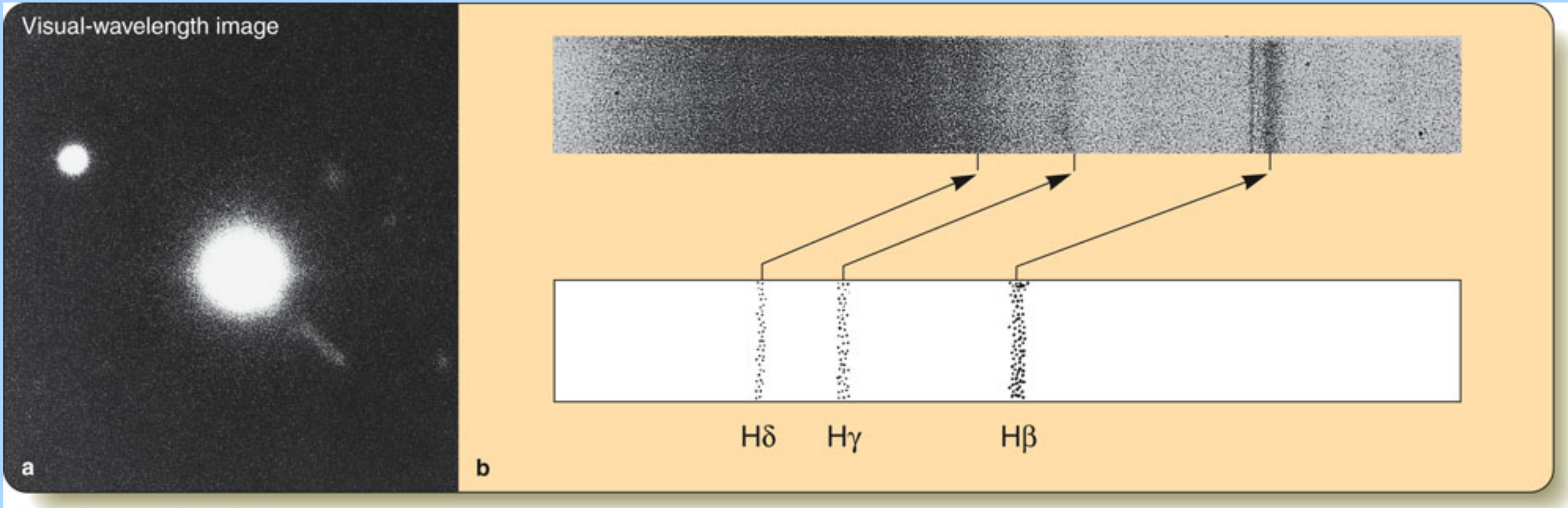
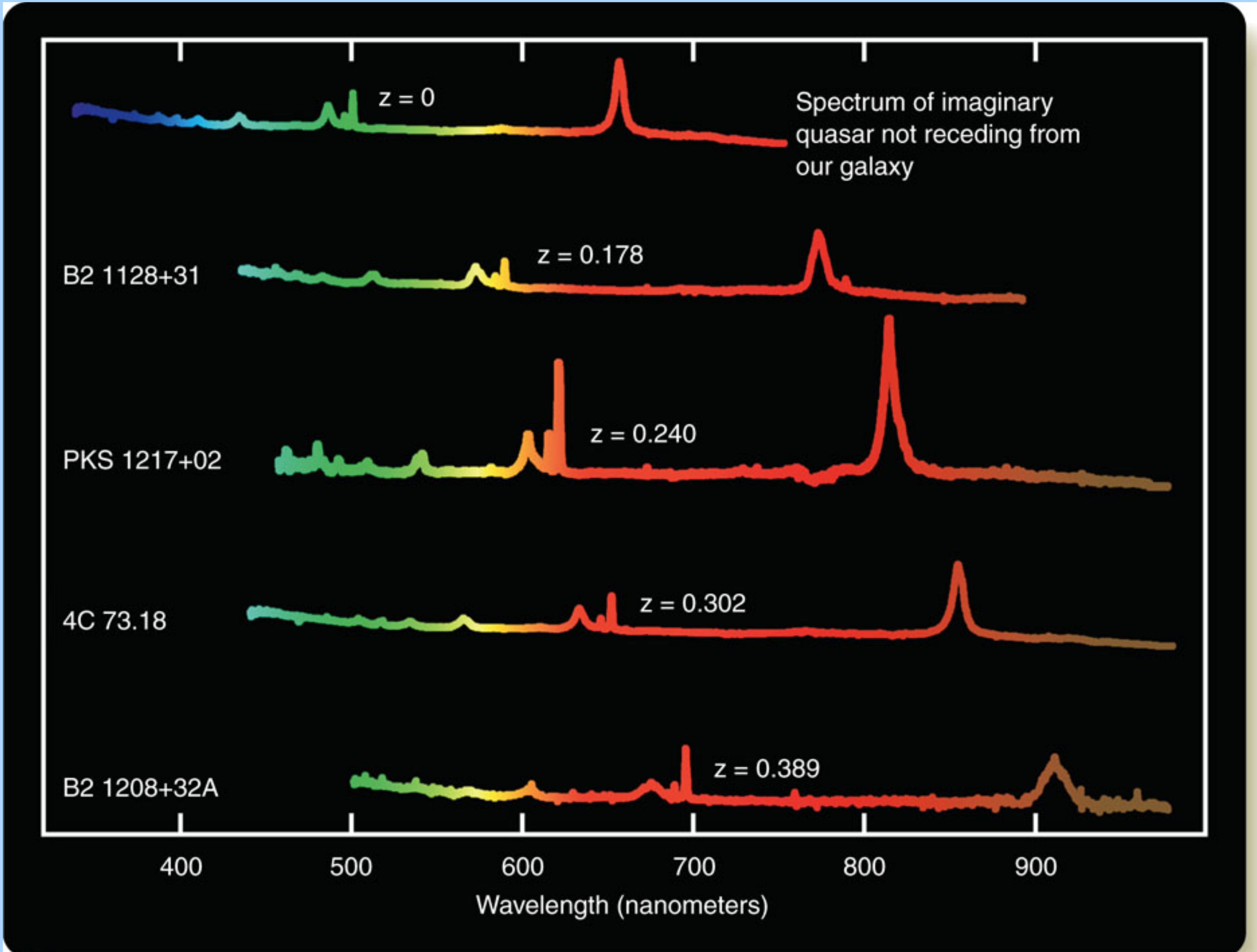
Quasars and Gravitational Lensing

Our galaxy is not the only one that gives strong evidence for the existence of a supermassive black hole at its center. Some other galaxies might have black holes with masses of more than one *billion* solar masses. When material falls into such a black hole, before it disappears it gets heated and we see flares in the light of the galaxy. These are **active galactic nuclei (AGNs)**. Similarly, **quasars** are flaring galactic nuclei that are primarily observed with look-back times of several billion years or more. Redshift 2 to 3 is very common for quasars. If the galaxies run out of gas to consume, the active nuclei turn off.

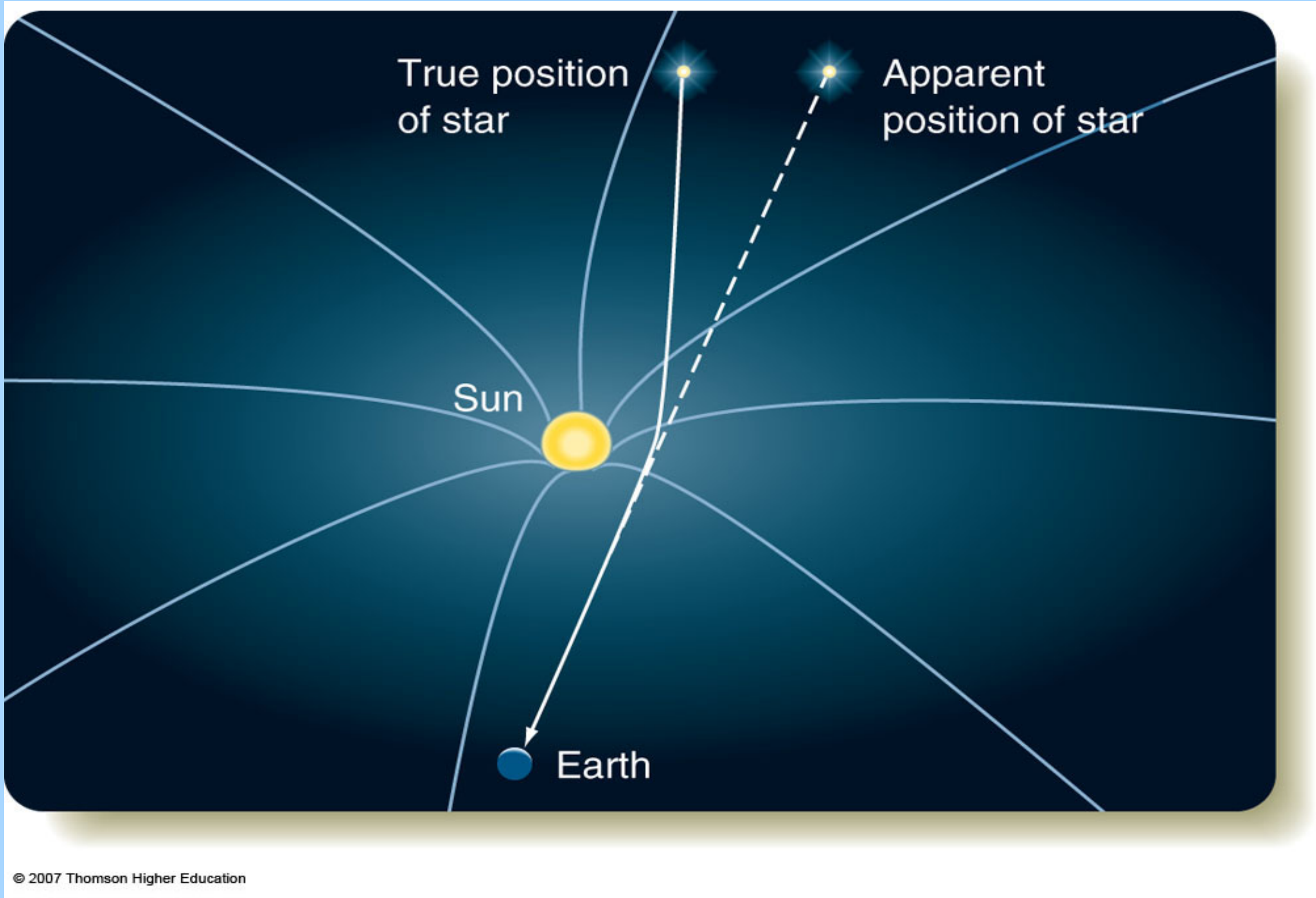


The spectral lines of quasar 3C 273 are shifted 0.158 in wavelength towards longer wavelengths. This is one of the nearest and brightest quasars (as far as apparent brightness goes).

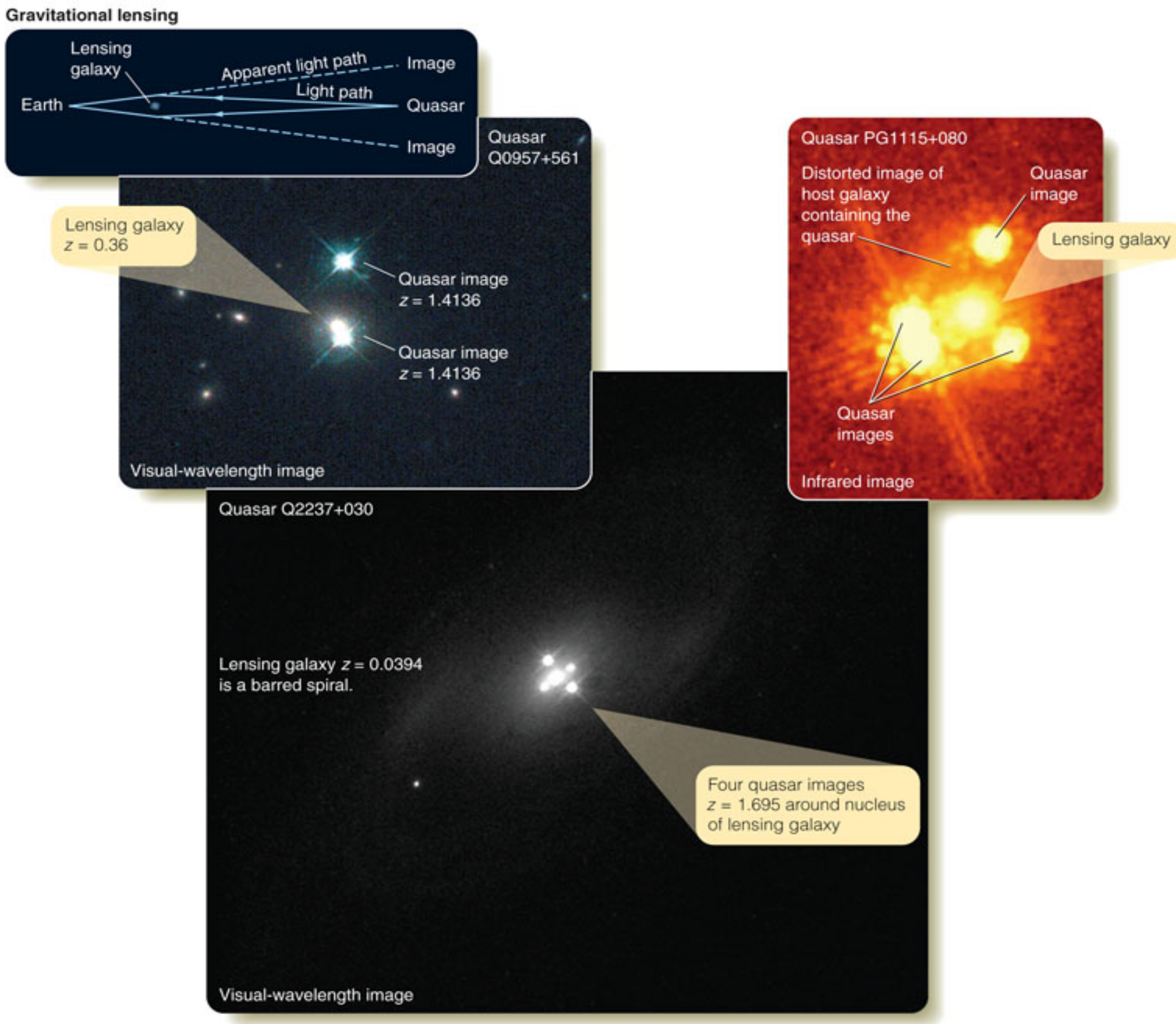

z = 0
Spectrum of imaginary quasar not receding from our galaxy
B2 1128+31
z = 0.178
PKS 1217+02
z = 0.240
4C 73.18
z = 0.302
B2 1208+32A
z = 0.389
400
500
600
700
800
900
Wavelength (nanometers)

Because of their great distances, spectra of quasars can be used to study the composition of intergalactic gas along the line of sight.

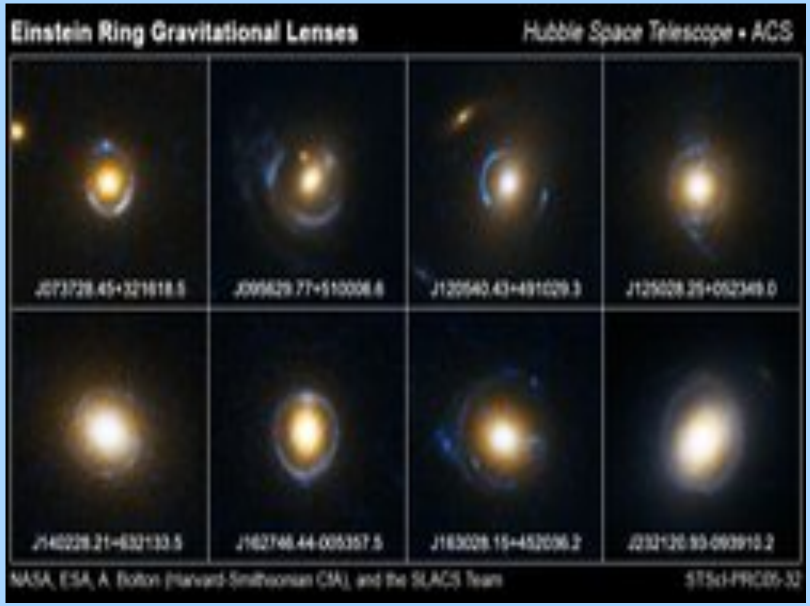
Just as the spectrum of the hot star δ Ori shows lines of interstellar calcium, many absorption lines in quasars are due to gas along the line of sight. We see clouds of hydrogen and deuterium at a whole range of redshifts up to the redshift of the quasar itself. (This is further evidence that the redshifts of quasars are indeed due to their being at great distances.)



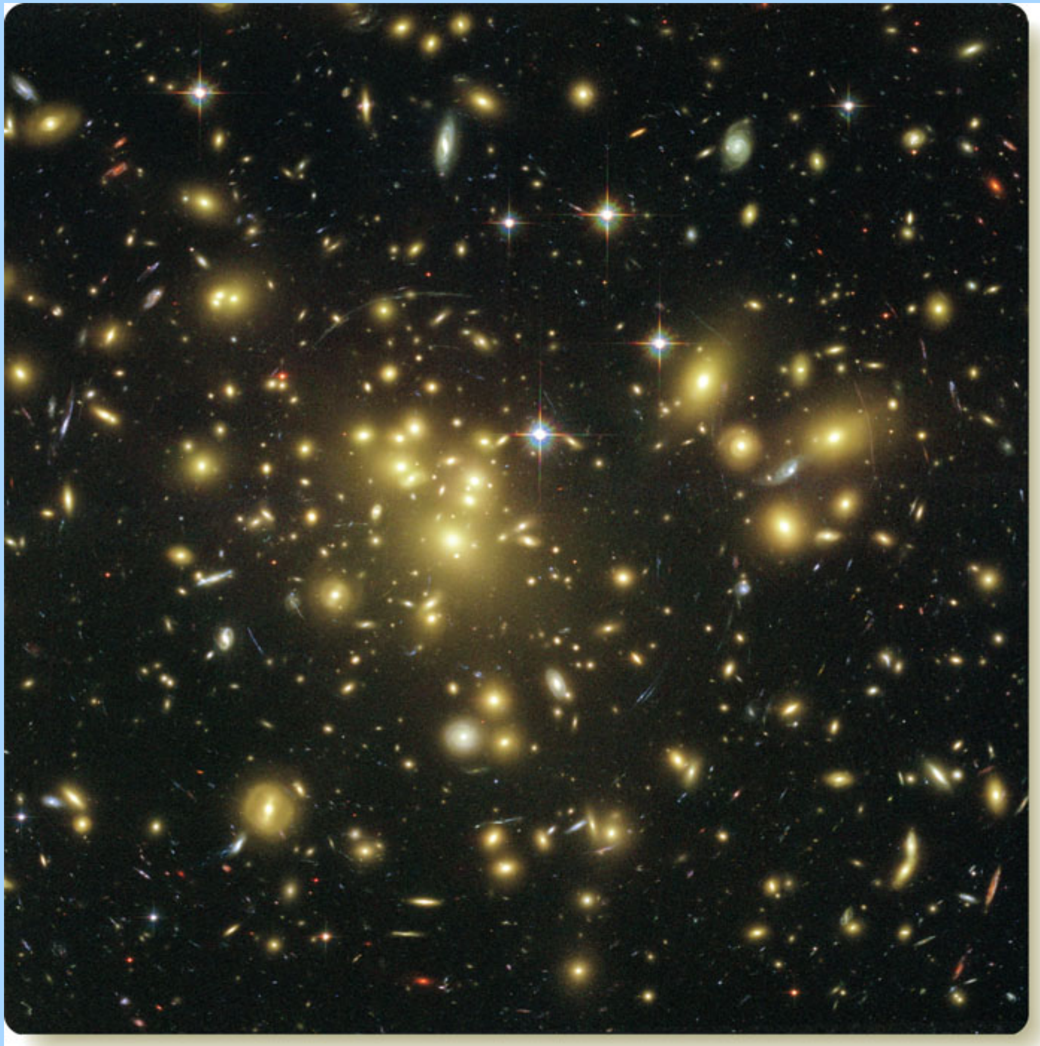
You will recall that during a total solar eclipse light rays from distant stars are slightly bent as they pass by the Sun.



We know of about 10 examples of distant quasars being lensed by intervening galaxies. One sees multiple images of the quasar. The foreground galaxy doing the lensing is usually fainter.



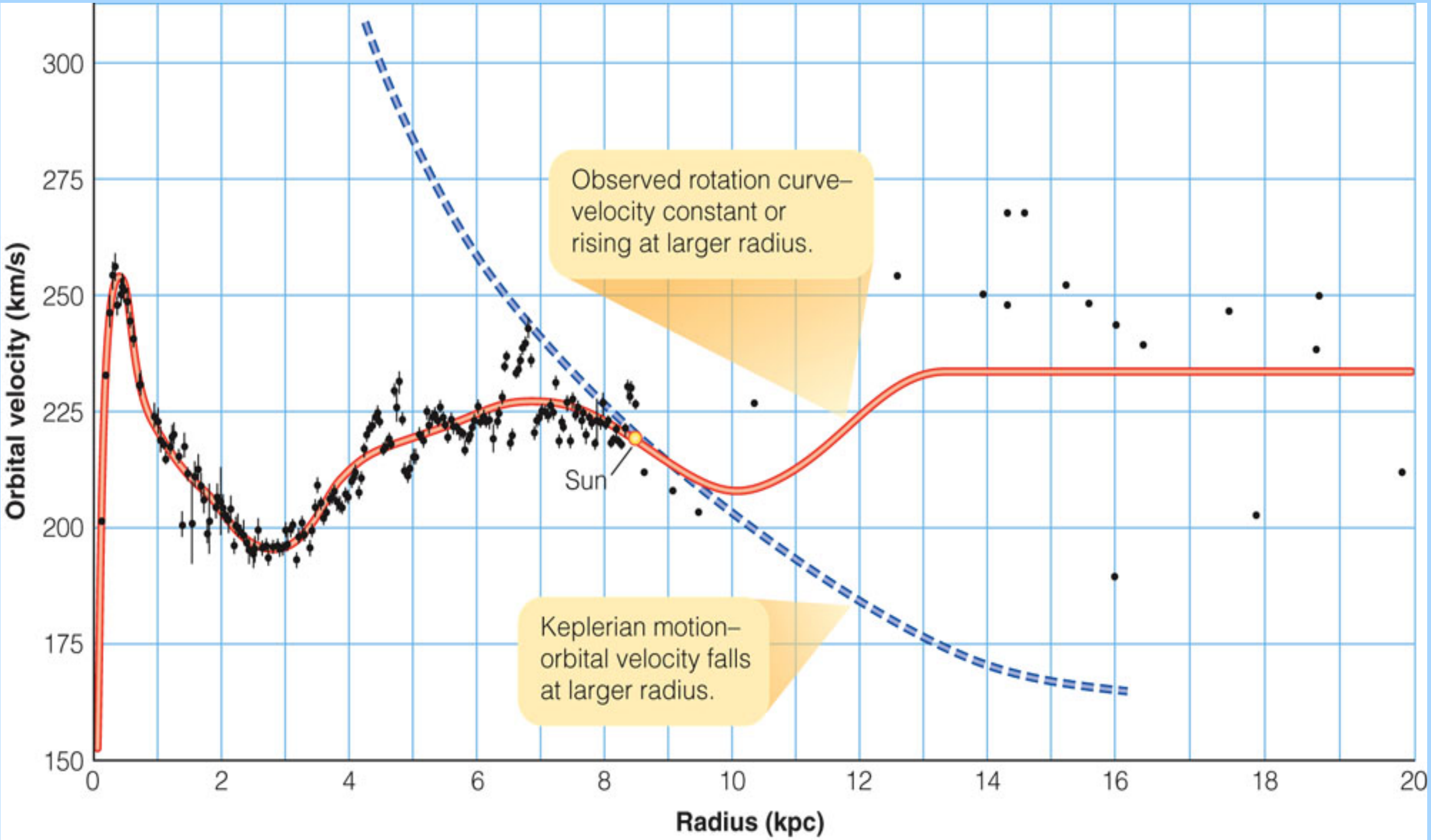
If the foreground galaxy is in a direct line to a more distant object, then one can observe an *Einstein ring*. Thus, a foreground galaxy can be a **gravitational lens**.



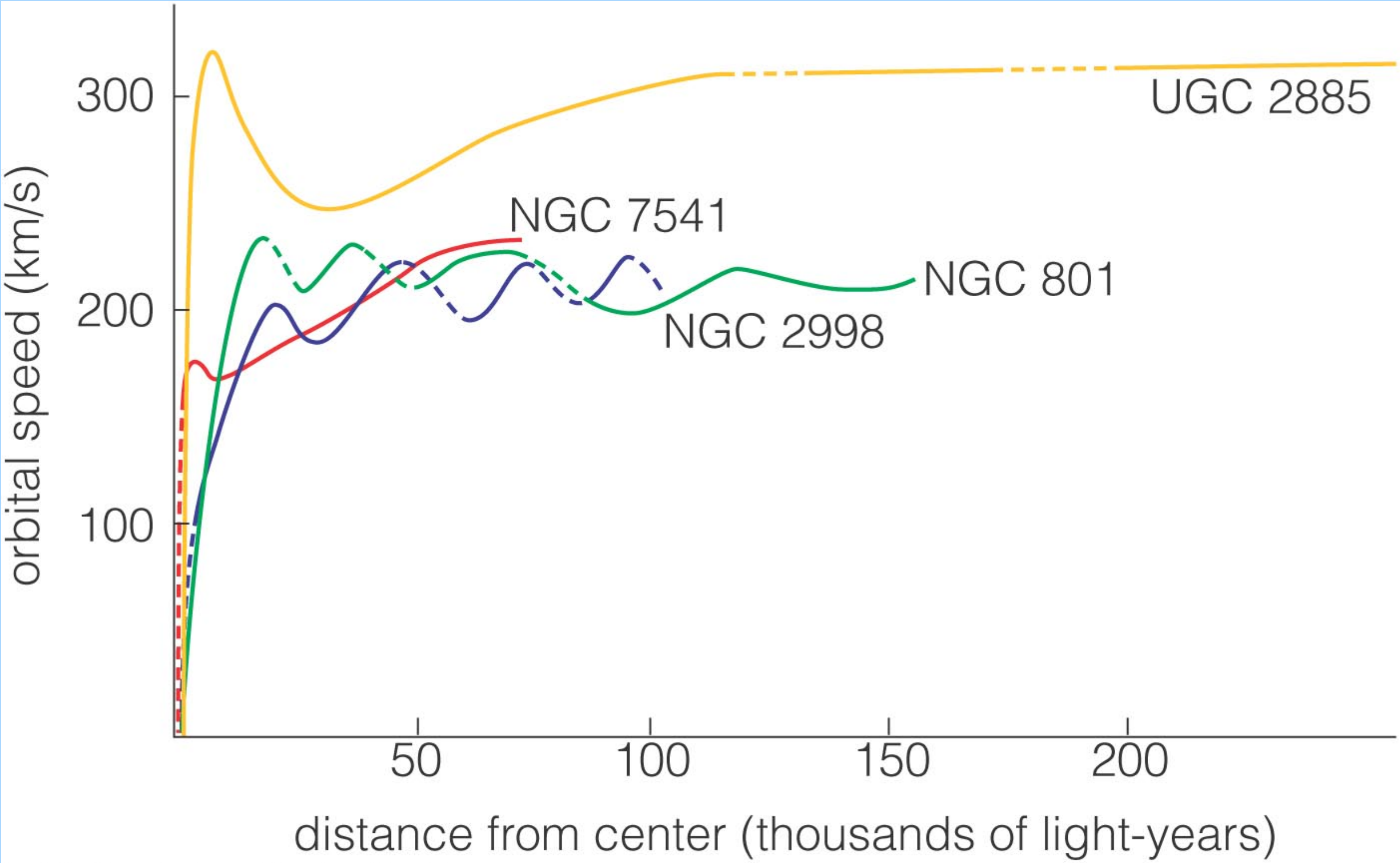
Galaxy clusters can lens the light of more distant galaxies, producing arcs of light. Analysis shows that clusters of galaxies contain much more mass than is attributable to luminous galaxies. This is strong evidence that the majority of mass of a cluster of galaxies is **Dark Matter**.

There was already evidence that our own Galaxy contained Dark Matter. This is deduced from the *rotation curve* of the Galaxy. If most of the mass were concentrated in the center, then the speeds of the stars orbiting the center of the galaxy should decrease with distance, like the planets in our solar system. In our Galaxy and others, the rotation curves flatten out, implying that each galaxy is embedded in a halo of material.

Regular matter (consisting of protons and electrons) interacts with light, but Dark Matter does not.



Rotation curve of our Galaxy.



Rotation curves of four galaxies.

Possibilities for the Dark Matter

neutrinos – both left over from the Big Bang and created since then. Since they move very fast, they are referred to as Hot Dark Matter.

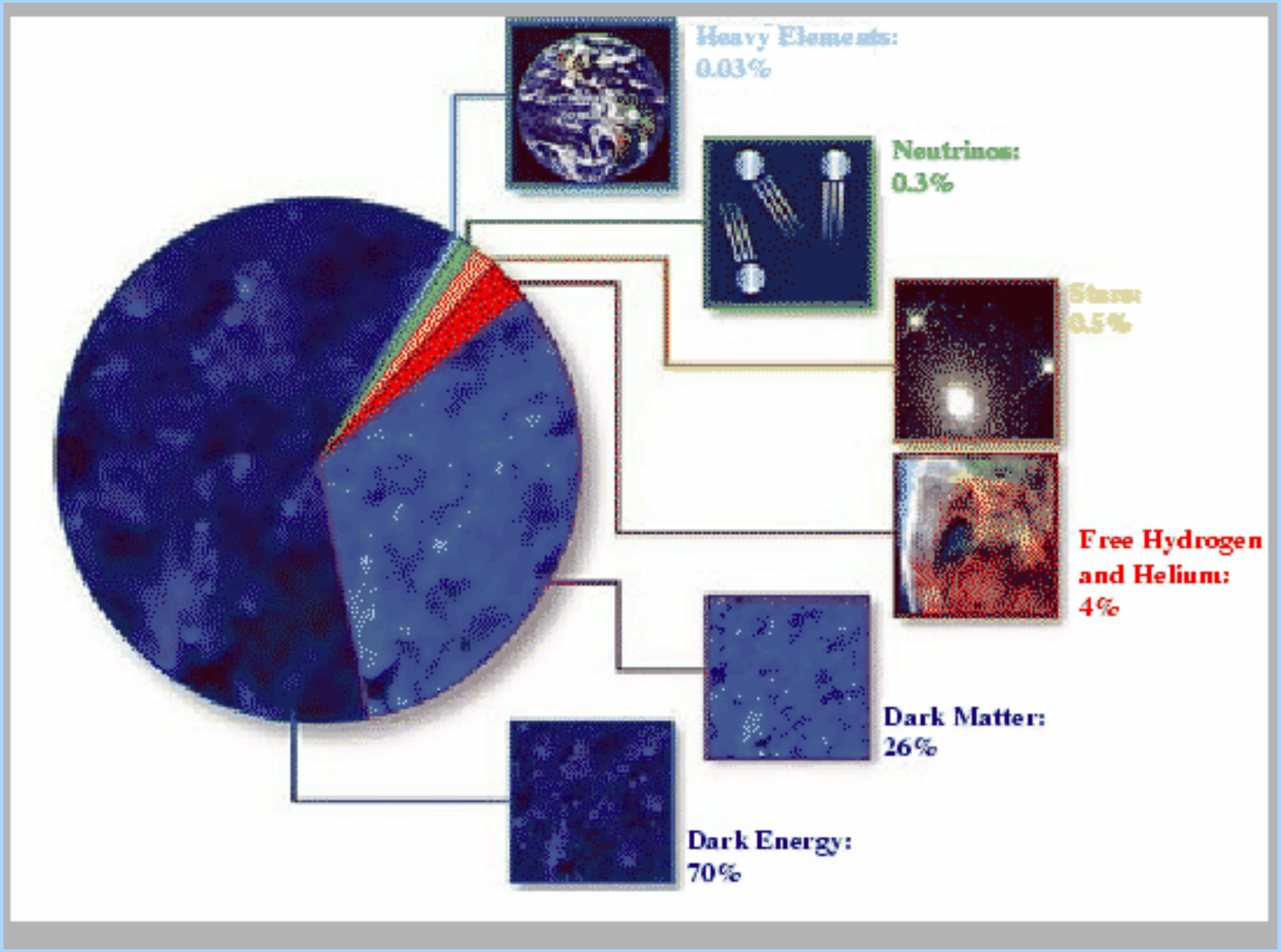
Weakly Interacting Massive Particles (WIMPs) – interact via the weak nuclear force

The Standard Model of particle physics predicts that there are certain "supersymmetric partners" of particles that we know. The lightest **neutralino** is a good candidate for Cold Dark Matter. A very light particle called the **axion** is also a possibility.

Cosmology

“Everything seems to indicate that the material content of the universe had a mighty beginning in time, being endowed at birth with vast reserves of energy, in virtue of which, at first rapidly, and then ever more slowly, it evolved into its present state.”

-- Pope Pius XII, 22 November 1951, in an address delivered to Pontifical Acad. of Sciences



The energy budget of the universe

Milestones in cosmology

1916/17 – Einstein's General Theory of Relativity implies that the universe should not be static. It should either be expanding or contracting. He postulated the existence of a cosmological constant to *make* it static.

1929 – Hubble discovers the expansion of the universe

1948-early 50's – George Gamow, Ralph Alpher, and Robert Herman work out the Big Bang theory

Features and Predictions of the Big Bang theory

1) Explains why the universe is expanding.

2) Original fireball should be detectable as a continuous spectrum corresponding to a black body with a temperature of a few degrees Kelvin. Build short wavelength radio telescope to check this.

3) Universe was hotter in the past. Check temperature of intergalactic space at high redshift.

4) Because of the extremely hot temperatures of the BB, some, deuterium, helium and lithium should have been produced in the first 3 minutes. Check D, He and Li abundances in the oldest stars in our Galaxy.

5) The expansion rate and mass density of the universe allows us to determine the age of the universe. The oldest stars in globular star clusters or in the central bulge of our Galaxy should be younger than the implied age of the universe.

The expansion of the universe implies that:

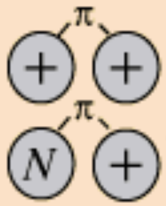
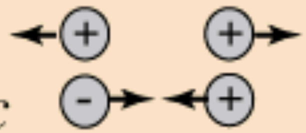
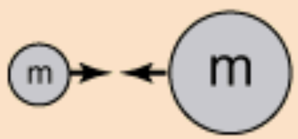
1) it is getting bigger with time

2) it was smaller in the past

3) long, long ago, it was very, very tiny

If we can reckon the expansion backwards in time to a moment when the whole universe fit in something smaller than an atom, then way back then it was hot enough to sustain nuclear fusion reactions.

Fundamental Forces

Force		Strength	Range (m)	Particle
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	 neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

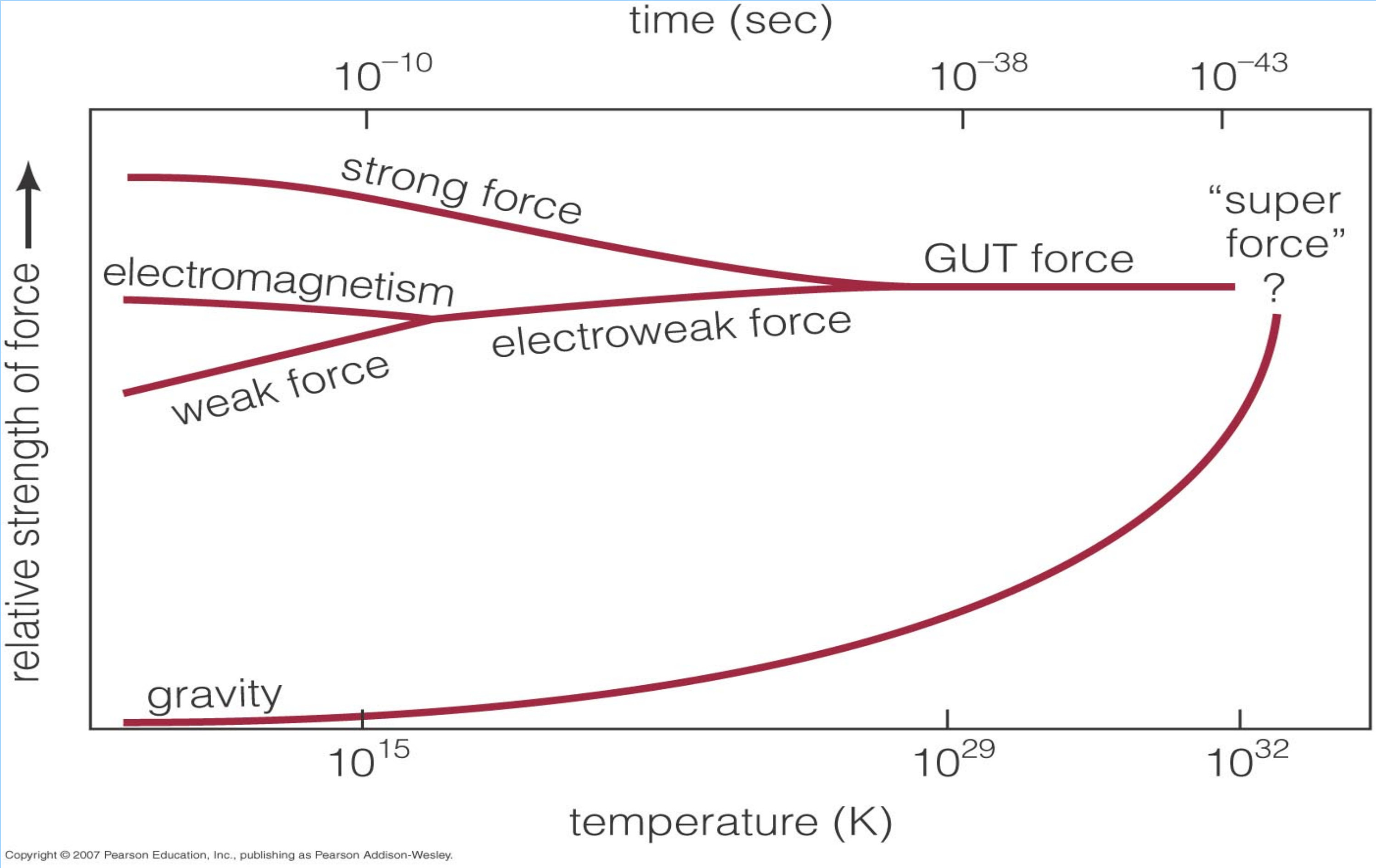
HyperPhysics***** Quantum Physics *R Nave*

You might be asking yourself, at what separation distance do we calculate the electromagnetic force to assert that it is 1/137 as strong as the strong nuclear force? That distance is called the "Compton wavelength".

The rest mass energy of a particle is $E = mc^2$. If we equate this to the energy of a photon $E = h\,\nu = h\,c\,/\,\lambda$, then

$$mc^2 = h\,c\,/\,\lambda$$

and the Compton wavelength $\lambda = h\,/\,mc$. For the proton the Compton wavelength is about 1.3 times 10^{-15} meters, which is only slightly larger than the size of the proton.



Shortly after the Big Bang the four forces in the universe became distinct. Prior to that they were "unified".

We can write down an expression for the temperature of the universe (T) as a function of the time (t) since the Big Bang. It can be shown that

$$T = (3\ c^2 / 32\ \pi\ G\ a_B\ )^{1/4}\ t^{-1/2} \quad ,$$

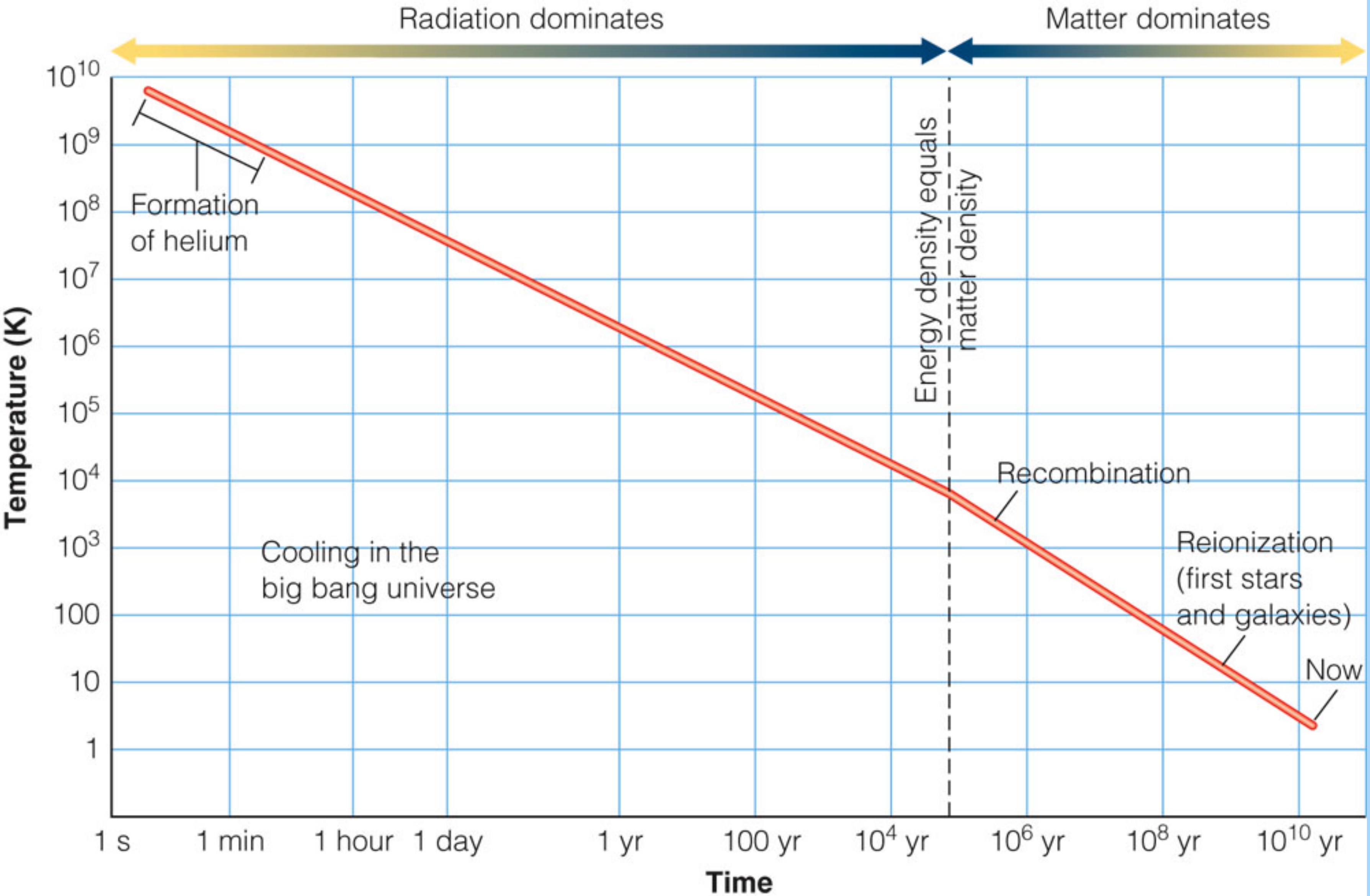
where a_B is the "radiation constant". In numerical terms

$$T \sim 1.519 \text{ X } 10^{10} / \text{sqrt}\ (t)$$

So, at one second after the Big Bang, the temperature of the universe was 15 billion degrees.

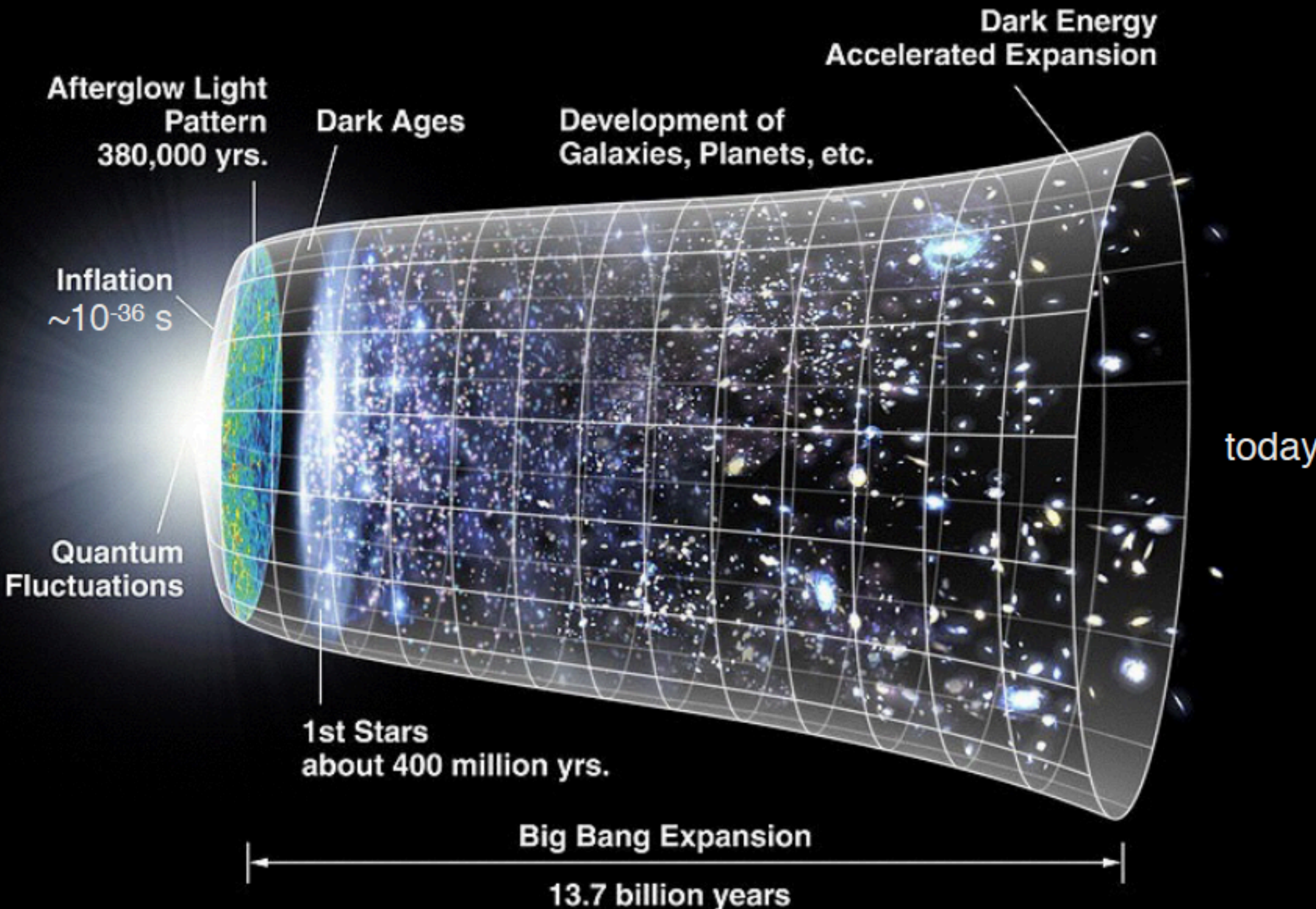
In the graph that follows, the dependence of temperature vs. time for the “radiation dominated universe” comes from the formula we just gave.

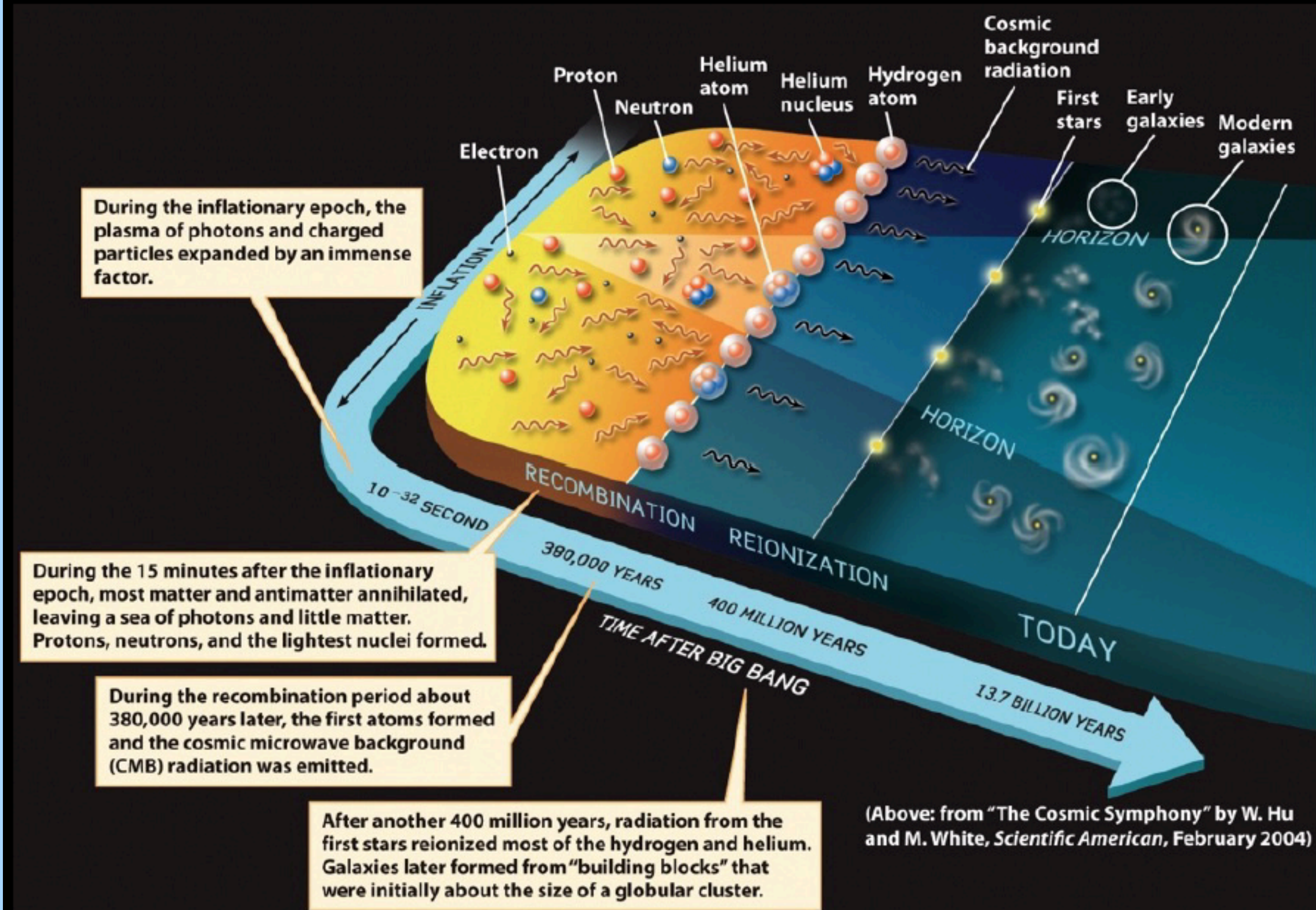
Note that the universe was hot enough to create some light elements in the first few minutes.



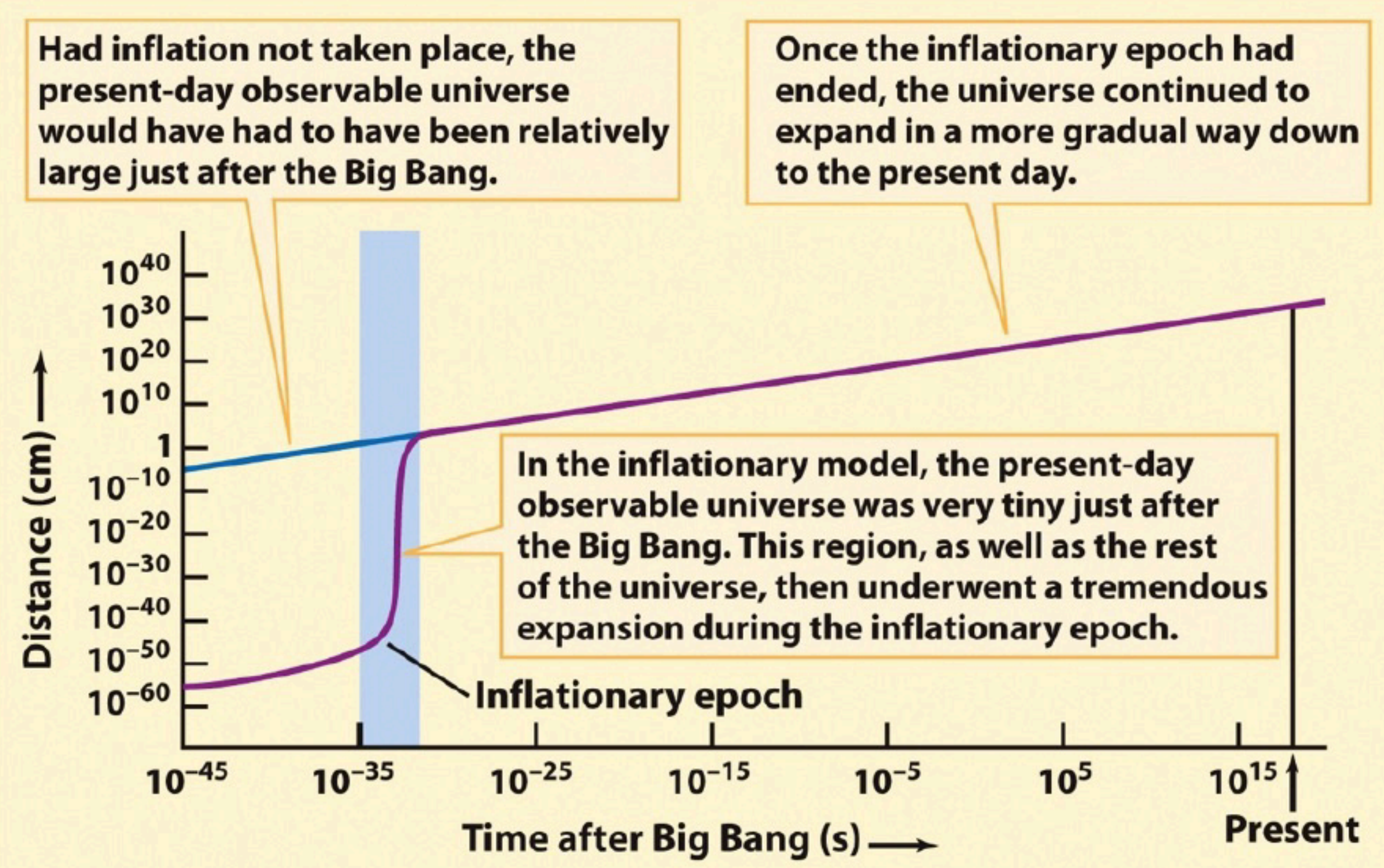
Radiation dominates
Matter dominates
Temperature (K)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
100
10
1
Formation of helium
Cooling in the big bang universe
Energy density equals matter density
Recombination
Reionization (first stars and galaxies)
Now
1 s
1 min
1 hour
1 day
1 yr
100 yr
10^4 yr
10^6 yr
10^8 yr
10^{10} yr
Time

Brief History of the Universe



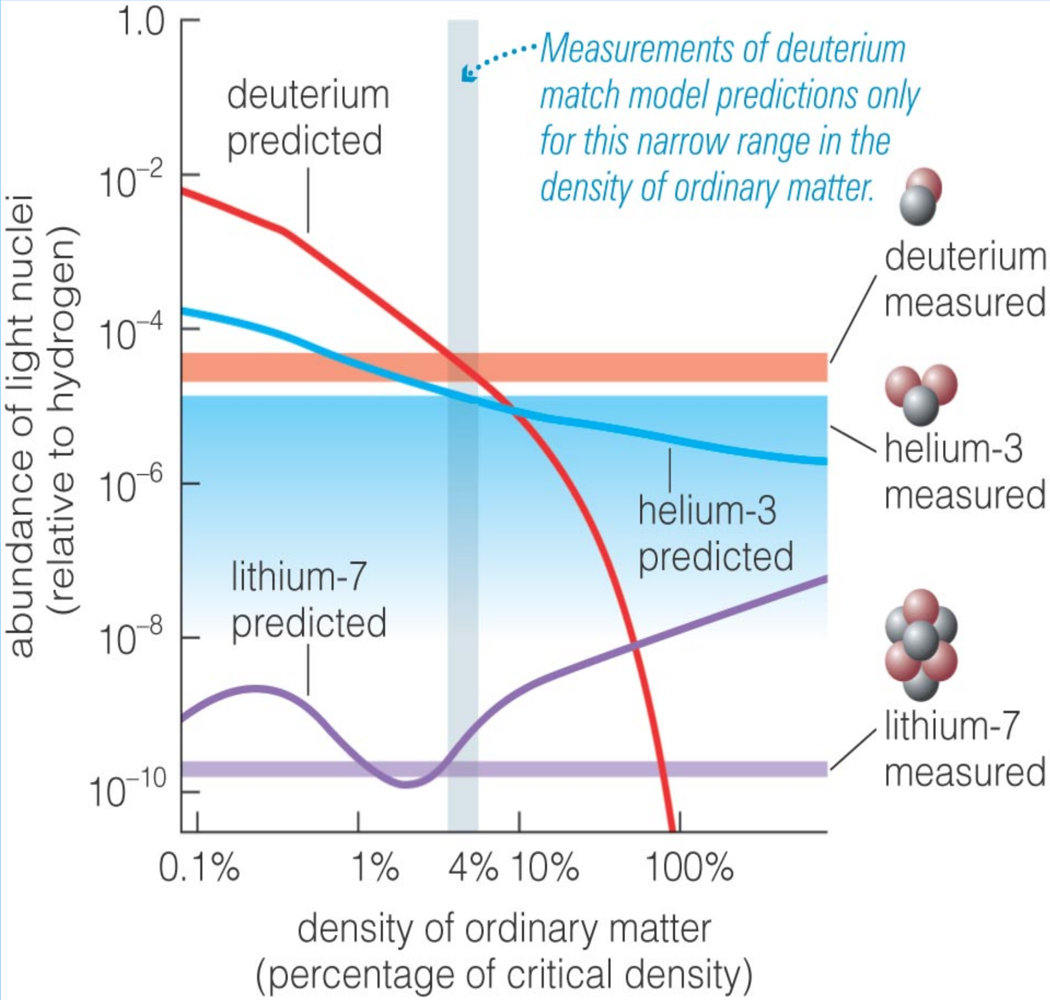


(Above: from "The Cosmic Symphony" by W. Hu and M. White, *Scientific American*, February 2004)



Had inflation not taken place, the present-day observable universe would have had to have been relatively large just after the Big Bang.
Once the inflationary epoch had ended, the universe continued to expand in a more gradual way down to the present day.
In the inflationary model, the present-day observable universe was very tiny just after the Big Bang. This region, as well as the rest of the universe, then underwent a tremendous expansion during the inflationary epoch.
Inflationary epoch
Distance (cm)
10^{40}
10^{30}
10^{20}
10^{10}
1
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
Time after Big Bang (s)
Present

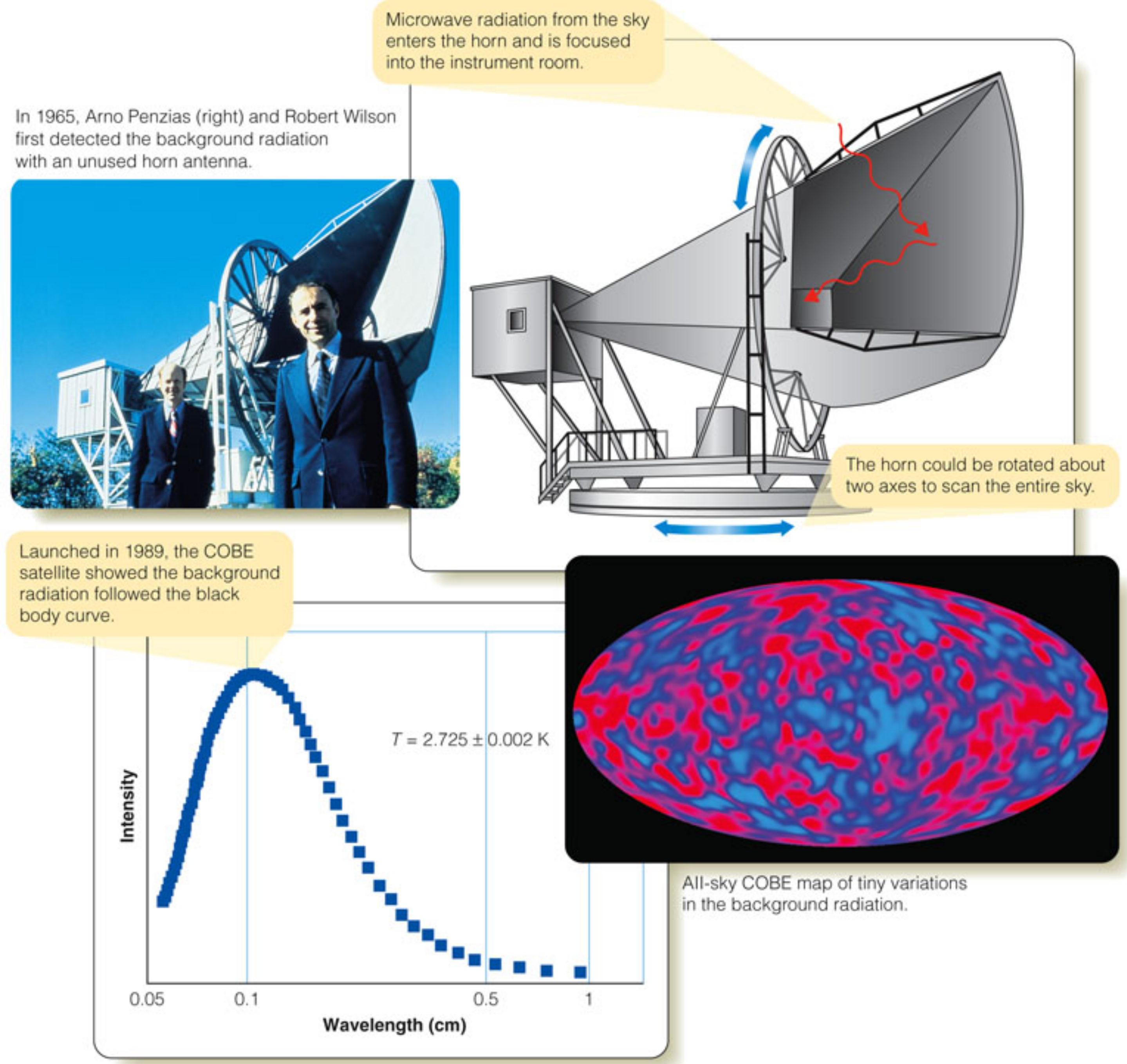
With all those high energy gamma rays running around in the moments after the Big Bang, many were energetic enough to create **matter-antimatter pairs**, such as protons and anti-protons. In most cases each particle of matter soon met its antimatter analog and they annihilated. But about one time out of a billion or more occurrences, the matter particle was not destroyed. This is why we have a universe full of matter and not equal amounts of matter and antimatter. (Seems kind of dodgy, doesn't it?) It has to do with something particle physicists call CP violation. C stands for "charge conjugation" and P stands for "parity". Look it up on the *Wikipedia*.....but it's beyond the scope of this course.



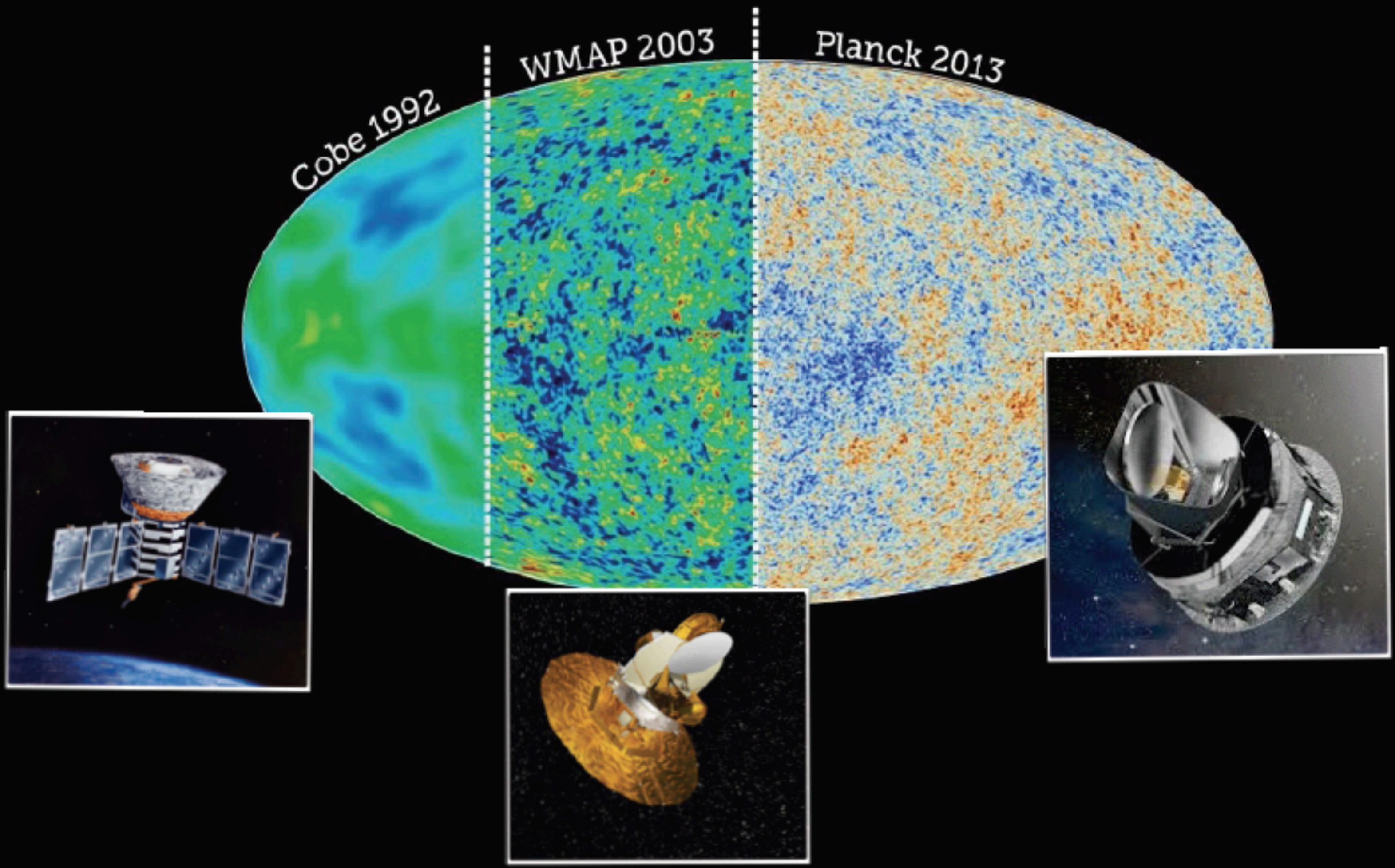
In the first 3 minutes after the Big Bang the universe created some H, deuterium, He, and a bit of Li. If we can measure the abun-dances of these elements in *very* old stars, we can check this prediction from Big Bang theory.

The abundances of light elements imply that the mean density of matter is small compared to the critical density.

Another prediction from the Big Bang theory was that the empy vacuum should not have a temperature of absolute zero. The fiery energy of the Big Bang has spread out over time, leaving a remant visible at mm wavelengths. Gamow, Alpher, and Herman originally suggested a temperature of about 5 K.
In 1965 Penzias and Wilson discovered the microwave background radiation. Its temperature is 2.73 deg K.


Microwave radiation from the sky enters the horn and is focused into the instrument room.
In 1965, Arno Penzias (right) and Robert Wilson first detected the background radiation with an unused horn antenna.
The horn could be rotated about two axes to scan the entire sky.
Launched in 1989, the COBE satellite showed the background radiation followed the black body curve.
T = 2.725 ± 0.002 K
Intensity
0.05
0.1
0.5
1
Wavelength (cm)
All-sky COBE map of tiny variations in the background radiation.

Over time, the measurements of the CMB became more and more precise:



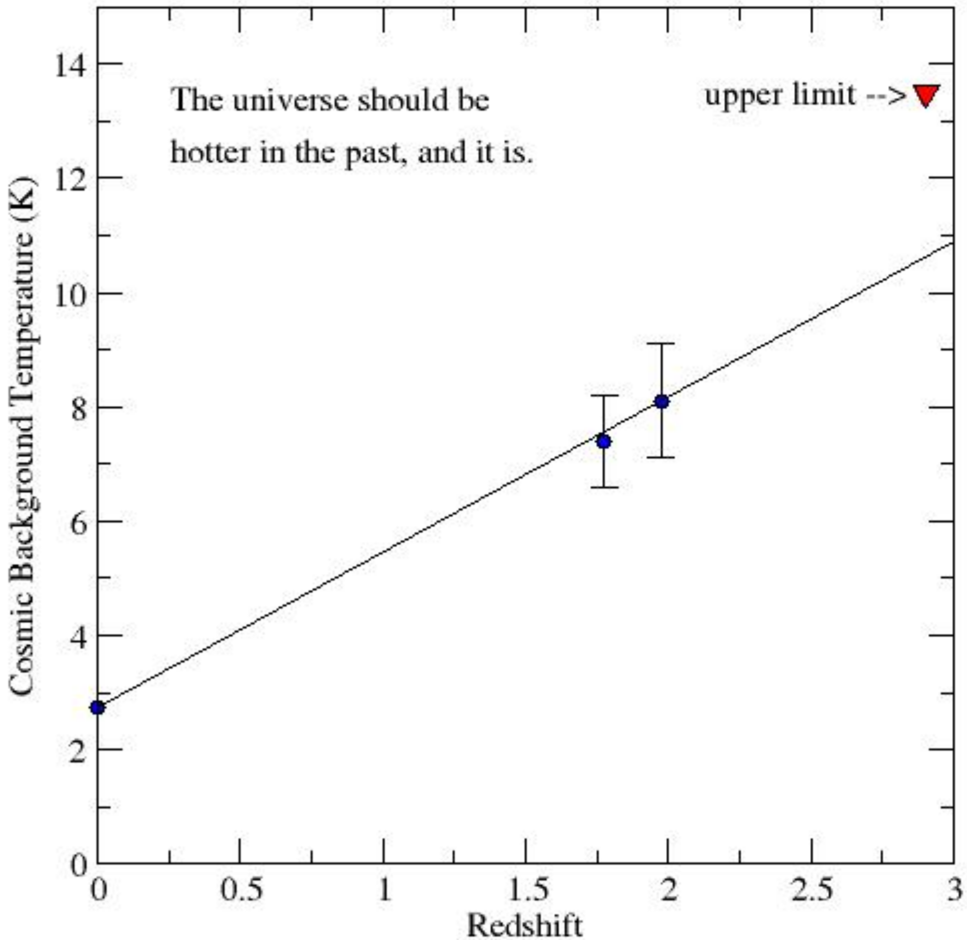
Nearly empty intergalactic space is not totally empty. For example, because of the universal distribution of the photons associated with the cosmic microwave background, every cubic centimeter of "empty" space contains on average 410 CMB photons (Peebles, *Principles of Physical Cosmology,* p.158). When the universe was smaller and warmer, this number was larger. There are also neutrinos leftover from the Big Bang (113 per cubic centimeter; Peacock, *Cosmological Physics*, p. 281, Peebles, p. 163).

Even without these CMB photons, an "empty" vacuum has a repulsive force that is causing the acceleration of the expansion of the universe.

Since the Big Bang theory explains the existence of the CMB as the cooling of a fireball, the CMB should be warmer in the past.

A telescope is a kind of time machine. The further out we look, the further back in time we look.

At high redshifts we can measure certain spectral lines of neutral interstellar carbon and derive the temperature of the CMB.

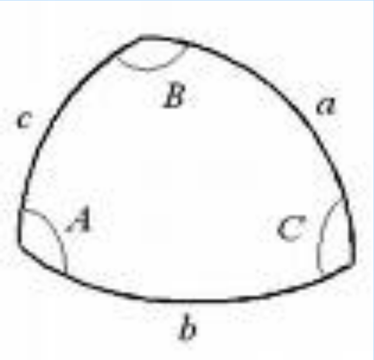


If we measured the universe to be colder than the Big Bang prediction, that would be evidence against the Big Bang theory, but this data *confirms* one of the theory's predictions.

Four dimensional space-time is not necessarily *flat*. What does this mean?

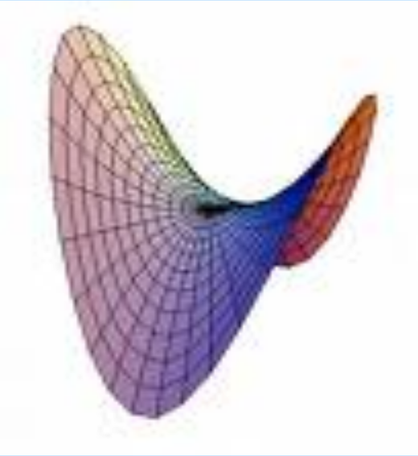
In a flat universe a *very* large triangle would have all the interior angles add up to 180 degrees, just like we learned in high school geometry class.

If the curvature of the universe is positive, then like this triangle drawn on a sphere, the sum of angles A, B, and C would add up to more than 180 degrees.



If the universe has *negative* curvature, then a very large triangle would be such that the sum of interior angles would add up to less than 180 degrees.

On this saddle-shaped surface (a hyperbolic paraboloid) a triangle would have negative curvature.



The galaxies attract each other gravitationally. The gravitational force acts as a braking effect on the expansion of the universe.

It turns out that the expansion will halt and the universe will re-collapse if the density is greater than some critical value:

$$\rho_C = \text{critical density} = 3\, H_0^{\,2} / (8\, \pi\, G) =$$

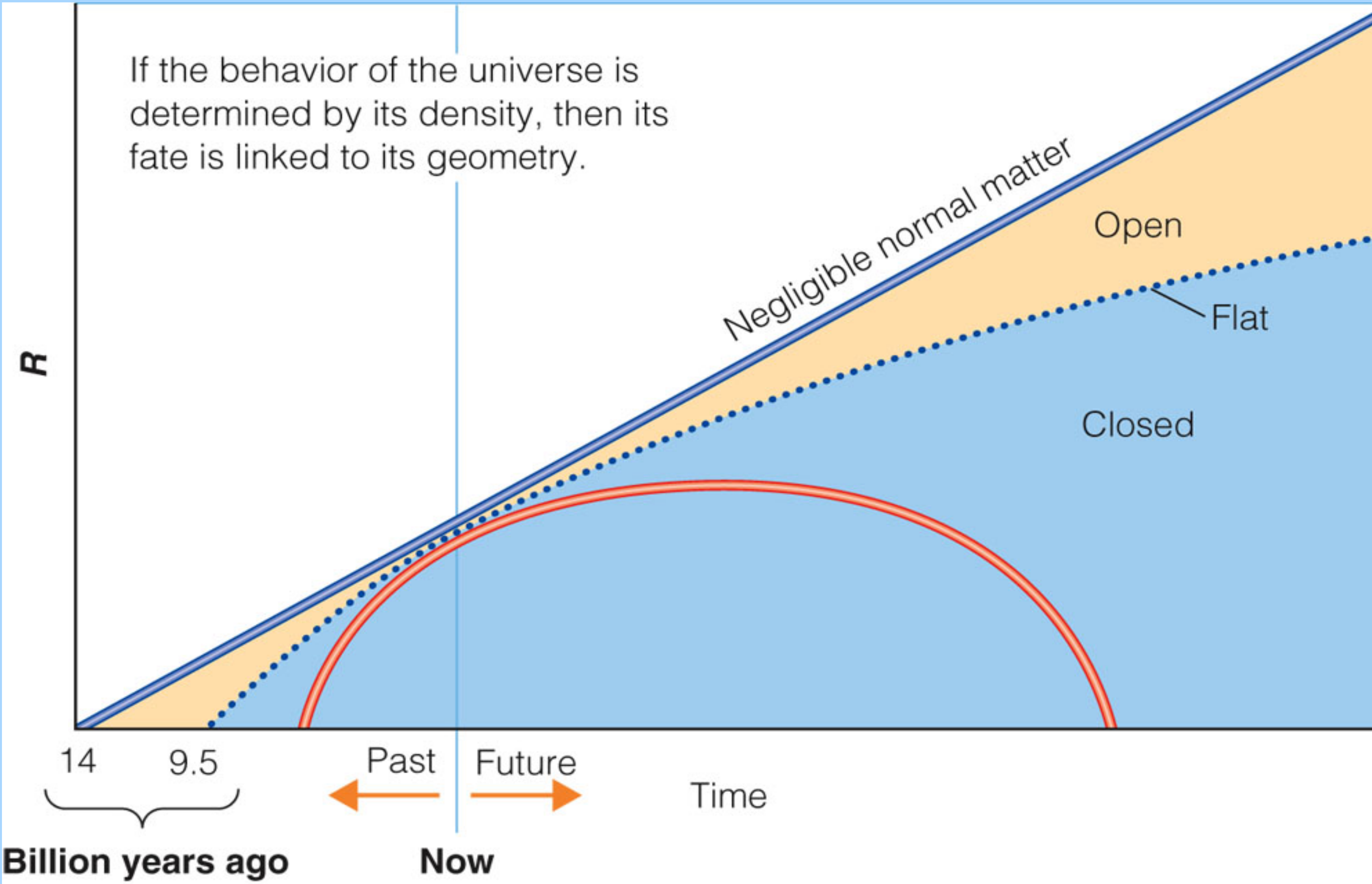
$$1.88 \times 10^{-33}\, H_0^{\,2}\ \mathrm{g / cm^3}$$

Since one hydrogen atom has a mass of 1.67×10^{-24} g, we are talking the equivalent of 6 hydrogen atoms per cubic meter to “close the universe”.

Prior to 1998 astronomers just wondered if the universe had enough mass density to halt the expansion. If the density of the universe just equalled the **critical density**, then the universe would coast to a halt after an infinite amount of time.

Ω_M = mean density of matter / critical density

If $\Omega_M = 1$, then the geometry is flat. If $\Omega_M > 1$, then the universe would recollapse and have positive curvature. $\Omega_M < 1$ would mean negative curvature and the universe would expand forever.


If the behavior of the universe is determined by its density, then its fate is linked to its geometry.
Negligible normal matter
Open
Flat
Closed
R
14
9.5
Past
Future
Time
Billion years ago
Now

About 1990 the evidence was that the oldest stars in our Galaxy were about 10-13 billion years old. So the age of the universe might be 14 or 15 billion years old.

Values of the Hubble constant based on the “infrared Tully-Fisher relation” were in the range 70 to 95 km/sec/Mpc.

What might that imply about the mean density of the universe?

Krisciunas (1993)

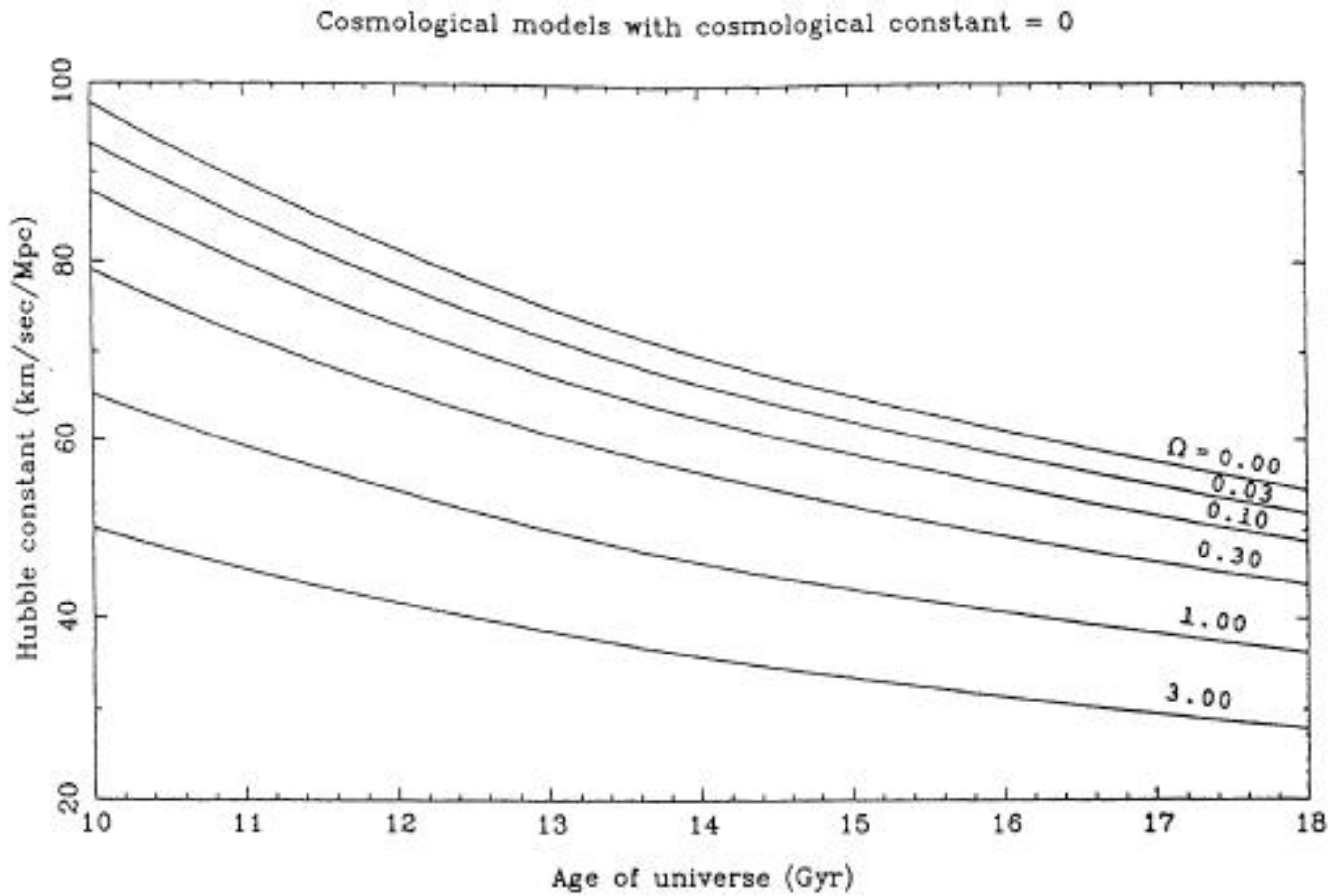


FIG. 3—Loci of constant Ω for a range of Hubble constants and values of the age of the universe (T_0). These models assume a zero cosmological constant.

If T_0= 15 Gyr and H_0 = 80, the mean density of the universe is less than zero. That can't be right!

The gravitational attraction of matter on other matter in the universe causes space-time to bend one way. If the vacuum of empty space had a kind of repulsive force, it could compensate for the gravitional effects of matter and give us flat space. Einstein postulated something of the kind in 1917.

From the dynamics of the clusters of galaxies we know that Ω_M is at least 0.2, maybe 0.3.

Krisciunas (1993)

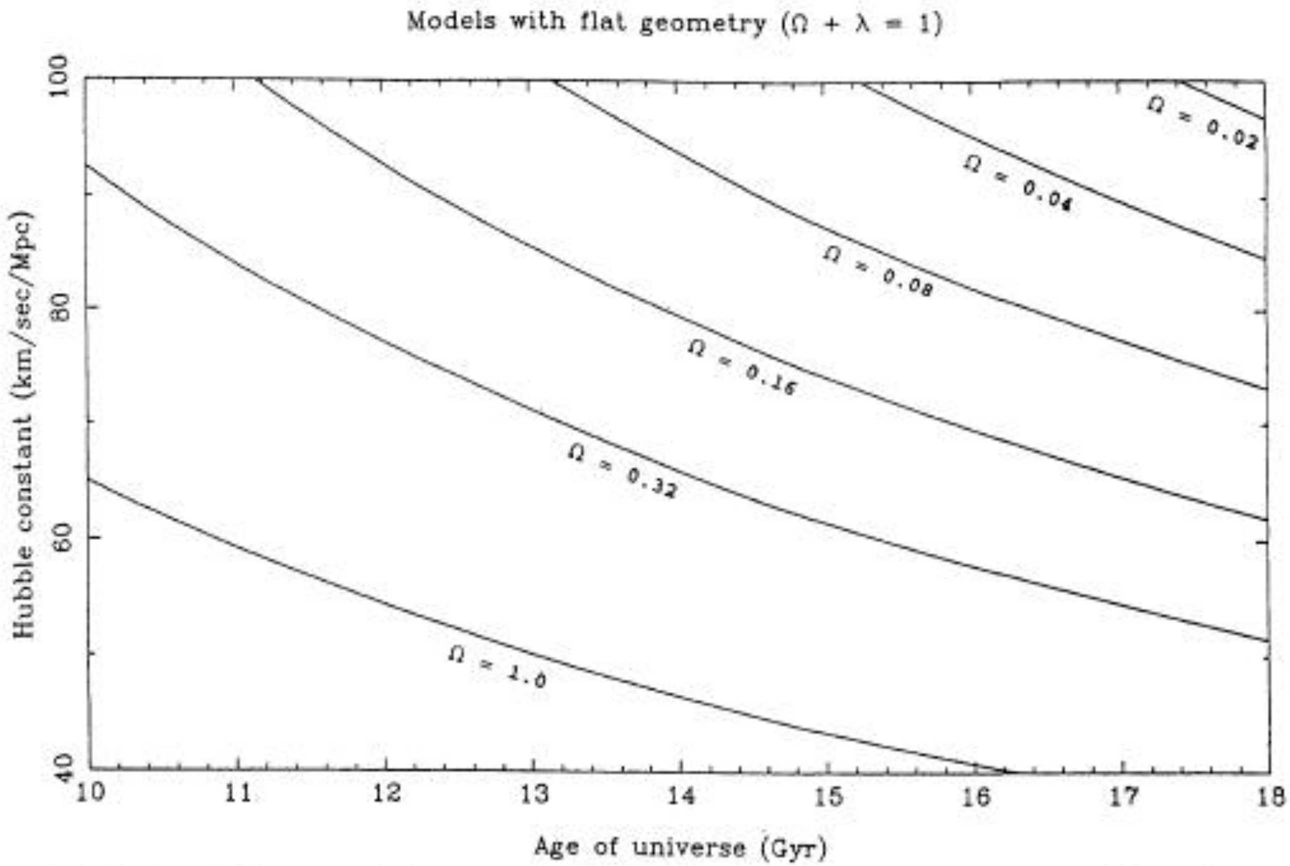


FIG. 5—Loci of constant Ω for a range of Hubble constants and values of the age of the universe (T_0), assuming the correctness of the condition stipulated by the inflationary scenario, $\Omega + \lambda = 1$.

A non-zero cosmological constant and flat geometry allow a “large” value of H_0 and an age of 14-15 Gyr.

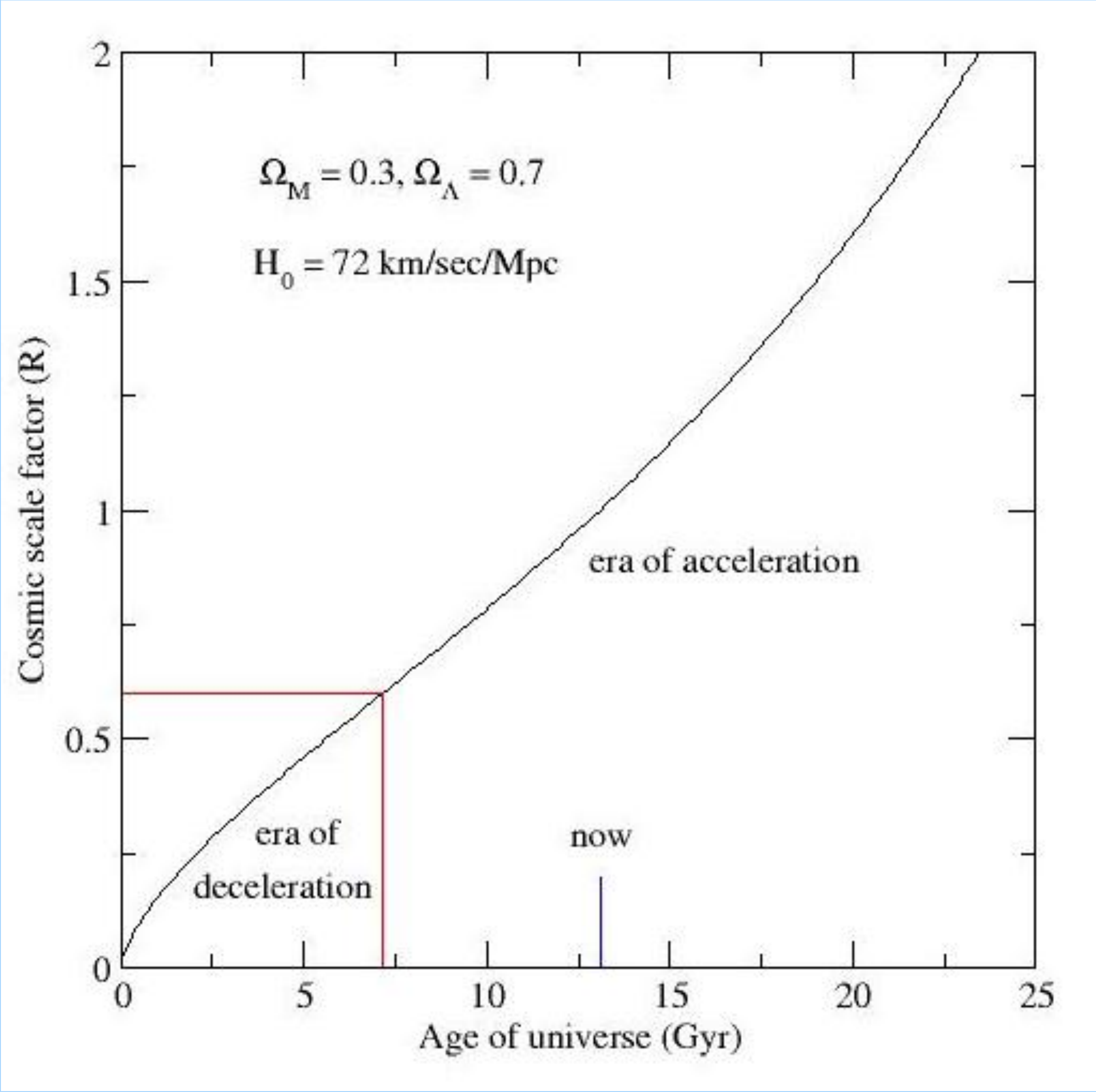
However, in 1998/99 two groups of astronomers discovered that the universe is *accelerating* in its expansion. This guarantees that the universe will expand forever.

The energy budget of the universe is something like this:

roughly 4 percent “regular” matter (made of protons, neutrons, and electrons)

26 percent dark matter

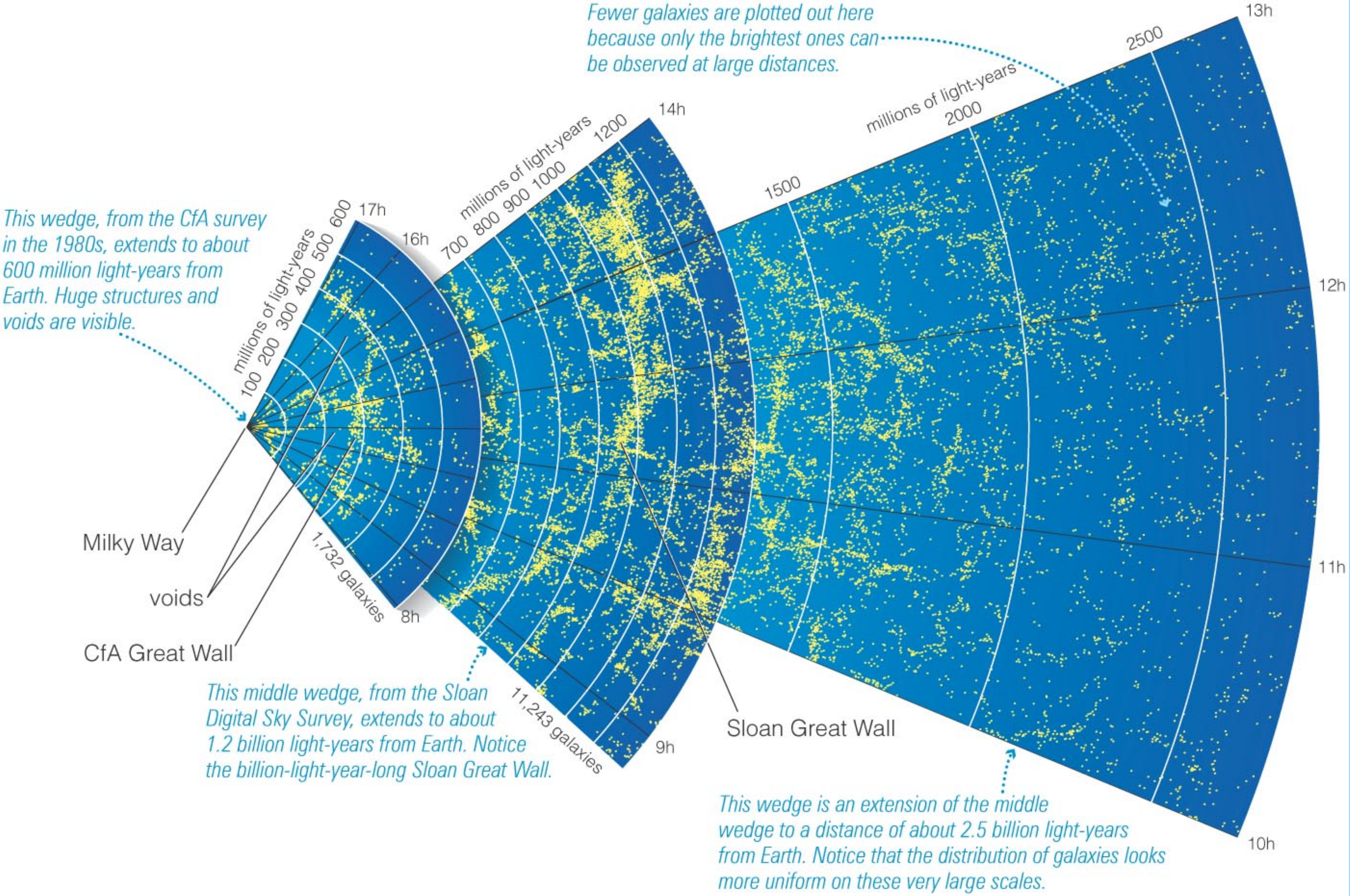
70 percent dark energy



About 7 billion years after the Big Bang the effect of the Dark Energy overcame the gravitational attraction of all the matter in the universe. The universe's expansion began to accelerate.

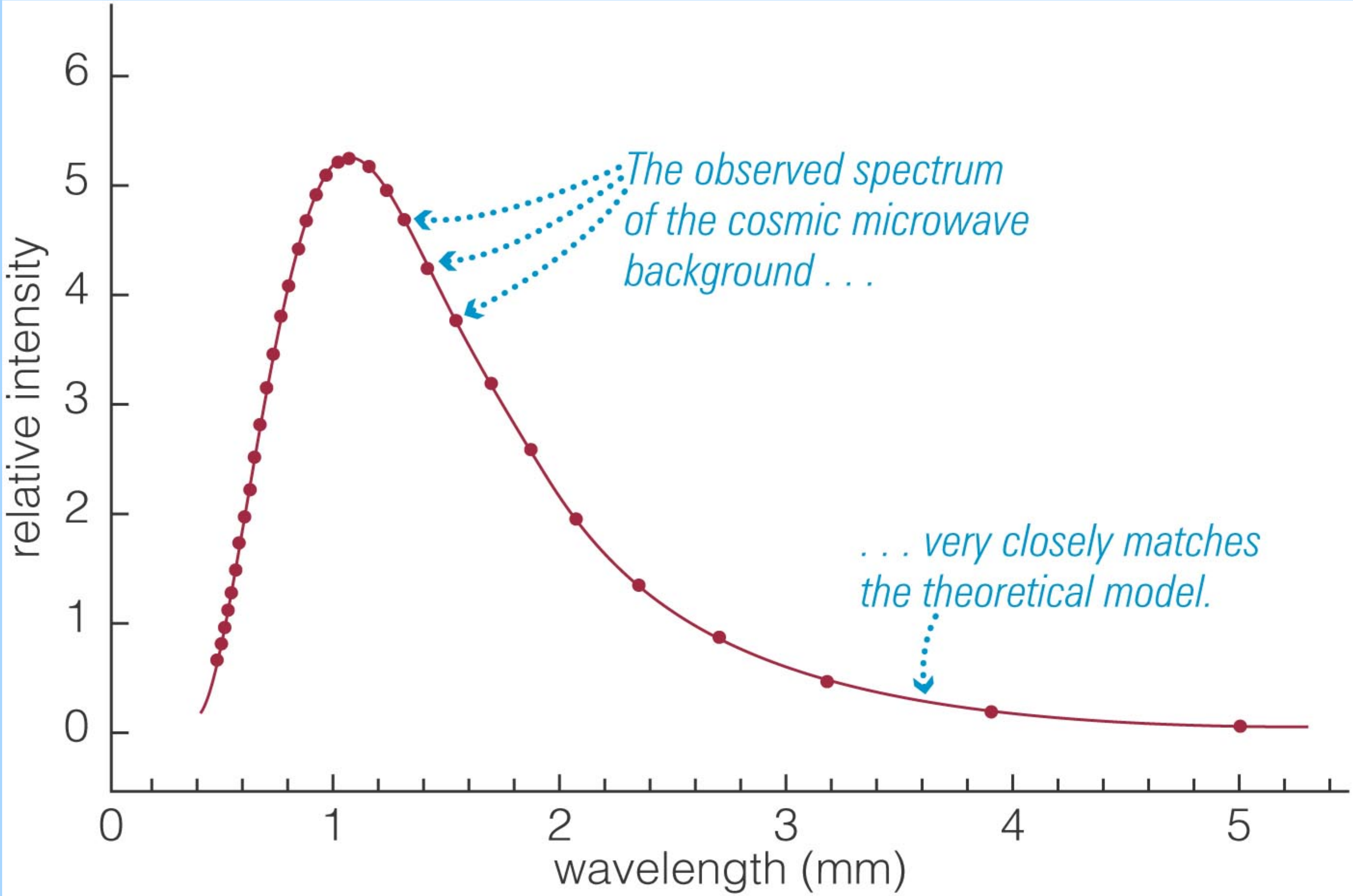
The dimensionless parameter $\Omega_\Lambda = \Lambda c^2 / (3 H_0^2)$, where Λ is the cosmological constant as Einstein originally introduced it in 1917. $1 / \mathrm{sqrt}(\Lambda)$ has units of length. This is the "length scale over which the gravitational effects of a nonzero vacuum energy density would have an obvious and highly visible effect on the geometry of space and time" (Abbott 1988, *Scientific American*, **258**, no . 5, May issue, 106). For $\Omega_\Lambda = 0.7$ and a Hubble constant of 72 km/sec/Mpc, the length scale is 2875 Mpc, which is half the size of the observable universe. No wonder we cannot measure this in the laboratory!

Correlations of the Large Scale Structure of the Universe and Variations in the Temperature of the Cosmic Microwave Background Radiation

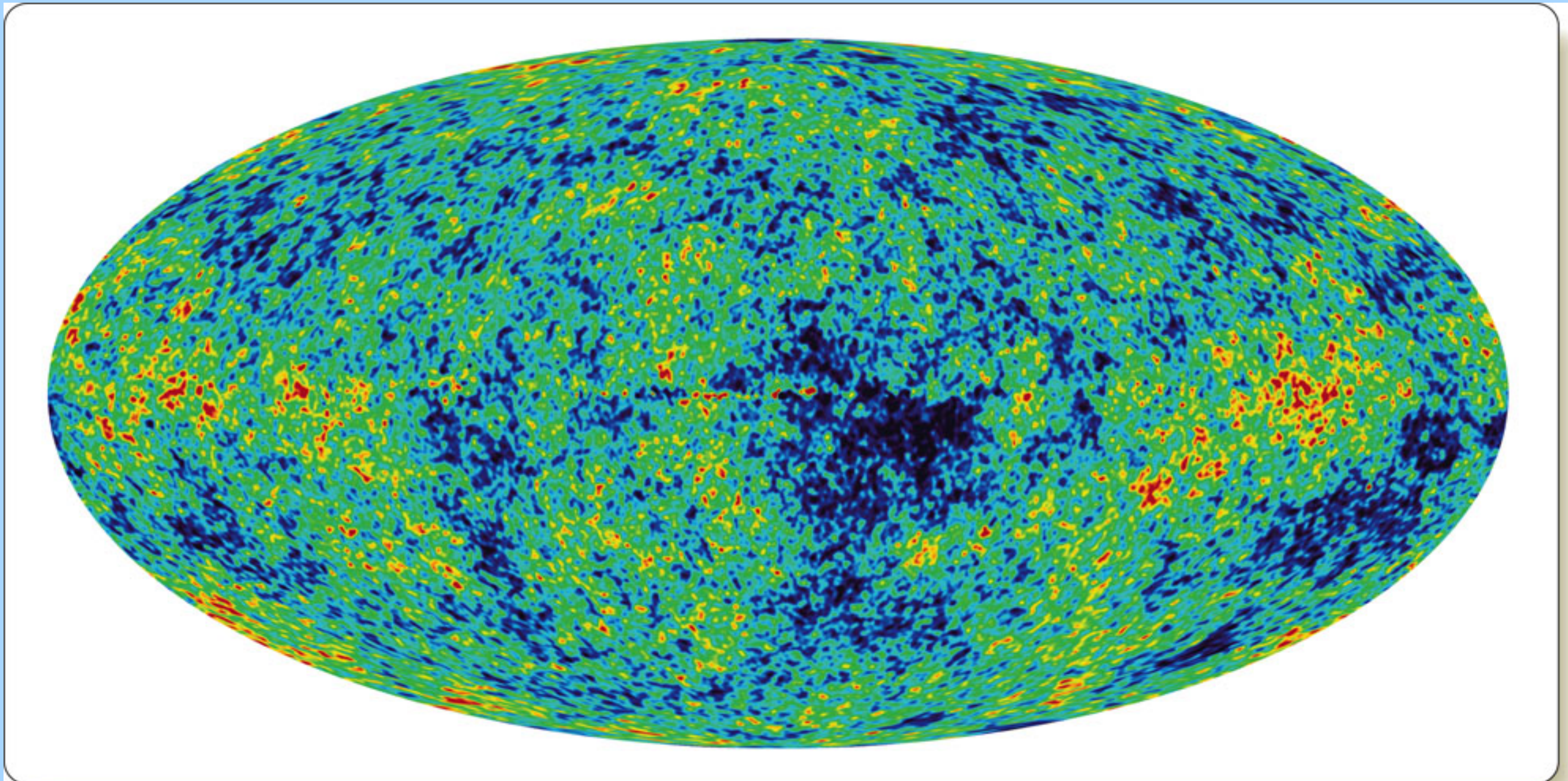

Fewer galaxies are plotted out here because only the brightest ones can be observed at large distances.
This wedge, from the CfA survey in the 1980s, extends to about 600 million light-years from Earth. Huge structures and voids are visible.
millions of light-years
100 200 300 400 500 600
17h
16h
8h
1,732 galaxies
millions of light-years
700 800 900 1000 1200
14h
9h
11,243 galaxies
millions of light-years
1500 2000 2500
13h
12h
11h
10h
Milky Way
voids
CfA Great Wall
Sloan Great Wall
This middle wedge, from the Sloan Digital Sky Survey, extends to about 1.2 billion light-years from Earth. Notice the billion-light-year-long Sloan Great Wall.
This wedge is an extension of the middle wedge to a distance of about 2.5 billion light-years from Earth. Notice that the distribution of galaxies looks more uniform on these very large scales.

We know that the large scale structure that the universe has a filamentary structure. There are concentrations of mass and voids with little mass. This *density* variations imply that there should be *temperature* variations in the cosmic microwave background radiation, corresponding to the state of the universe a few hundred thousand years after the Big Bang.

These variations were first measured by the Cosmic Background Explorer (COBE), a satellite launched in 1989. The temperature of the cosmic microwave background radiation only varies 0.001 percent over the whole sky.

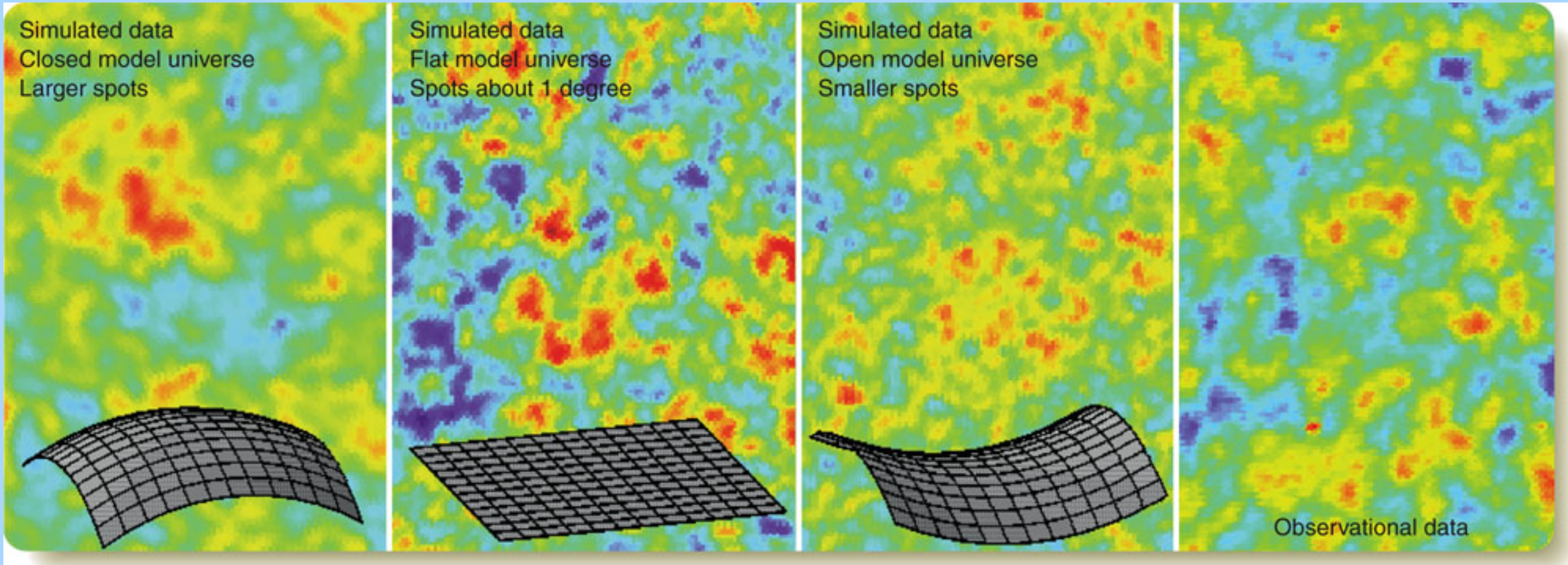


relative intensity
6
5
4
3
2
1
0
0
1
2
3
4
5
wavelength (mm)
The observed spectrum of the cosmic microwave background . . .
. . . very closely matches the theoretical model.



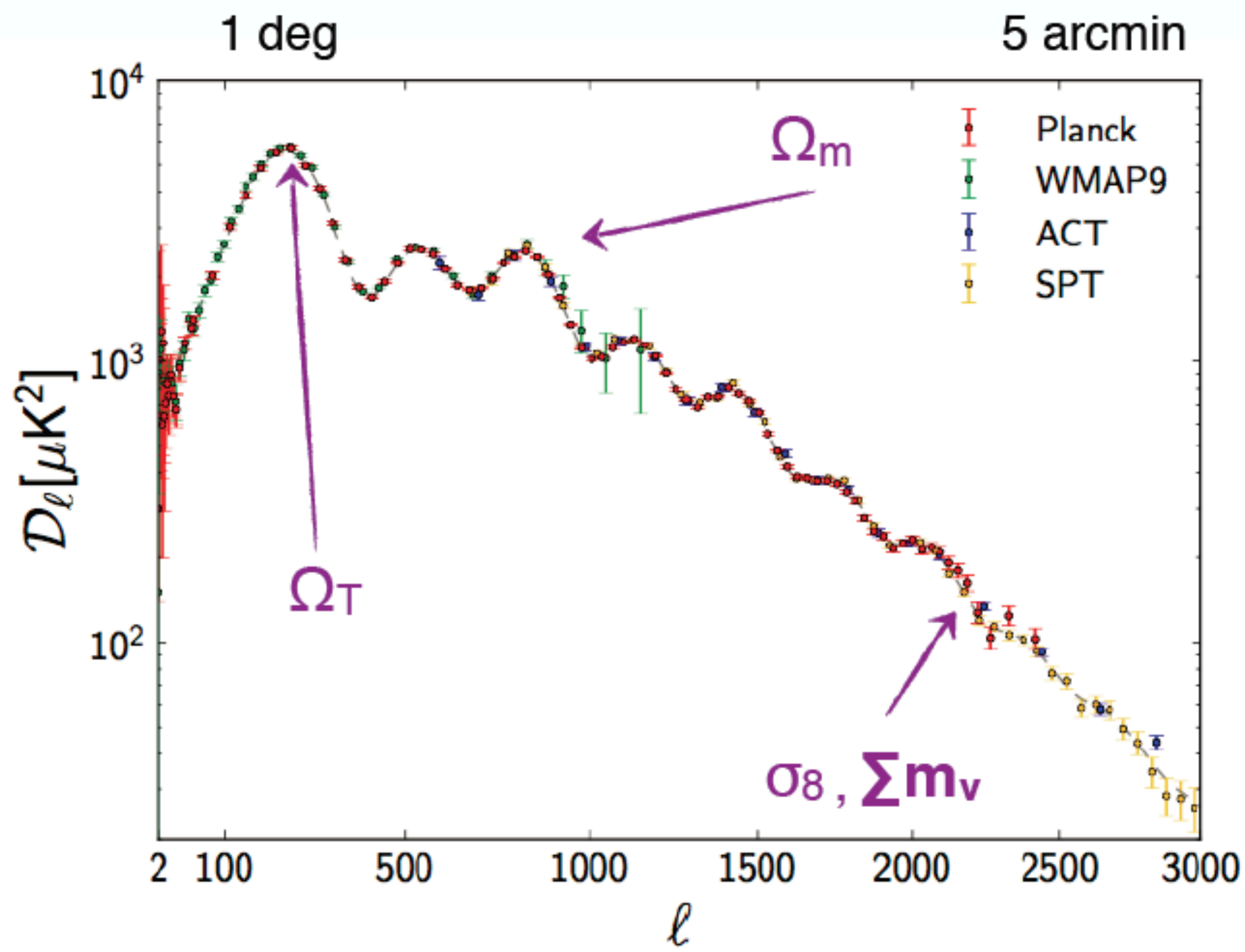
Slight variations of the temperature of the cosmic microwave background radiation, as measured with the WMAP satellite. Where the universe was colder at this epoch, clusters of galaxies formed billions of years later.

We have evidence that the universe is flat from more than just supernova data. The mottled nature of the maps of the cosmic microwave background tells us something about the geometry of the universe. The characteristic angular size of the hotter and cooler spots of the CMB is 1 degree, just about what one would expect for flat geometry.


Simulated data
Closed model universe
Larger spots
Simulated data
Flat model universe
Spots about 1 degree
Simulated data
Open model universe
Smaller spots
Observational data

The angular power spectrum of the CMB

tells us the composition of the Universe
380,000 years after the Big Bang



Other Proof that the Geometry of the Universe is Flat

A billion years after the Big Bang the universe was composed of many, many young galaxies. These galaxies, and their associated Dark Matter, exerted gravitational attraction on each other.

Consider Type Ia supernovae. We believe we can determine their absolute magnitudes (M) at the time of maximum light. They are standardizable candles in optical bands, and standard candles in infrared bands. Since

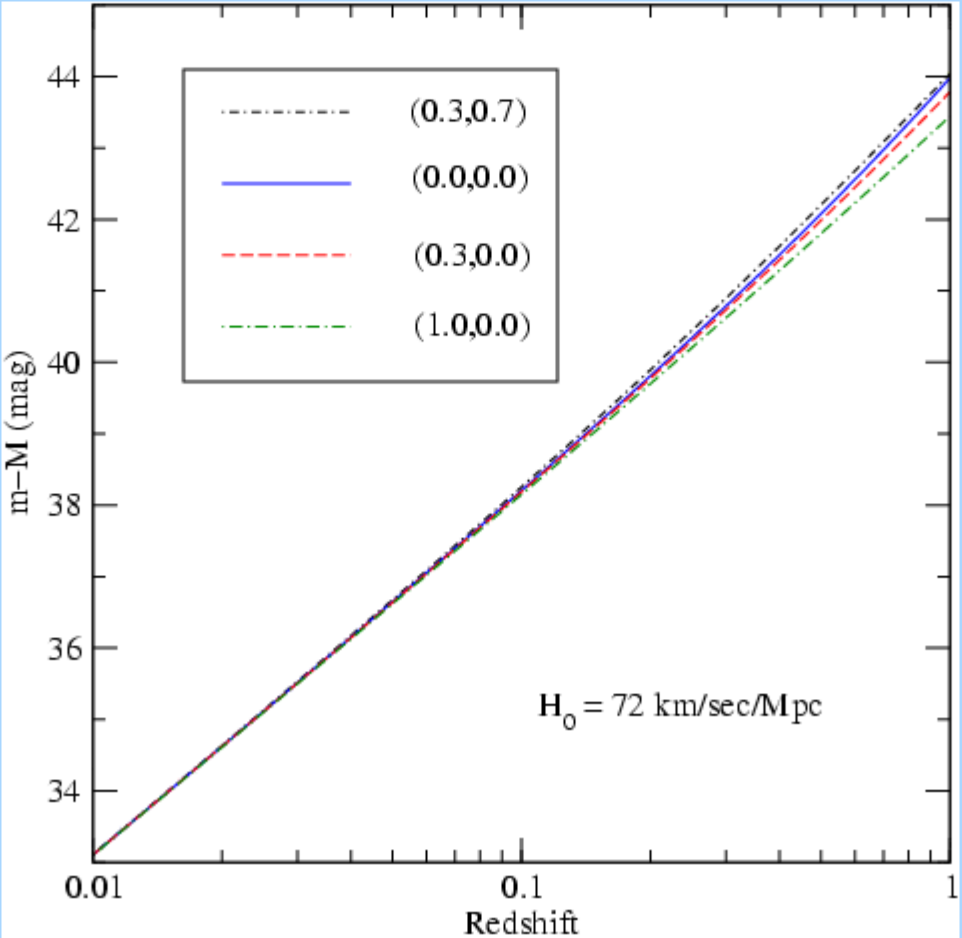
$$M_V = m_V + 5 - 5 \log d \quad ,$$

m−M is a function of the distance *d*. m−M is called the "distance modulus".

Objects at higher and higher redshift are seen further and further back in time. Here is a table of lookback times:

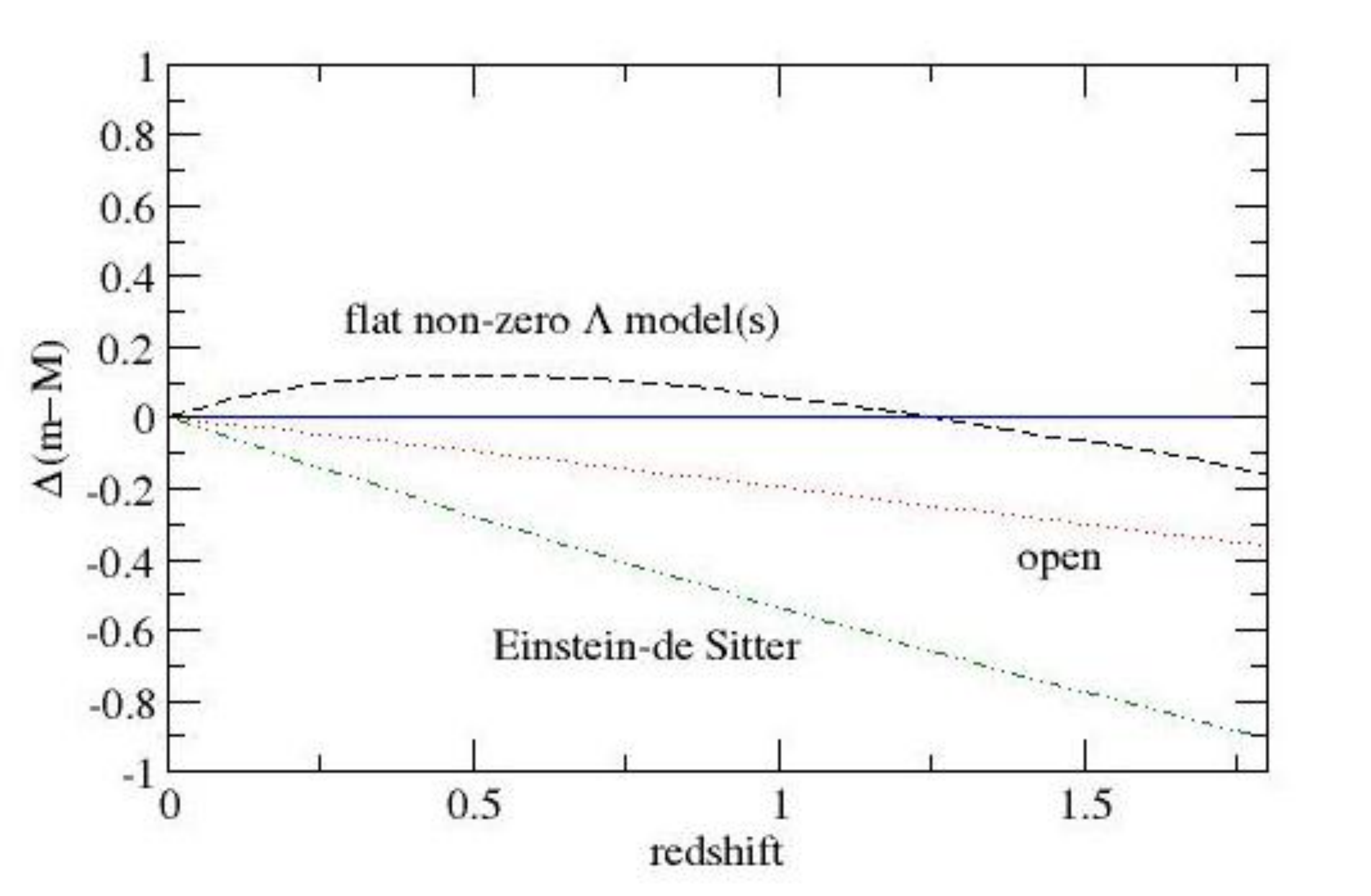
redshift (z)	lookback time (billions of years)
0.2	2.36
0.3	3.32
0.4	4.16
0.5	4.90
0.6	5.55
0.7	6.13
0.8	6.64
1.0	7.50
1.7	9.44

Assumes Hubble constant of 72 km/sec/Mpc, total mass density 0.3 of critical density, and scaled Dark Energy of 0.7.



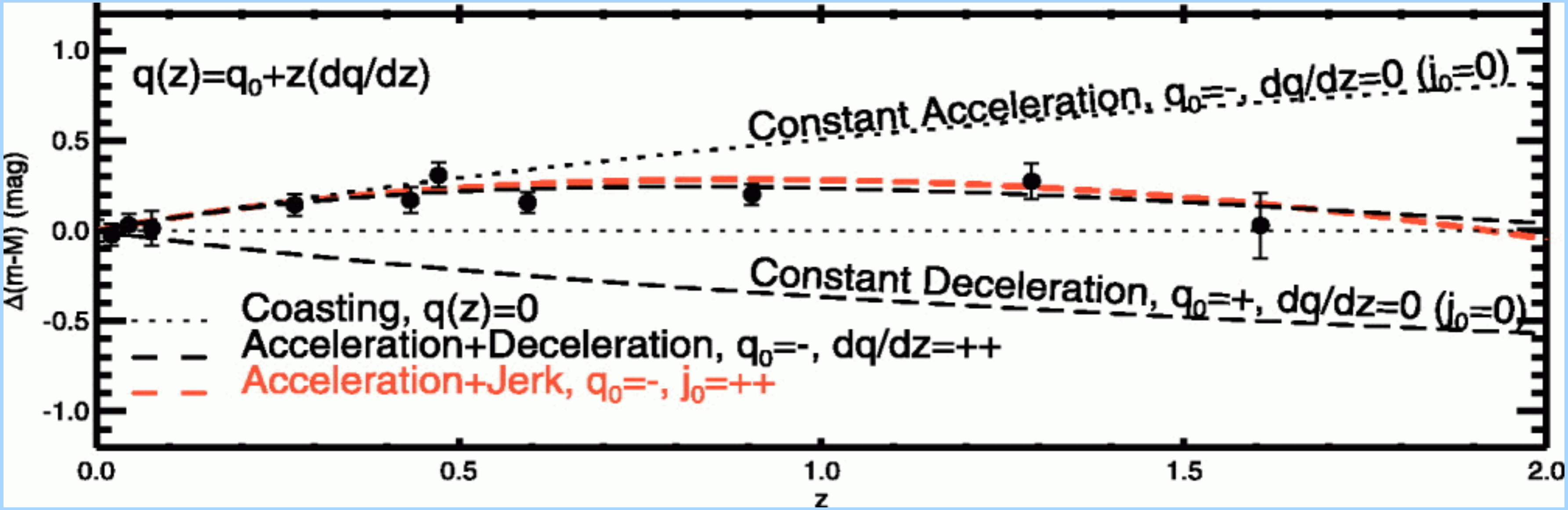
The distance modulus vs. log (redshift) for various cosmological models (Ω_M , Ω_Λ).

Only at redshifts greater than 0.2 do the lines start to diverge from each other to a significant extent.

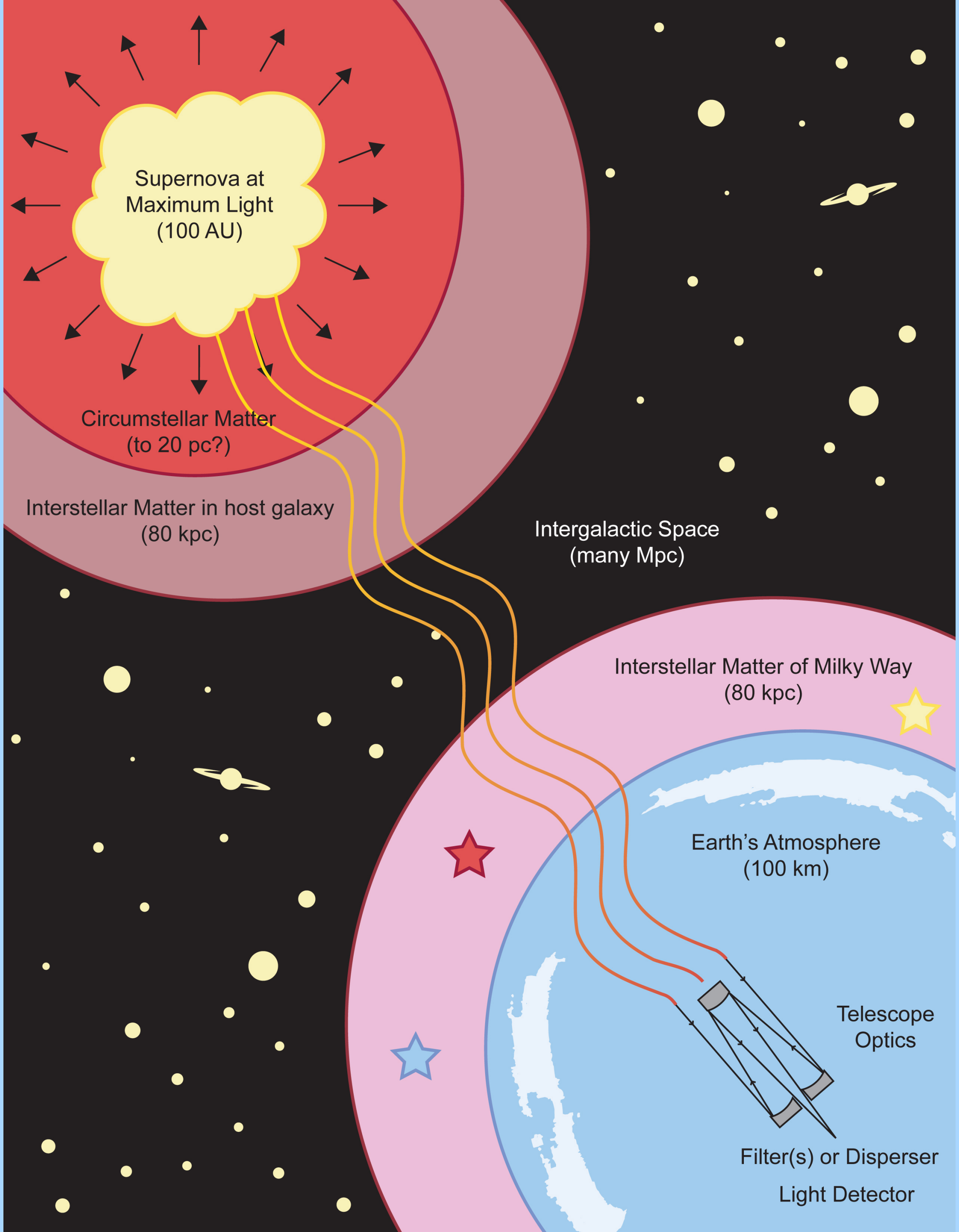


If we pick the "empty universe" (0.0, 0.0) model as a reference, here is a differential Hubble diagram. Prior to 1998 the expectation was that SN data would lie along the "open" line.

Observations of Type Ia supernovae from the ground and with the Hubble Space Telescope showed that the objects were "too far away" (the SNe were too faint). The universe was not decelerating, as had been thought. It has been accelerating since 7 billion years after the Big Bang.



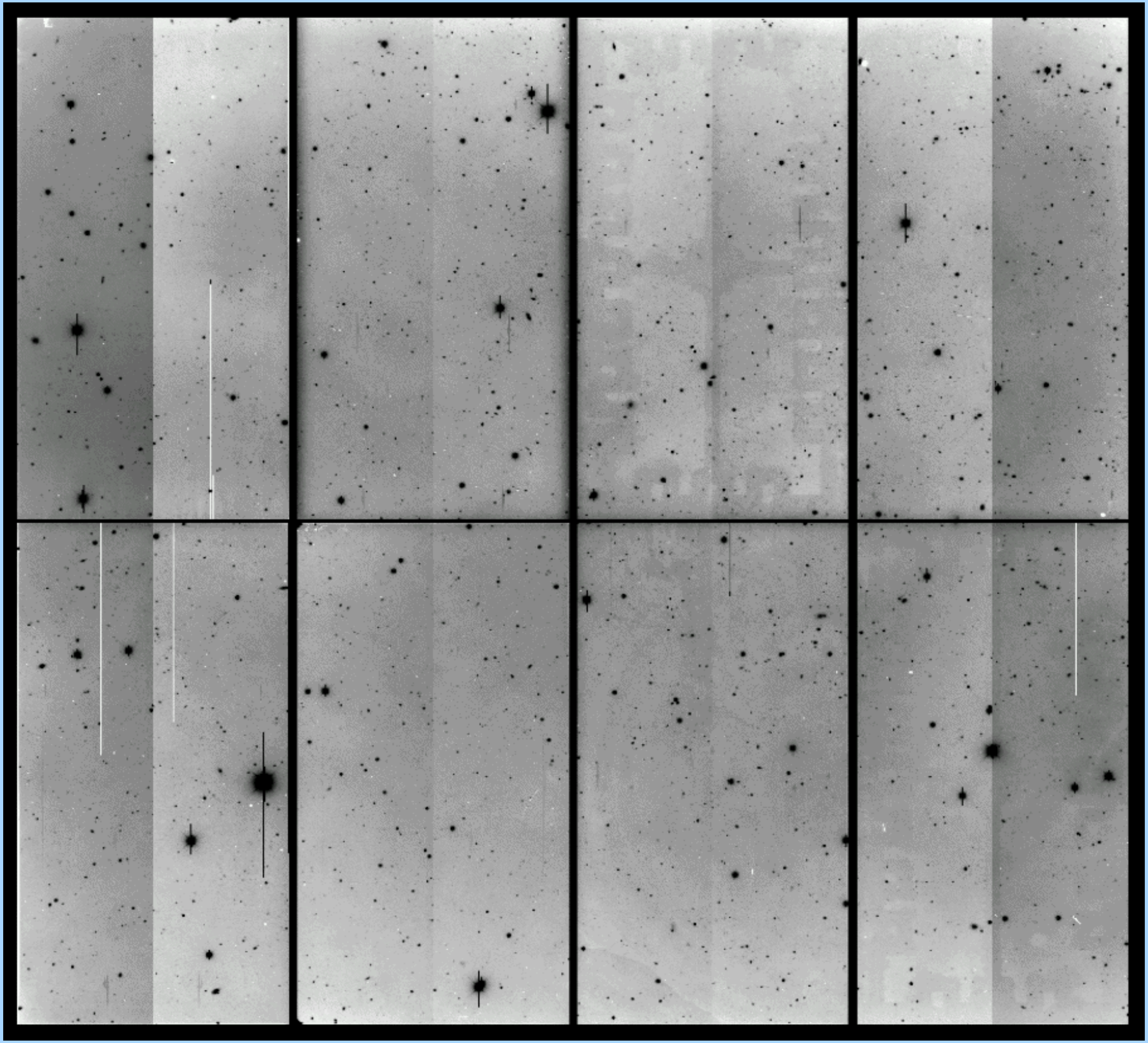
Riess et al. (2004)

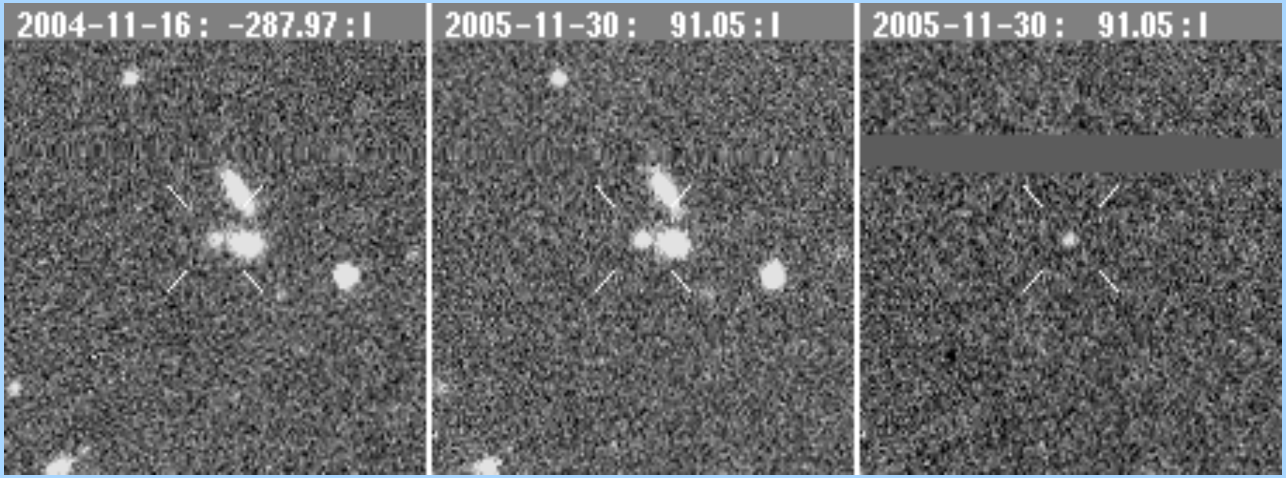


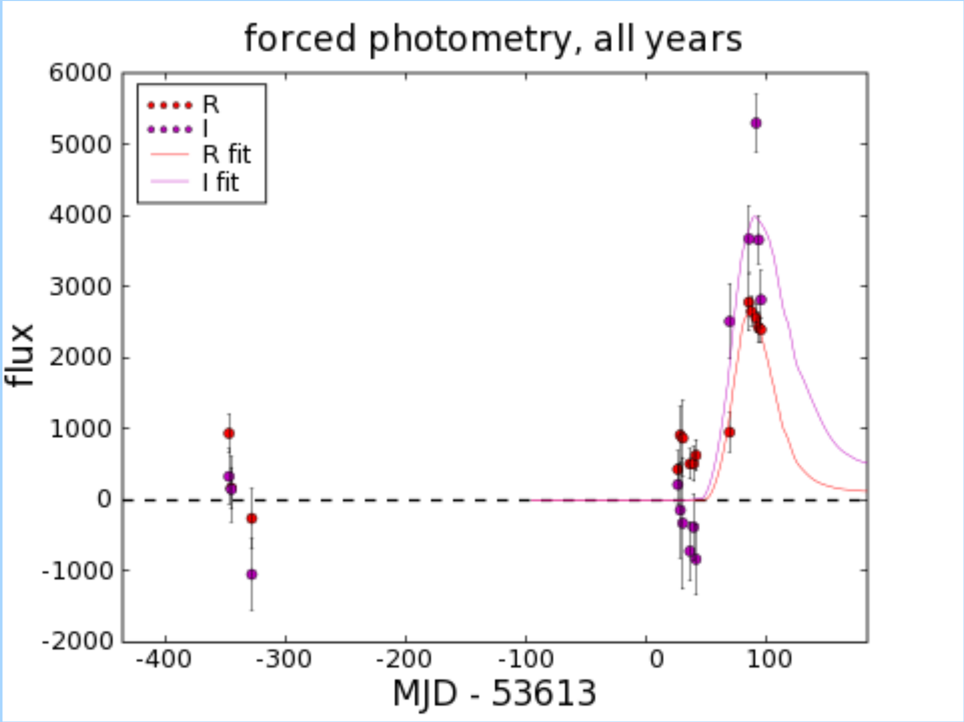
The light of a supernova passes through all sorts of regimes on the way to our detectors.

The light curve of a Type Ia supernova is powered by the radioactive decay of ^{56}Ni and ^{56}Co.

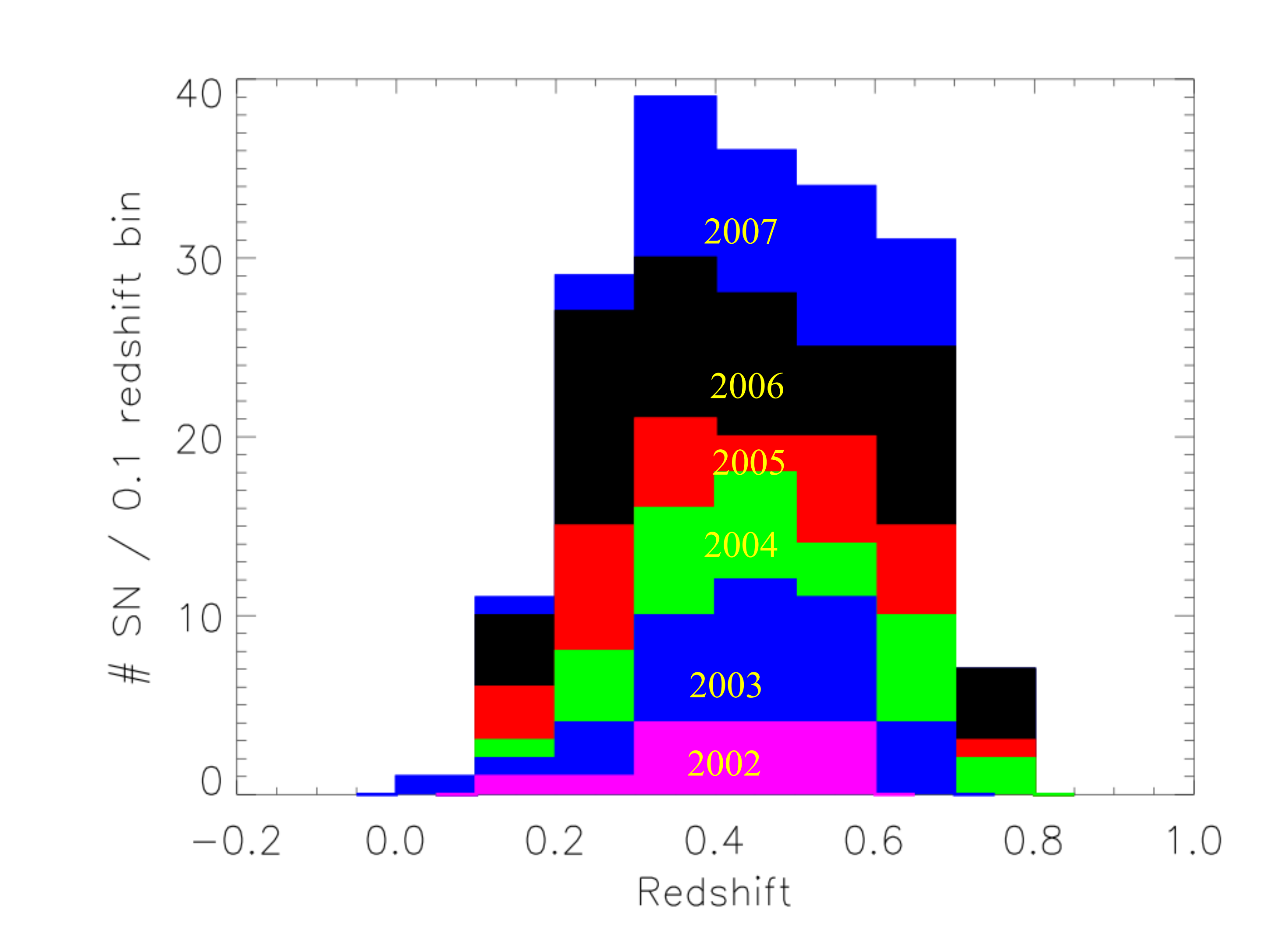
Using the 4-m telescope at Cerro Tololo Inter-American Observatory, we accomplished the ESSENCE project. We discovered over 200 Type Ia supernovae from redshift 0.2 to 0.8. Except for some measurements done with the Hubble Space Telescope, all of the photometry has been carried out on the same telescope with the same filters.



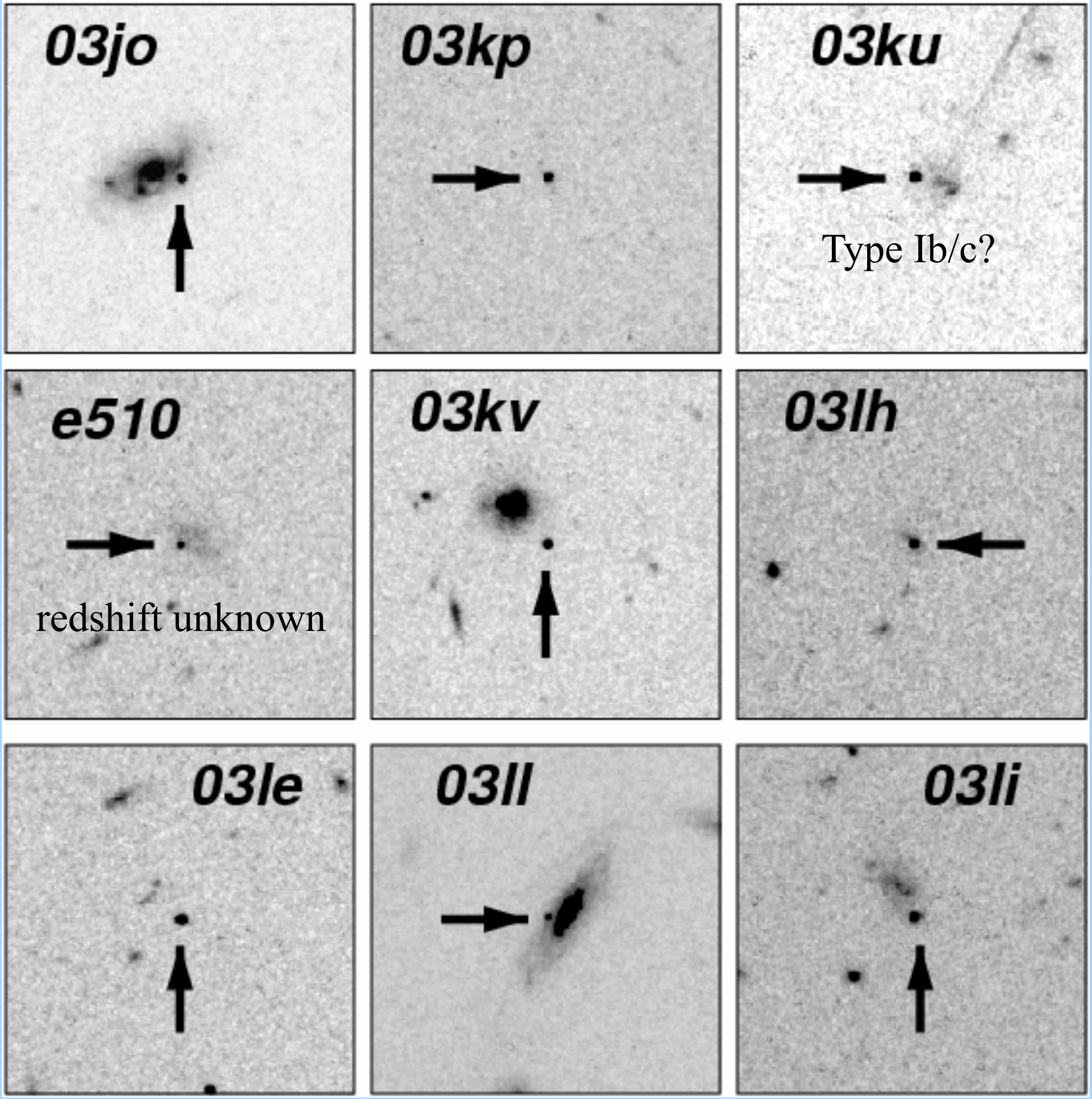




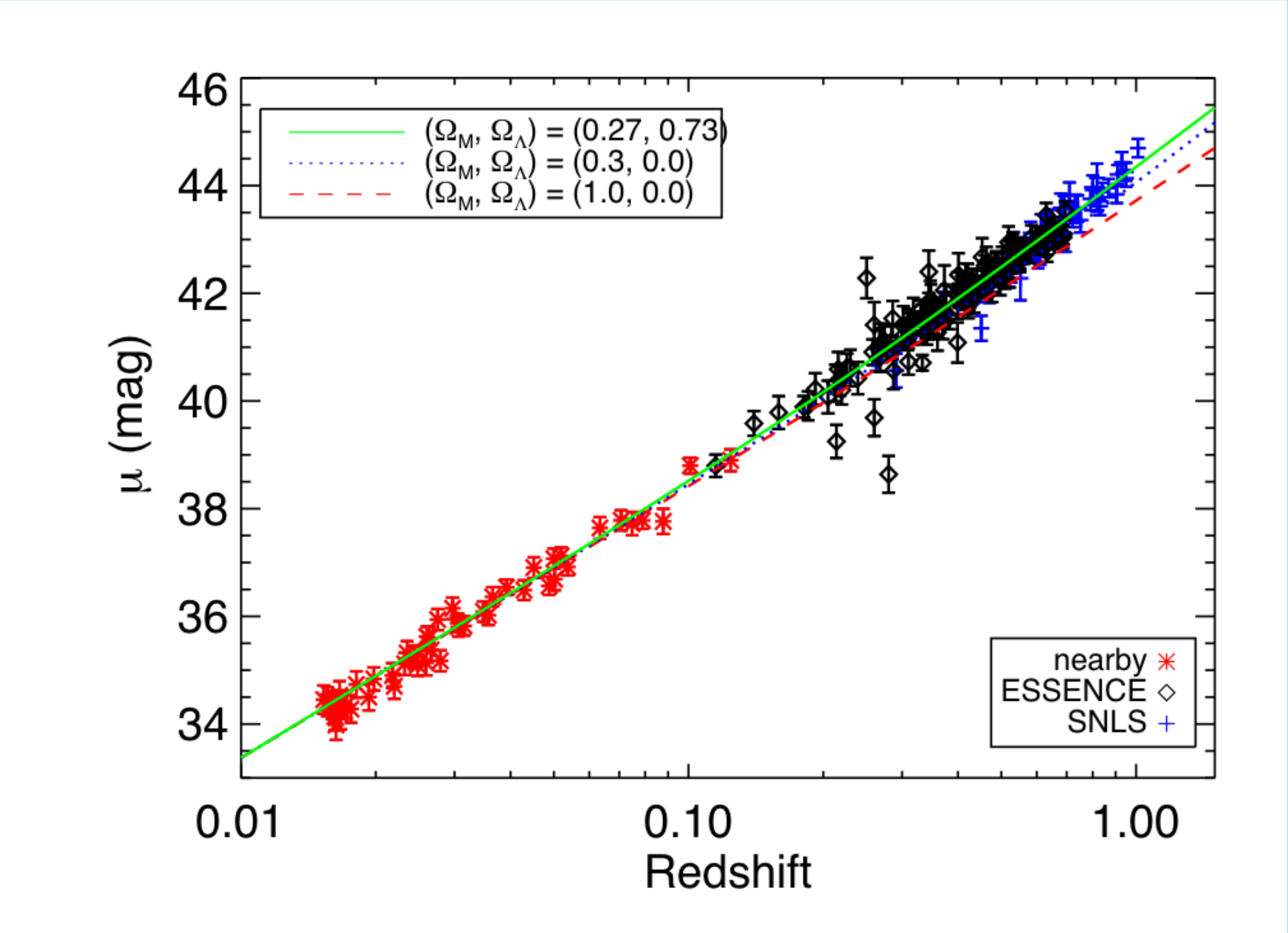
The data pipeline helped identify transient objects and produce preliminary light curves.



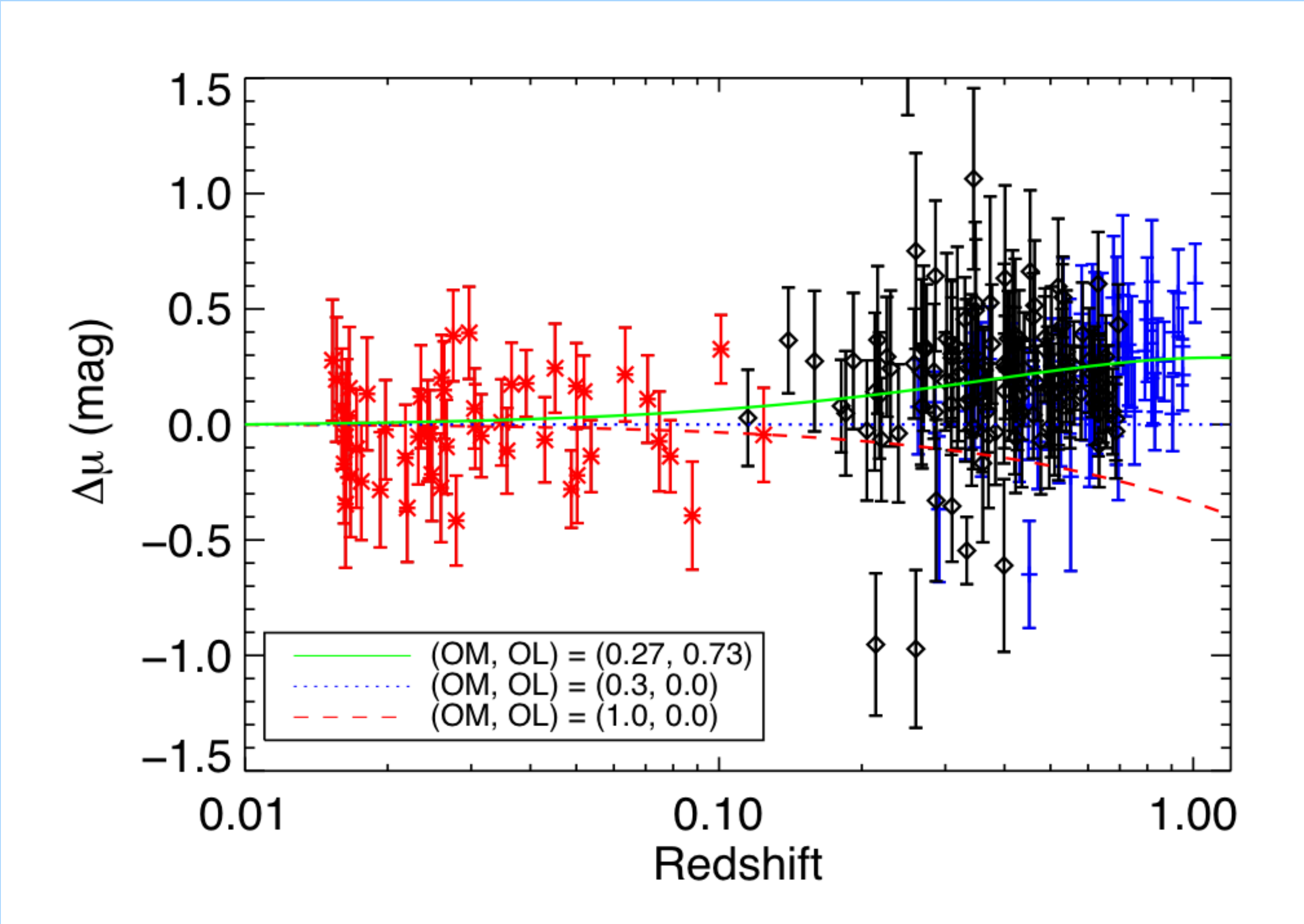
Redshift distribution of ESSENCE SNe.



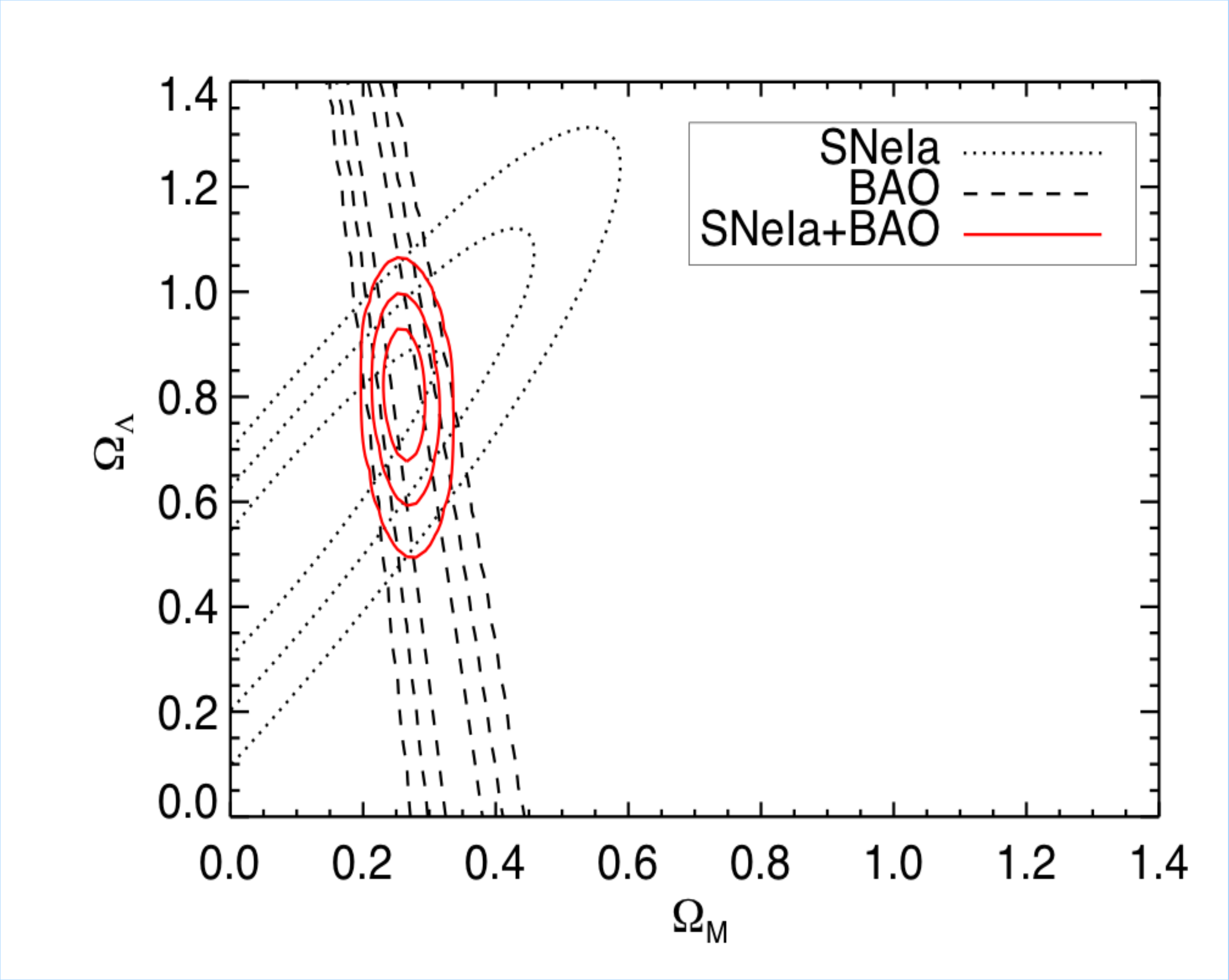
Some of the ESSENCE SNe are in *very* faint host galaxies.



Preliminary ESSENCE Hubble diagram, along with some SNe from the SN Legacy Survey.



Recently discovered high redshift SNe are "too faint" by ¼ of a magnitude for the "open" model to fit the data.



Evidence is that $\Omega_M \sim 0.27$ and that $\Omega_M + \Omega_\Lambda = 1$. This implies that the geometry of the universe is flat.

In 1917 Einstein was contemplating some consequences of his theory of General Relativity and realized that the universe should either be expanding or contracting. To keep it static (neither expanding nor contracting) required adding a new parameter to one of his equations. This is referred to as the "cosmological constant". Once Hubble discovered the expansion of the universe in 1929, Einstein considered the idea of a cosmological constant to be have been a mistake.

However, now, with the discovery of the acceleration of the expansion, the cosmological constant and other forms of Dark Energy are very much back in favor.

If the vacuum of empy space exerts a repulsive force on all other space, then this should ensure the perpetual expansion of the universe. It will *not* recollapse in an eventual Big Crunch.

In the early 1980's the theory of *inflation* was devised to explain a number of features of the universe (its geometric flatness, and how remote corners of the universe could be in causal contact with each other). The universe may have increased in size by a factor of 10^{60} in the first 10^{-35} of a second after the Big Bang. A cosmological constant-like force operated for a short time and then turned off. 7 billion years later a new version of a repulsive force caused the expansion of the universe to accelerate.

Successes of the Big Bang and inflation theories:

1) cosmic microwave background radiation was found (with $T = (1 + z) * 2.73$ K)

2) variations of temperature in the CMB have been observed over the sky that correlate with the kind of large scale structure we see in today's universe

3) primordial abundances of D, He, Li are consistent with predictions

4) oldest stars in galaxy are 10 to 13 billion years old, a bit less than age of universe

5) geometry of the universe is flat