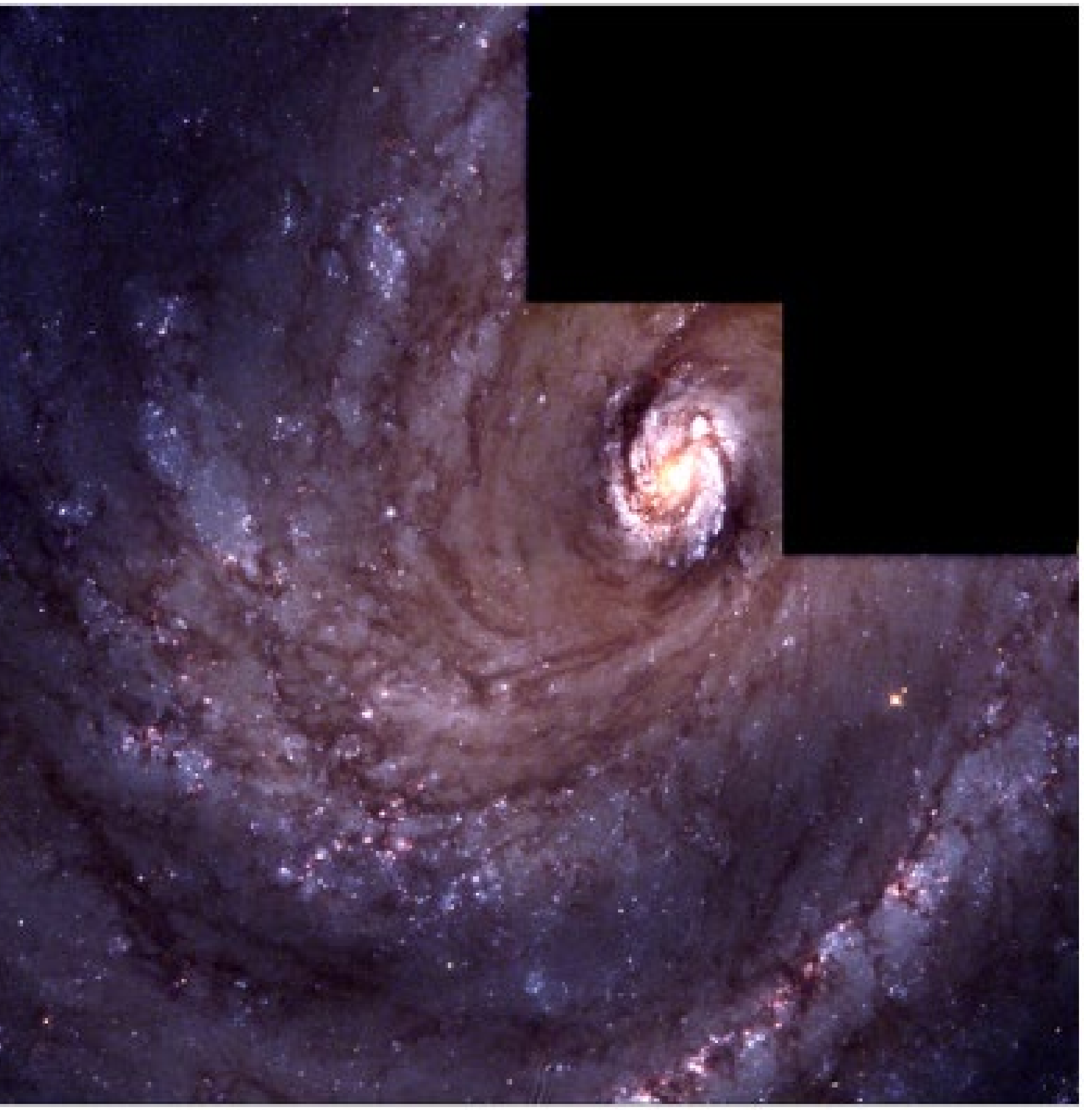
Both types of Cepheids and *RR Lyrae* stars all exhibit distinct period-luminosity relationships as shown below.

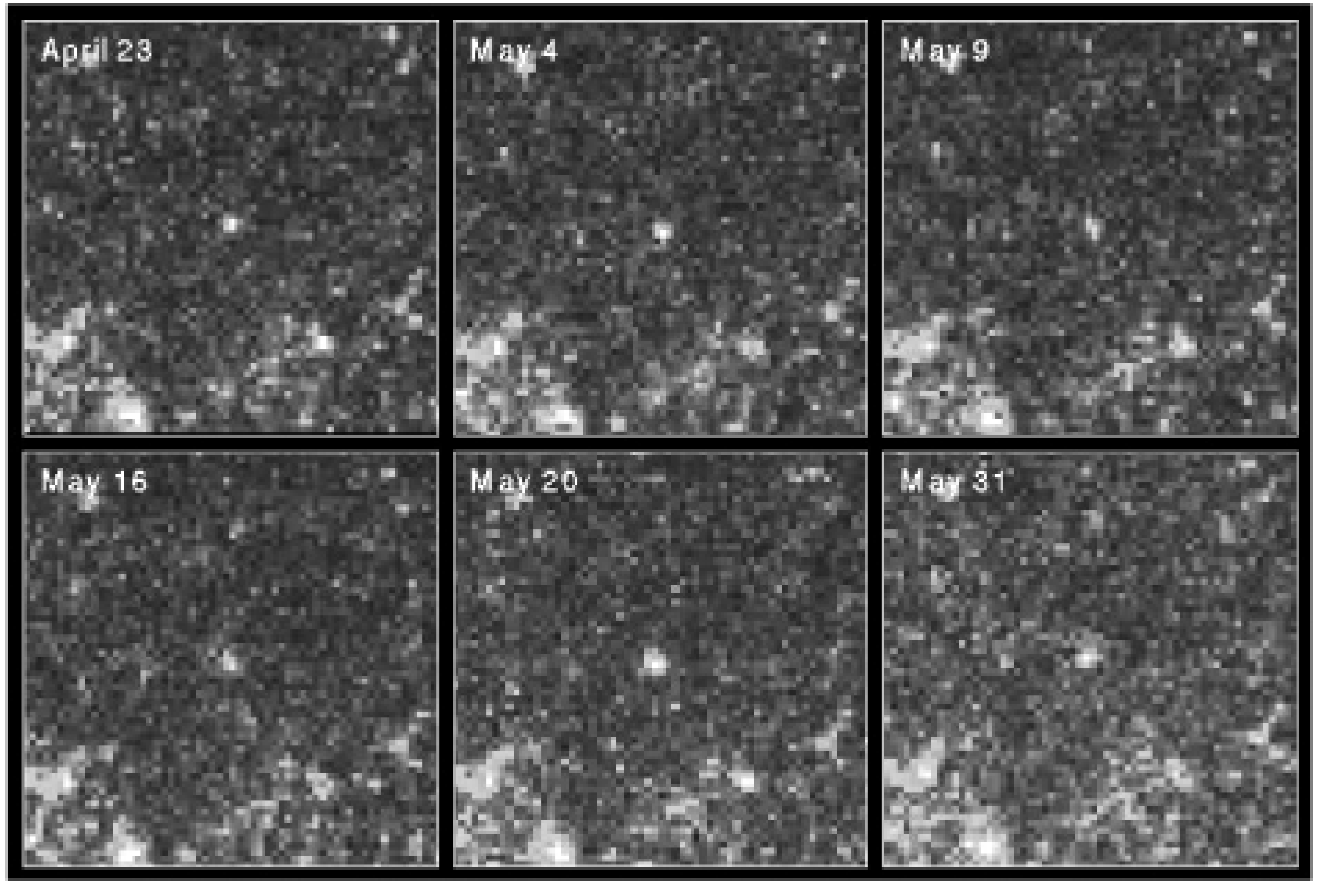


Period-luminosity relationship for Cepheids and RR Lyrae stars.

Let us now see how this relationship can be used to determine the distance to a Cepheid. For this procedure we will assume that we are dealing with a Type I, Classical Cepheid but the same method applies for *W Virginis* and *RR Lyrae*-type stars.

We must take some care, since different types of pulsating stars fall on different period-luminosity relationships.





b

A Cepheid varying in brightness over several weeks.

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

3. White dwarf supernovae.
   a) Some of the brightest objects we know of.
   b) Visible out to distance of 10 billion light years!
   c) Because explode after threshold mass exceeded during gradual mass accretion in binary system, we believe all happen in nearly exactly the same way.
   d) Thus, all should have nearly exactly same luminosity.
   e) These are the best “standard candles” we know of.
   f) At tremendous distances, these objects are receding from us so rapidly (we will come to this), that their characteristic pattern of luminosity growth and decay takes measurably longer (an effect of Einstein’s theory of relativity).

3. White dwarf supernovae.

The subject of the double star systems and their evolution that produces white dwarf supernovae, as described at some length in the lecture at this point, is laid out in some detail in the set of slides entitled:

Lect13-stars2-4-8-19-CONTD

which can be found on the course Web site.

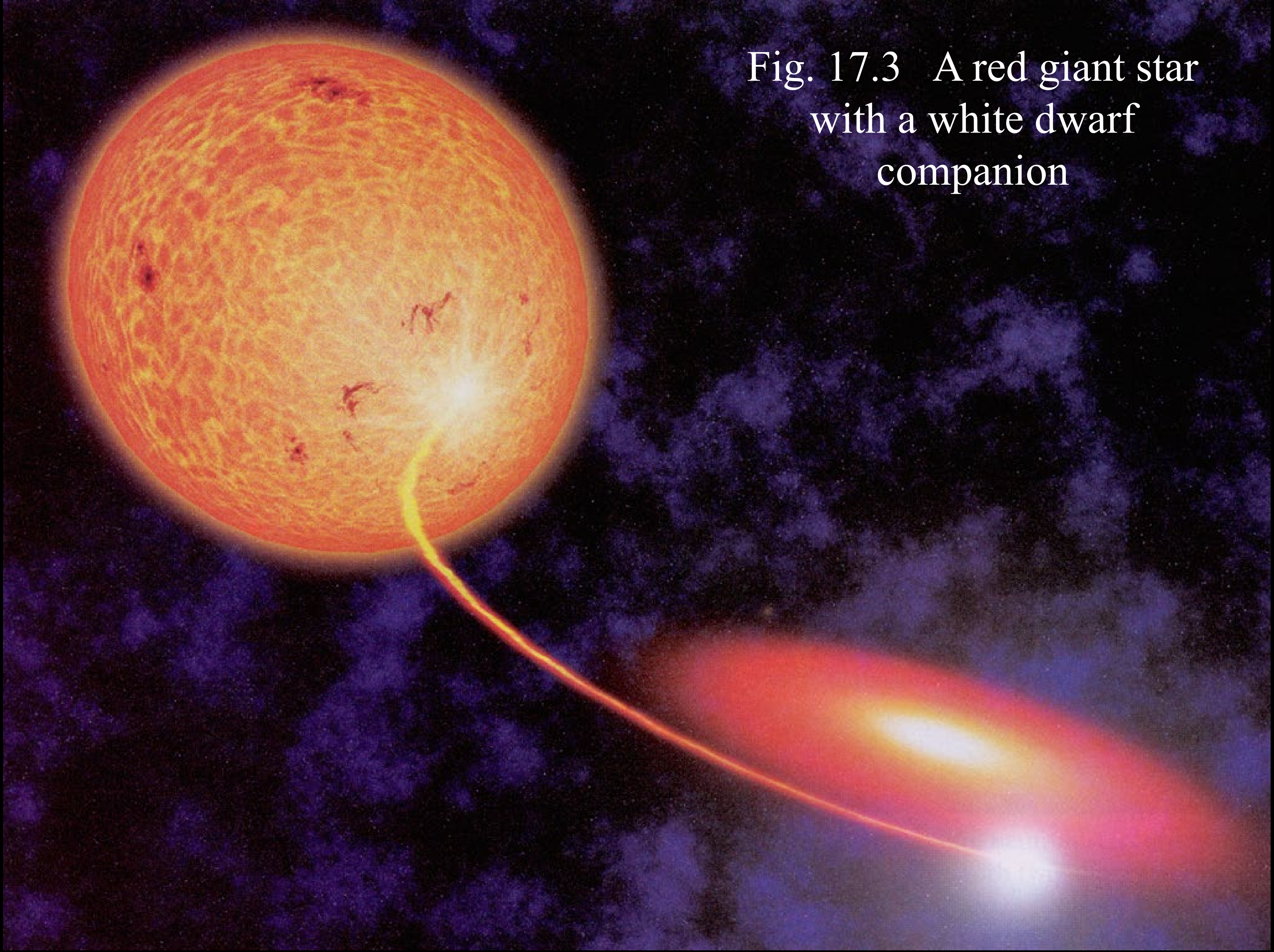
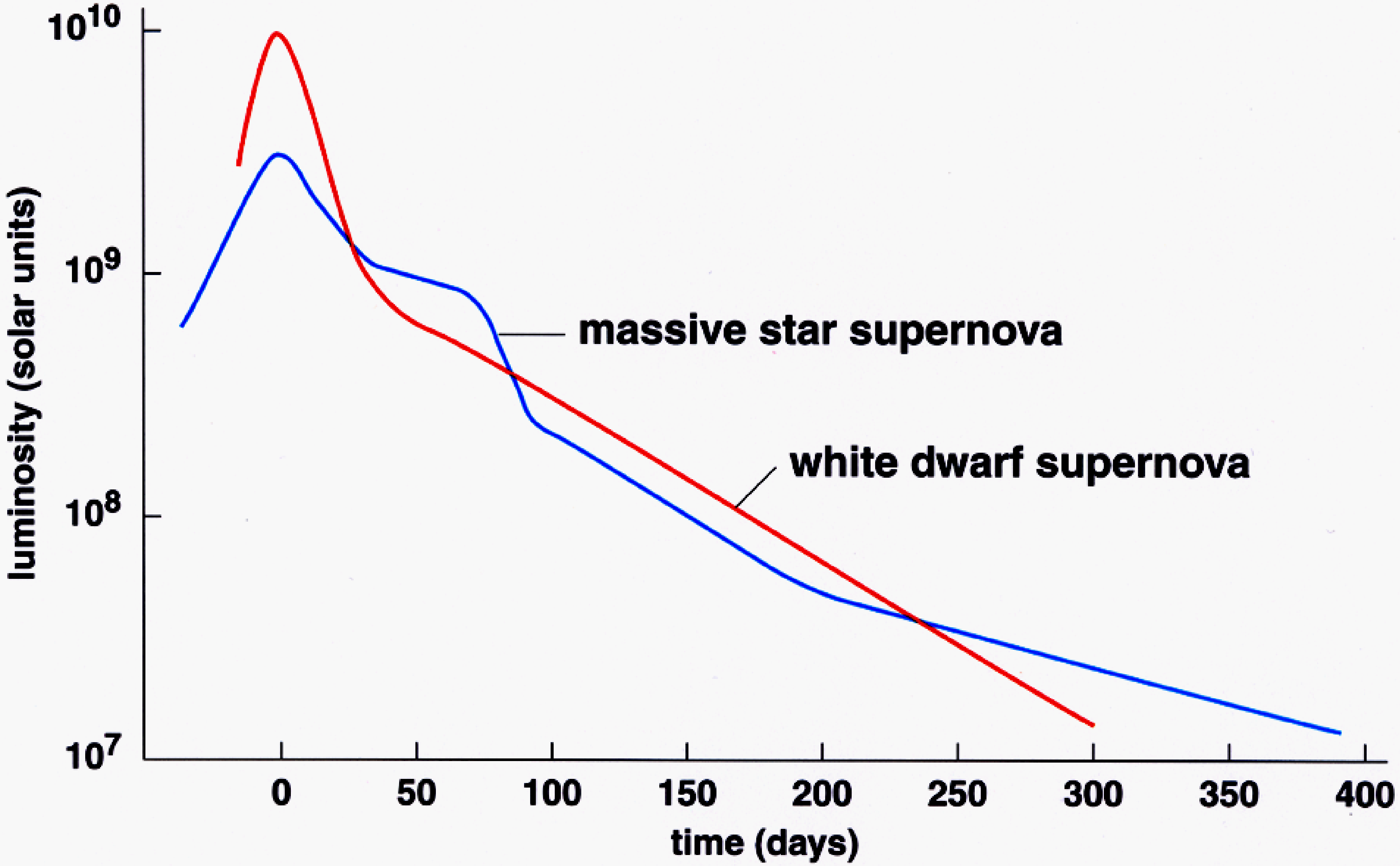
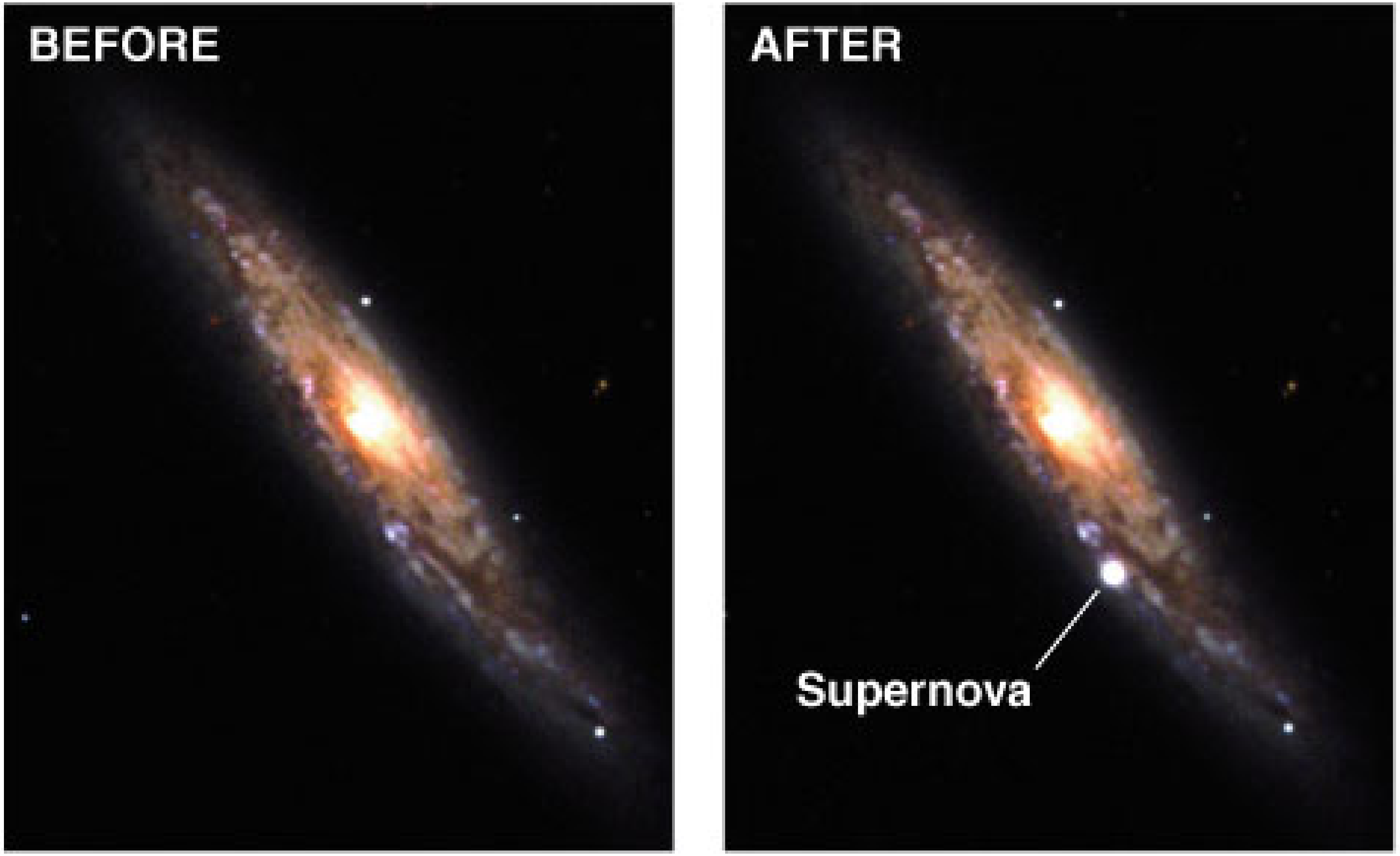
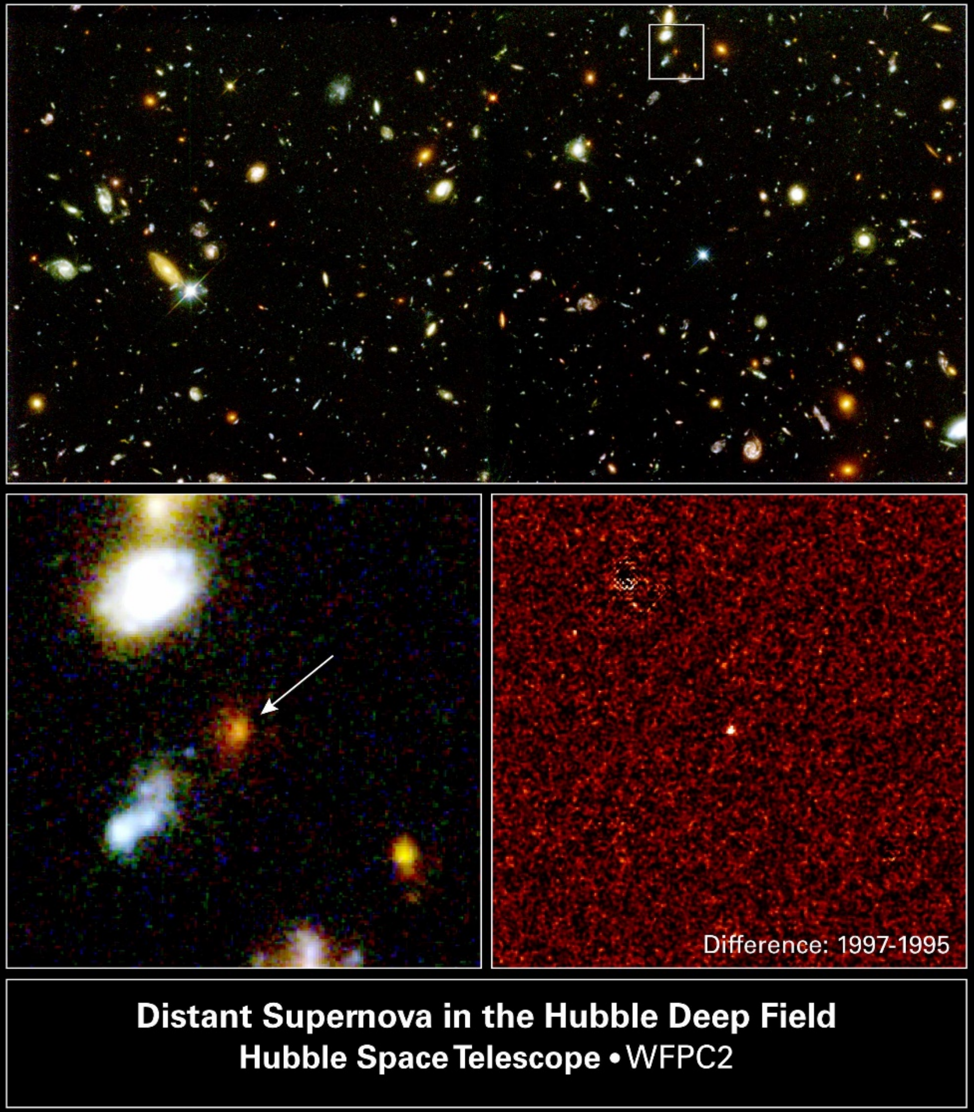


Fig. 17.3 A red giant star with a white dwarf companion

Figure 17.5 Typical light curves for white dwarf and massive star supernovae




BEFORE
AFTER
Supernova



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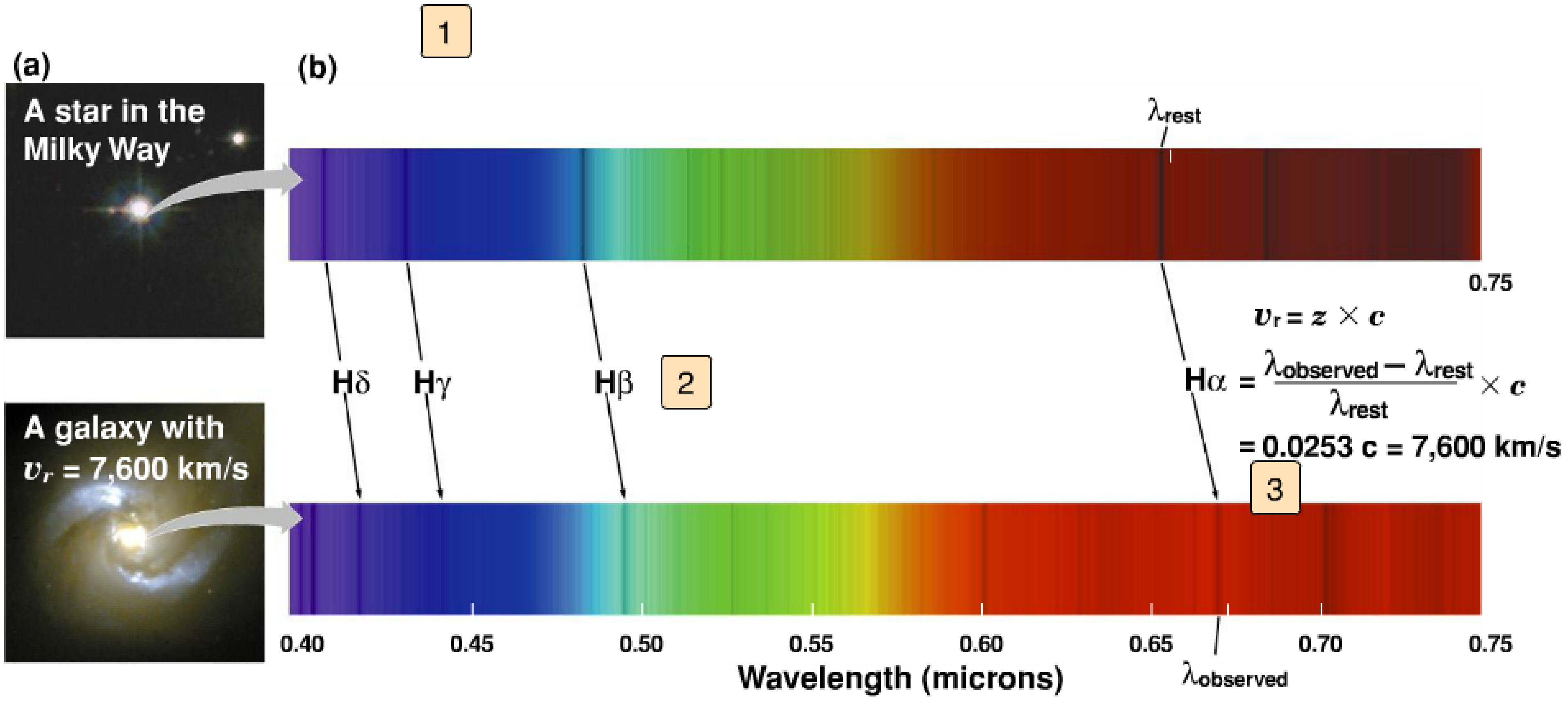
Hubble Space Telescope observation in 1997 of a supernova 10 billion light years distant provides evidence that the expansion rate of the universe first slowed and then later accelerated.

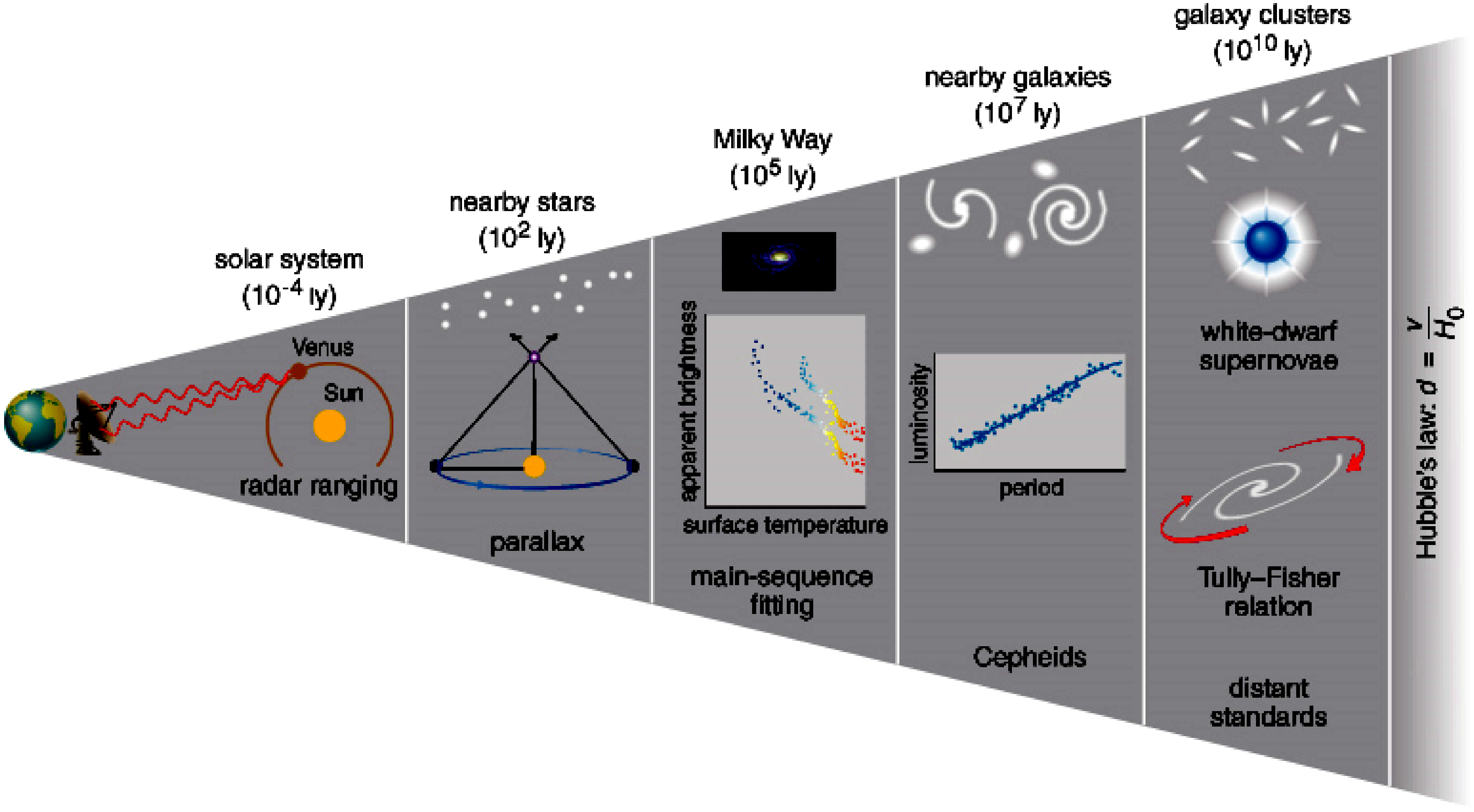
Although this stellar explosion is among the brightest beacons in the universe, it could not be seen directly in the Hubble images. The stellar blast is so distant from Earth that its light is buried in the glow of its host galaxy.

This example should give you an idea of how certain or uncertain our measurements of distance based upon white dwarf supernovae are when we apply the technique at this extreme distance.

3. Doppler shift.

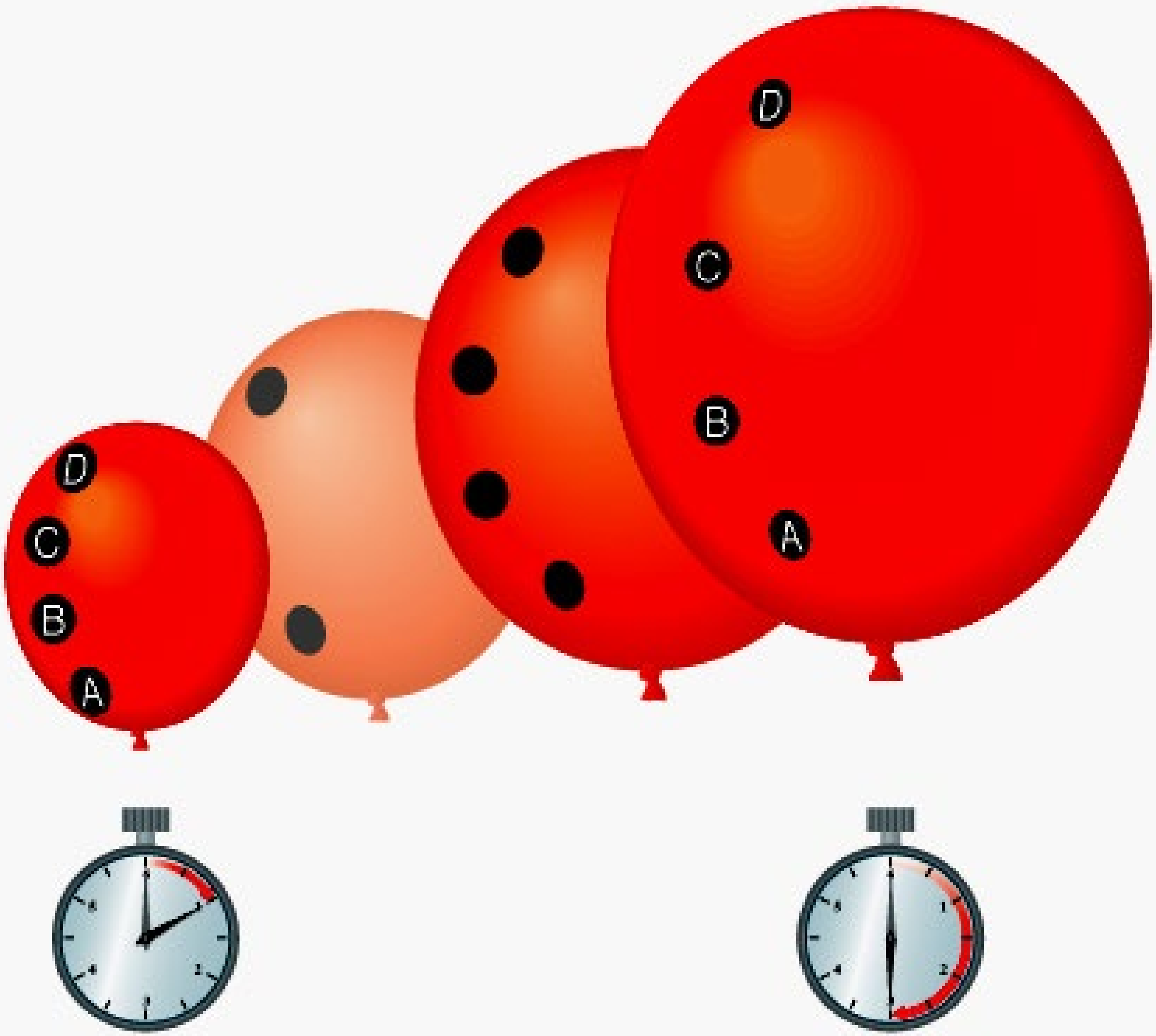
   a) Hubble first established that the Andromeda Galaxy was not a star cluster in our galaxy, but another entire galaxy.
   b) He did this with Cepheid variables.
   c) He noticed that the distance to a galaxy is related linearly to the amount that its light is shifted toward the red part of the spectrum by the Doppler effect.
   d) The "Hubble Constant," H, relates the redshift to the distance.
   e) H has units of km/sec/Mpc (and a new consensus value of 72 ± 10%).
   f) Refer to your lab on this subject.
   g) If we believe that white dwarf supernovae are standard candles, then we conclude that as we go to extremely great distances, H changes very slightly in value.
   h) This slight change can tell us about the total amount of matter in our universe.


1
(a)
(b)
A star in the Milky Way
λrest
0.75
vr = z × c
Hδ
Hγ
Hβ
2
Hα = (λobserved − λrest) / λrest × c
= 0.0253 c = 7,600 km/s
3
A galaxy with vr = 7,600 km/s
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
Wavelength (microns)
λobserved

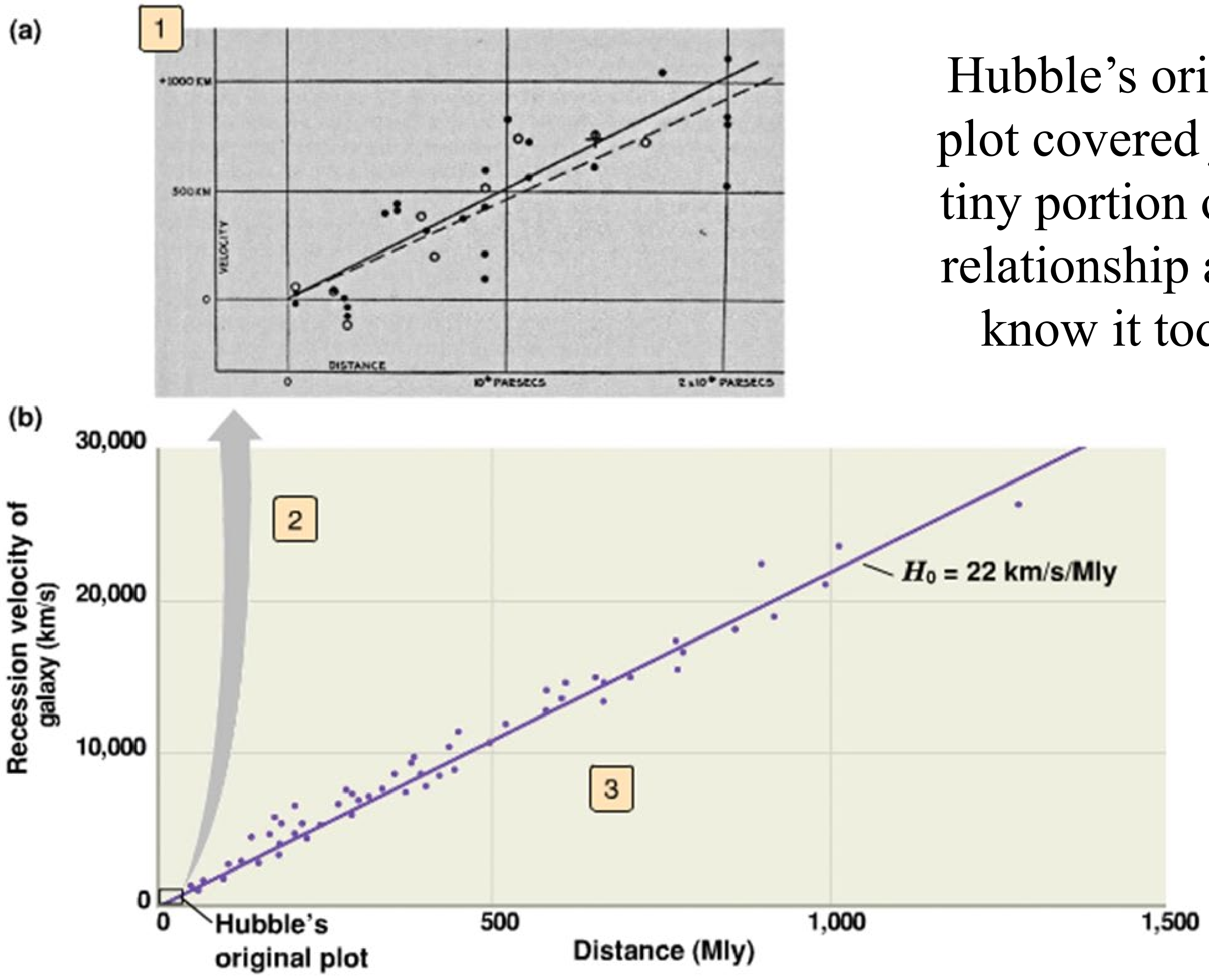


The distance chain.

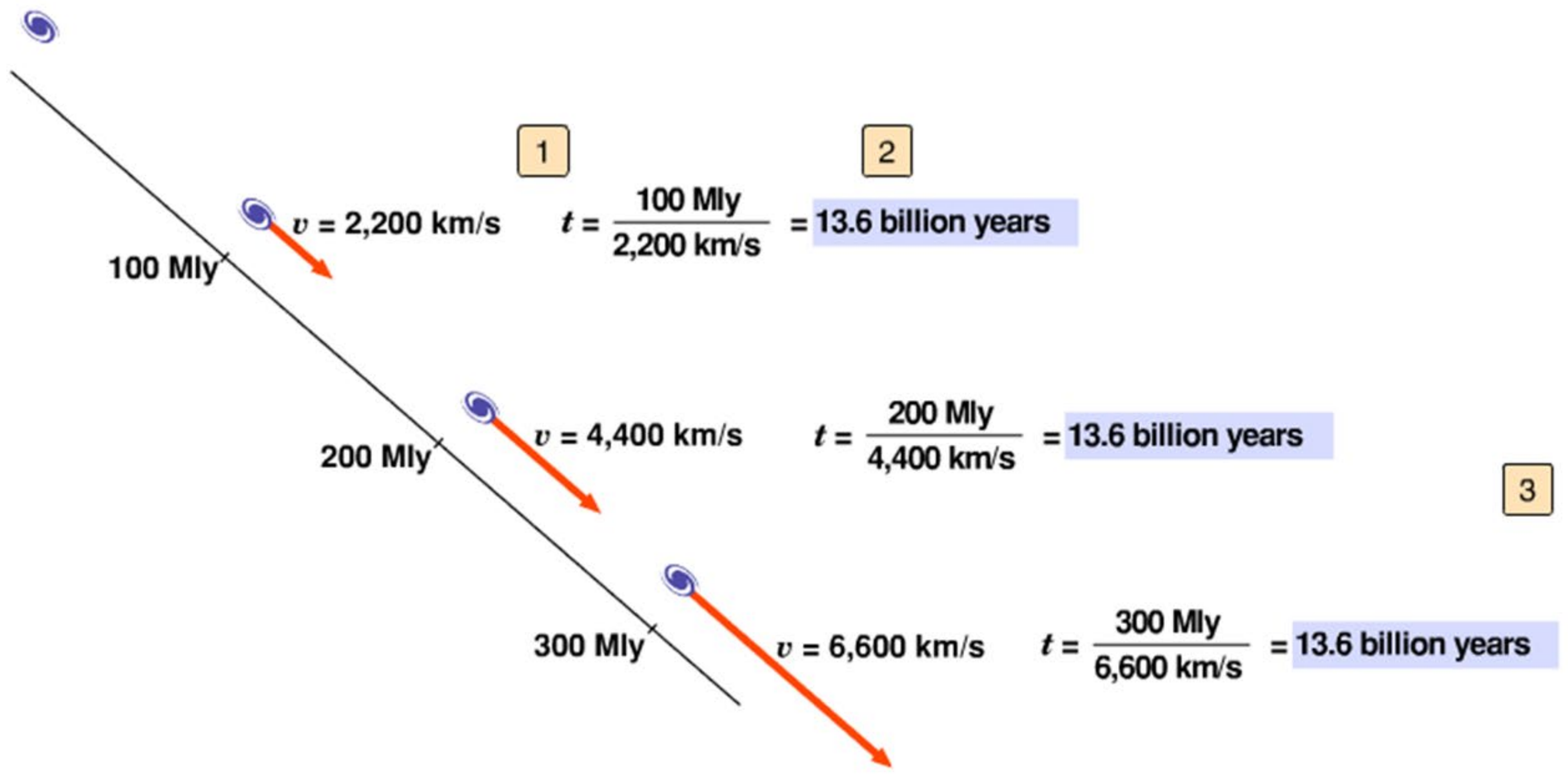
- Hubble's "law" implies that the universe is expanding.
- That is the only way to get everybody receding from us.
- The indication is that the universe was always expanding
- The rate of expansion appears to be increasing slightly.
- We see no "center" of this expansion, since we see no part of the universe that does not participate in the expansion.
- Can use expanding balloon as a guide to understanding.
- In this analogy, the entire universe is the *surface* of the balloon.
- Just the surface.
- The center of expansion of the balloon is not on its surface.
- If we consider only the surface of the balloon, there is no center of the expansion.
- The surface of the balloon is not expanding *into* anything.
- It is just expanding.
- Mind bending stuff.


D
C
B
A
D
C
B
A

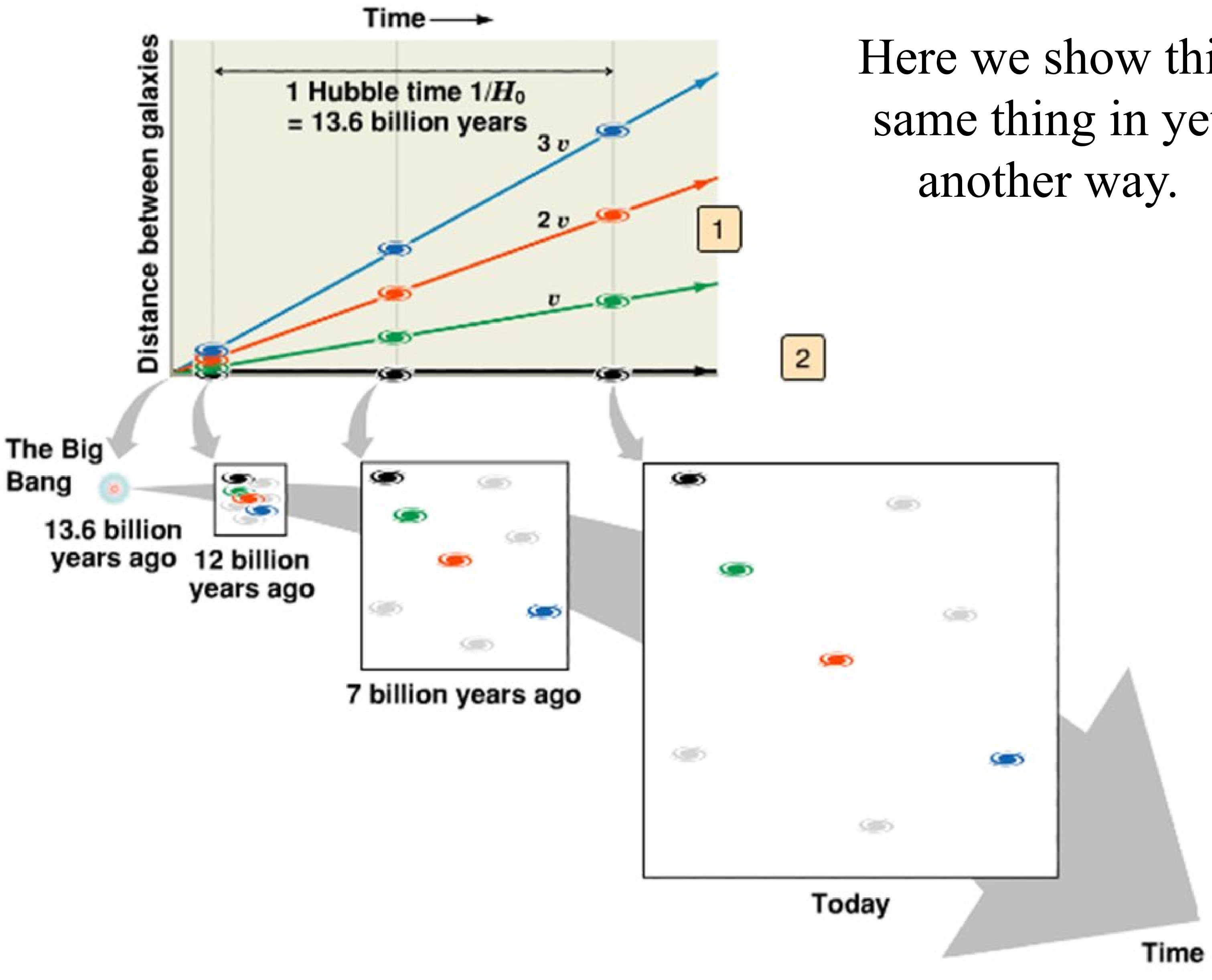
- A linear relationship between distance and recession velocity implies a rate of overall expansion that is constant in time.
- In this case, everything was very close together at a special time in the past.
- This time, the age of the universe, is just $1/H$.
- If $H = 72$ km/s/Mpc, then the age of the universe is 14 Gyr.
- Observations of the most distant white dwarf supernovae imply that H was smaller in the past
- The uncertainty in this statement is huge.
  Don’t plan your life, or your philosophy, around it.



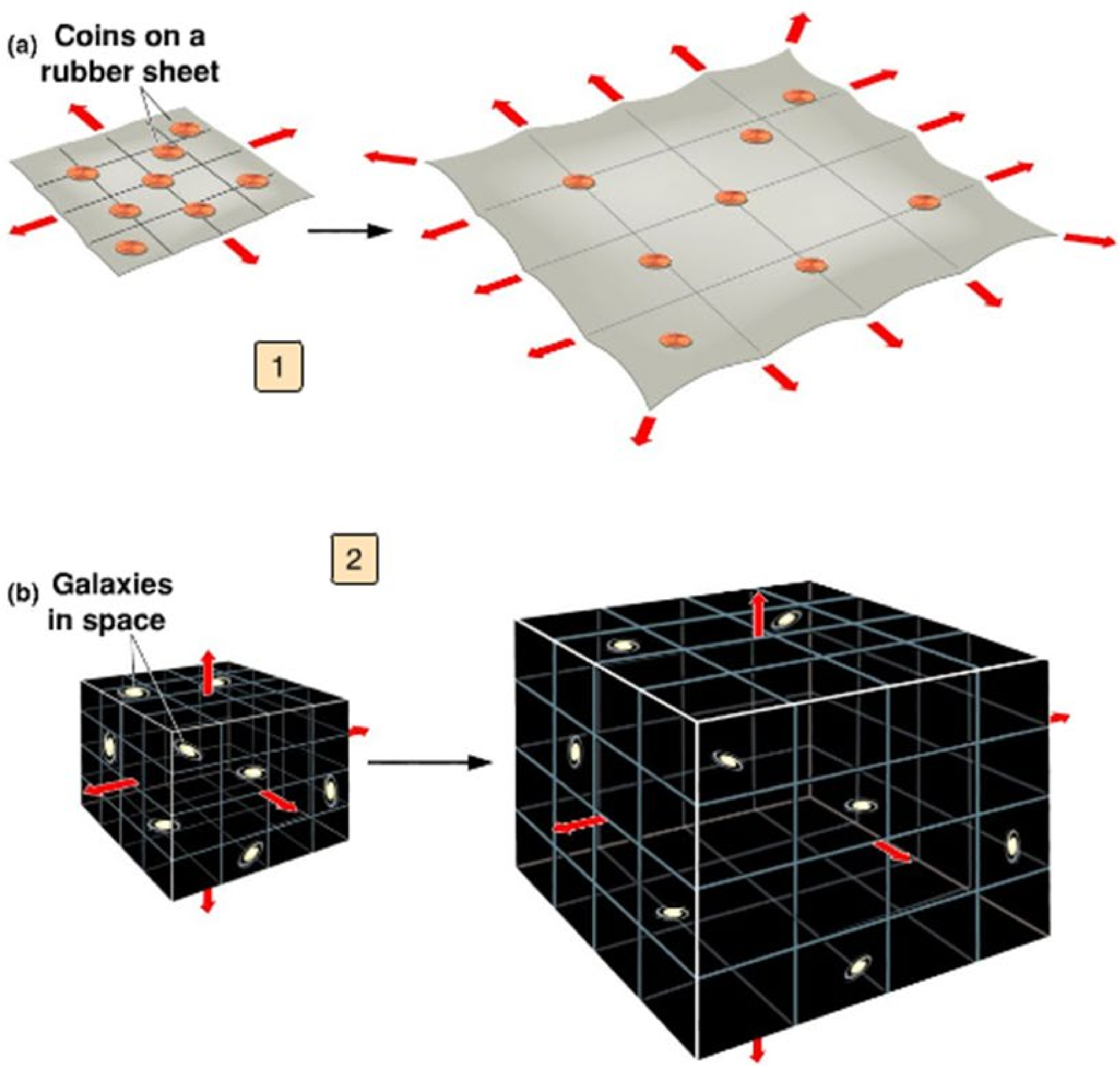
Hubble's original plot covered just a tiny portion of the relationship as we know it today.

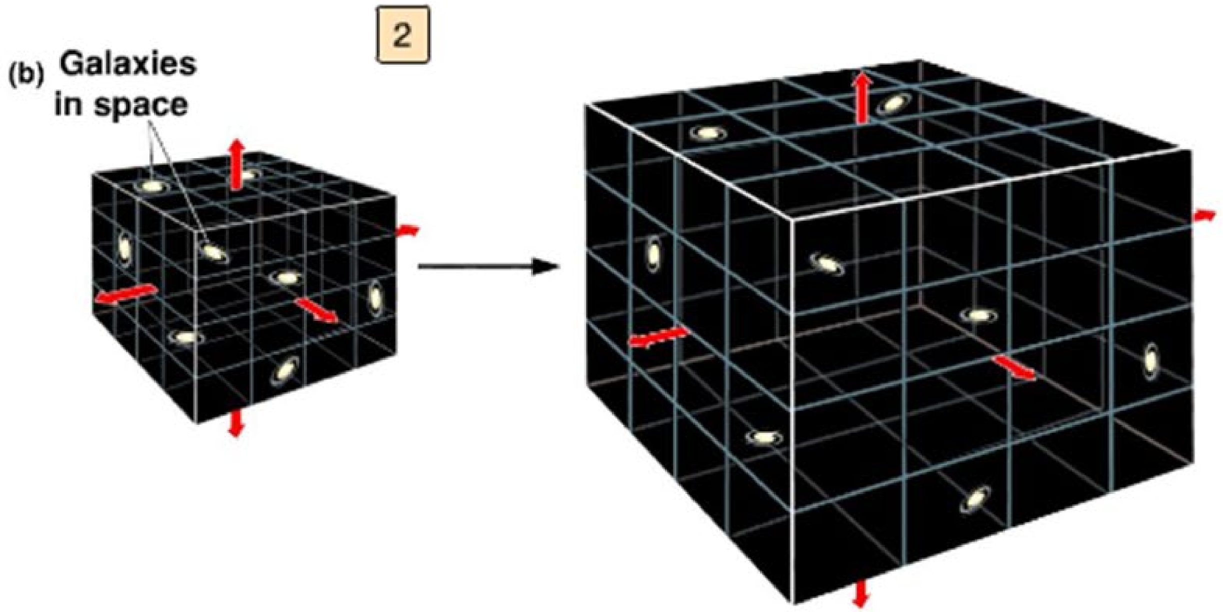


In this diagram, we show time after the Big Bang as increasing in the vertical direction. The distances and recession velocities shown for the 3 other galaxies imply that they and we were all at the same spot (the location of the Bang) 13.6 billion years ago.



Here we show this same thing in yet another way.


(a) Coins on a rubber sheet
1
2
(b) Galaxies in space

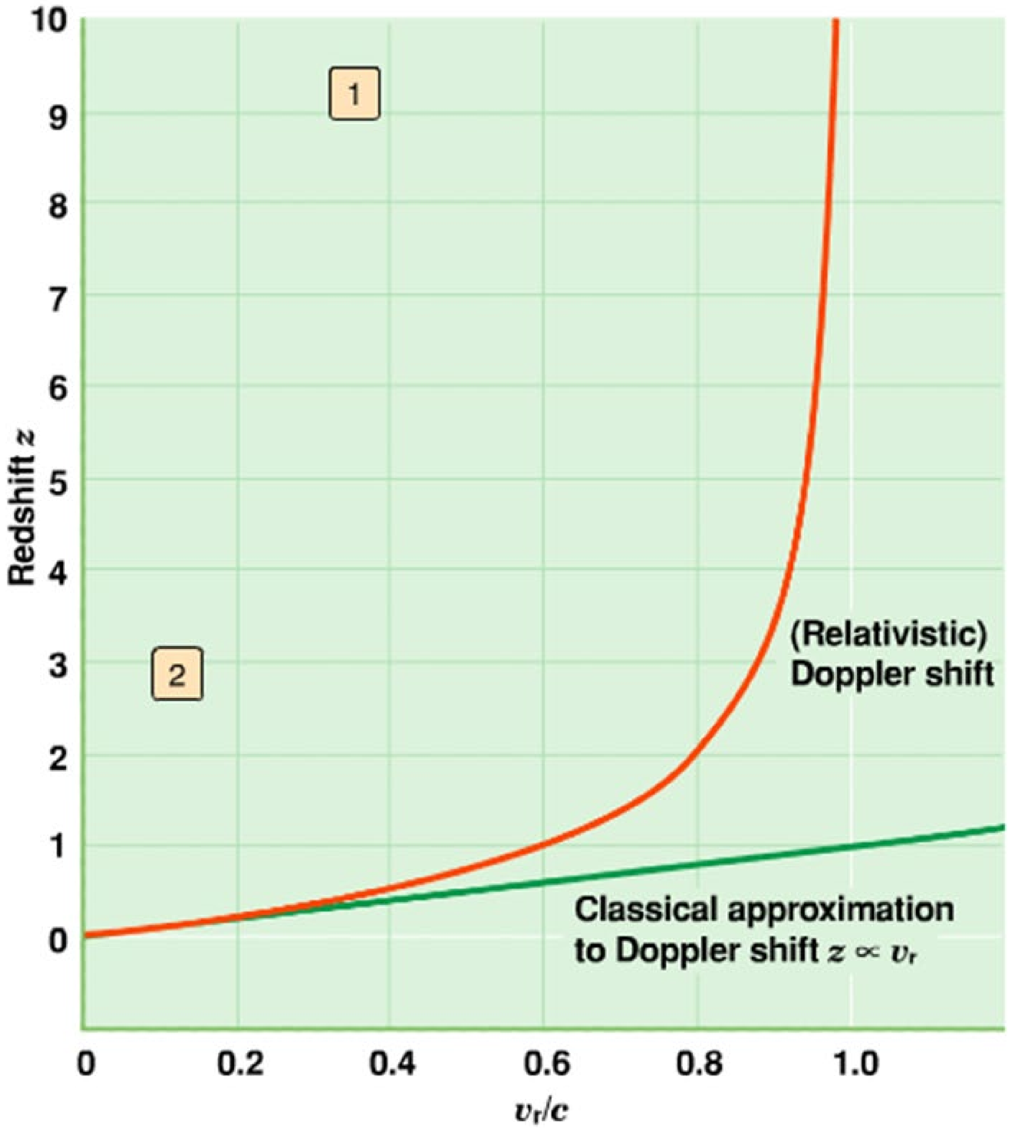


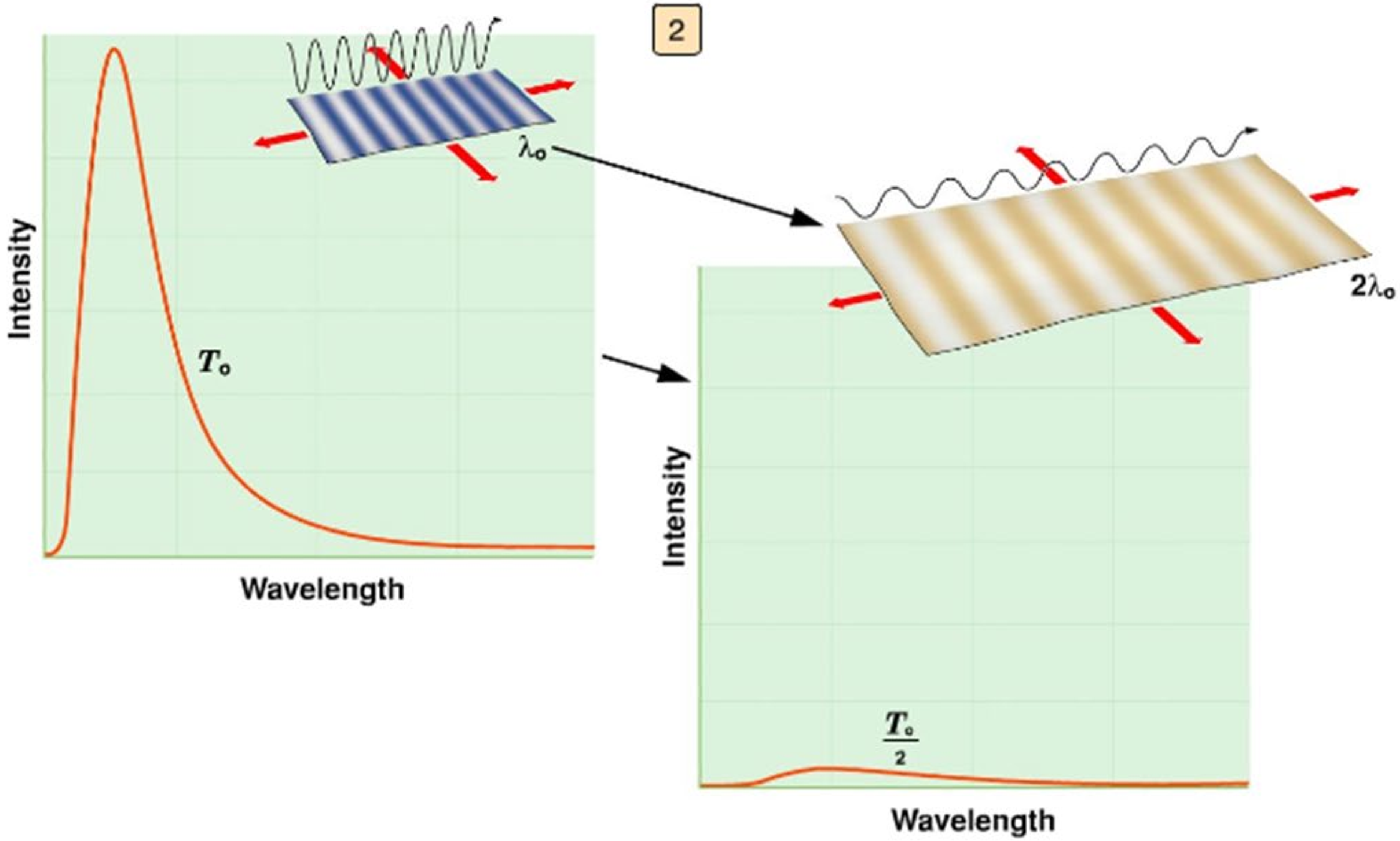
(c) W. W. Norton and Company

Our idea is that although the space between galaxies expands, galaxies themselves are not expanding, because they are held in together by their self-gravity.

The thought is that you aren't expanding either.

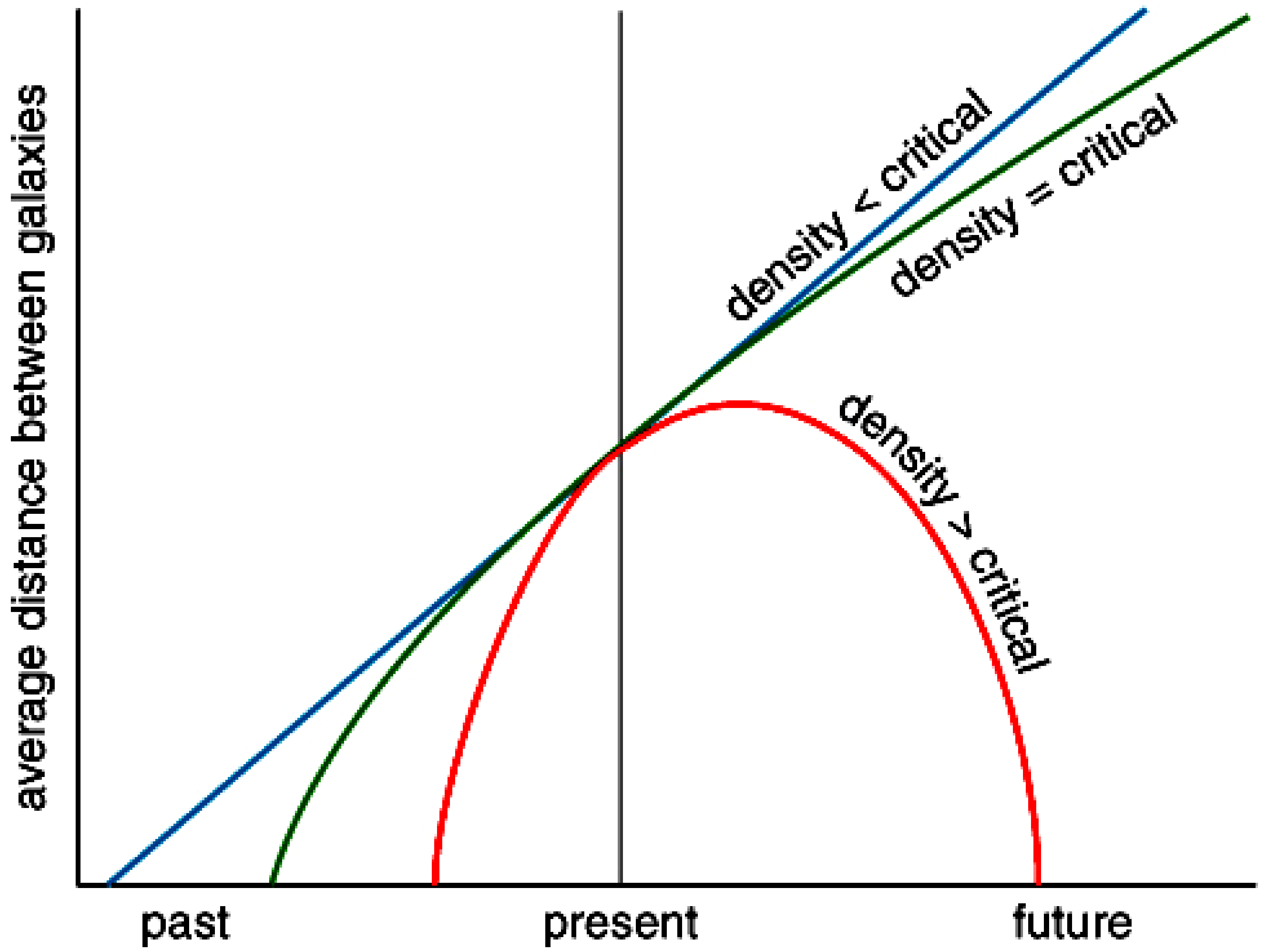
Einstein's theory of relativity tells us that the recession velocity cannot exceed the speed of light. As this speed approaches the speed of light, the corresponding red shift approaches infinity, as shown in this diagram.

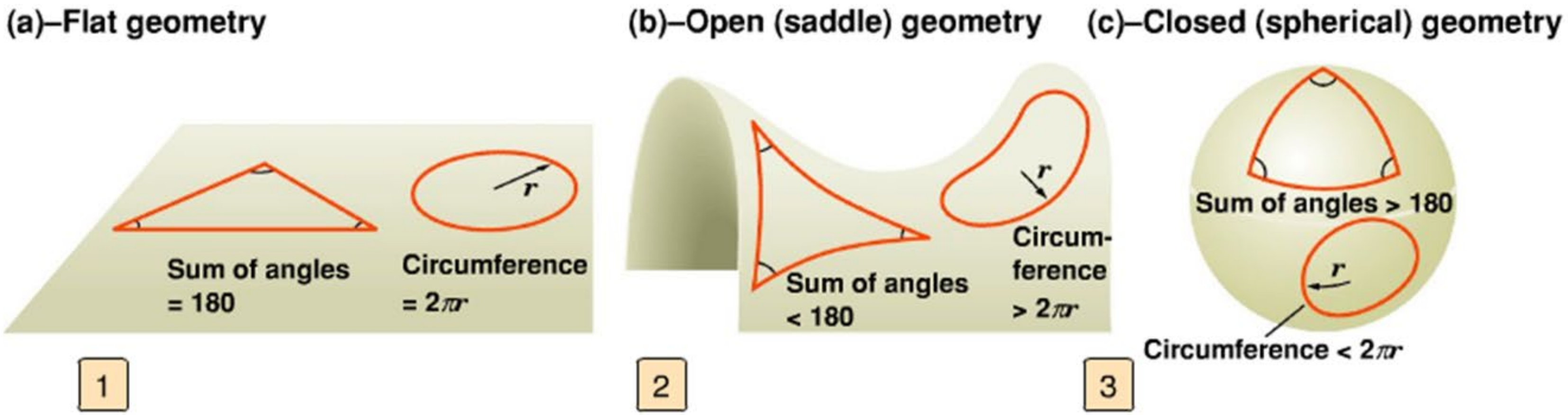




The "cosmological redshift" is illustrated in this diagram. As the universe expands, the wavelengths of light waves expand with it. This is a small effect, unless we look back in time really far.

- Einstein’s theory says that if there is enough mass in the universe, the expansion will ultimately cease, and then reverse to produce a contraction back to everything in the same place again.
- People worry about whether the universe has the *critical density* required to reverse the expansion.
- I can’t see what difference it makes, myself. The expansion remains unexplained.


average distance between galaxies
density < critical
density = critical
density > critical
past
present
future



By measuring the sums of the included angles in triangles constructed from sides that are straight lines, or by measuring the circumference of a carefully drawn circle, Einstein tells us that we can tell what type of universe we are living in. But it is really hard to draw those triangles and to measure the circumference accurately enough to get the needed reading, because the differences from Euclid's "normal" geometry of "flat" space are so incredibly small.

An analogy for the situation is a planet that has been blown to bits by the evil empire.

- If the empire did not use enough explosive, then the little pieces of the planet will not achieve escape velocity, and they will fall back together again as a result of their gravitational attraction.
- If the empire invested heavily in explosives, the bits of the planet will have enough energy to overcome their gravitational attraction and to escape to infinite separation (in infinite time).
- There is a critical case right in between.
- In the case of the universe, our life span is so short compared to the time for the explosion to develop, that essentially no event in our lives will depend upon whether the explosion was sub- or super-critical.
- Even if science can tell us which case applies, the answer to the question probably has no consequence of any significance for us.
- But if you told me that you could prove to me you knew the answer, I would probably ask you to do so.

It appears that at the beginning of time, at "the Big Bang," an awesome amount of energy was released (created?).

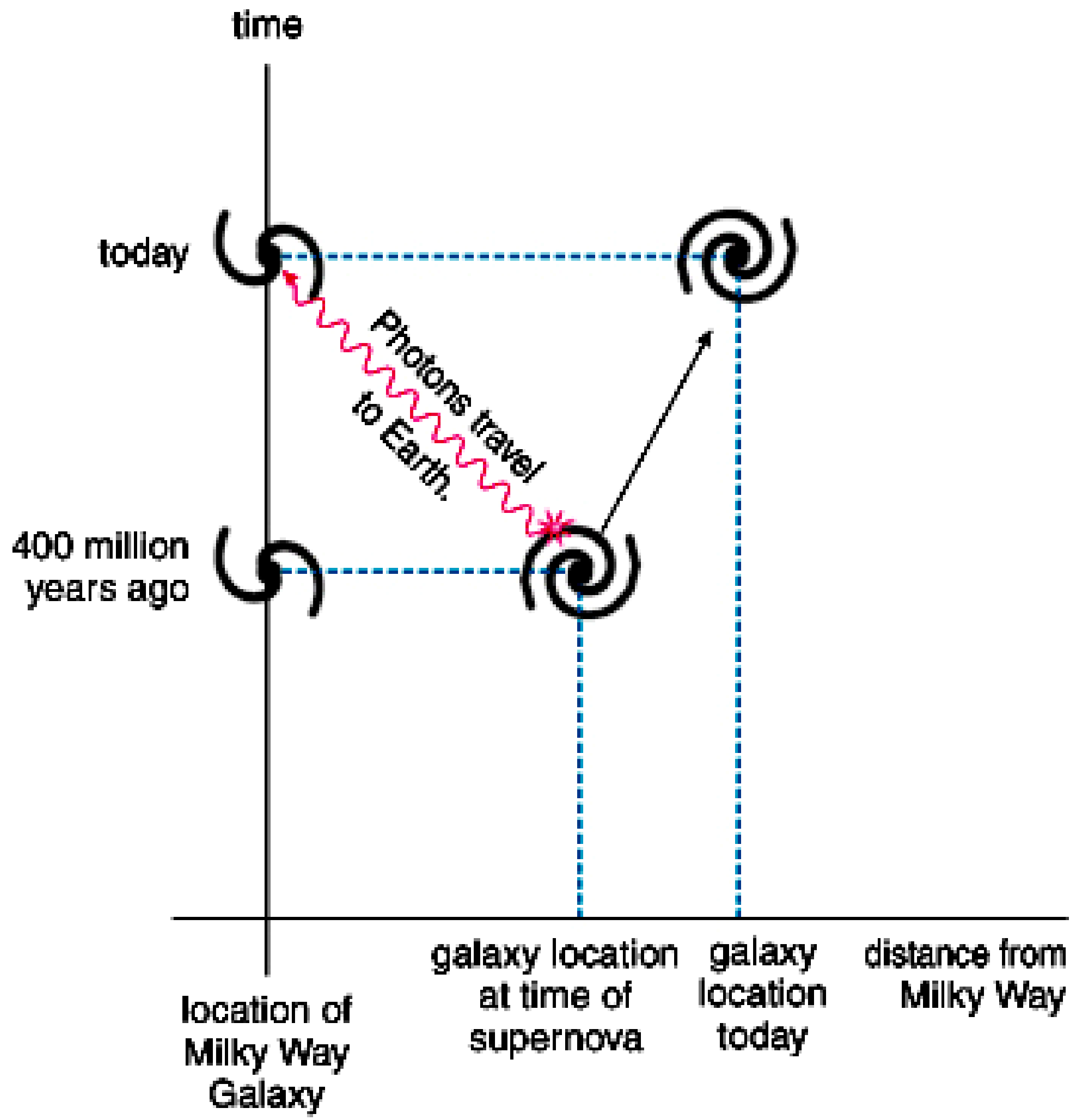
- Was this the act of creation?
- Or was there something before that?
- Is it just our part of the cosmos that exploded, and might there be some other part of creation that so far has been invisible to us?
- As far as we can tell, we (the universe) have just been coasting since the Big Bang, with no energy lost or gained, but just changing from one form to another.
- Is life just one of those "forms" of energy?
- Is there any significance to life, to this apparent explosion? (Can it have been a mistake?)
- It's hard to see how you or anyone else could get much of a grip on these questions, *using the scientific method of course*.
- But then, who in the time of Ptolemy would ever have imagined that we would ever know what we have been discussing in this course so far?

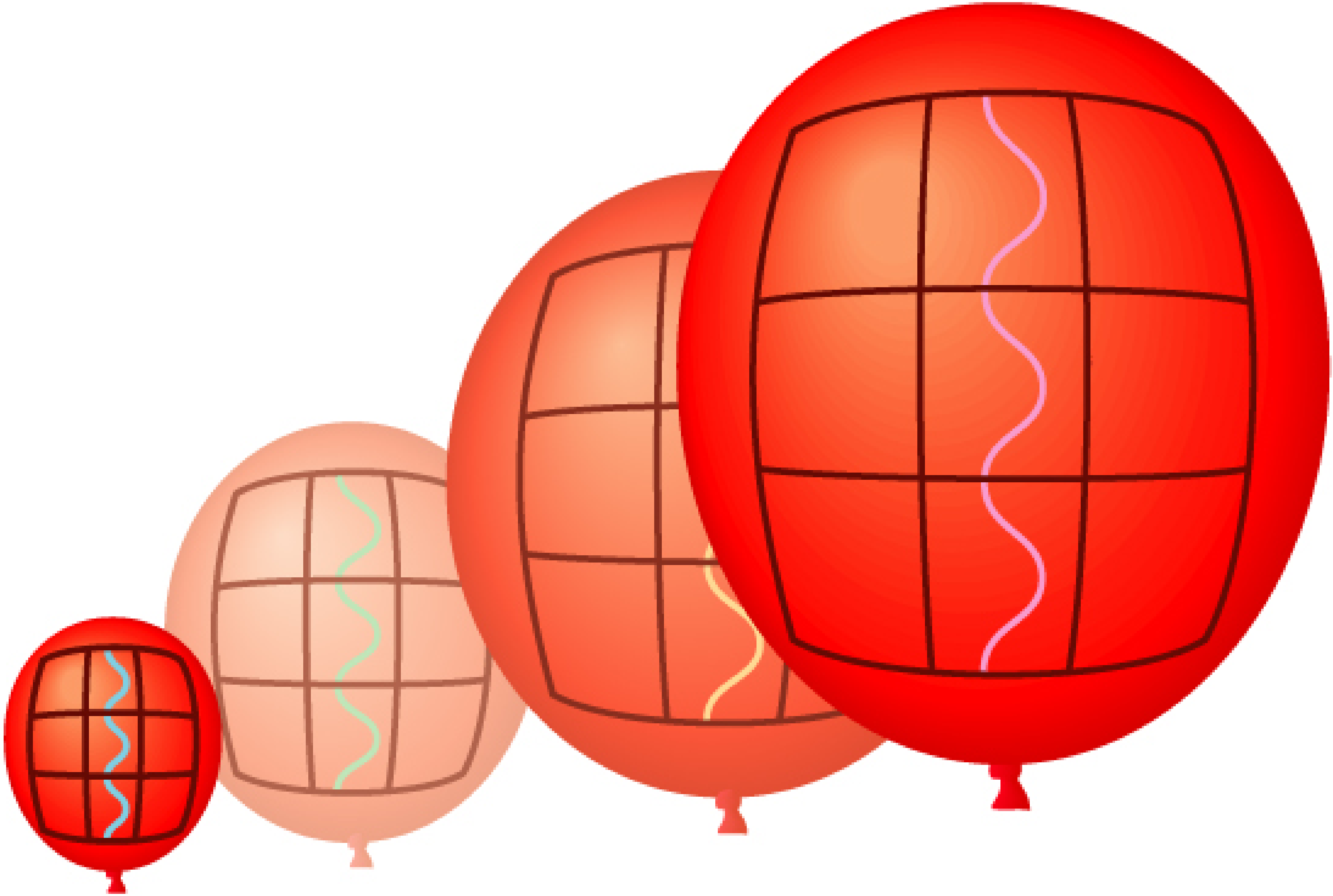
The age of the universe depends upon the value of the Hubble constant, H, and on the density of the universe.

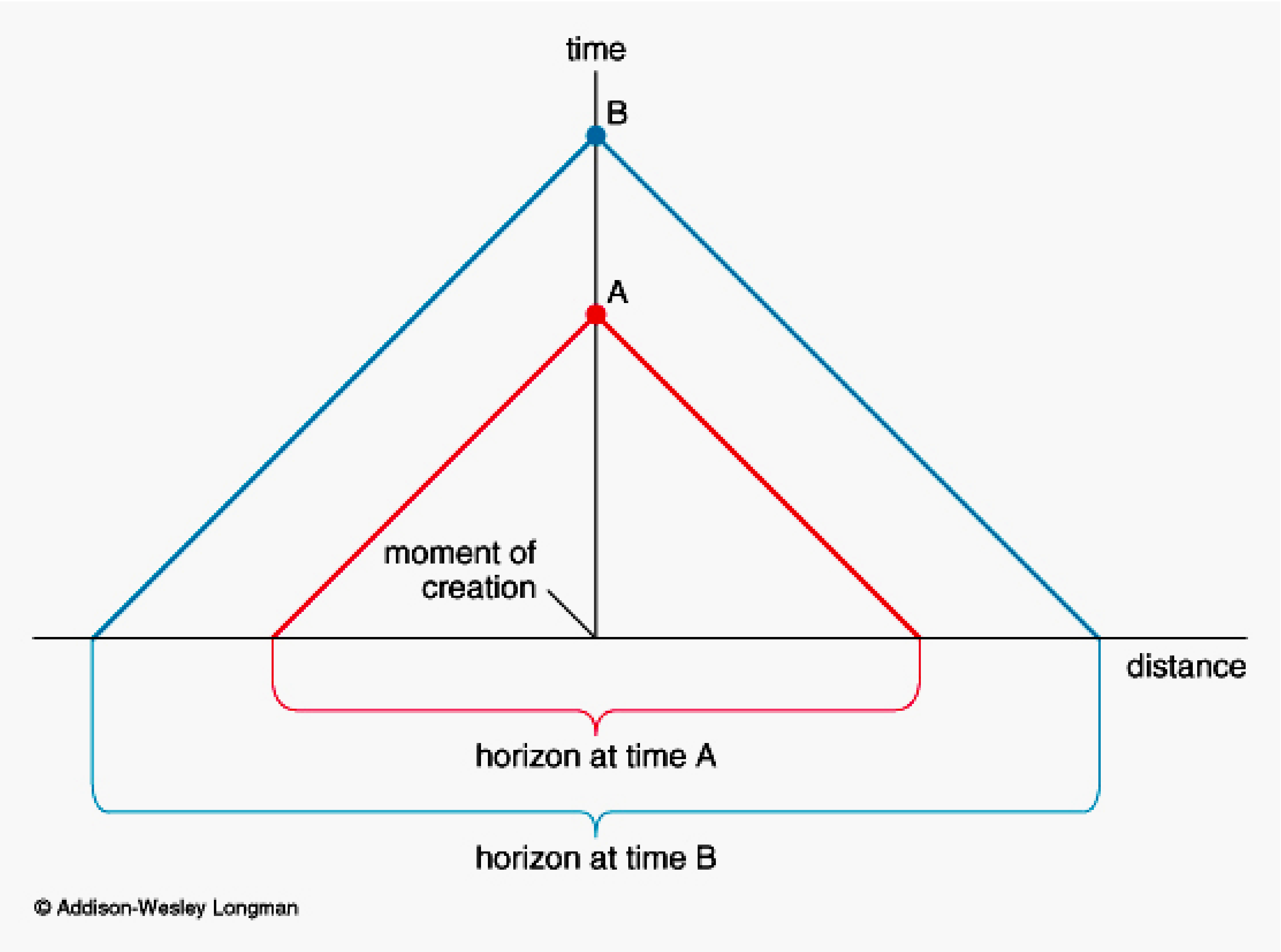
- H between 50 and 80 km/sec/Mpc ←→ 12 to 20 billion years (for a low density universe).
- H between 50 and 80 km/sec/Mpc ←→ 8 to 13 billion years (for a critical density universe).
- If the density is above critical, we get ages for the universe that are smaller than our best estimates of the ages of the oldest globular cluster stars.

<u>Other weird concepts:</u>

- Cosmological red shift: as light travels to us, its wavelength expands along with the universe, which produces a red shift.
- Horizon: we can only see out to a distance equal to the speed of light times the age of the universe.
- Light coming from our horizon was emitted at the moment of creation.
- We can see more of creation every day. (*Is there a problem here?*)


time
today
400 million
years ago
Photons travel
to Earth.
galaxy location
at time of
supernova
galaxy
location
today
distance from
Milky Way
location of
Milky Way
Galaxy




time
B
A
moment of
creation
distance
horizon at time A
horizon at time B
© Addison-Wesley Longman

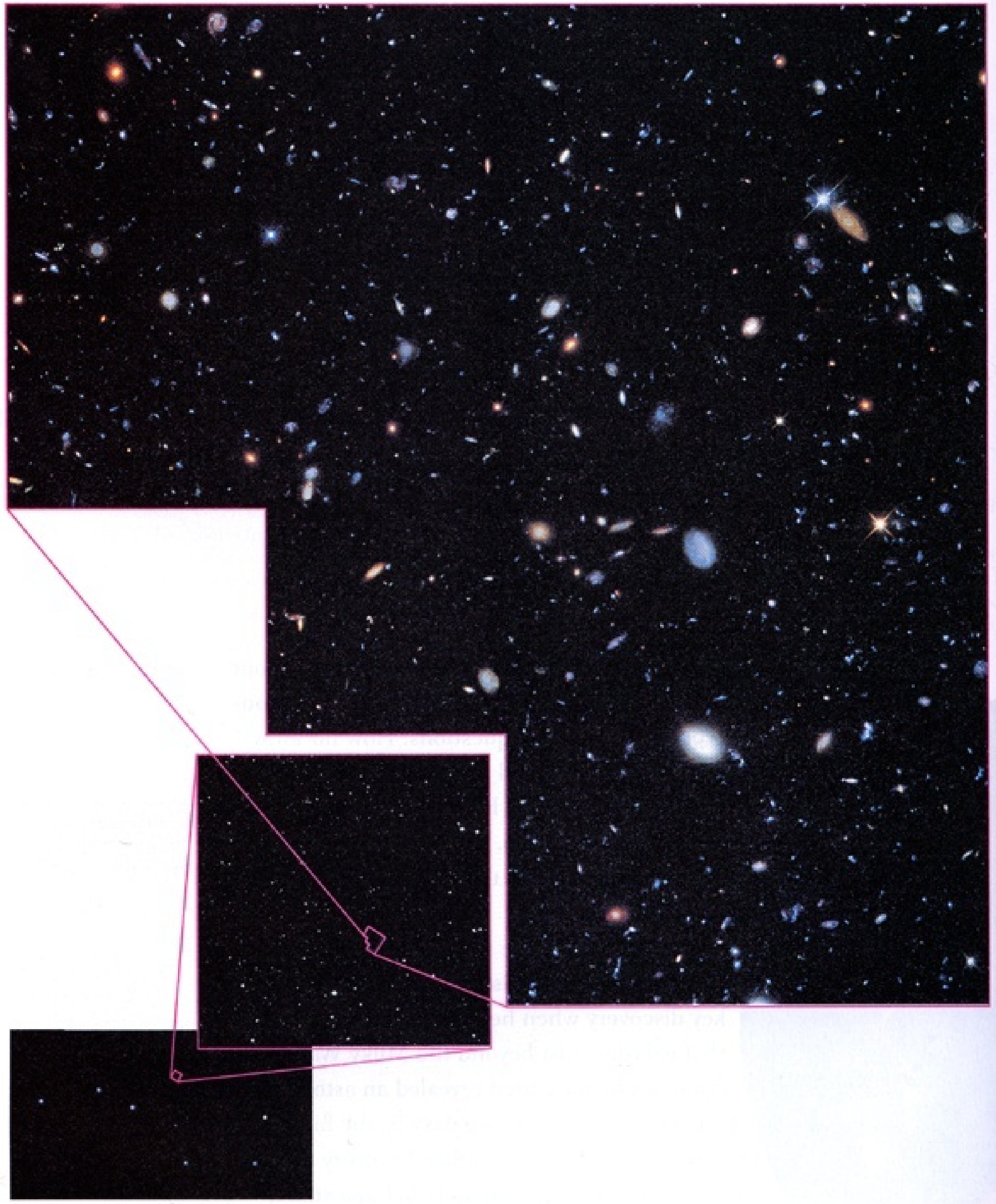
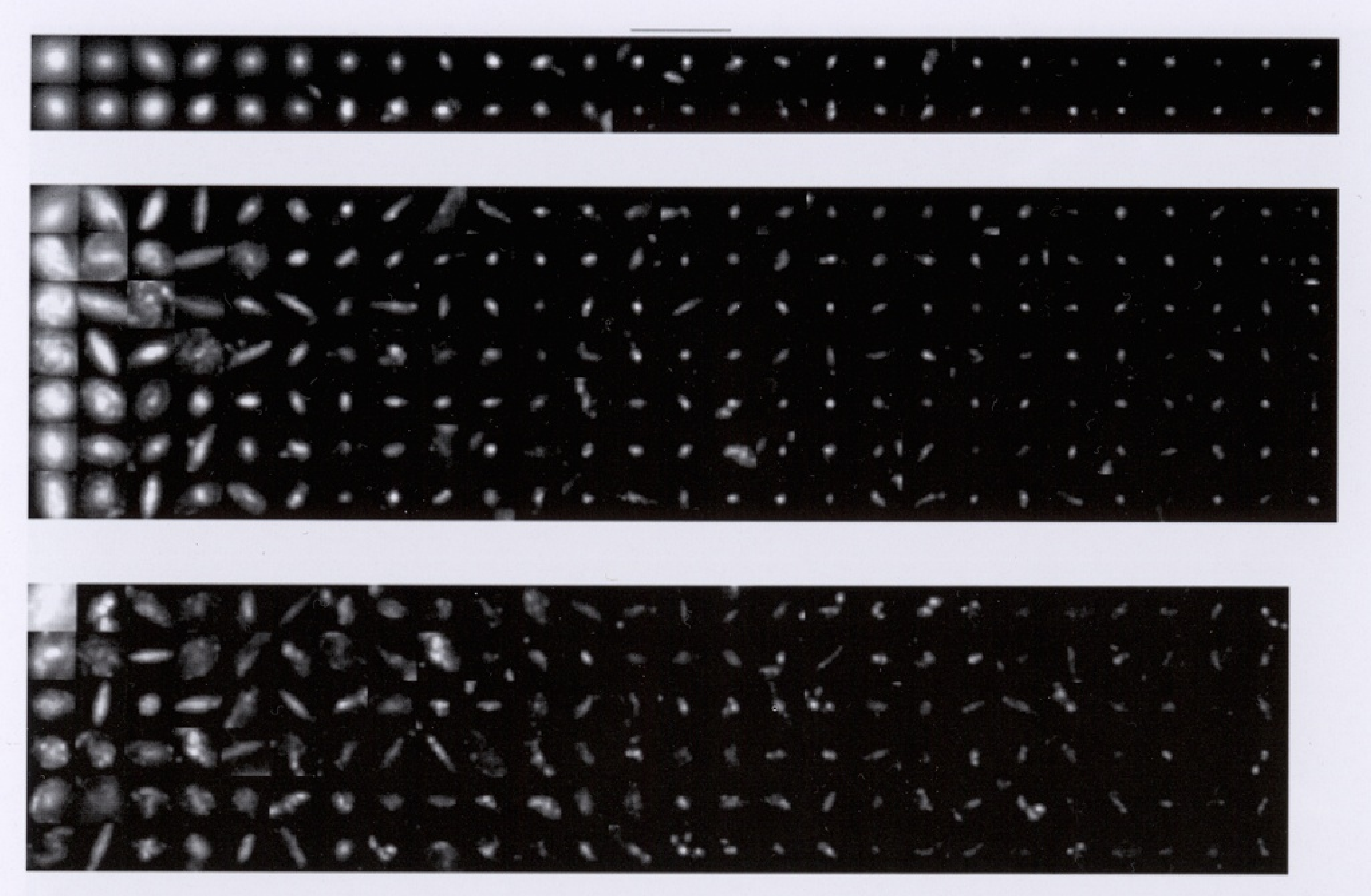
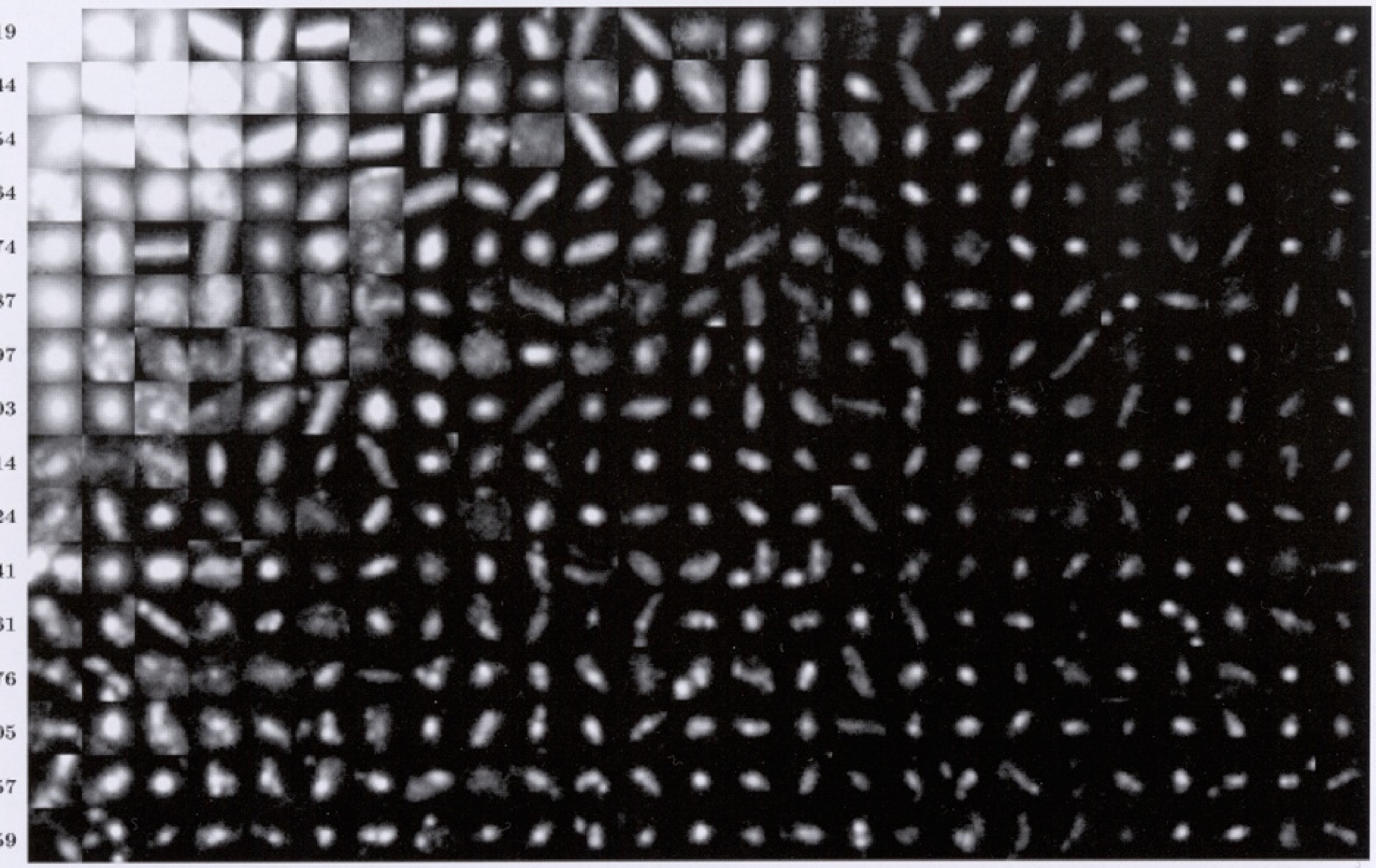


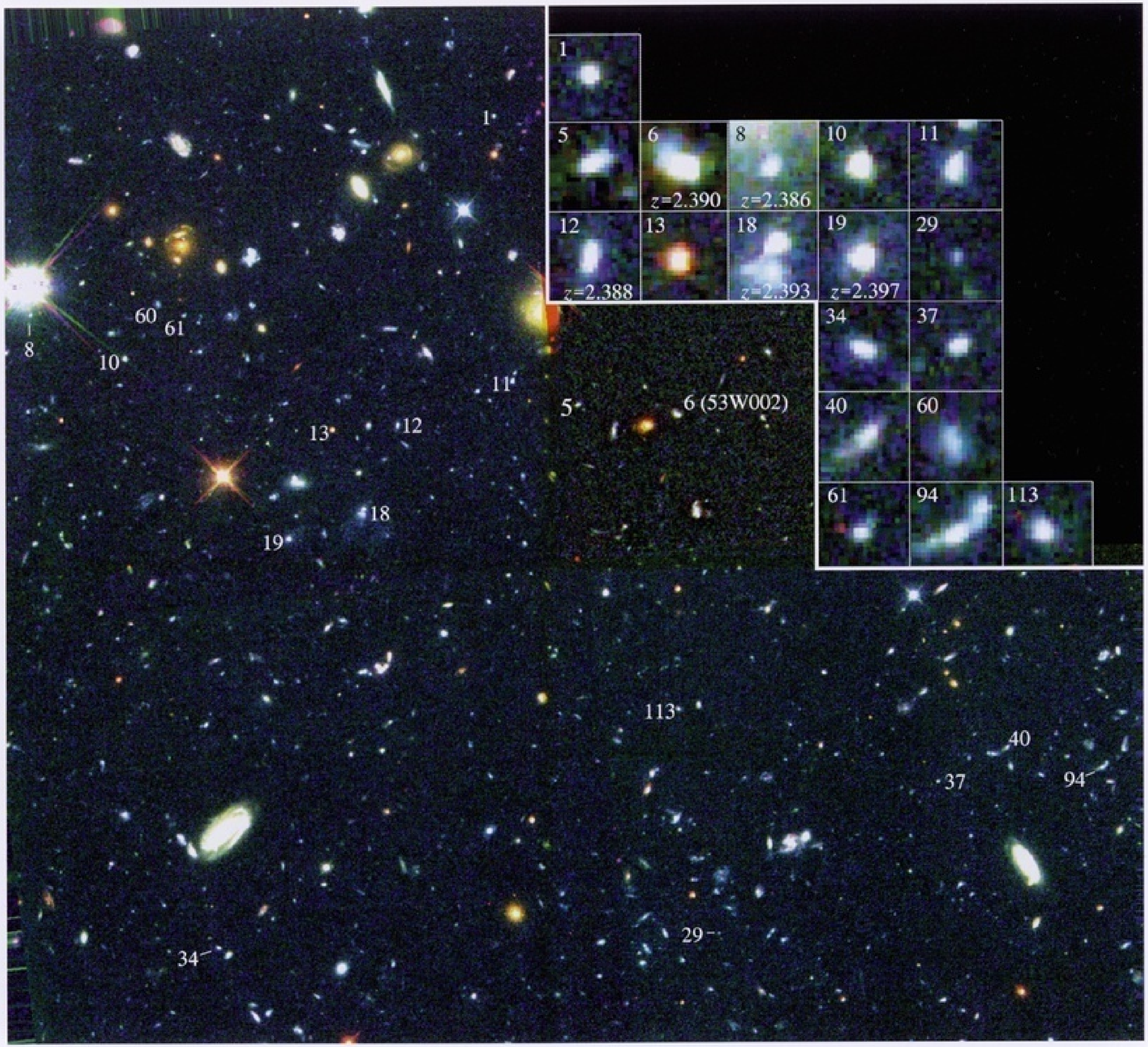
FIGURE 19.1 The Hubble Deep Field, an image composed of 10 days of exposures taken with the Hubble Space Telescope. Some of the galaxies pictured are three-quarters of the way across the observable universe. The field itself is located in the Big Dipper.



Galaxies of the Hubble Deep Field sorted by morpholog-ical type.



The galaxies of the Hubble Deep Field are here sorted by redshift (vertical axis) and brightness (horizontal axis).



18 young galaxies, or their precursors, were found in this deep Hubble image. The objects are thought to be 2000 to 3000 light years in diameter, much smaller than present-day galaxies. They are also close enough together to collide within the next few billion years.

Hubble Goes 'Deep' to Sample Young Galaxies

STScI-PRC2003-18a

NASA's Hubble Space Telescope reached back to nearly the beginning of time to sample thousands of infant galaxies. This image, taken with Hubble's Advanced Camera for Surveys, shows several thousand galaxies, many of which appear to be interacting or in the process of forming. Some of these galaxies existed when the cosmos was less than about 2 billion years old. The foreground galaxies, however, are much closer to Earth. Two of them [the white, elongated galaxies, left of center] appear to be colliding.

This image represents less than one-tenth of the entire field surveyed by Hubble. The full field, consisting of about 25,000 galaxies, is part of a larger survey called the Great Observatories Origins Deep Survey (GOODS), the most ambitious study of the early universe yet undertaken with the Hubble telescope. This survey targeted two representative spots in the sky - one in the Northern Hemisphere and the other in the Southern Hemisphere.

This image represents the southern field, located in the constellation Fornax. The entire GOODS survey reveals roughly 50,000 galaxies. Astronomers have identified more than 2,000 of them as infant galaxies, observed when the universe was less than about 2 billion years old.

Because infant galaxies are very faint and very rare, astronomers are using Hubble to search for them over a relatively wide swath of sky. In fact, the new observations cover about 60 times the area of the original Hubble Deep Field Observations, obtained in 1995. Astronomers also are using the Chandra X-ray Observatory to search the GOODS fields for the earliest black holes in the universe. The Space Infrared Telescope Facility (SIRTF) will sample these same fields soon after it is launched in August 2003.

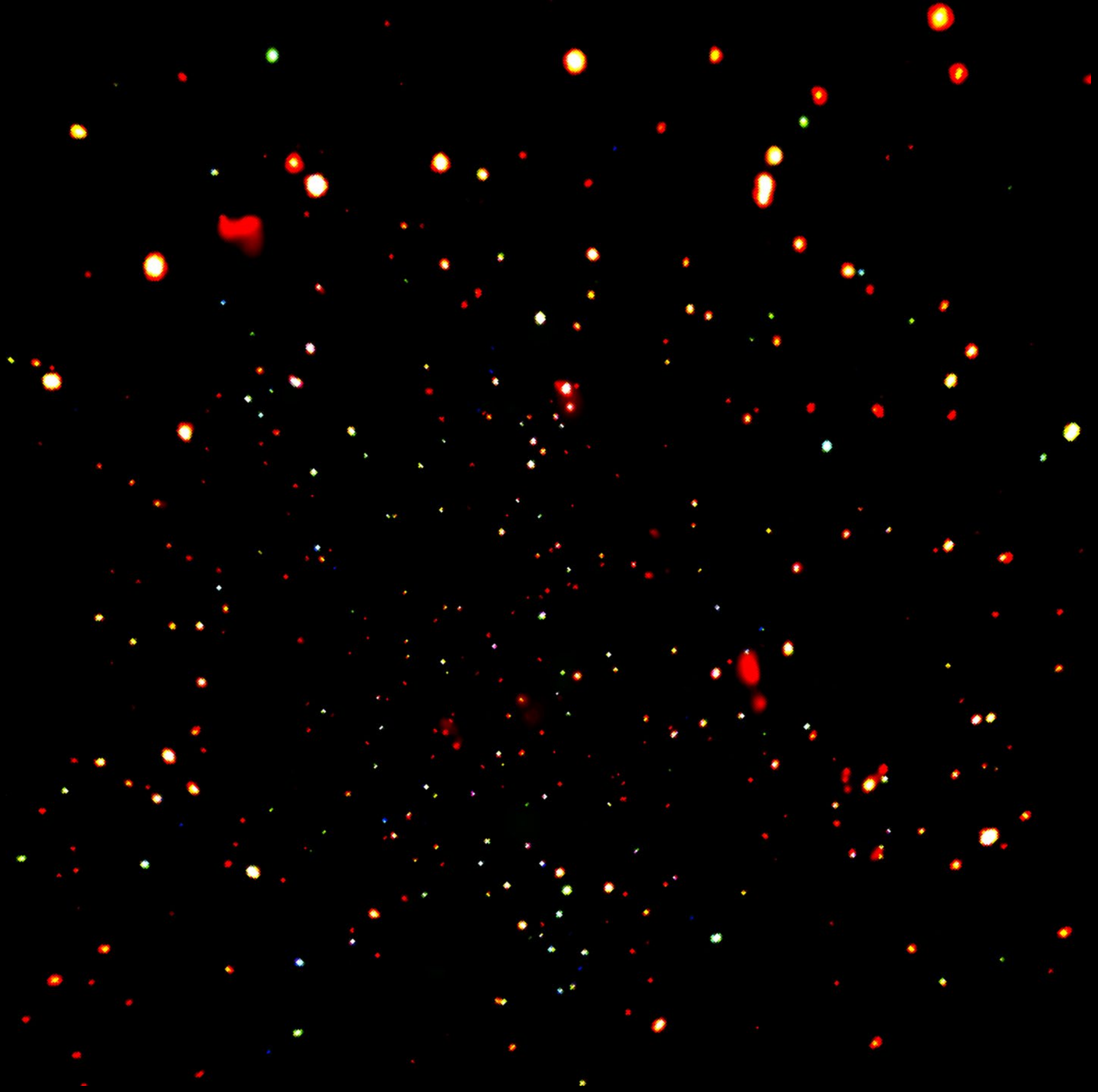
Hubble observes a new deep field in the southern hemisphere.

Chandra Deep Field-North

STScI-PRC2003-18b

The Chandra Deep Field-North image was made by observing an area of the sky over half the size of the full moon for 23 days. It is the most sensitive or "deepest" X-ray exposure ever made. By combining the Chandra and Hubble data for this field, astronomers can take a census of the fraction of young galaxies that contain active supermassive black holes back to a time when the universe was only about one billion years old, less than 10 percent of its present age. The data show that these very distant supermassive black holes are rare, more so than some expected.

Credit: *NASA/CXC/Penn State/D.M. Alexander, F.E. Bauer, W.N. Brandt et al.*



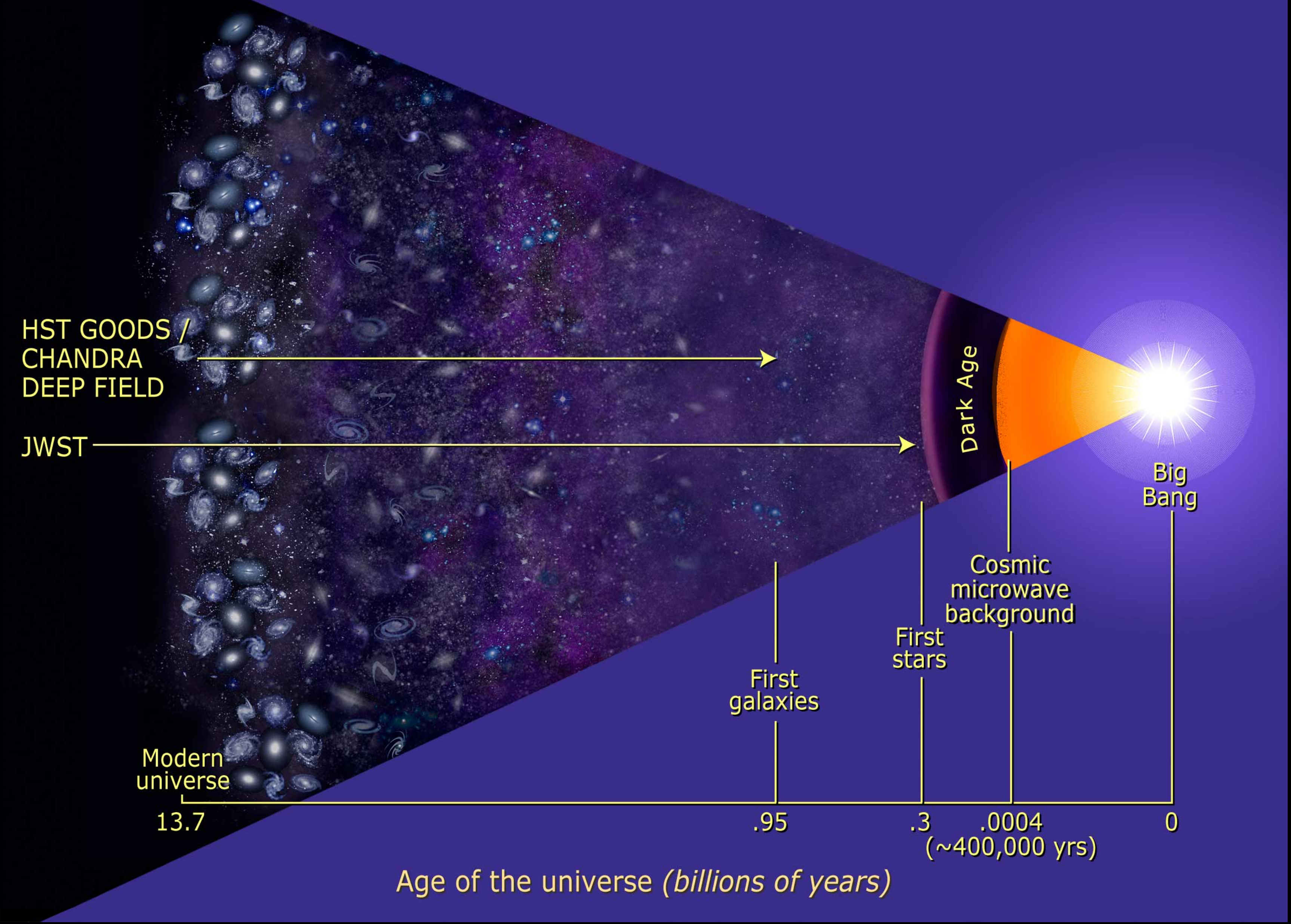
This is the
Chandra
Deep Field,
North
(HST)

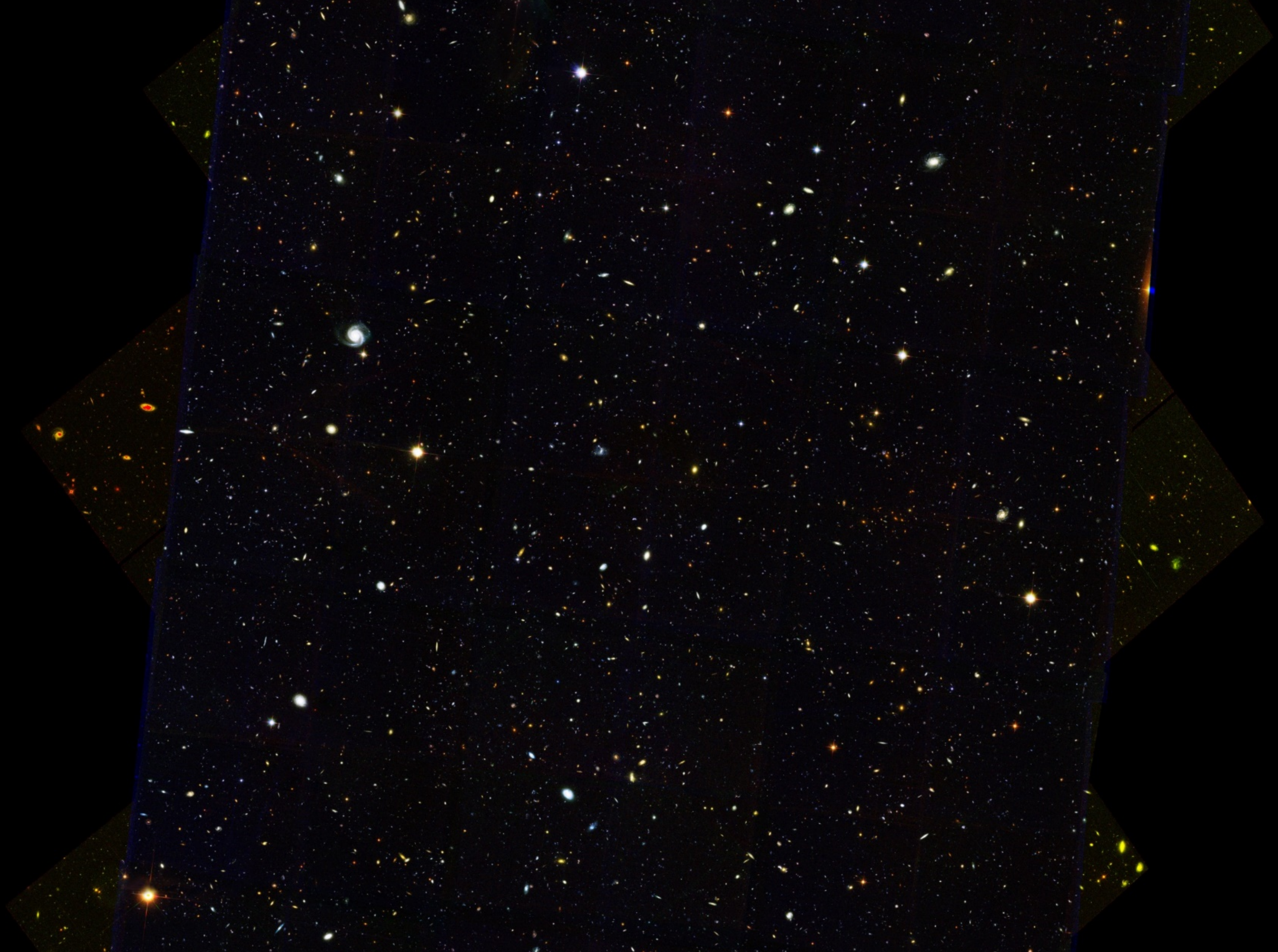
Cosmic Timeline

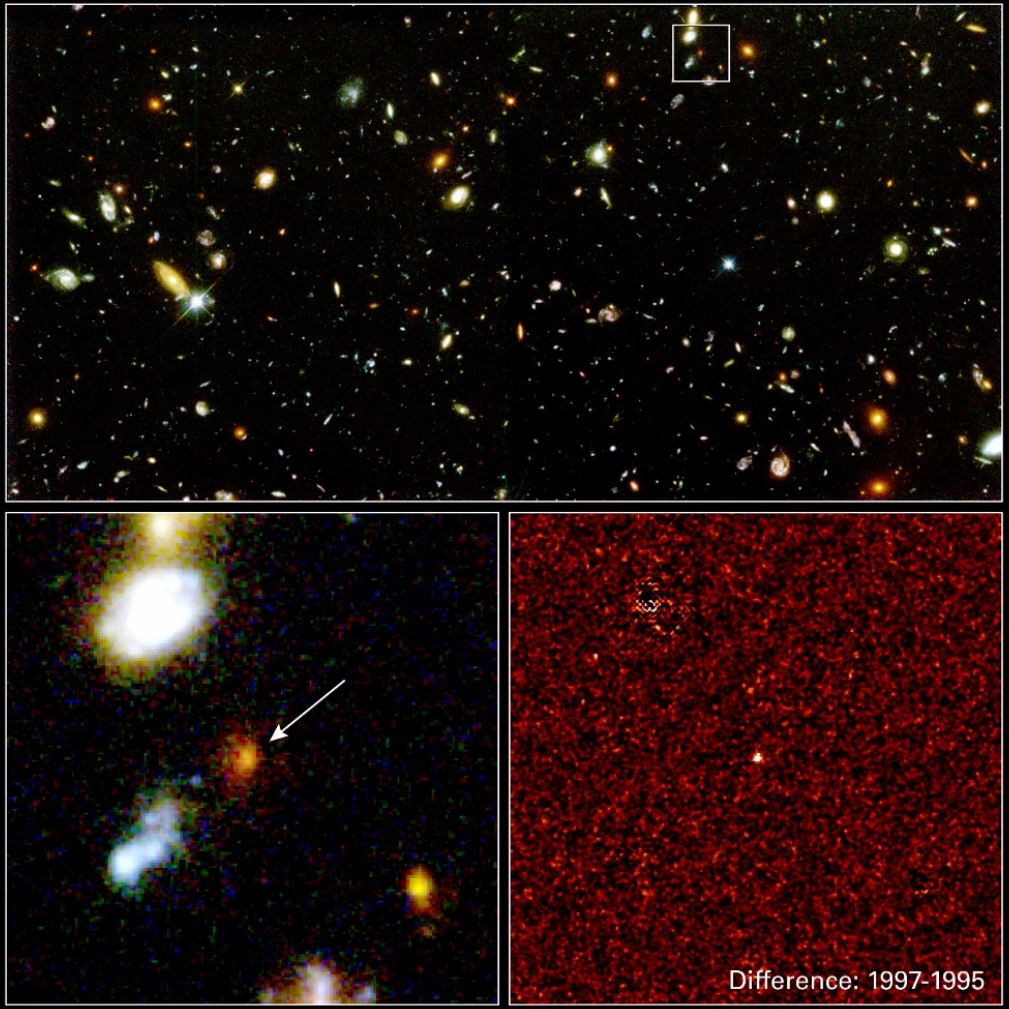
Observatories continue to reach farther back in time to study the evolution of stars and galaxies. This illustration shows that the Chandra X-ray Observatory and the Hubble Space Telescope's Advanced Camera for Surveys looked back billions of years to see the first galaxies. Their combined effort was part of the Great Observatories Origins Deep Survey (GOODS). Hubble's successor, the James Webb Space Telescope (JWST), will gaze even farther back in time to the birth of the first stars.

When we look back in time in this way, it becomes inescapable to conclude that the universe is evolving and changing in time. In the 1950s, some astronomers advocated a view in which the universe was in a statistically steady state. This "steady state universe" is simply inconsistent with the Hubble Telescope's Deep Field observations.

Seeing back into the cosmos







Distant Supernova in the Hubble Deep Field
Hubble Space Telescope • WFPC2

NASA and A. Riess (STScI) • STScI-PRC01-09

Hubble Space Telescope observation in 1997 of a supernova 10 billion light years distant provides evidence that the expansion rate of the universe first slowed and then later accelerated.

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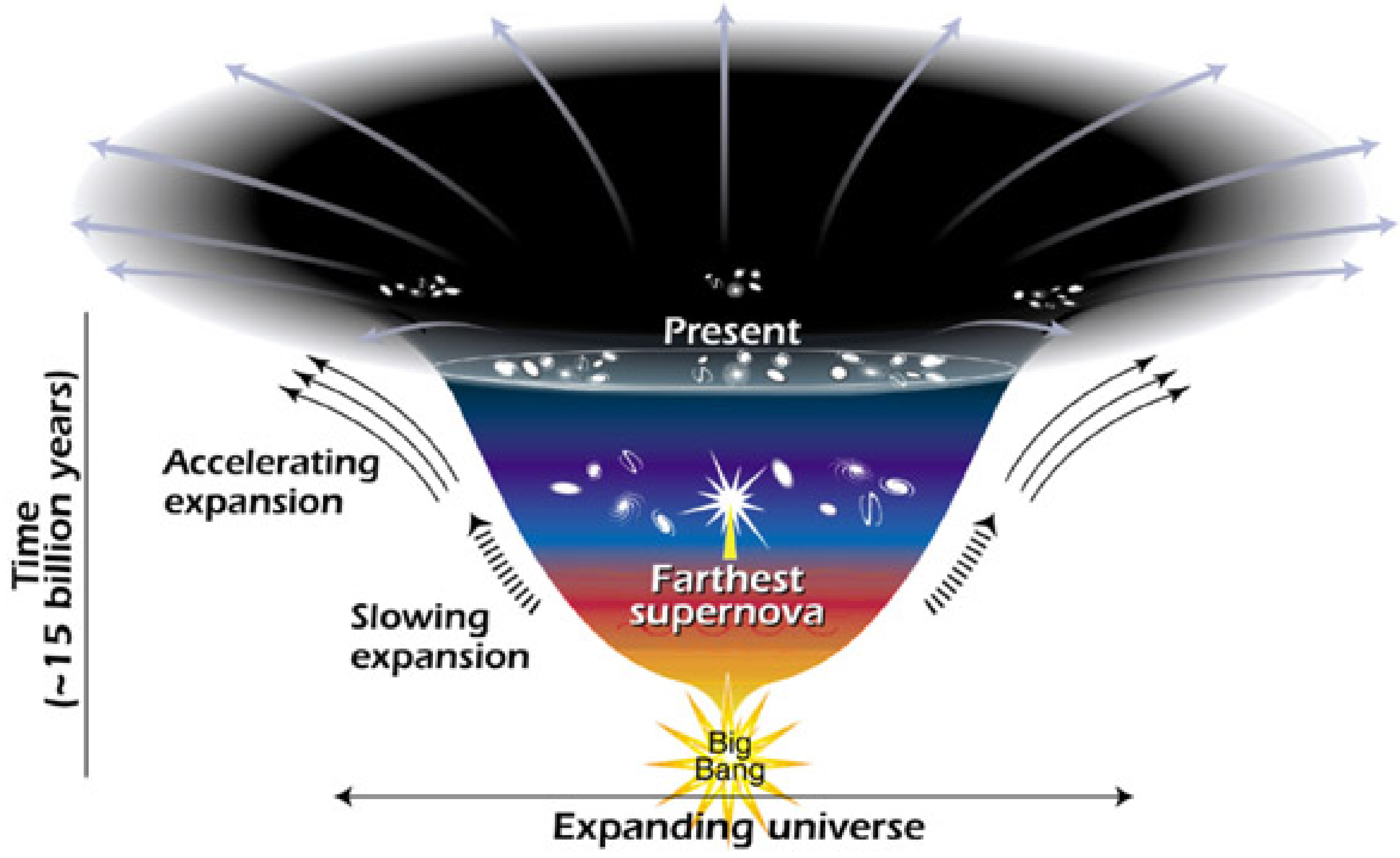

This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

- NASA's Hubble Space Telescope has seen a burst of light from an exploding star located much farther from Earth than any previously seen - a supernova blast in the early universe that is casting light on a mystery of truly cosmic scale.
- This stellar explosion is extraordinary not only because of its tremendous distance, 10 billion light-years from Earth, but also because its discovery greatly bolsters the case for the existence of a mysterious form of "dark energy" pervading the universe. The concept of dark energy, which shoves galaxies away from each other at an ever-increasing speed, was first proposed, and then discarded, by Albert Einstein early in the last century.

The Hubble discovery also reinforces the startling idea that the universe only recently began speeding up, a discovery made about three years ago when the unusually dim light of several distant supernovas suggested the universe is expanding more quickly than in the past, but there were alternate explanations. The more distant supernova (redshift z=1.7) refutes these alternatives and offers the first tantalizing observational evidence that gravity began slowing down the expansion of the universe after the big bang. Only later did the repulsive force of dark energy win out over gravity's attractive grip.

"The supernova appears to be one of a special class of explosions that allows astronomers to understand how the universe's expansion has changed over time, much as the way a parent follows a child's growth spurts by marking a doorway," said Adam Riess of the Space Telescope Science Institute (STScI), Baltimore, MD. "This supernova shows us the universe is behaving like a driver who slows down approaching a red stoplight and then hits the accelerator when the light turns green." The team of astronomers, led by Riess, made the discovery by analyzing hundreds of images taken by Hubble in infrared and visible light to study how galaxies formed. Fortuitously, one of those galaxies contained a supernova previously discovered by astronomers Ron Gilliland, STScI, and Mark Phillips, Carnegie Institutions of Washington.

- The record-breaking supernova appears brighter than it should if the universe had been expanding at a steady rate. The reason is that a decelerating universe holds galaxies relatively close together and objects in them would have appeared brighter because they would be closer. "Long ago, when the light left this distant supernova, the universe may have been slowing down due to the mutual tug of all the mass in the universe," said Riess. "Billions of years later, when the light left more recent supernovas, the universe had begun accelerating, stretching the expanse between galaxies and making objects in them appear dimmer."

•Observations of several distant supernovas by two teams of astronomers in 1998 led to the prediction that the universe got the "green light" to accelerate when it was half its present age. Astronomers say the new Hubble findings rule out other explanations.

•Riess' collaborators include Peter Nugent (Lawrence Berkeley National Laboratory), Brian Schmidt (Mount Stromlo Observatory), and John Tonry (Institute for Astronomy). NASA's Hubble Space Telescope is a project of international cooperation between NASA and the European Space Agency.

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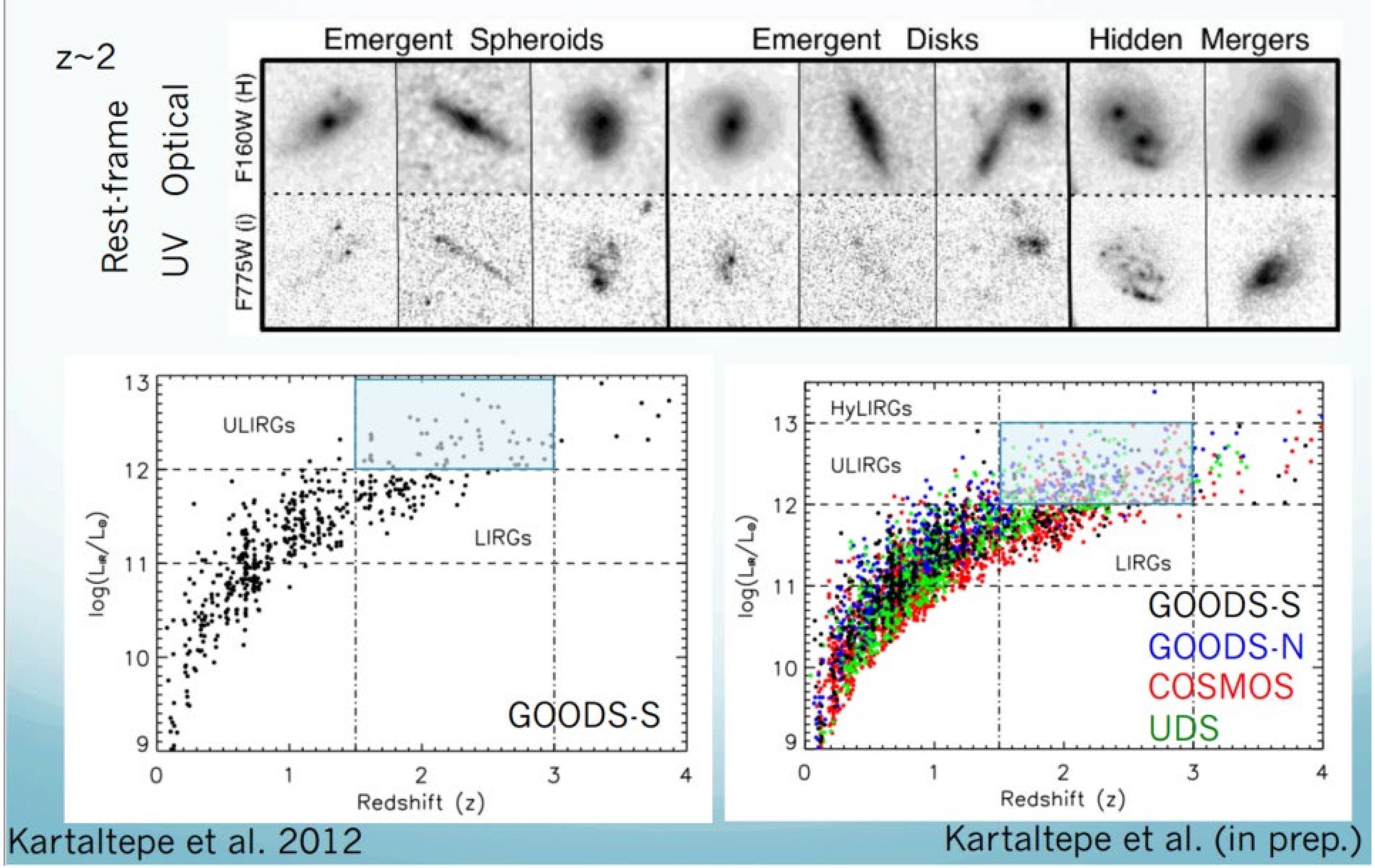
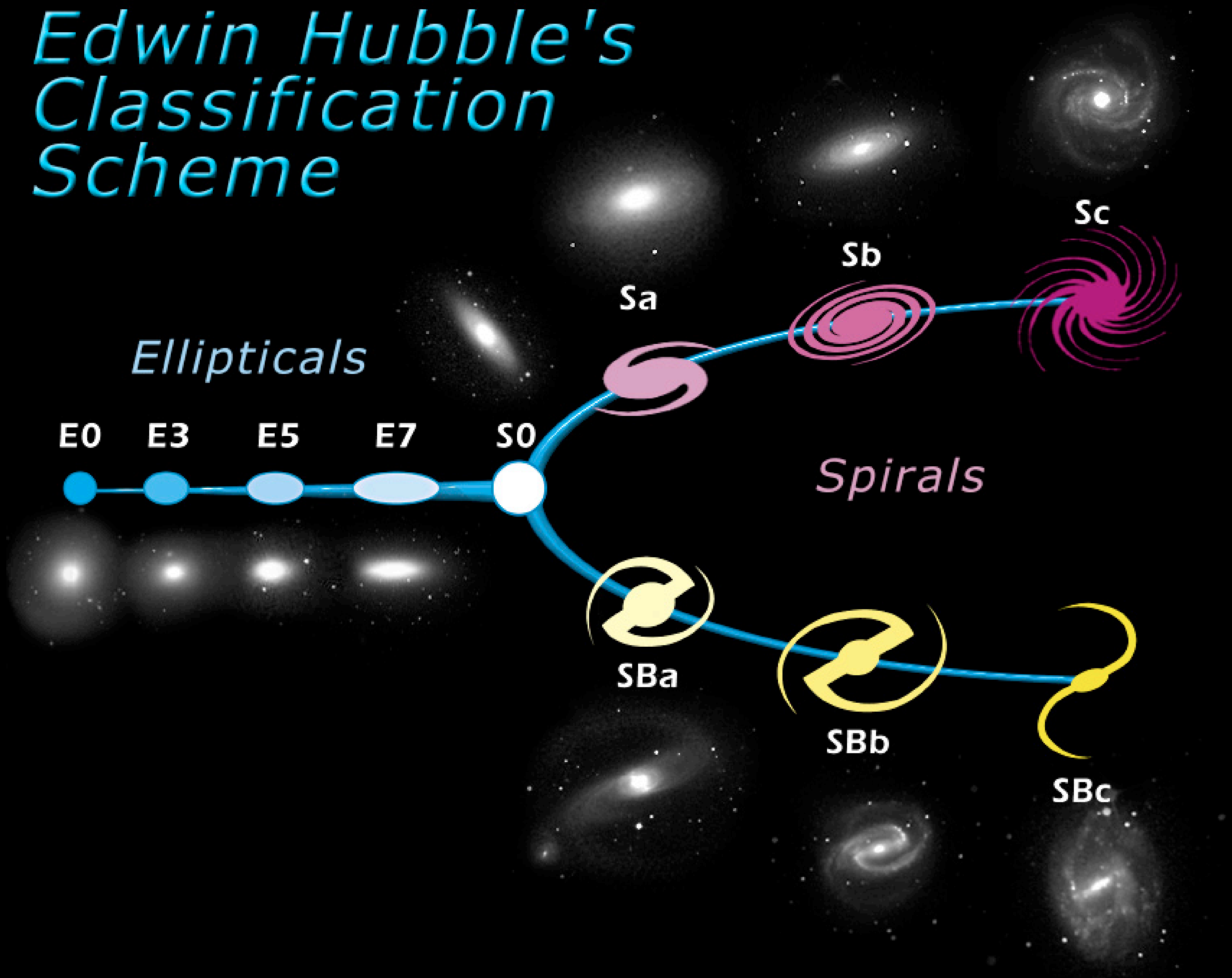
- **AUGUST 15, 2013:** Looking 11 billion years back in time to when the universe was very young, astronomers have found that the anatomy of distant galaxies is not that different from galaxies seen in the nearby universe today. The results come from the Hubble Space Telescope Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). The largest project in the history of Hubble, it aims to explore galactic evolution in the early universe, and the very first seeds of cosmic structure at less than 1 billion years after the Big Bang.
- Previous studies of this early epoch were inconclusive because they were limited to visible light. Because of the stretching of light by the expansion of the universe the visible light detected in distant galaxies actually maps only the ultraviolet emissions of the galaxies. Because this radiation only comes from regions of active star formation the galaxies appeared to be clumpy and messy, with no resemblance to the galaxy shapes we see around us today. By observing the galaxies in infrared light with Hubble's Wide Field Camera 3, astronomers could observe how these distant galaxies would appear normally in visible light if their radiation were not stretched to infrared wavelengths by the expanding universe. For more information about this study, visit:http://www.spacetelescope.org/news/heic1315 .



Comparison of appearance of galaxies (in their rest frames) in UV and in visible light. The UV appearance suggests less well-formed structure, but this is in fact misleading.


Edwin Hubble's Classification Scheme
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E0
E3
E5
E7
S0
Sa
Sb
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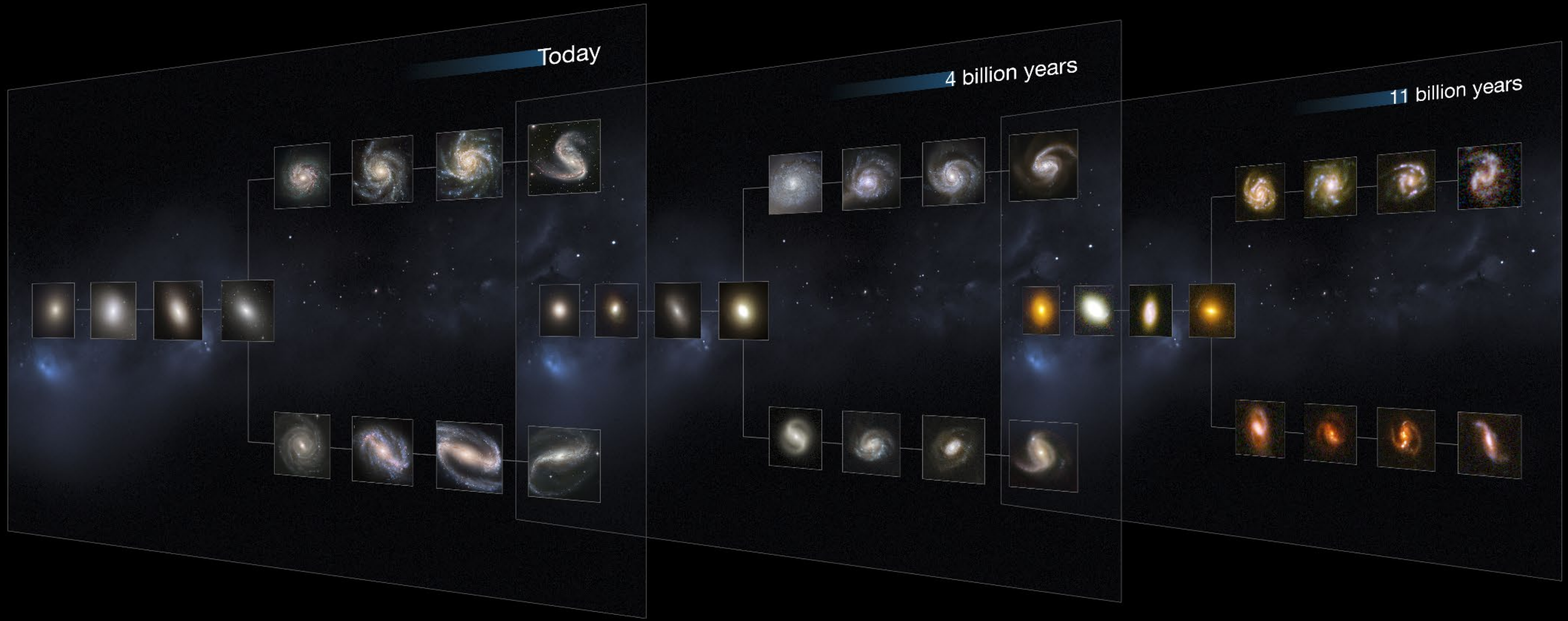
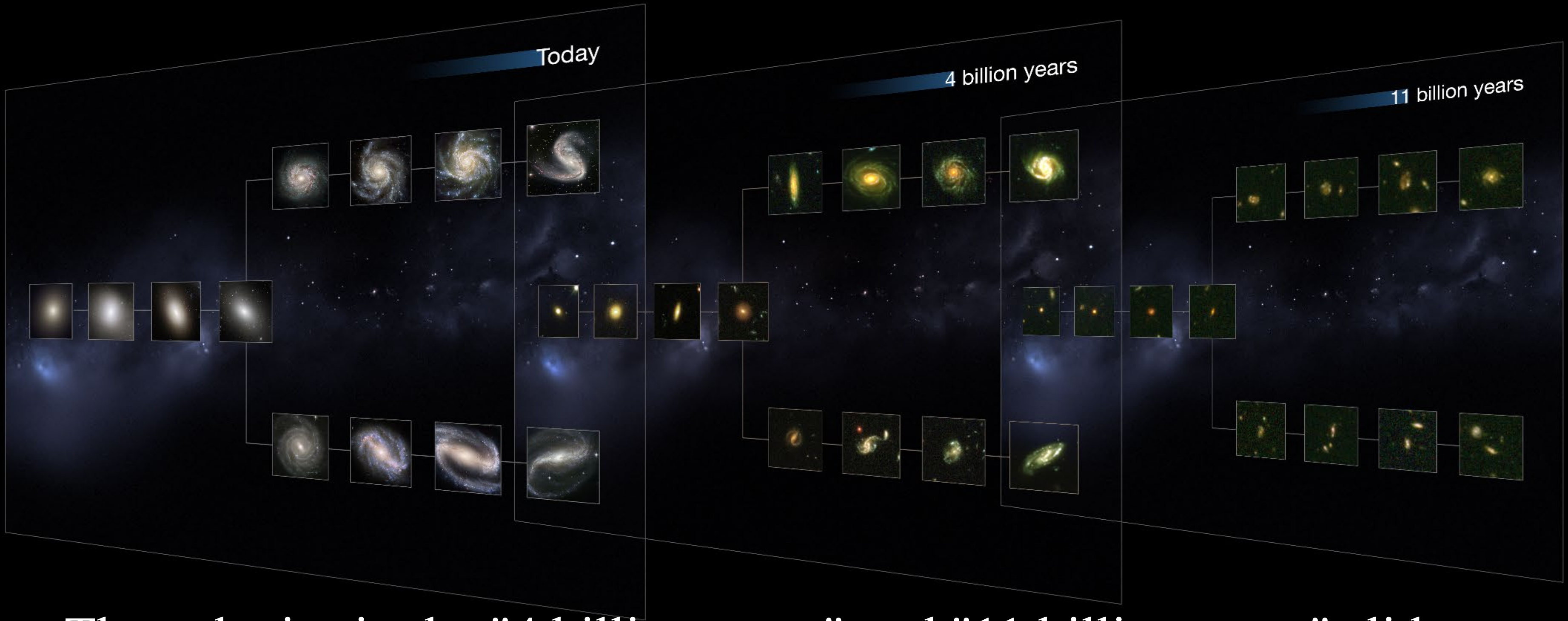
Spirals
SBa
SBb
SBc



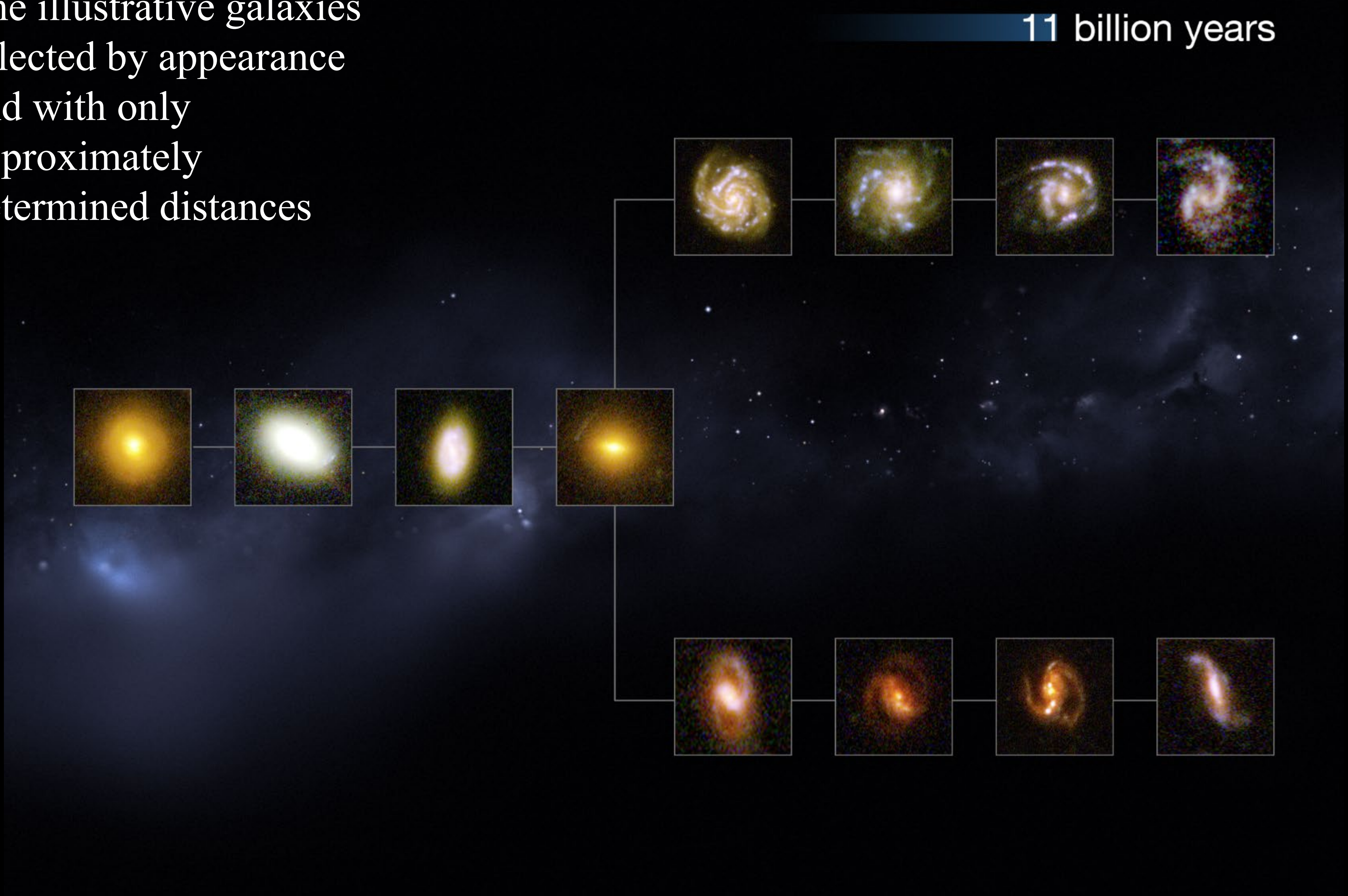
Real shapes of extremely distant galaxies as seen in near infrared light, and therefore seen as they would appear in visible light were they located much closer to us. When seen in infrared light, it is clear that the full range of galaxy morphological types was already in place as long as 11 billion years ago. However, these larger, more “mature” galaxies were rarer this long ago.

This image is illustrative. the Hubble images of nearby and distant galaxies used were selected based on their appearance; their individual distances are only approximate

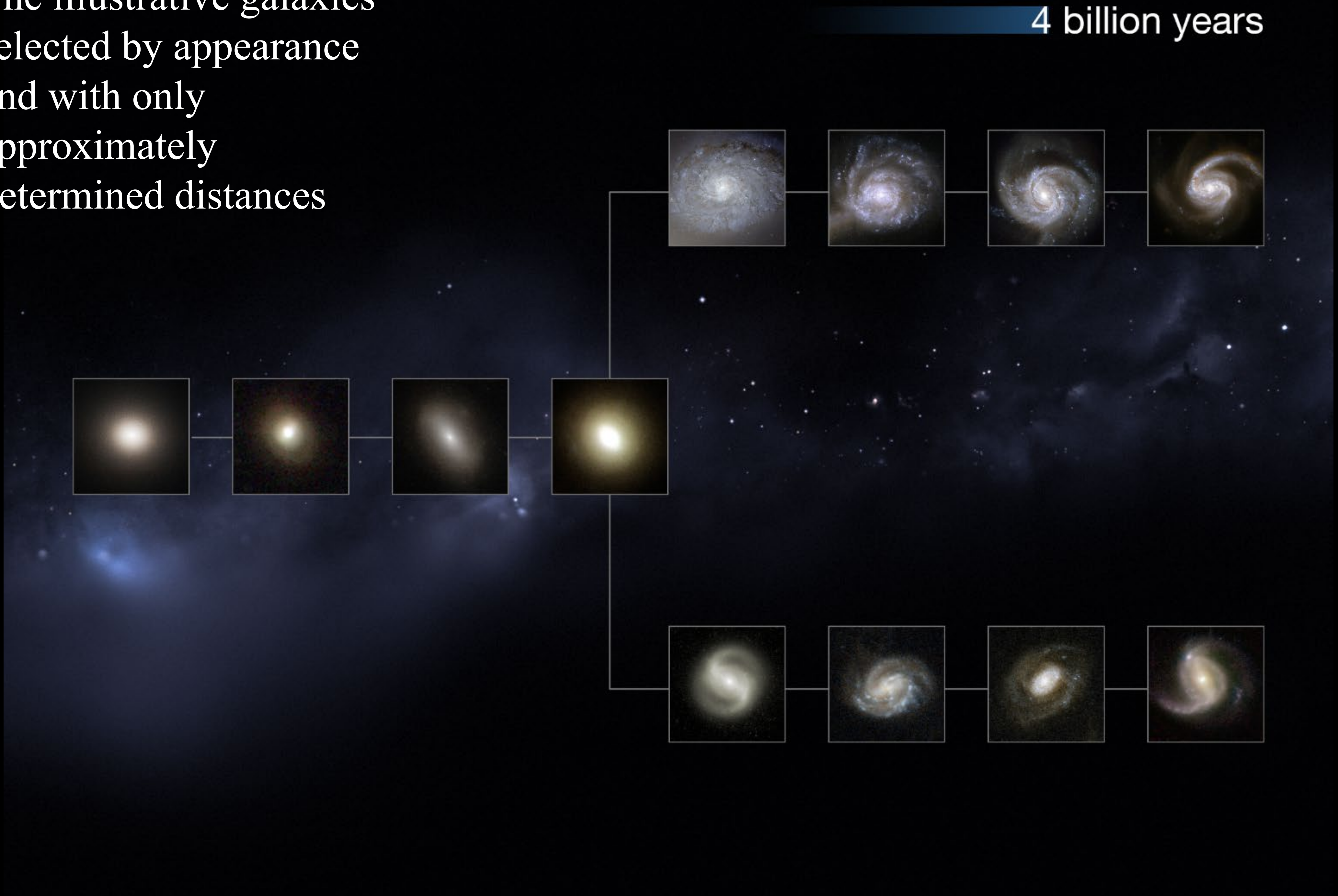


The galaxies in the "4 billion years" and "11 billion years" slides are all taken from CANDELS data. The present-day Universe shows big, fully formed and intricate galaxy shapes. As we go further back in time, they become smaller and less mature, as these galaxies are still in the process of forming. As far back as 11 billion years, it becomes difficult to distinguish between the different types visually, but this new study has found the sequence to be in place at these times.

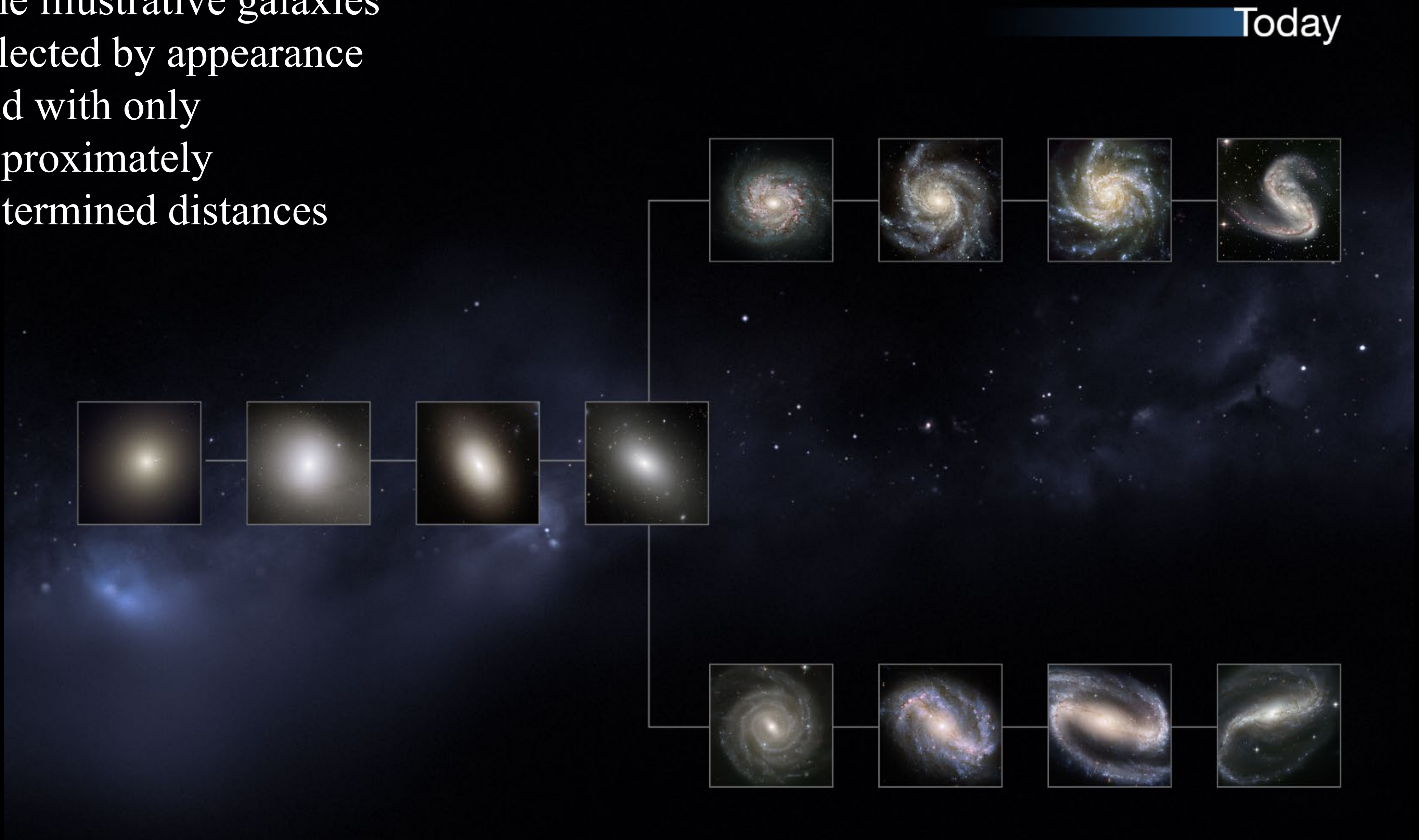
The illustrative galaxies selected by appearance and with only approximately determined distances



The illustrative galaxies selected by appearance and with only approximately determined distances



The illustrative galaxies selected by appearance and with only approximately determined distances



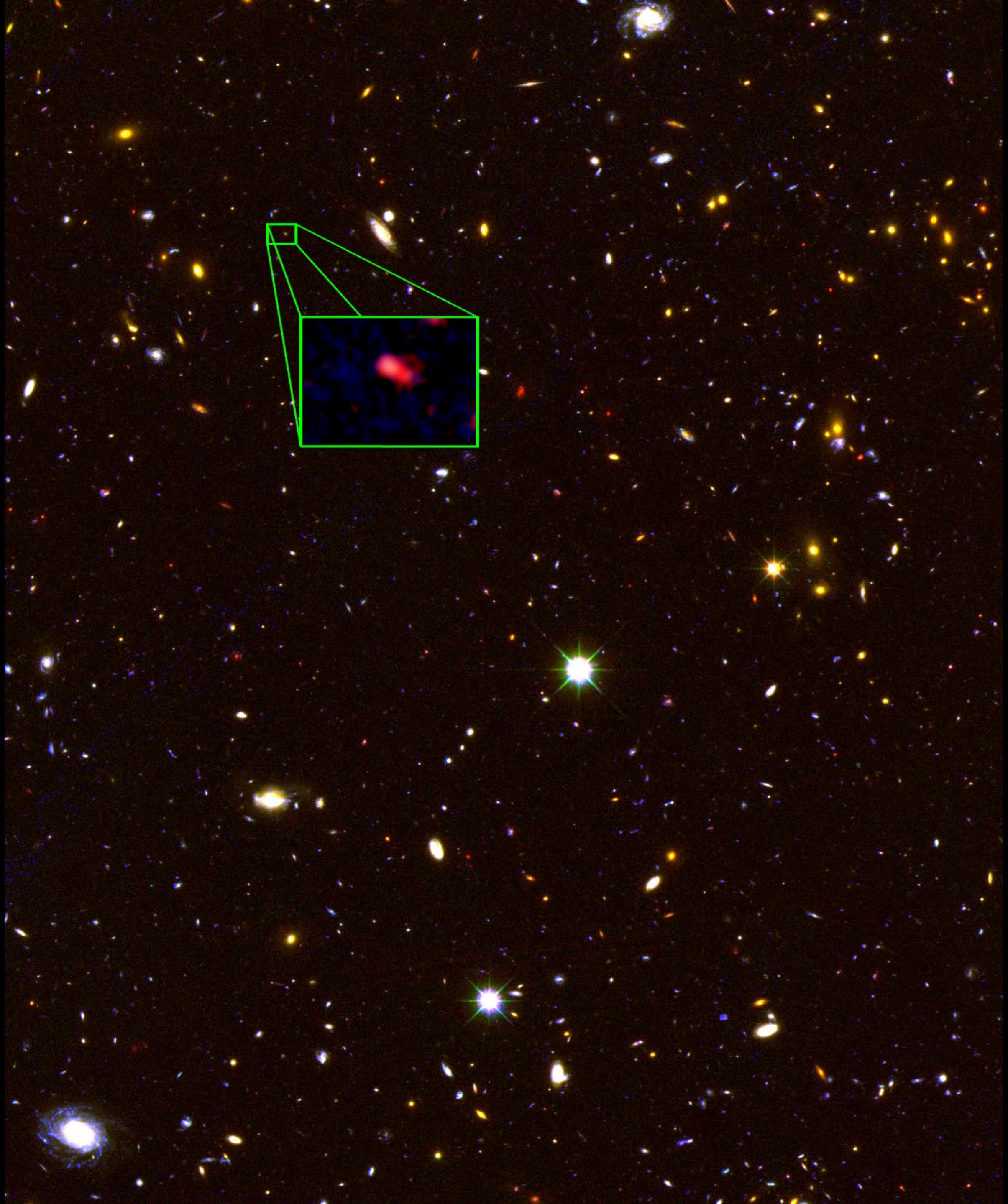
OCTOBER 23, 2013: A team of astronomers has discovered a galaxy that sets the current distance record for galaxies whose distance has been definitively measured by spectroscopic redshift. The galaxy is seen as it was at a time just 700 million years after the Big Bang, when the universe was only about 5 percent of its current age of 13.8 billion years. This galaxy and dozens of others were selected for follow-up observations from the approximately 100,000 galaxies discovered in the Hubble Space Telescope CANDELS survey (Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey). The team used the Keck I Telescope in Hawaii to measure the redshift of the CANDELS galaxy, designated z8_GND_5296, at 7.51. This is the highest galaxy redshift ever confirmed. The spectral redshift of galaxies is caused by the expansion of space from the Big Bang.

Galaxy with largest distance determined from its redshift.

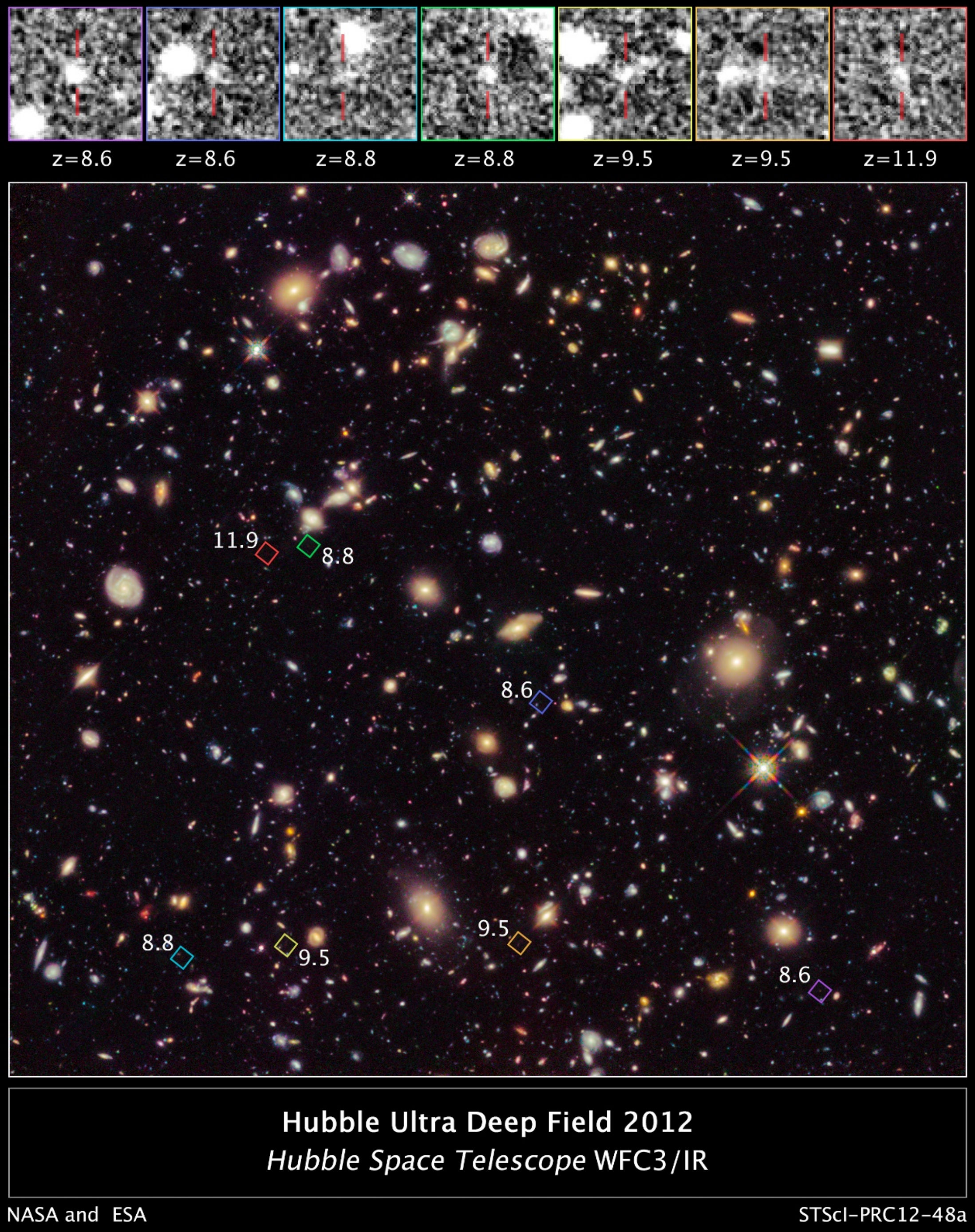
This galaxy is seen at about 700 million years after the big bang (thus about 13 billion light years away).

It was found in the Hubble CANDELS/ GOODS-N survey field.

(Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey)



•**DECEMBER 12, 2012:** Using NASA's Hubble Space Telescope, astronomers have uncovered a previously unseen population of seven primitive galaxies that formed more than 13 billion years ago, when the universe was less than 3 percent of its present age. The deepest images to date from Hubble yield the first statistically robust sample of galaxies that tells how abundant they were close to the era when galaxies first formed. The results show a smooth decline in the number of galaxies with increasing look-back time to about 450 million years after the big bang. The observations support the idea that galaxies assembled continuously over time and also may have provided enough radiation to reheat, or reionize, the universe a few hundred million years after the big bang. These pioneering observations blaze a trail for future exploration of this epoch by NASA's next-generation spacecraft, the James Webb Space Telescope. Looking deeper into the universe also means peering farther back in time. The universe is now 13.7 billion years old. The newly discovered galaxies are seen as they looked 350 million to 600 million years after the big bang. Their light is just arriving at Earth now.



Seven extremely distant galaxies, located in the Hubble Ultra Deep Field