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School of Mathematical and Computing Sciences
Te Kura Pangarau, Rorohiko

Einstein’s cosmological legacy: From the big bang to black holes

Matt Visser

Overview:

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2005 marks 100 years since Einstein discovered $E=mc^2$, and 90 years since he formulated the theory of general relativity --- his theory of gravity.

This theoretical framework underpins all modern cosmology and astronomy and governs how we think about our Universe.

A gentle introduction to what it's all about, and why scientists are so enthusiastic!

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"It is important to keep an open mind; just not so open that your brains fall out"

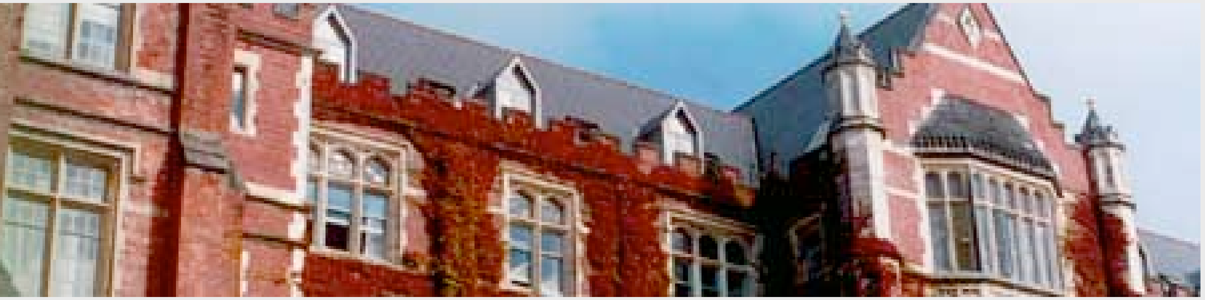
--- Albert Einstein

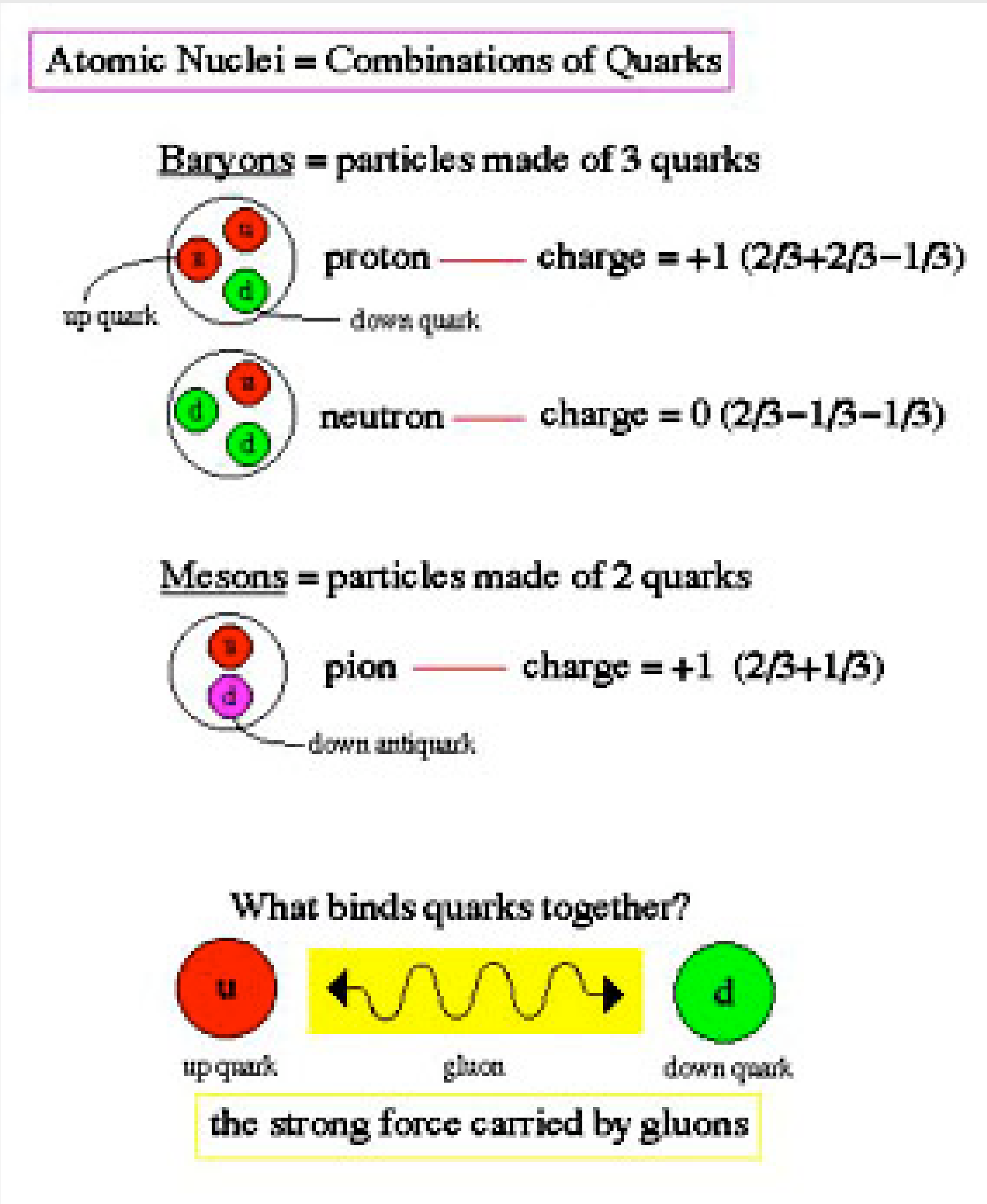
What is cosmology?

Cosmology is the scientific study of the overall structure of our universe.

Cosmology deals with many issues: the very distant past, the origins of the universe itself, the average distribution of galaxies, and to some extent predictions of the future behaviour of our universe.

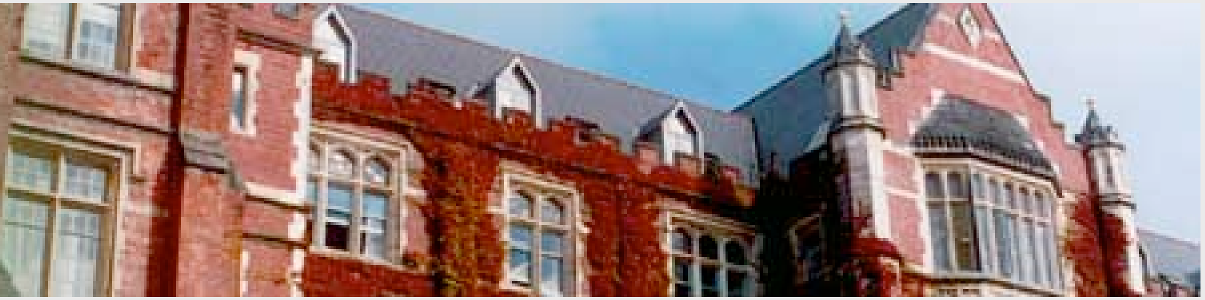
The best model we currently have to explain what we see in our telescopes is the "Big Bang model", which is very good at describing the bulk of observations
--- but there are still a lot of details to work out.





Tomorrow!
Prof Frank Close
Cambridge

The Particle Odyssey



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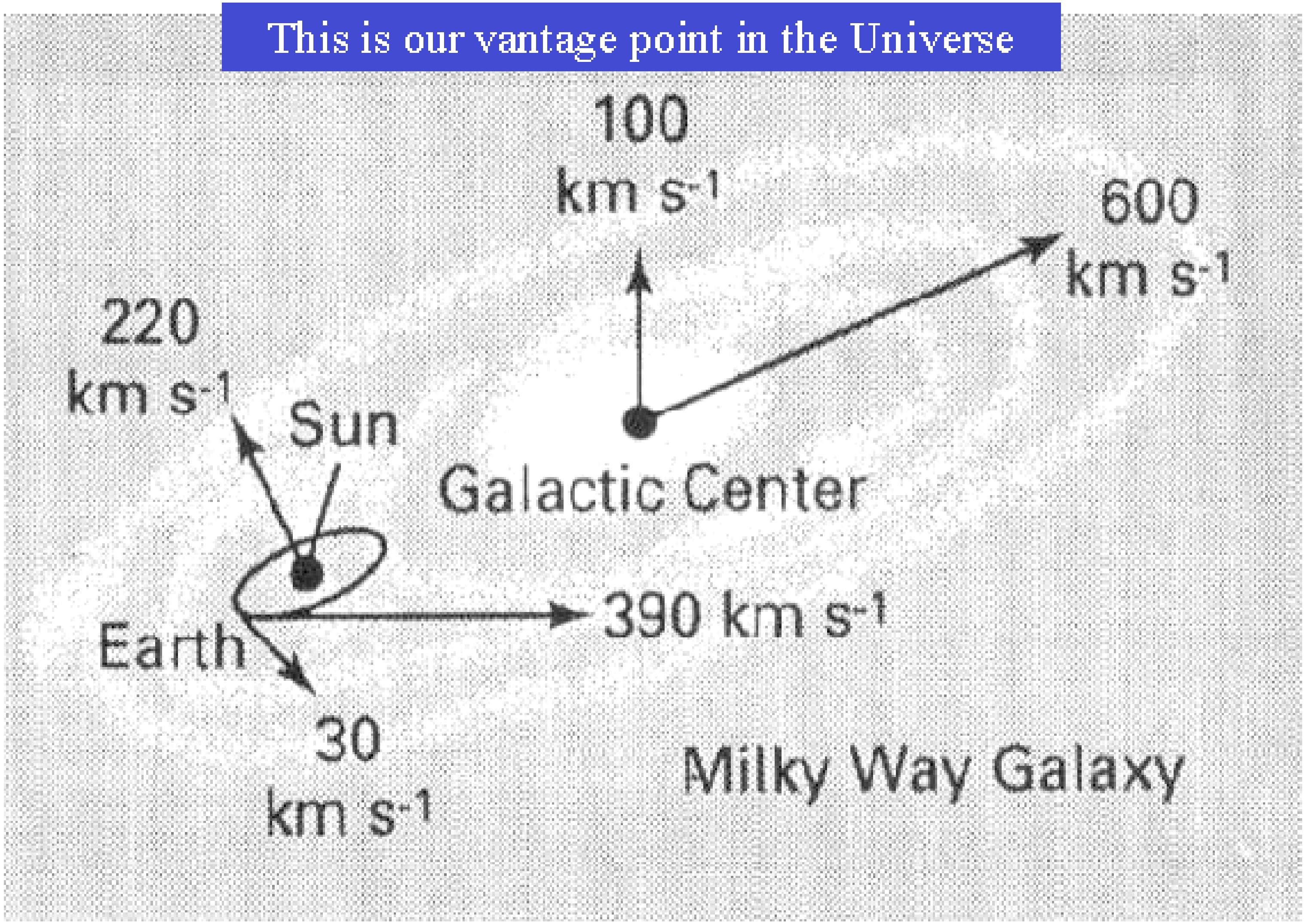
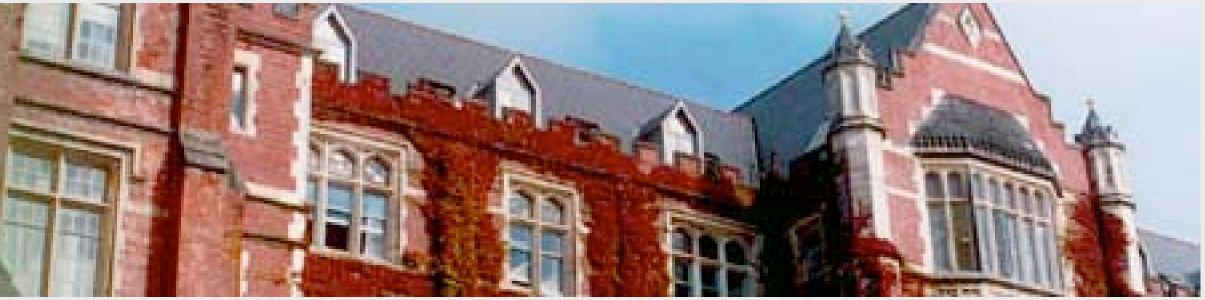
This is our vantage point in the Universe





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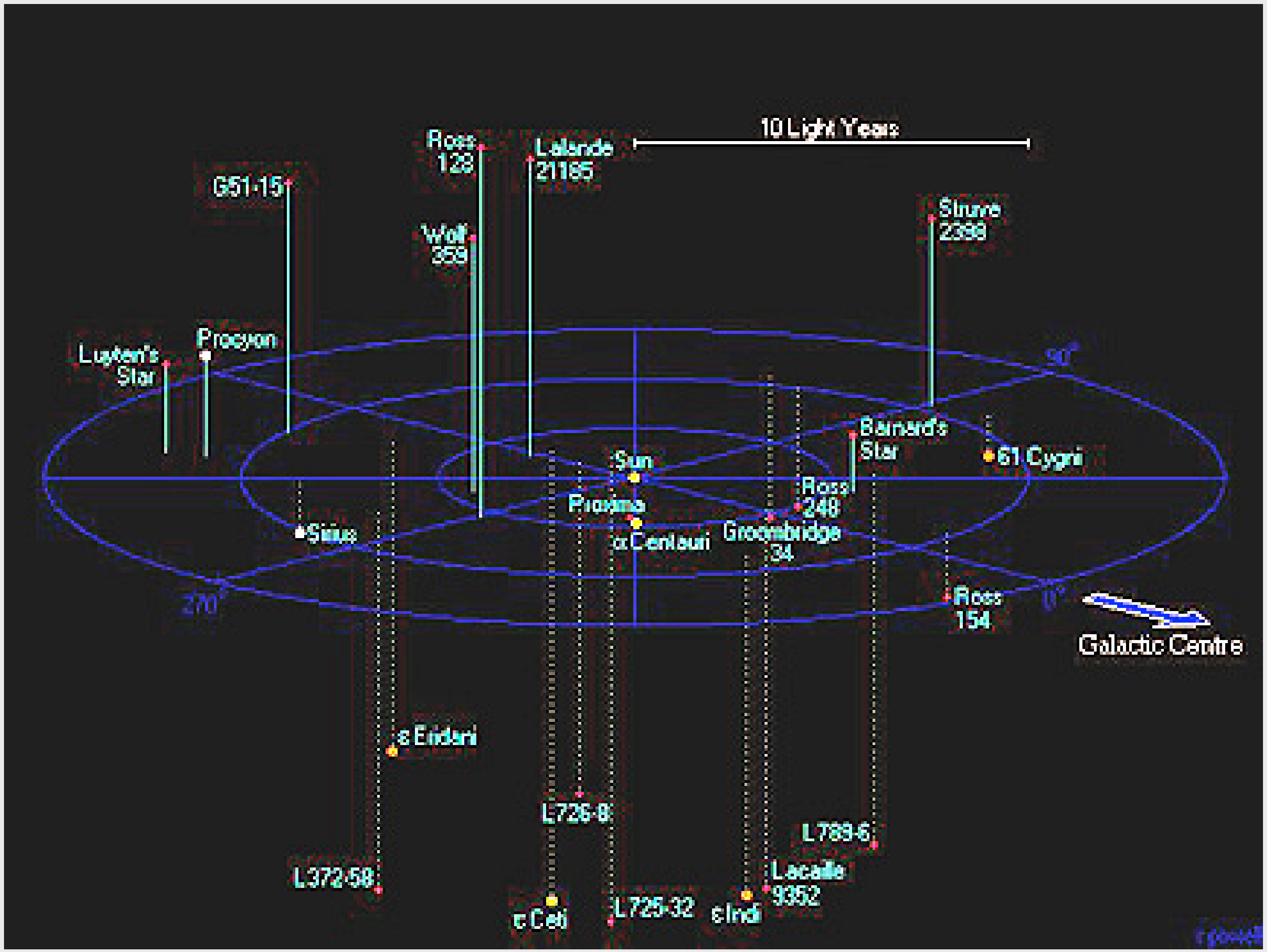
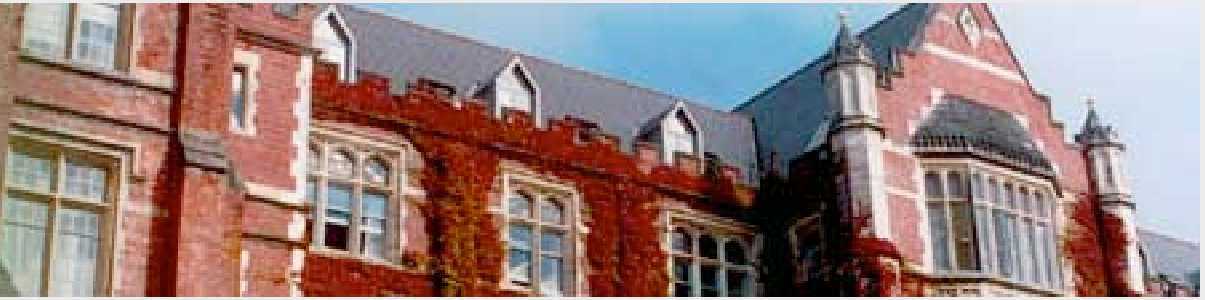
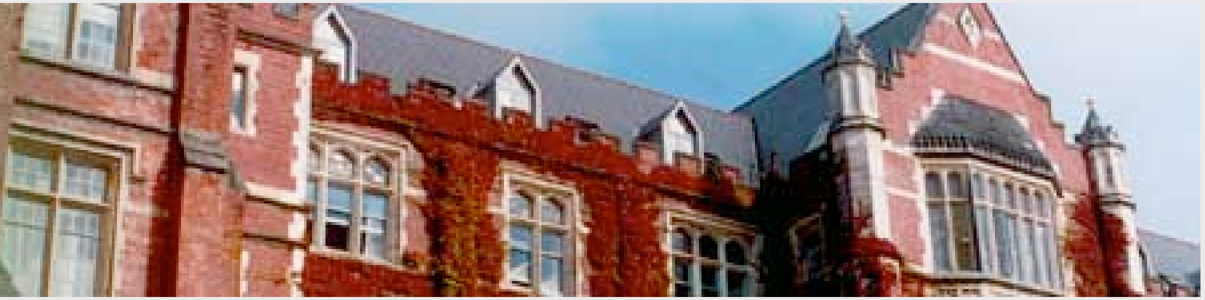


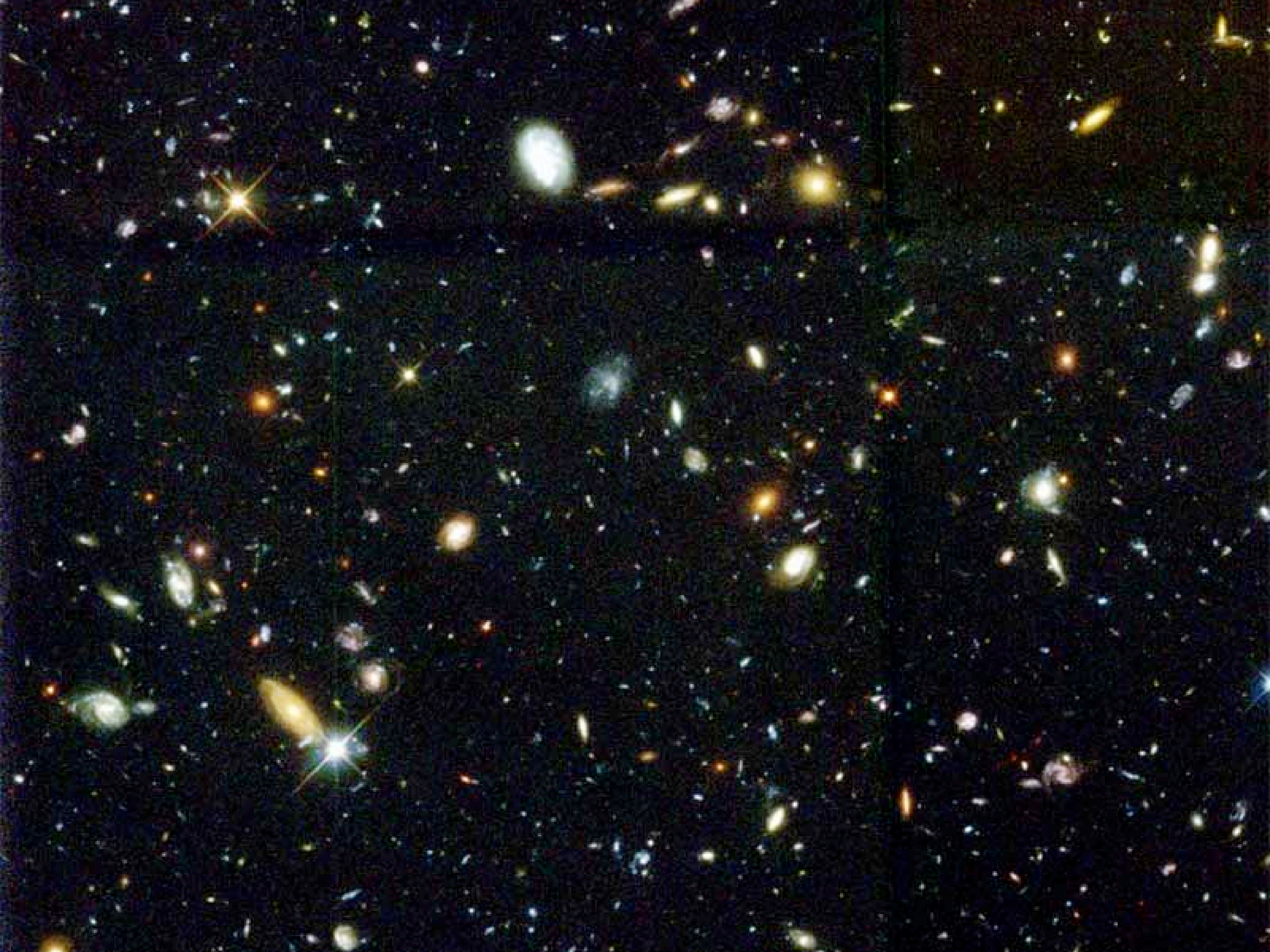
Magellanic clouds

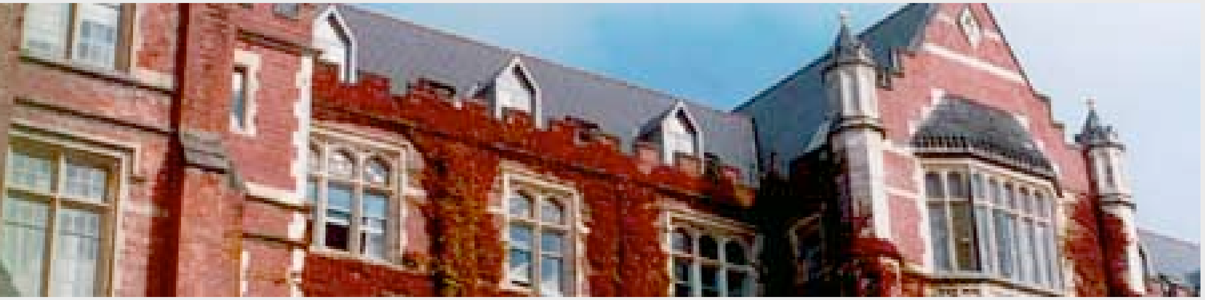


Andromeda galaxy




Local Group
Andromeda Galaxy
Milky Way





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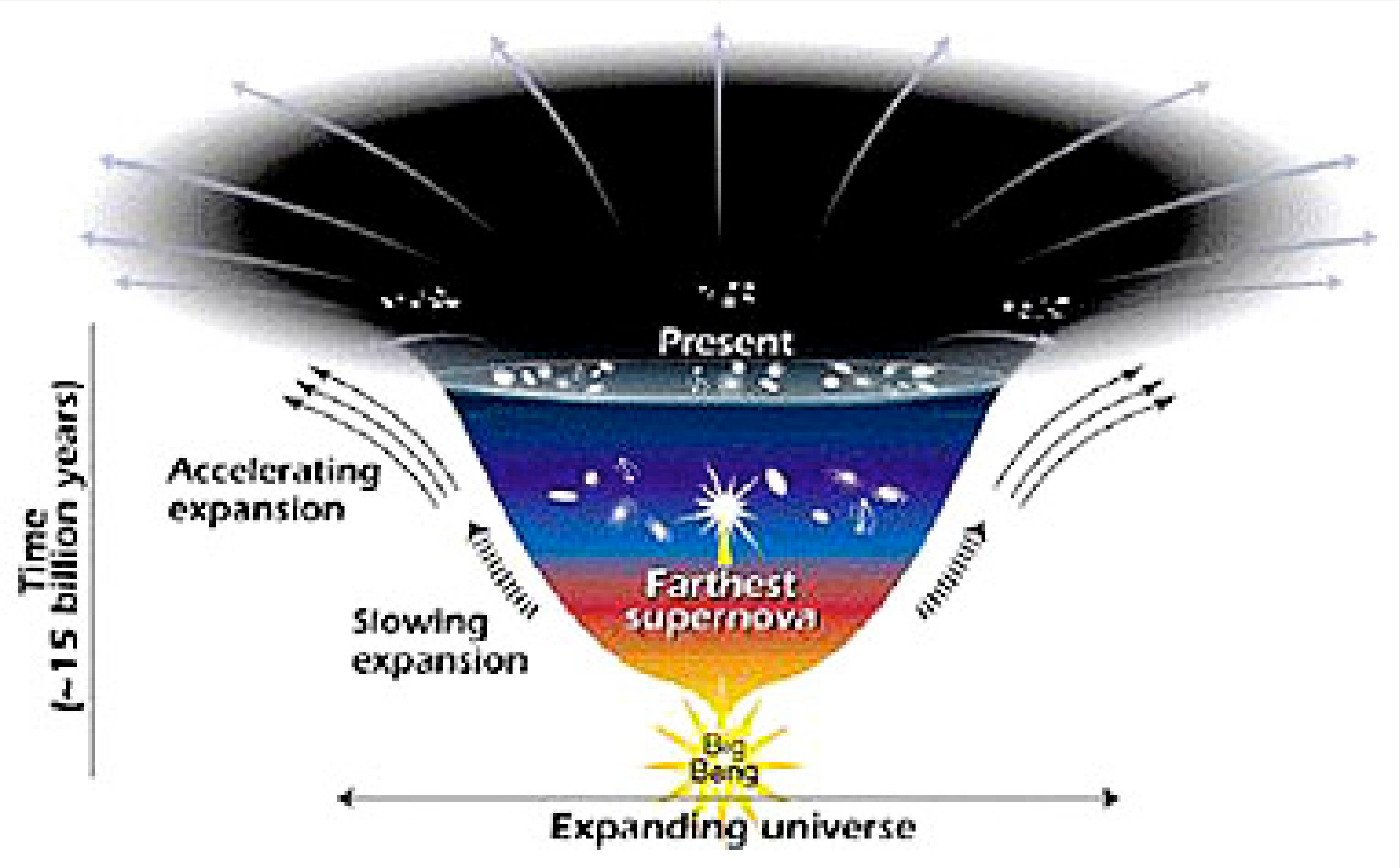

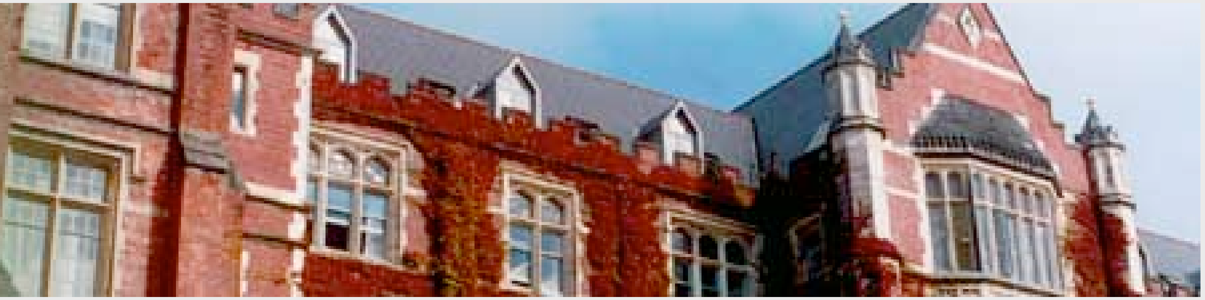

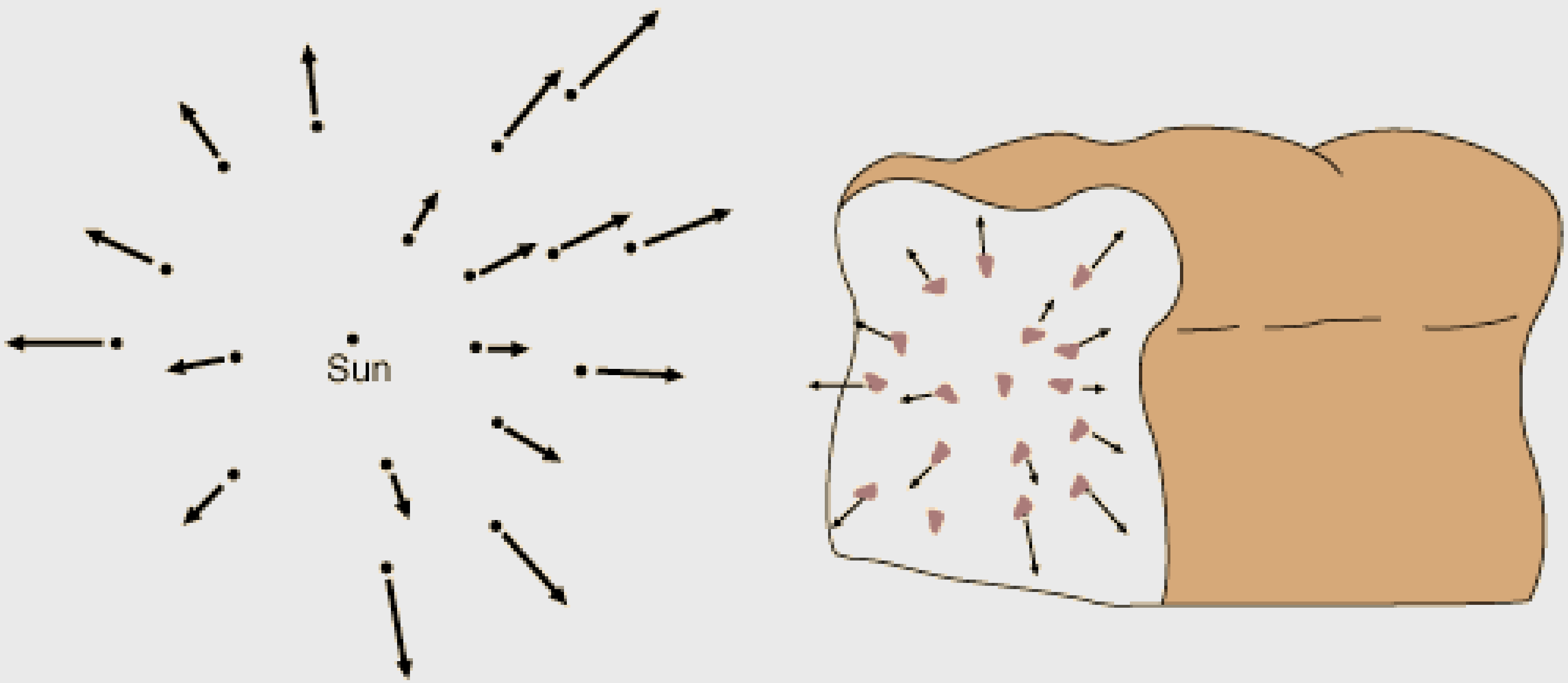
Sun

The big picture:

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Broadly speaking (rounding all numbers for simplicity):

As far as we can tell the universe began in a big explosion approximately 14,000,000,000 years ago [14 thousand million years ago, 14 US billion], give or take the odd 1,000,000,000 years.

Ever since then, the universe has been expanding and (apart from a few blips) cooling down, with the first stars and galaxies being born about 12,000,000,000 years ago.

The big picture:

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Our solar system, (including our star, the Sun, and our planet, Earth), was born about 4,500,000,000 year ago.

The universe is still expanding, and we can measure the rate of expansion (to within 10% or so).

We describe the rate of expansion by a formula called the Hubble law.

Now these are some pretty strong statements...

The Cosmic Picture

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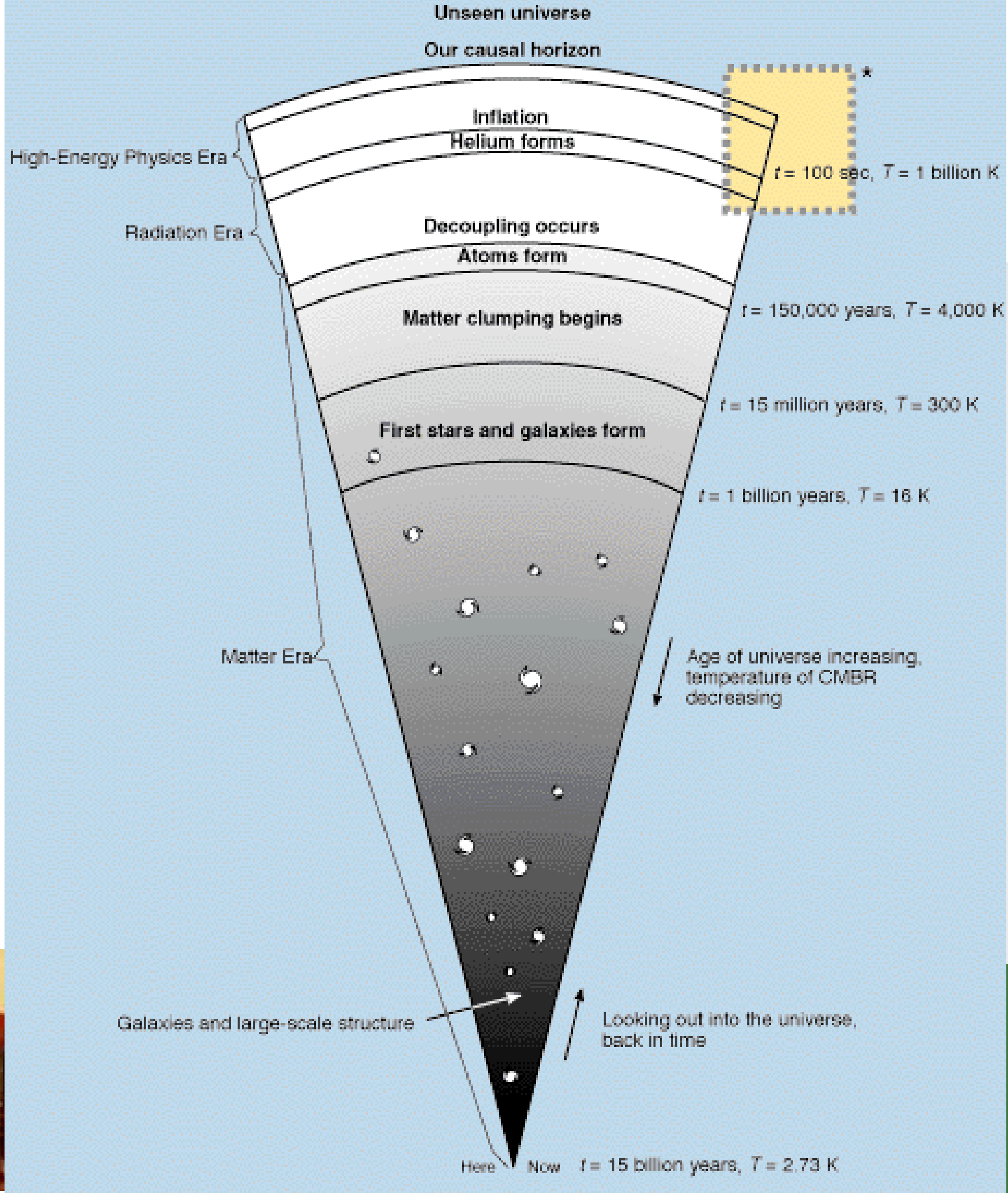

Justifying the big picture:

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A full justification would require a long and tedious analysis --- there's plenty of good technical books on cosmology if you really want the gory details.

An important point (often misunderstood) is the difference between "solid scientific fact" and "plausible extrapolation".

Roger Penrose (Oxford) has developed an interesting classification of scientific ideas into "Superb", "Useful", and "Tentative".

Superb, Useful, Tentative:

Superb theories are fundamental theories for which the data is so compelling, and for which the theories are so well understood, that to deny them is simply perverse.

The word "theory" should only be applied to ideas in the "superb" category, though most lay-people [and more than a few scientists] get this wrong.

Superb, Useful, Tentative:

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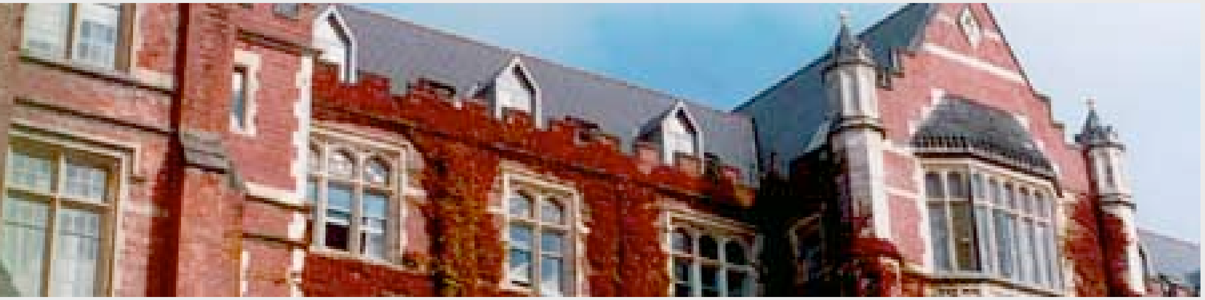
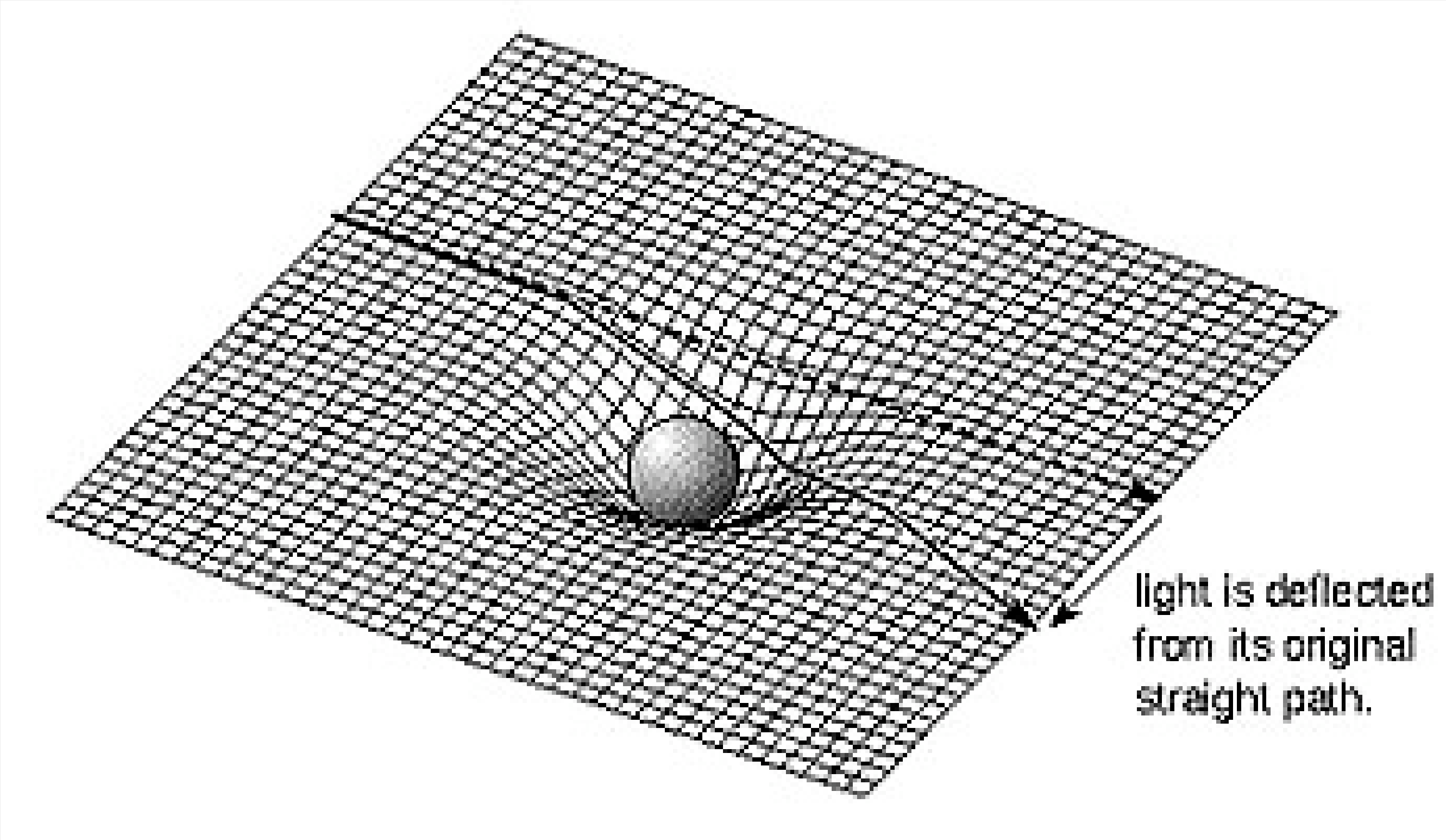
Examples of superb theories are:

Einstein's theory of special relativity,
Einstein's theory of gravity (the general relativity),
Quantum theory,
the theory of biological evolution.

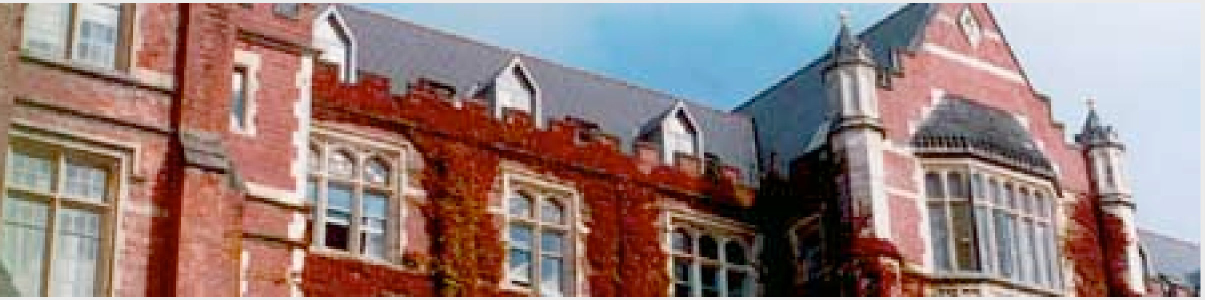
Theory to a scientist means:

"established beyond any reasonable doubt".





Einstein's general relativity predicts that gravity will "bend" starlight.



Gravitational Lens in Abell 2218 HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

Superb, Useful, Tentative:

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Useful models (and you should not really use the word theory here, make sure to call them "models") are good workhorse collections of ideas that work well for day to day purposes, but are in some sense provisional --- no one should be too surprised if they were eventually altered in some significant way.

A good example of this is the standard model of particle physics, which we eventually expect to be replaced by some "grand unified theory" [GUT], though we have not yet developed any really compelling candidate GUT to do the job.

Superb, Useful, Tentative:

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Tentative ideas are by definition at the forefront of research --- they may be exciting, innovative, surprising, and should be backed up by some serious high-quality calculations or observations.

But the "cutting edge" of research is also the "bleeding edge" of research --- and because they lie at the "bleeding edge", tentative ideas are by definition constantly subject to revision.

Superb, Useful, Tentative:

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Examples of tentative ideas are all current attempts at developing quantum gravity.

For example, "string theory" should not really be called a "theory", since the current complex of "string ideas" are, as yet, a complicated collection of very tentative ideas still struggling to become a useful model, let alone a superb theory.

The same can be said about all other current attempts at developing quantum gravity.

Superb, Useful, Tentative:

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Unfortunately the mass media tends to uncritically lump the whole lot together, making it difficult for the outsider (and even the insider) to tell how seriously to take a given news item.

Superb, Useful, Tentative:

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Where in this hierarchy does the "Big Bang" fit?

Parts of the Big Bang, those to do with the present-day expansion of the universe and the recession of galaxies are certainly in the "superb" category.

Given the present-day data, to reject the recession of galaxies and the Hubble law is simply perverse.

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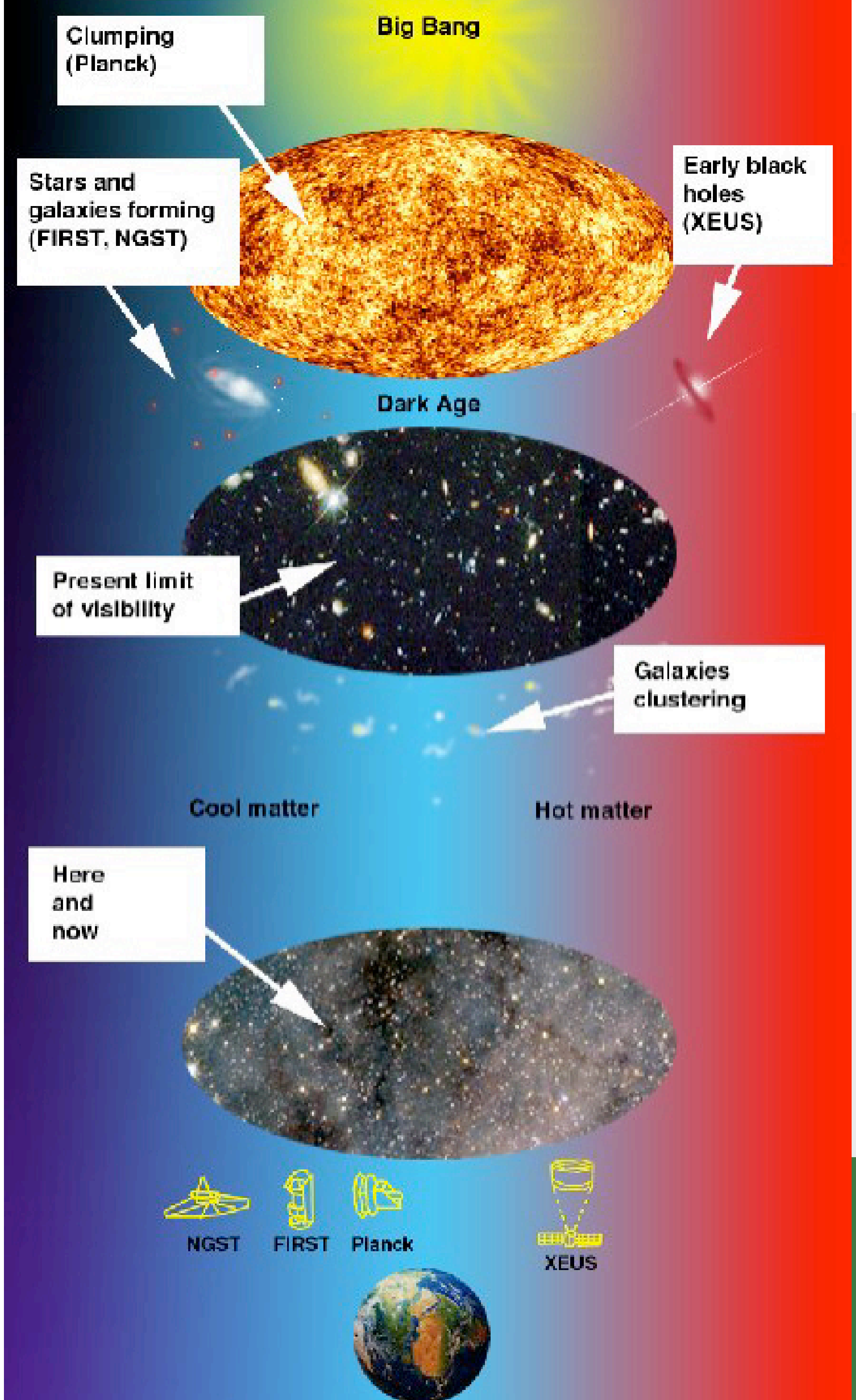
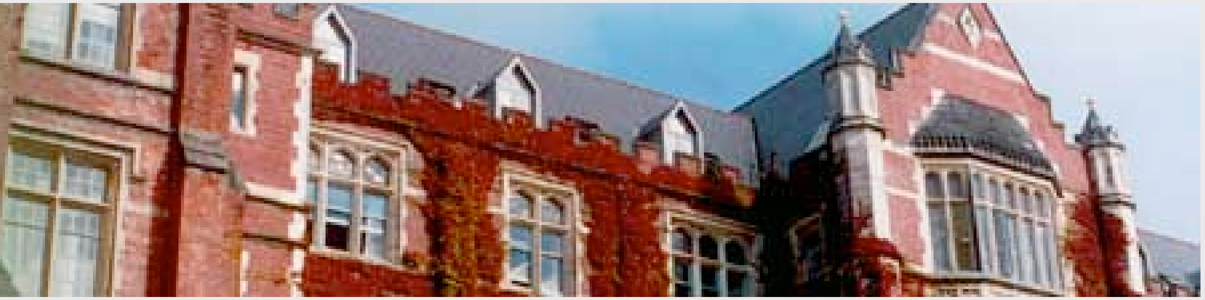
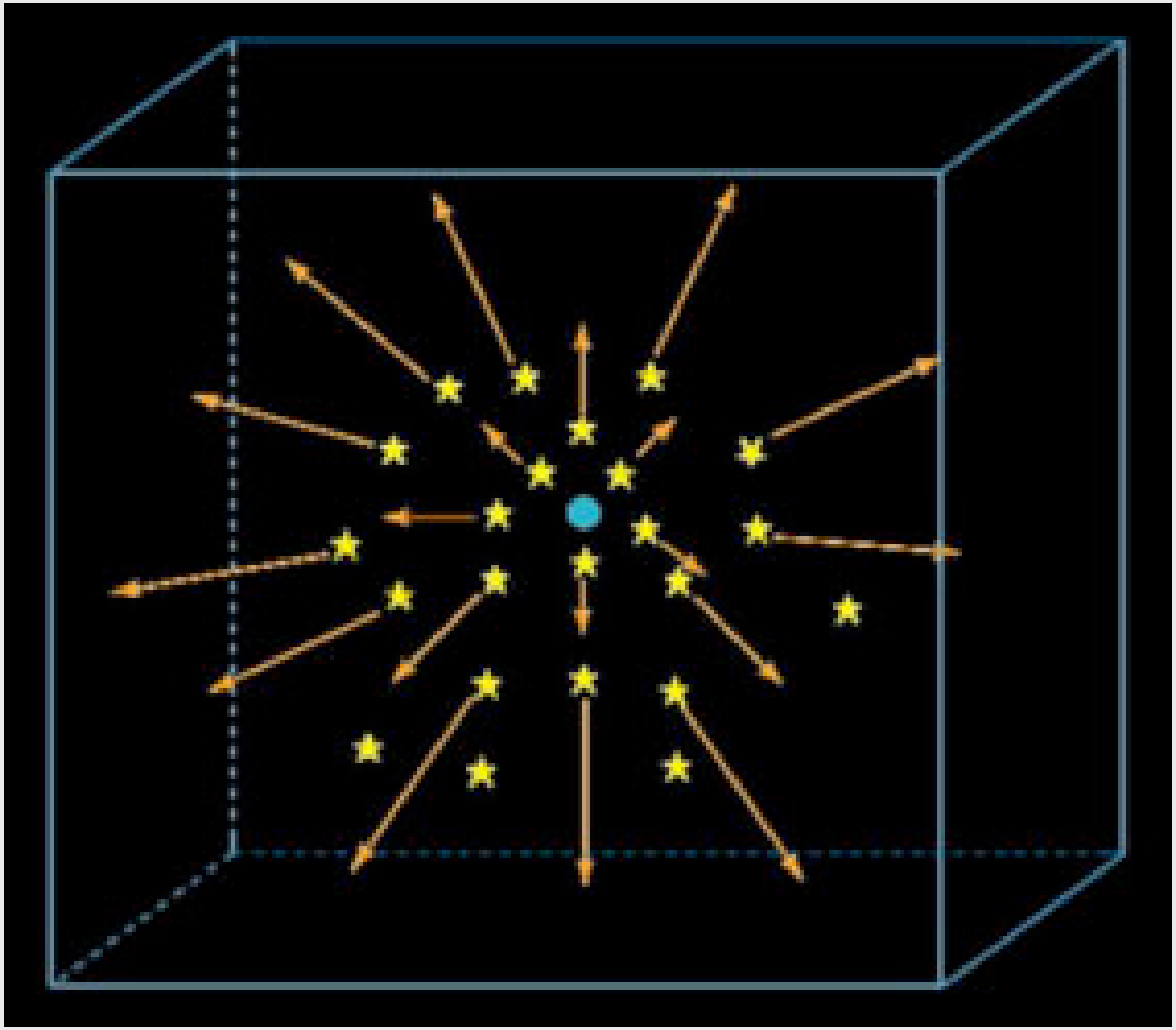


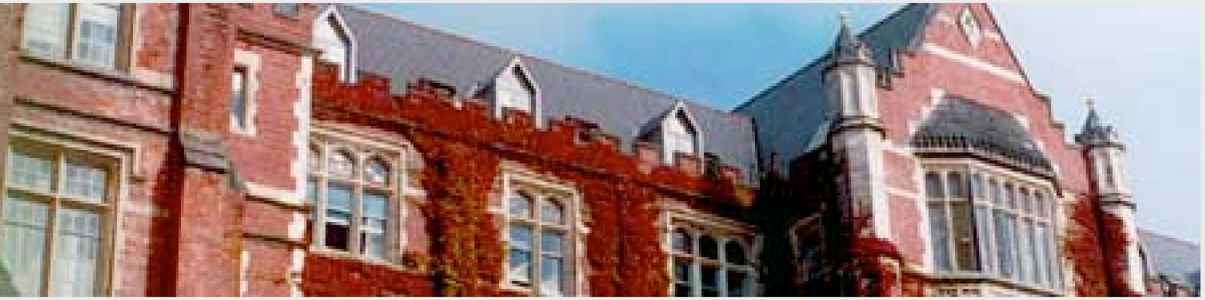
Hubble law:

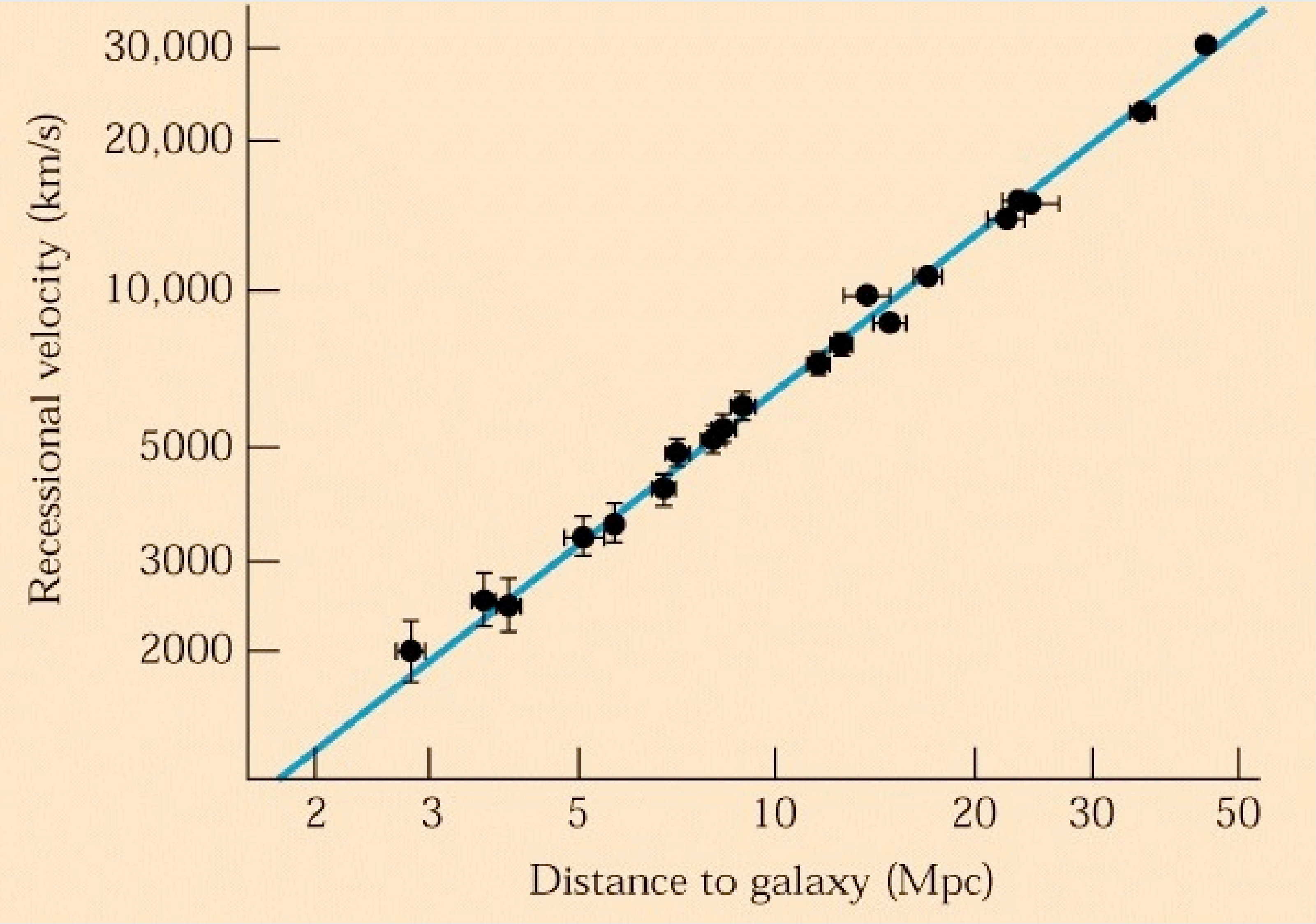
No matter what spin you put on the data, some form of the Hubble law will survive: the galaxies are by and large moving away from us with a speed proportional to their distance.

And if you back-track this expansion by about 13,000,000,000 years you will find that the universe then was much smaller than the universe is now --- roughly 1,000 times smaller in every direction, and so 1,000,000,000 times smaller in volume, with an average temperature that is about 1,000 times larger than today.








Recessional velocity (km/s)
30,000
20,000
10,000
5000
3000
2000
2
3
5
10
20
30
50
Distance to galaxy (Mpc)

Cosmic microwave background:

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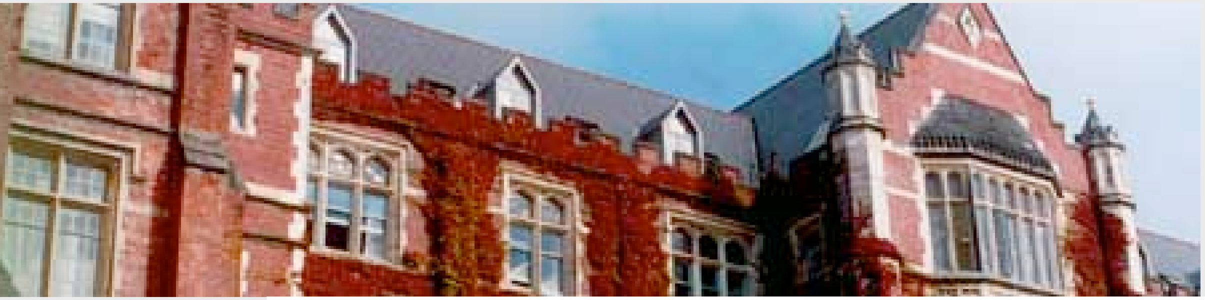
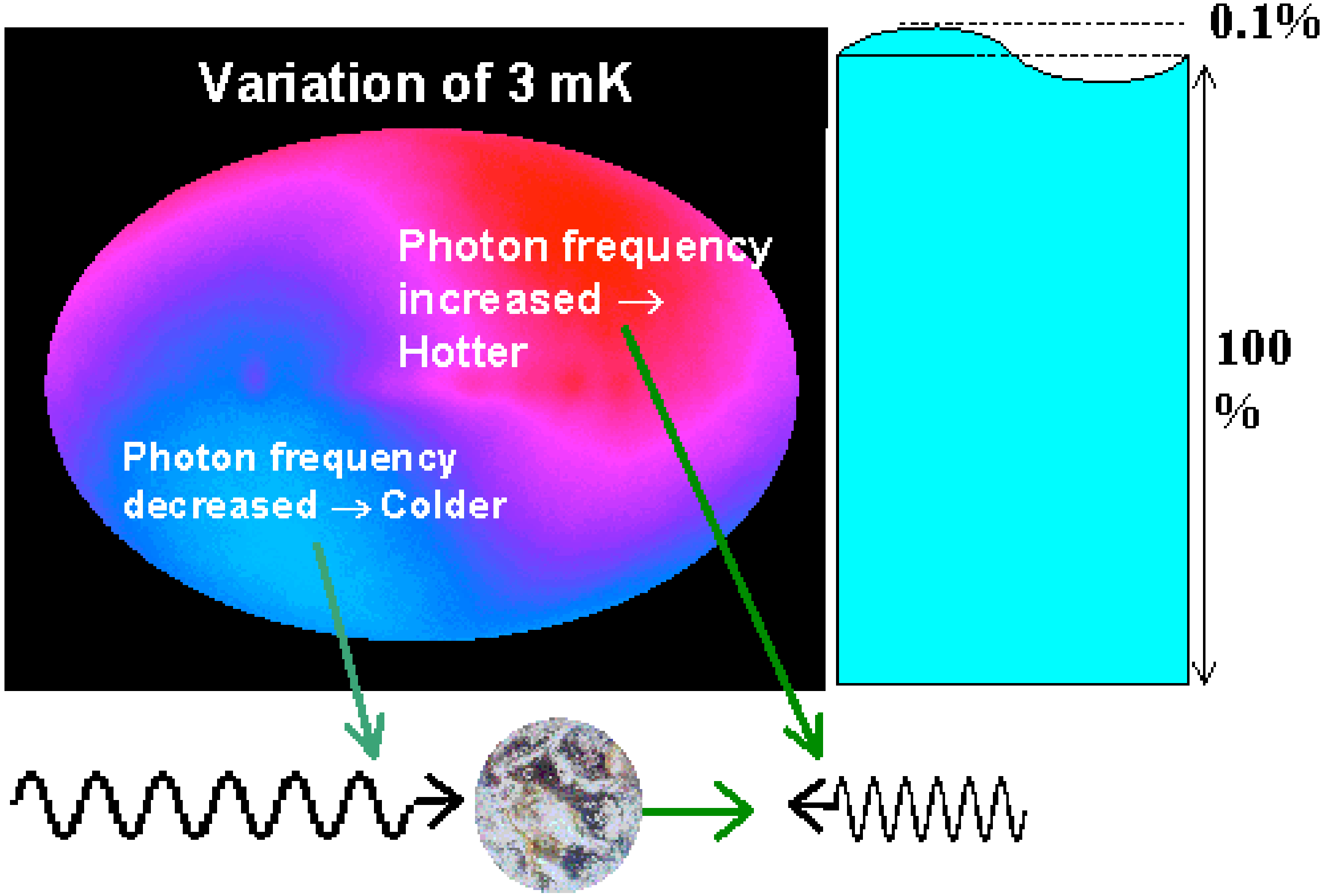
The average temperature today, as measured by the cosmic microwave background [CMB], is about 2.7 Kelvin, and about 13,000,000,000 years ago the temperature of the CMB was about 2,700 Kelvin, in the range where temperature begins to rip neutral Hydrogen atoms apart to form a plasma of protons and electrons.

These key features of the Big Bang are well enough established that they will survive any conceivable upheaval in cosmology.



SMALL VARIATIONS IN T_{CBR} DETECTED BY COBE DMR



Standard cosmological model:

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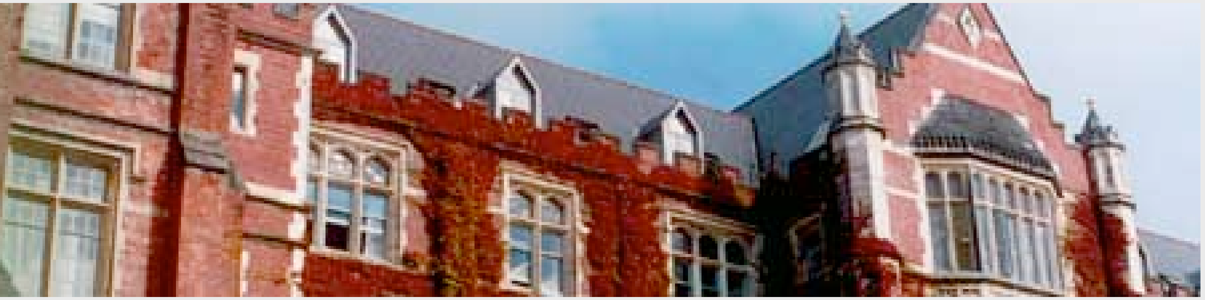
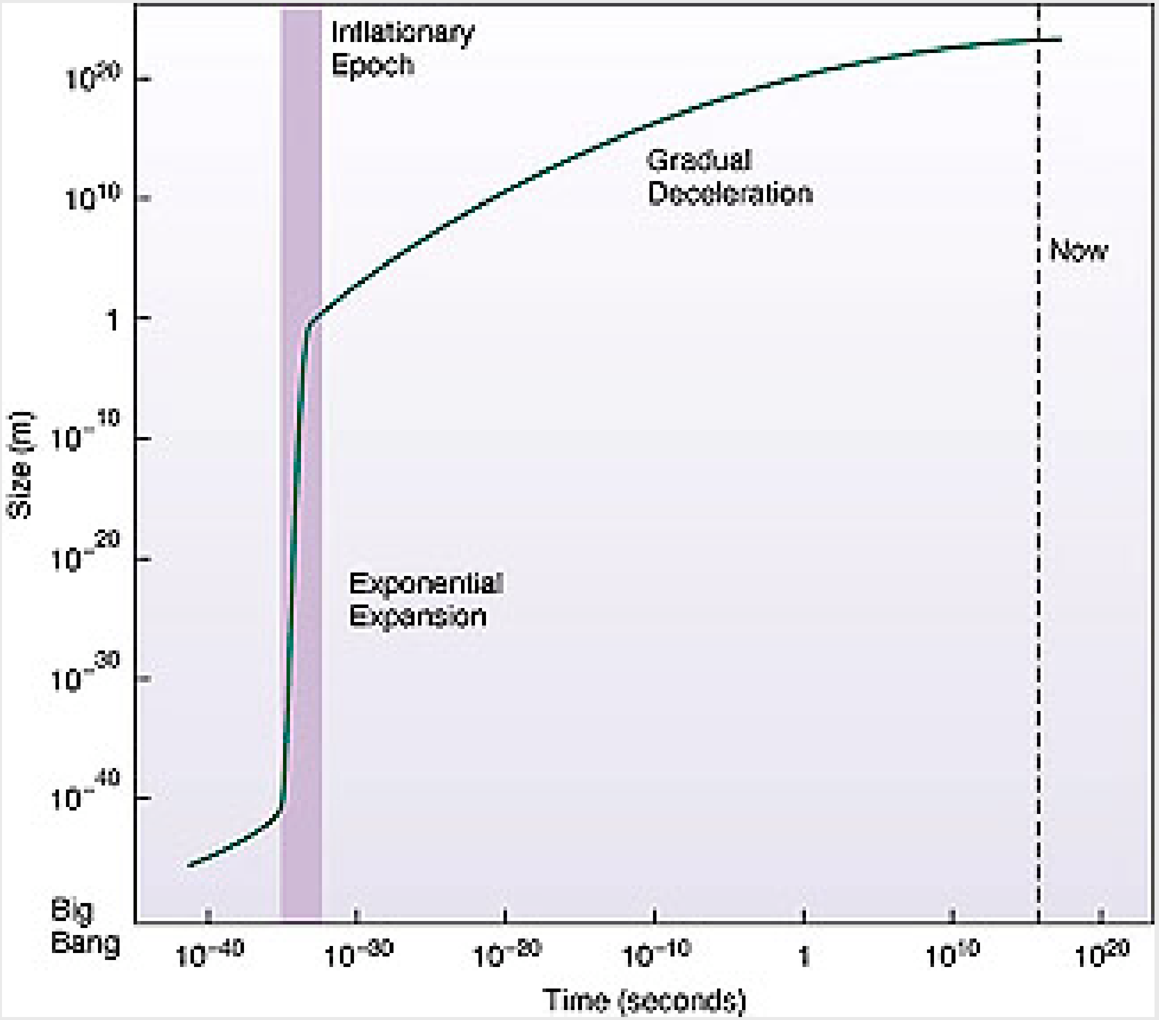
But the Big Bang is more than these key features, once you add some more flesh to the Big Bang it becomes the "Standard Cosmological Model", and some of these add-ons are in the "useful" category rather than the "superb" category.

Here I am referring, for instance, to "cosmological inflation", which is a period of anomalously rapid expansion in the early universe.





Cosmological inflation.

What goes around comes around?

Cosmological inflation:

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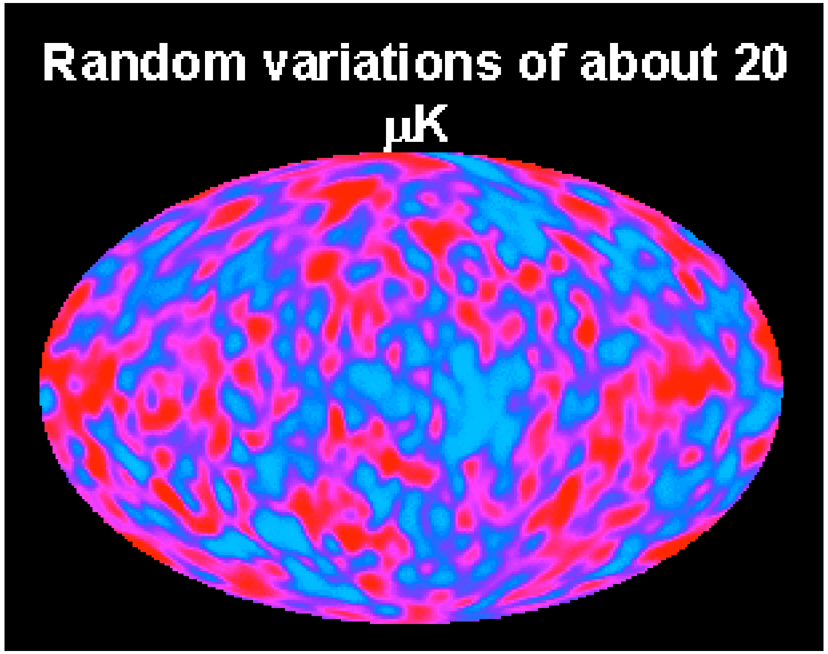
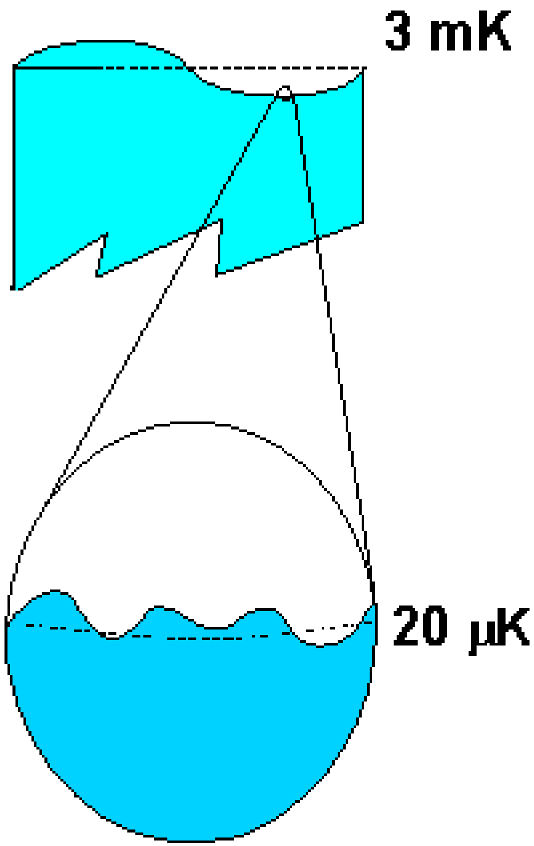
"Cosmological inflation" allows the expansion of the universe to speed up and slow down.

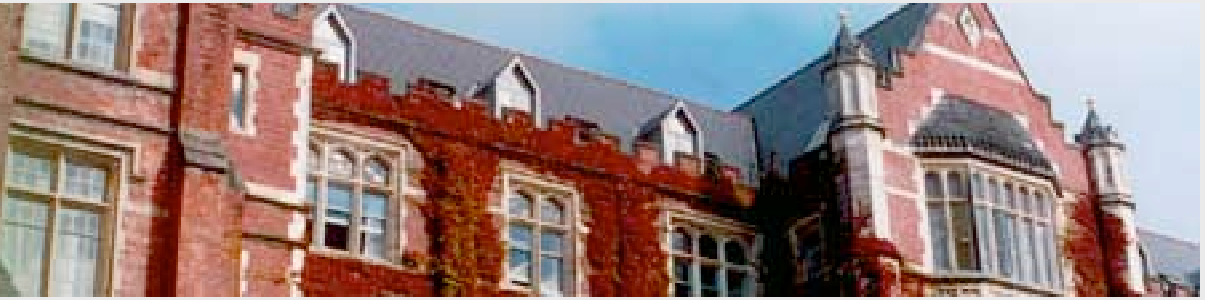
Cosmologists need this to make some of the details of the extensions to the Big Bang work just right.

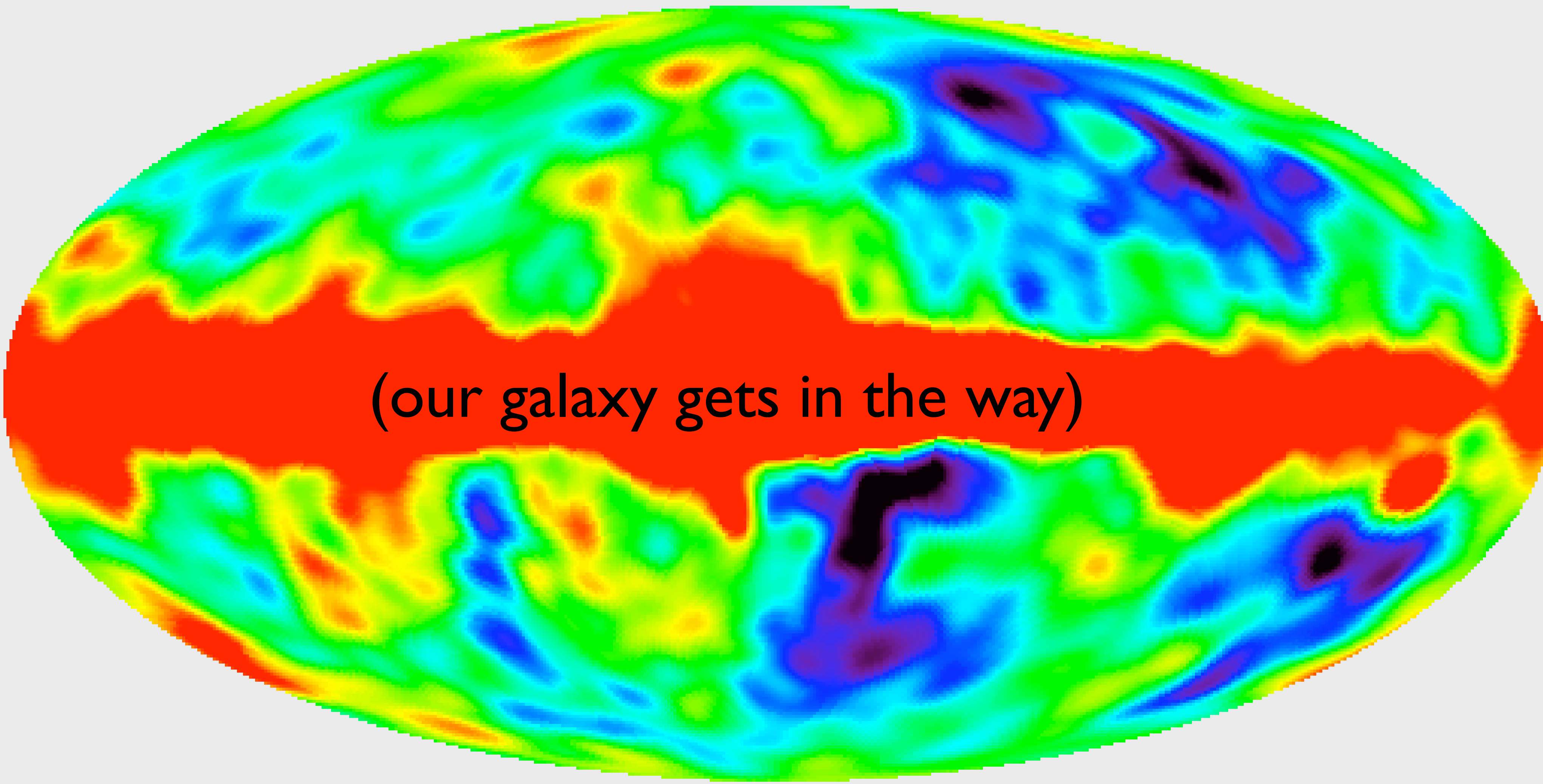
Essentially all cosmologists agree that there was such a period of anomalously rapid expansion, but there is a lot of quite legitimate disagreement as to precisely how the expansion during the inflationary epoch was driven.

EVEN SMALLER VARIATIONS IN T_{CBR}









Small fluctuations in the cosmic microwave background

The accelerating universe?

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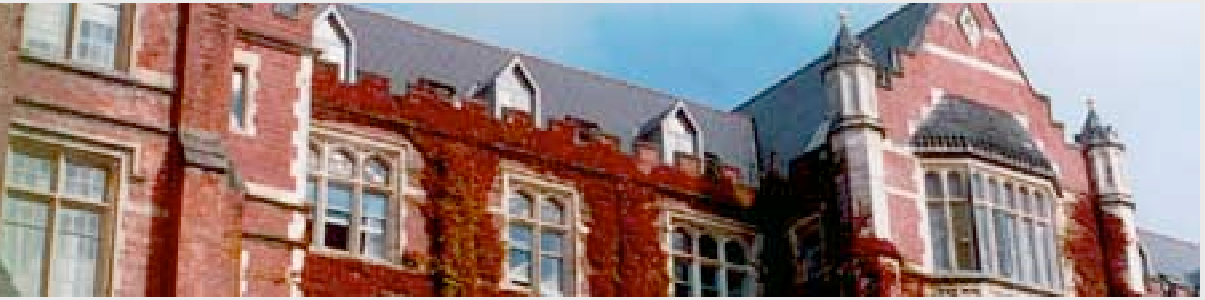
Some aspects of modern cosmology are still at the tentative level.

For instance, I would still judge the idea of the "accelerating universe", the suggestion that the present-day expansion of the universe is accelerating (not decelerating) as "tentative".

Now there is lots of good data supporting the idea of the "accelerating universe", and I am not suggesting that this idea is wrong --- but this definitely is "bleeding edge" research.




The expanding universe
Present
Expansion slows down
Expansion speeds up
Big Bang
Farthest supernova
~15 billion years

The accelerating universe?

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Because this is “bleeding edge” research, it is still potentially subject to revision.

Given a few more years of data, and a few more years of theoretical analysis, I would expect the idea of the accelerating universe to move into the “useful” category.

(Given a few decades of new data and analysis, this idea might move into the “superb” category, but it is simply too soon to tell.)

Summary so far:

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I hope I have given you some overall feel for what is "rock solid" in cosmology, what is "generally accepted", and what is "still under debate".

It is also important to realise that these distinctions, between superb/useful/tentative, apply in all branches of science --- not just cosmology and physics.

Superb, Useful, Tentative:

Mathematics is a special case in that we do not need to perform experiments or make observations, we can judge the correctness of a mathematical theory based on pure logic.

However in the experimental and observational sciences (Physics, Chemistry, Biology, Astronomy, Cosmology) we need more than just pure logic --- we need to look at the world around us to verify that our ideas correspond to empirical reality.

If not --- modify your ideas.

Hubble law:

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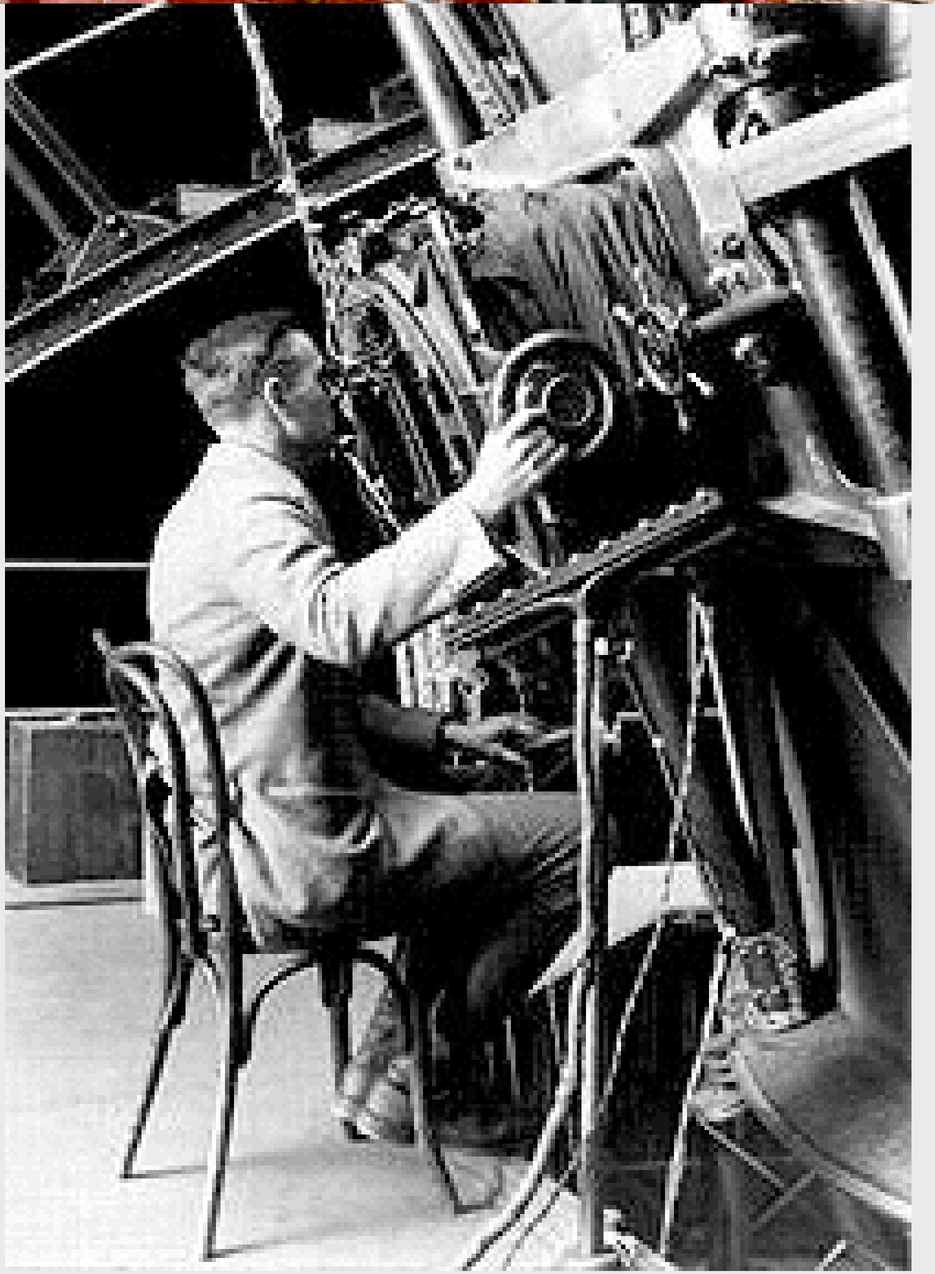
The Hubble law is the statement that by and large, and on the average,other galaxies are moving away from our own (the Milky way) with:

(speed of recession) proportional to (distance).

The proportionality constant is called the Hubble parameter and we can write the equation:

$$v = H_0 d.$$



Edwin Hubble

Hubble law:

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The best estimates we have [2005] of the Hubble parameter are:

H_0 = 72 (kilometres/second)/Megaparsec
[plus or minus 10%]

The "plus or minus 10%" is important --- observational measurements of the precise proportionality parameter are difficult.

Hubble law:

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The linear Hubble law is not absolute, there are deviations both at small distances (meaning the nearby galaxies), and at very large distances (once we get near the "edge of the visible universe").

At short distances the deviations from the Hubble law are due to so-called "peculiar velocities".

Think of the galaxies as a "gas" in an expanding background --- there are random velocities superimposed on the overall flow.

Hubble law:

At larger distances things are more subtle --- as we look out to very large distances, then because light travels at a finite speed we are also looking back in time.

But as the universe ages, the Hubble parameter can also change, the Hubble parameter need not be a constant.

In addition, at large distances one begins to see effects due to the curvature of space.

The net effect is that there will be some sort of series expansion:

$$v = H_0 d + K_2 d^2 + K_3 d^3 + \ldots$$

Hubble law:

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Cosmologists can [as of 2005] measure the first coefficient H_0 to within 10%.

The next coefficient is what most of the major fuss is about, as measuring that coefficient is crucial to testing whether or not the expansion of the universe is accelerating or decelerating.

Until about 5 years ago, 2000, almost everyone expected the expansion to be decelerating.

The consensus now [2005] is that the expansion is accelerating, but this measurement should still be viewed as "tentative".

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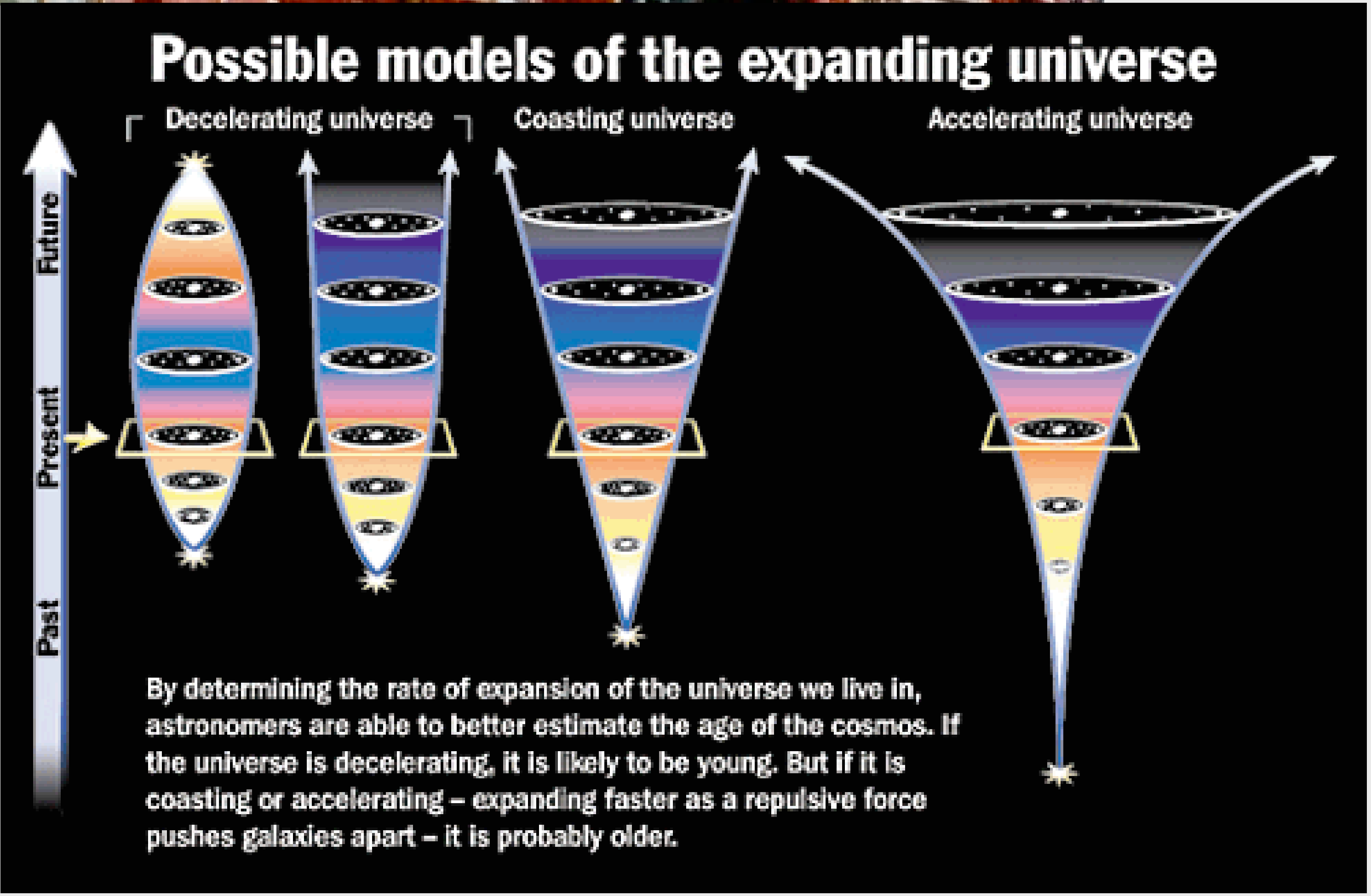
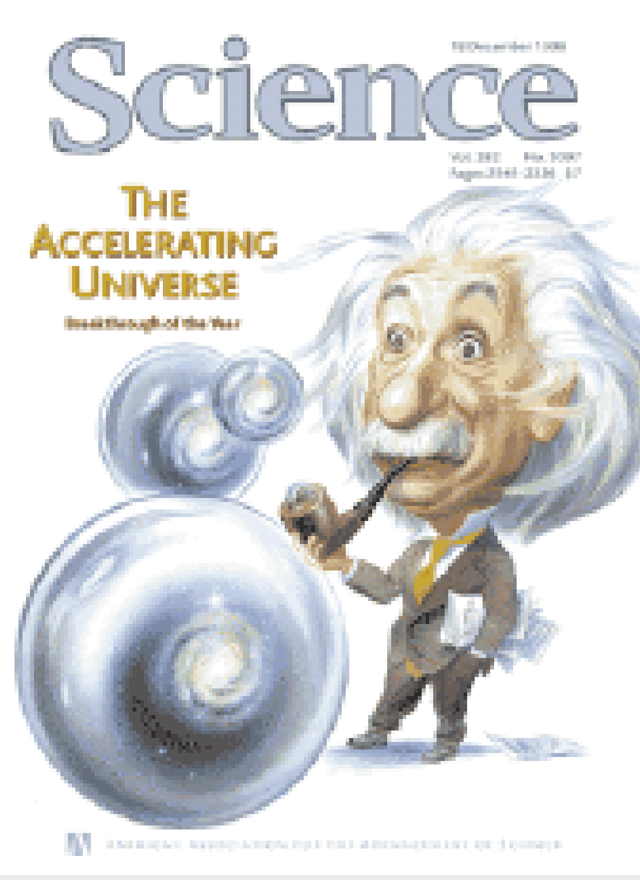




Hubble law:

Now measuring the velocity of recession, v, is "easy".

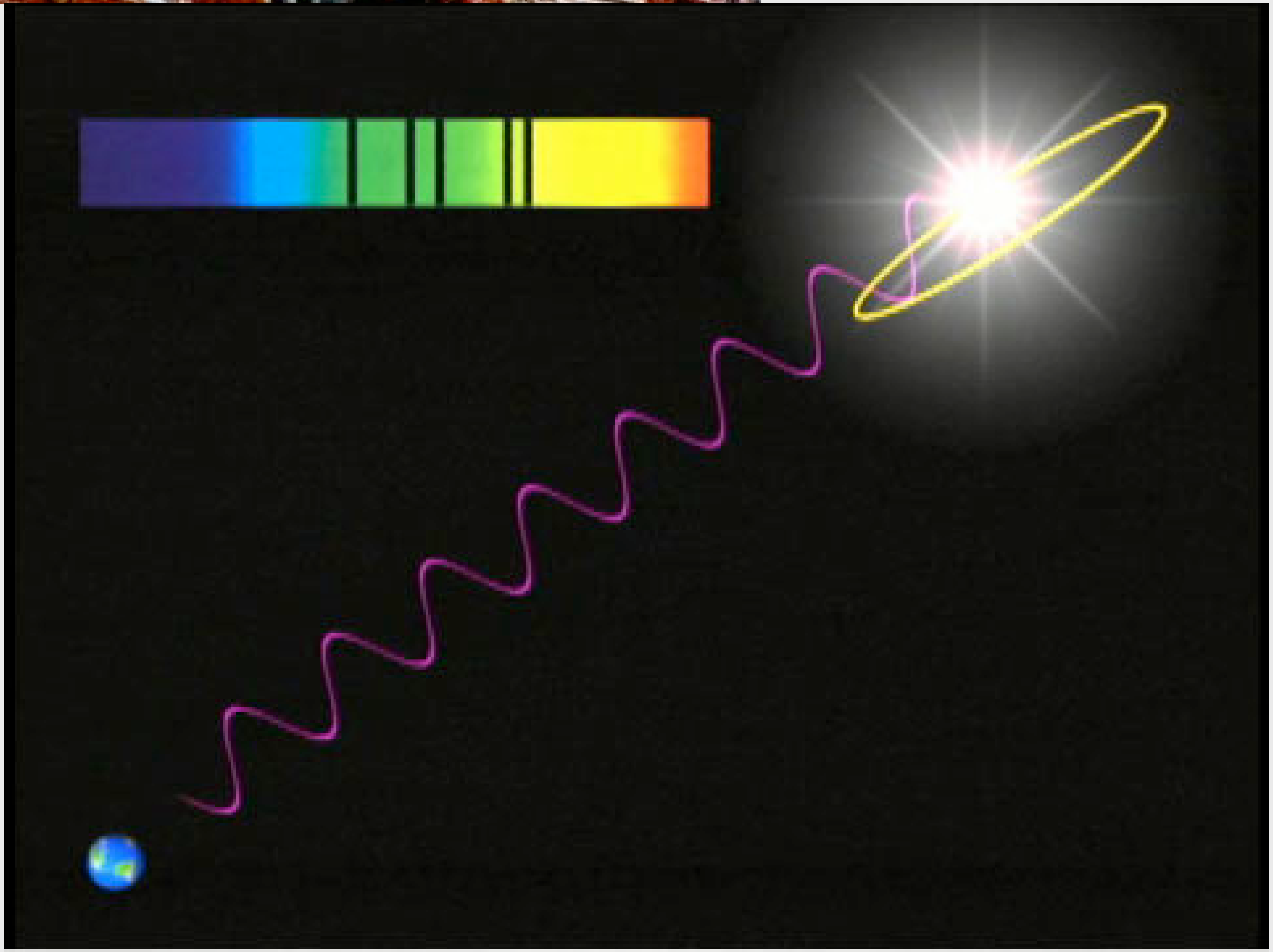
Astronomers do this using the Doppler effect --- a galaxy that is moving away from us has the frequency of its light decreased, and the wavelength of its light increased.

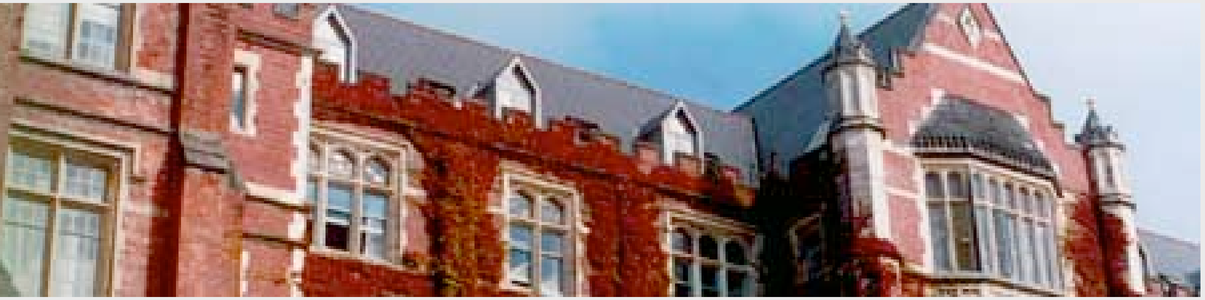
So its light is reddened, and this "red shift" is related to the velocity.

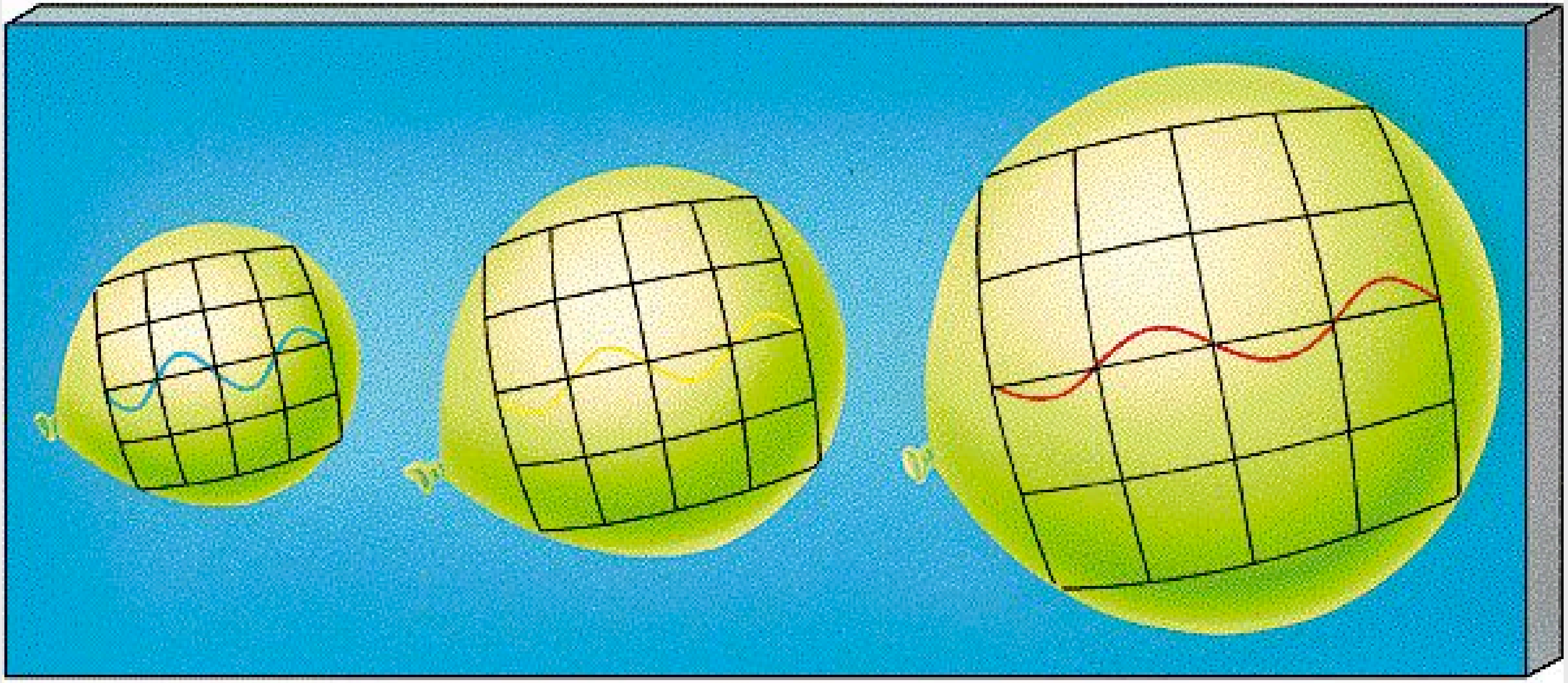
(A similar effect occurs when the whistle of a passing train seems to shift its frequency as it passes a stationary observer at the side of the tracks.)

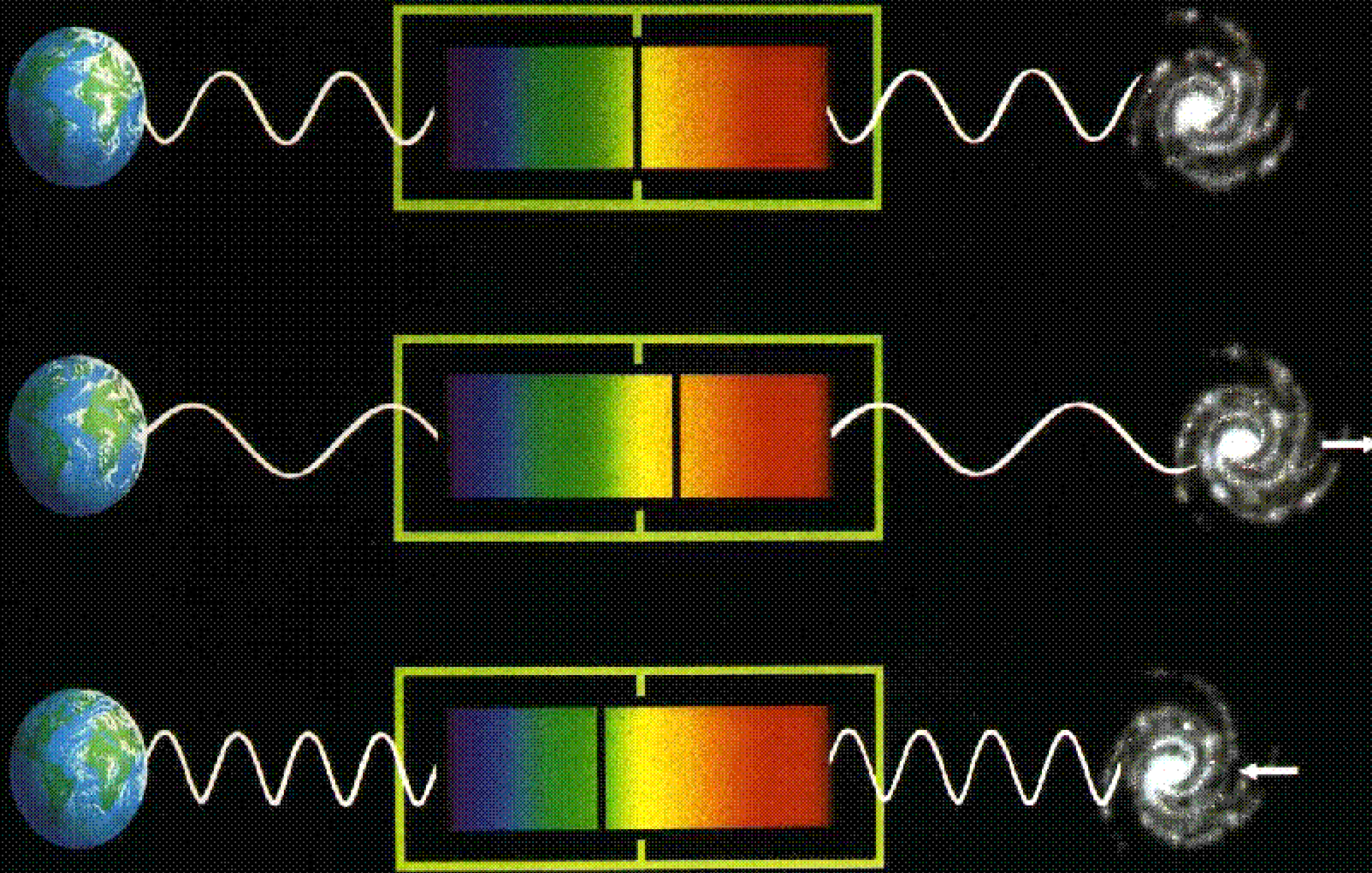
Hubble law:

The way you detect red-shift in galaxies is by looking for the pattern of spectral lines from particular atoms and molecules and seeing how far you have to shift the pattern to make it line up with the same pattern of spectral lines observed in the laboratory here on Earth.









Hubble law:

Most of the individual stars you can see in the night sky with the naked eye are in our own Milky way galaxy and have negligible redshift.

Several nearby galaxies can just barely be made out by naked eye observations (the clouds of Magellan, the Andromeda galaxy).

Most galaxies need serious telescopes in order to see them (eg, the Hubble space telescope).

Hubble law:

Even with powerful telescopes, almost all visible galaxies have redshift less than one.

Two effects account for this: First is sheer distance, large redshift is correlated with large distance and so the inverse square law of luminosity guarantees that far away objects are very dim.

Secondly, because of the finite speed of light, looking further out means you are also looking further back in time --- eventually you get to a stage where the first galaxies have not yet formed.

Hubble law:

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The furthest visible galaxies are at about redshift 4, and theoretical calculations indicate that the very first stars formed at about redshift 10.

So in this sense our telescopes (specifically the Hubble space telescope) are now [2005] looking out almost to the "edge of the universe".

(With the "edge of the universe" being defined by the formation of the very first stars.)

Hubble law:

To accurately measure the Hubble parameter H_0, and the so-called deceleration parameter, we need accurate distance determinations to galaxies at medium to high redshift (say, redshift 1/2 to redshift 4).

Measuring distances is much much more difficult than measuring redshift and this is where all the technical arguments lie.

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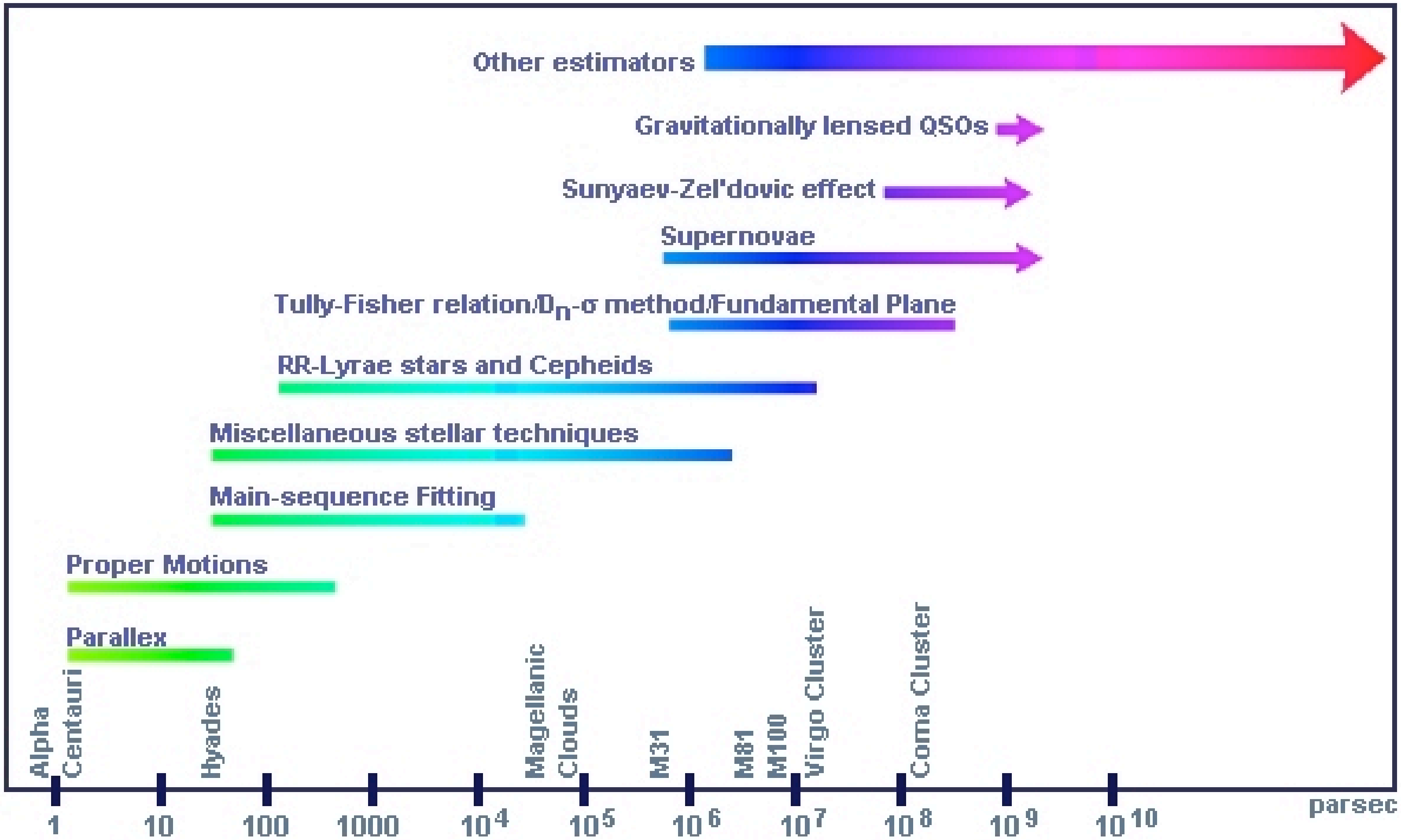

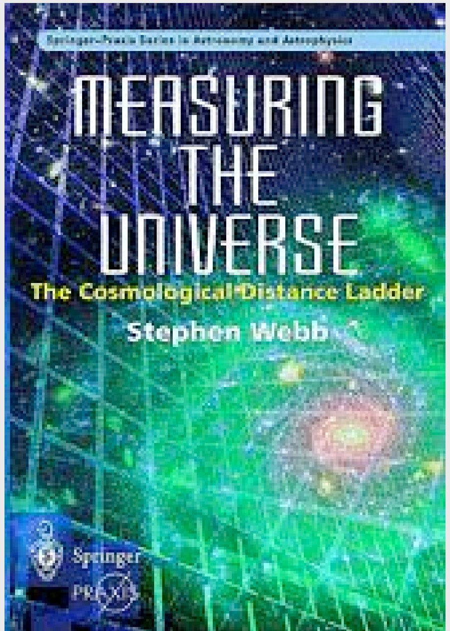

Hubble law:

Measuring relative distances (the ratio of distances) at low to medium redshift (say, redshift = 1/100 to redshift =1/2) is not too difficult,

This is enough to tell you that the Hubble law is linear for low to medium redshift.

But evaluating the proportionality constant requires absolute measures of distance (not just ratios of distances), and this is difficult.

Hubble law:

Measuring absolute distances to medium to high redshift galaxies is still “bleeding edge” research.

Measuring absolute distances to nearby low-redshift galaxies is comparatively easier, but even here the observational uncertainties are at about the 5% level.

Hubble law:

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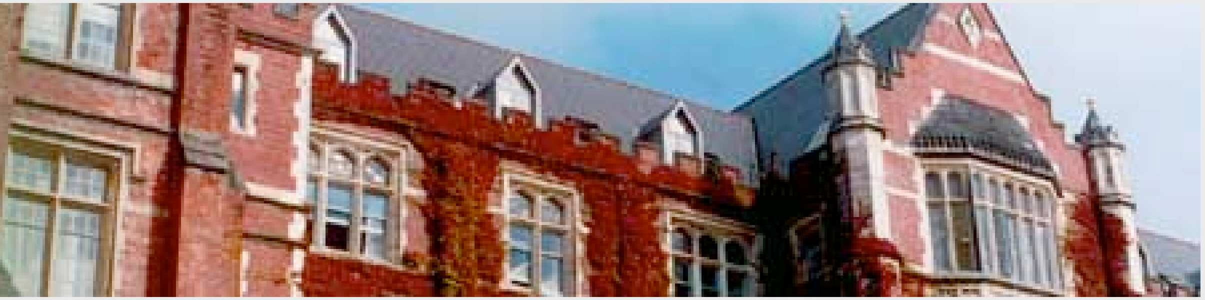
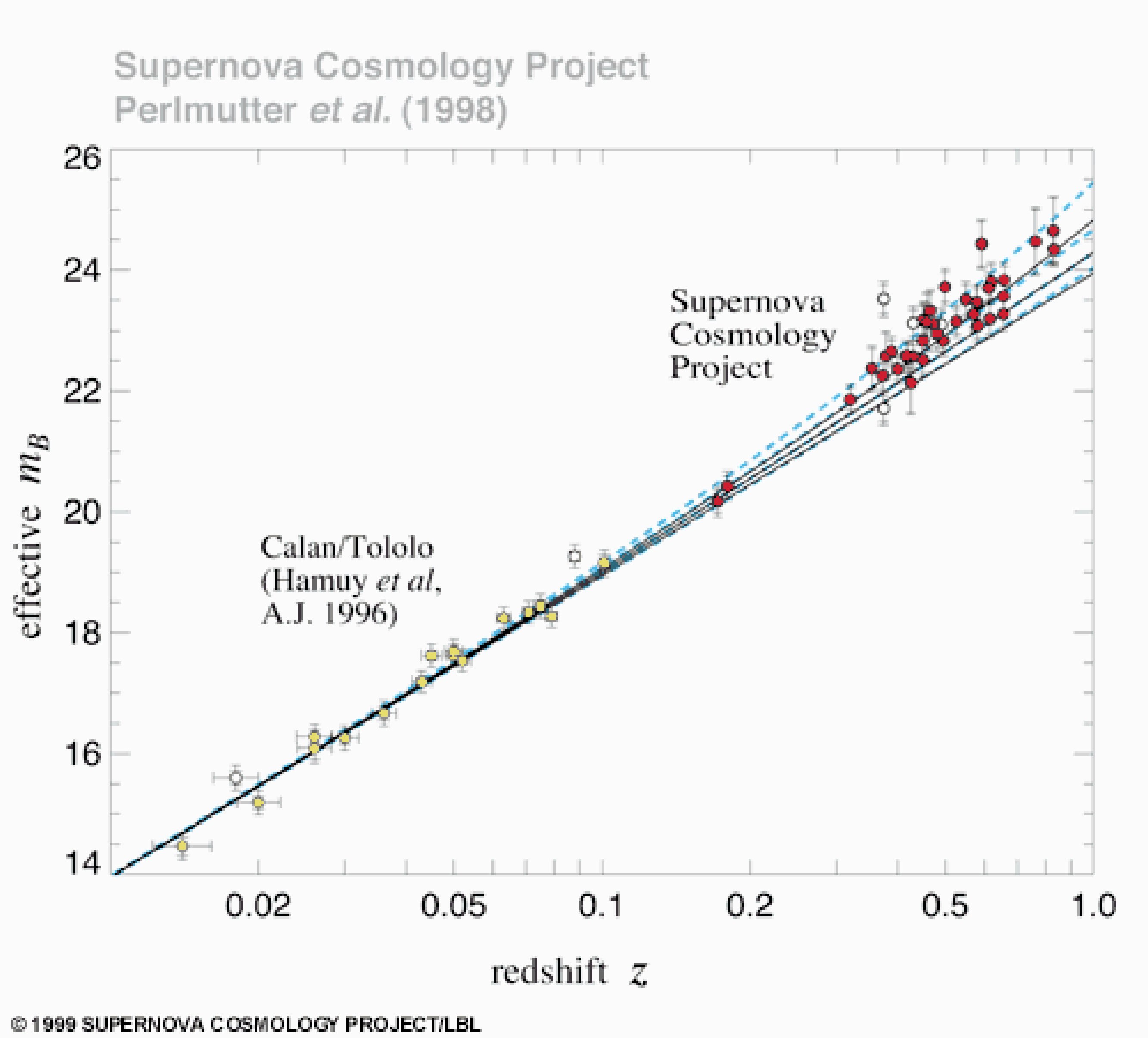
In summary, the expansion of the universe is a real phenomenon, and the Hubble law cosmologists use to describe this effect is "rock solid" cosmology.

The specific value of the coefficients in the Hubble law is more uncertain with value of the Hubble parameter still being uncertain to about 10%.

The second quadratic term in the Hubble law is even more difficult to measure, but measuring this coefficient is essential to determining whether or not the expansion of the universe is accelerating or decelerating.




Supernova Cosmology Project
Perlmutter et al. (1998)
26
24
22
20
18
16
14
effective m_B
Supernova
Cosmology
Project
Calan/Tololo
(Hamuy et al,
A.J. 1996)
0.02
0.05
0.1
0.2
0.5
1.0
redshift z
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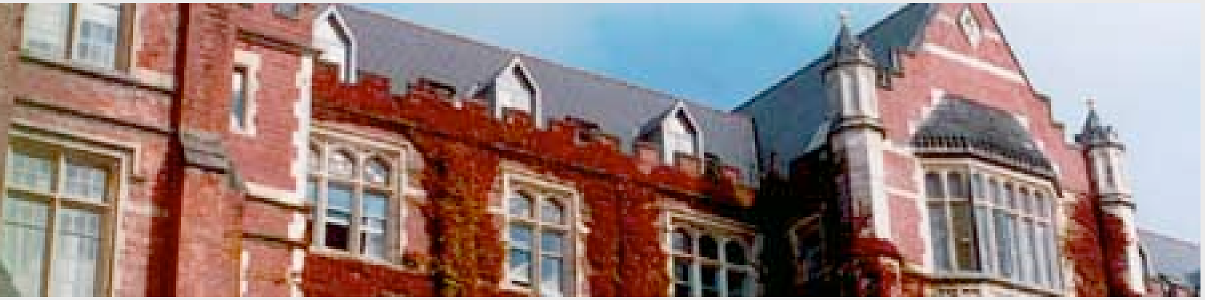

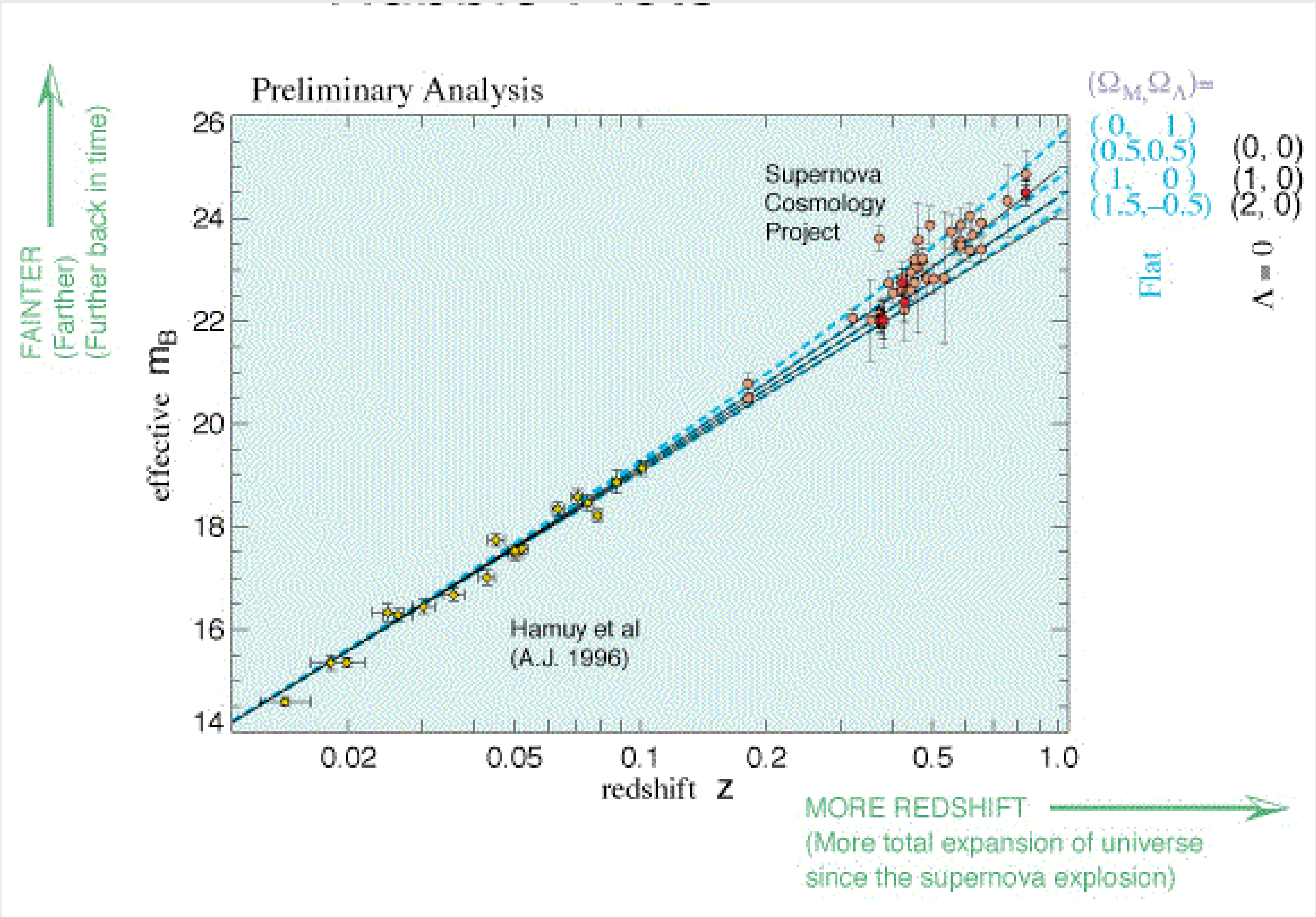

Preliminary Analysis
Supernova
Cosmology
Project
Hamuy et al
(A.J. 1996)
effective m_B
redshift z
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
$(\Omega_M,\Omega_\Lambda)$ =
(0, 1)
(0.5,0.5)
(1, 0)
(1.5,–0.5)
(0, 0)
(1, 0)
(2, 0)
Flat
$\Lambda = 0$
FAINTER
(Farther)
(Further back in time)
MORE REDSHIFT
(More total expansion of universe
since the supernova explosion)

Conclusions:

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1) The "big bang" is alive and well...

2) There is a lot of good high-quality data coming in, this helps keep the theorists on track...

3) There is a lot of room for debate at the margins, but the core of the "big bang" is rock solid.

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