# AST 301
# Introduction to Astronomy


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AST 301 (Lacy), course website

# Topics for this week

What does Hubble’s law tell us about the Universe?

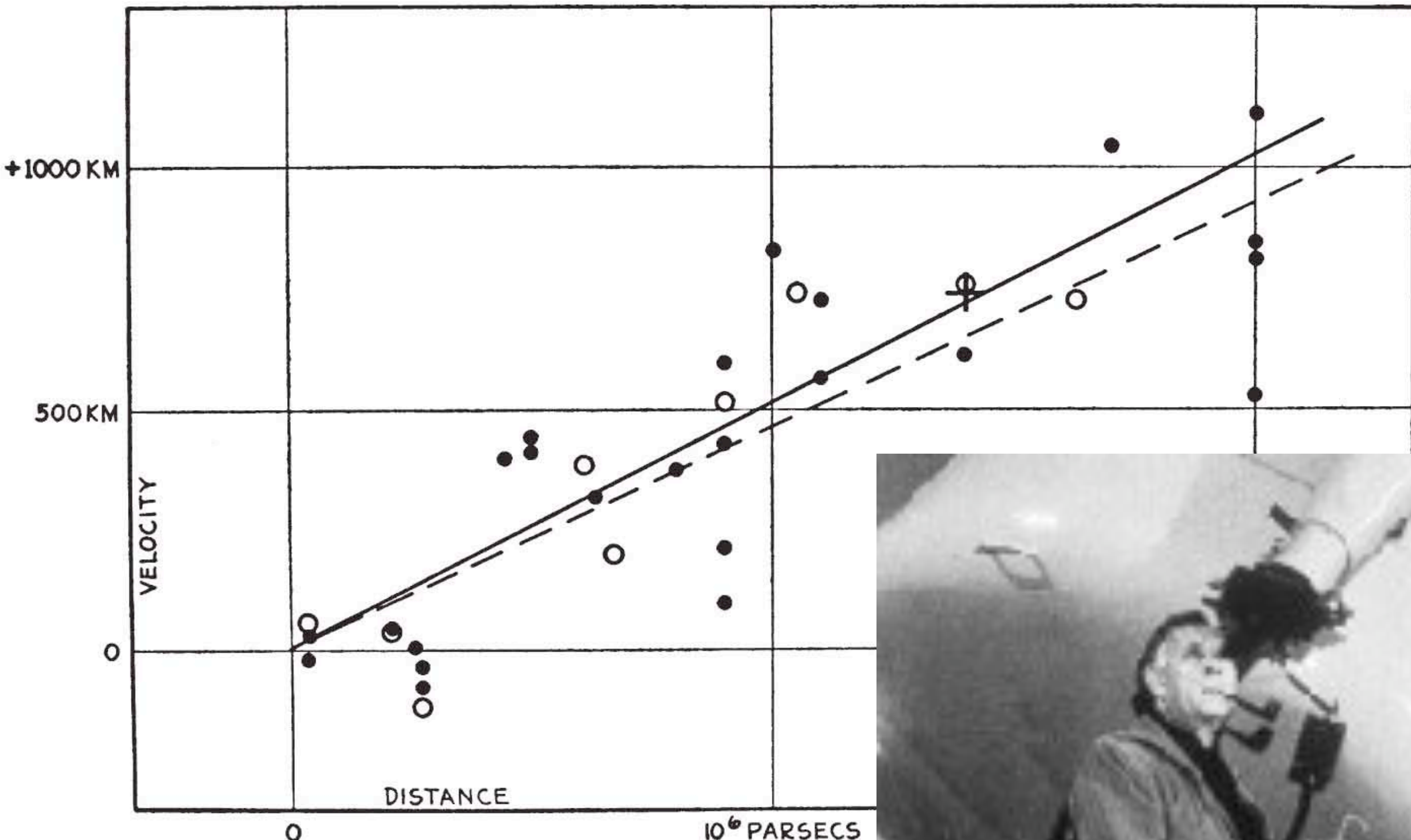
What is the Universe made of?

What are dark matter and dark energy?

Is the rate of expansion of the Universe changing?

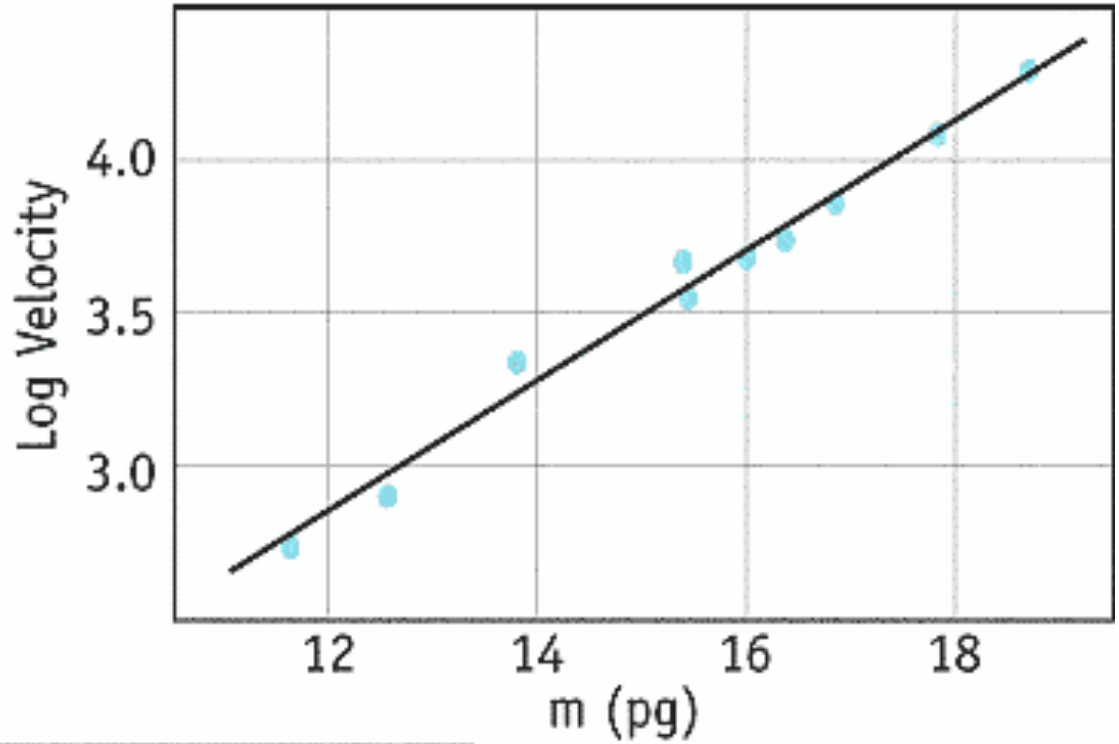
Will the Universe pull back together some day?

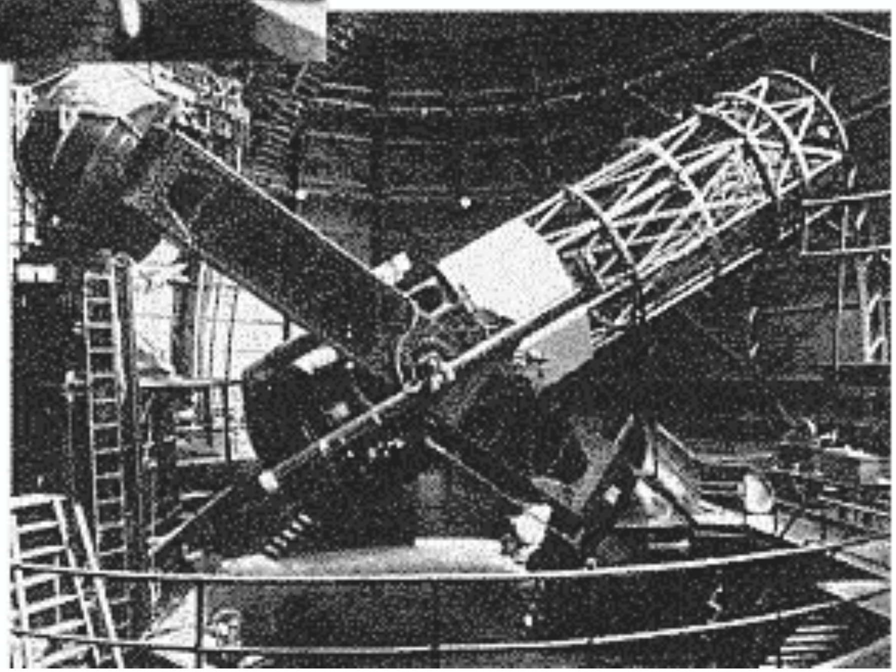
# Hubble's original diagram






Edwin Hubble



Mt. Wilson
100 Inch
Telescope

# The interpretation of Hubble's law

The best way to look at the motion of the other galaxies away from us is not to say that the galaxies are flying through space.

Instead, we think that space is stretching.

It's like the stretching surface of a balloon.

The writing on the balloon isn't moving on the rubber.

But the distance between letters increases as the rubber stretches.

It's easier to understand the stretching of a balloon since as the 2-D surface of the balloon stretches it moves into a different place in 3-D space.

It's hard to understand how 3-D space can be stretching.

Maybe it is moving into a different place in a $4^{th}$ dimension that we aren't aware of.

# Expanding space

Even if Hubble's law would look the same from all places, is there actually some galaxy that we're all moving away from?

Does the Universe have a center or edges?

What is the Universe expanding into?

This isn't a problem if the Universe is infinite.

It would have no edges then.

But the Universe might be finite.  We don't know.

Even then it would not have a center or edges.

Like the surface of a sphere has no center or edges.

The best way to look at the expansion of the Universe is to say that space is expanding.

# Turning Hubble's law around

Once we know that more distant galaxies have greater redshifts, we can use a galaxy's redshift to estimate its distance.

speed = Hubble's constant x distance, so

distance = speed / Hubble's constant

From their redshifts, we know that most of the galaxies in the Hubble (Space Telescope) "Deep Field" picture are very distant.

Since light took a long time to get to us, we are seeing them as they were long ago.

# Stretching photons

Saying that space is expanding does not mean that galaxies are expanding or the solar system is expanding.

Gravity keeps the stars orbiting in a galaxy and the planets orbiting in the solar system. The sizes of their orbits don't change.

But the expansion of space does affect photons as they travel to us across space from distant galaxies.

As they travel through expanding space, the wavelength of the light in a photon is stretched.

If space stretches by a factor of 2 while a photon is traveling, the wavelength of the light also stretches by a factor of 2.

This is another way of looking at the redshifts of distant galaxies.

# What is the Universe made of?

Stars and planets are made of protons, neutrons, and electrons. These particles are called baryonic matter [although strictly speaking only protons and neutrons are baryons (heavy particles); electrons are leptons (light particles)].

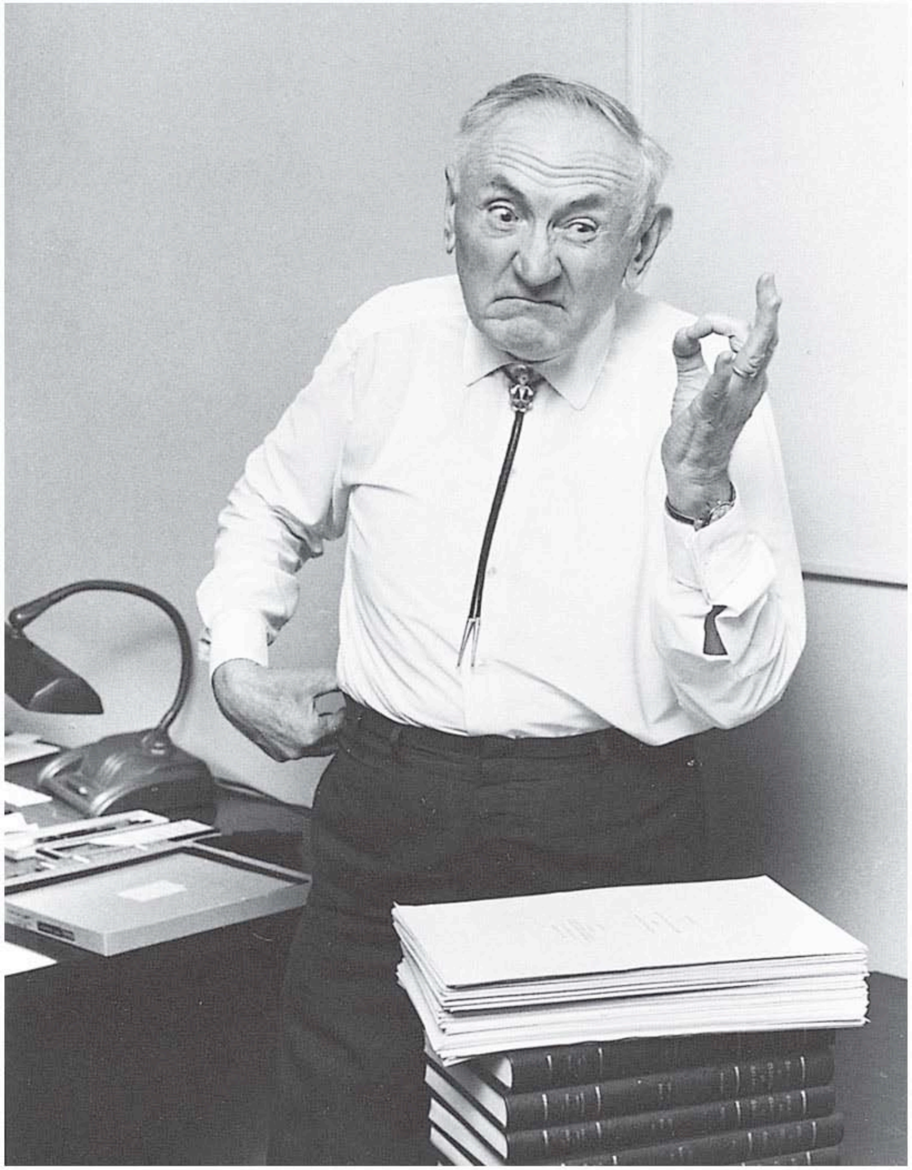
But we have reasons to believe that there are other unseen kinds of matter in the Universe.

One is dark matter, which seems to dominate the mass of the Milky Way and other galaxies.

The first evidence for dark matter was the motions of galaxies in clusters, observed by Fritz Zwicky.

Although galaxies don’t move on circular orbits, we can us a form of Kepler’s 3$^{rd}$ law to calculate the mass that they orbit around, and it appears to be larger than the mass of the stars we can see in the galaxies.

# Fritz Zwicky

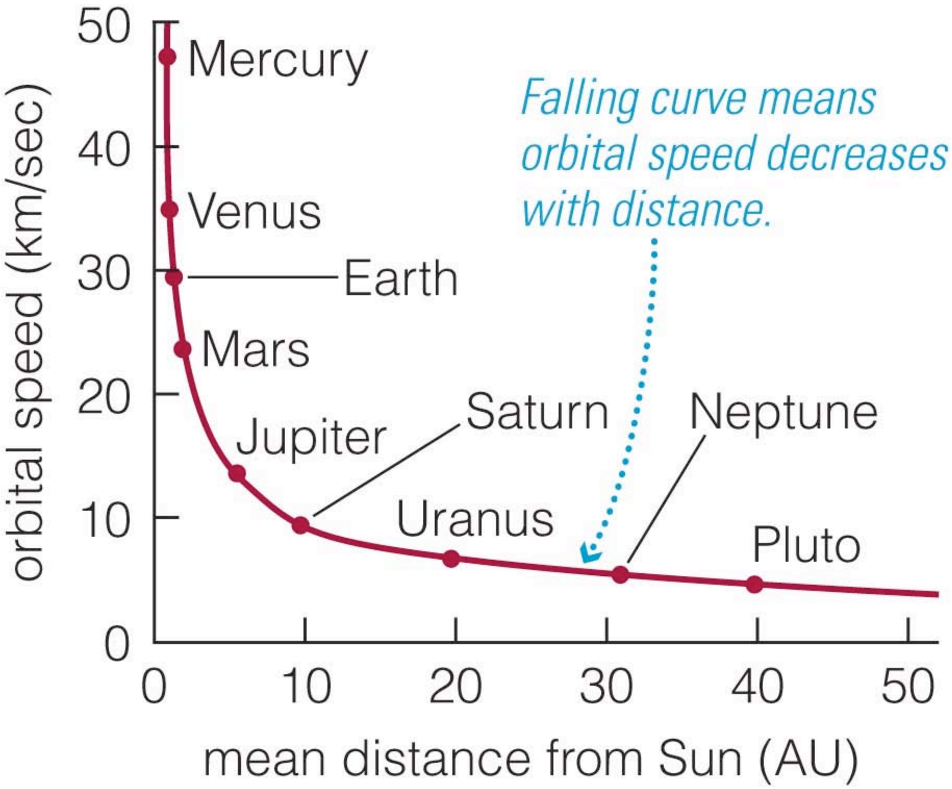


# Dark Matter in galaxies

More convincing evidence of dark matter was found by Vera Rubin, who measured masses of galaxies from the orbital speed of stars in spiral galaxies.

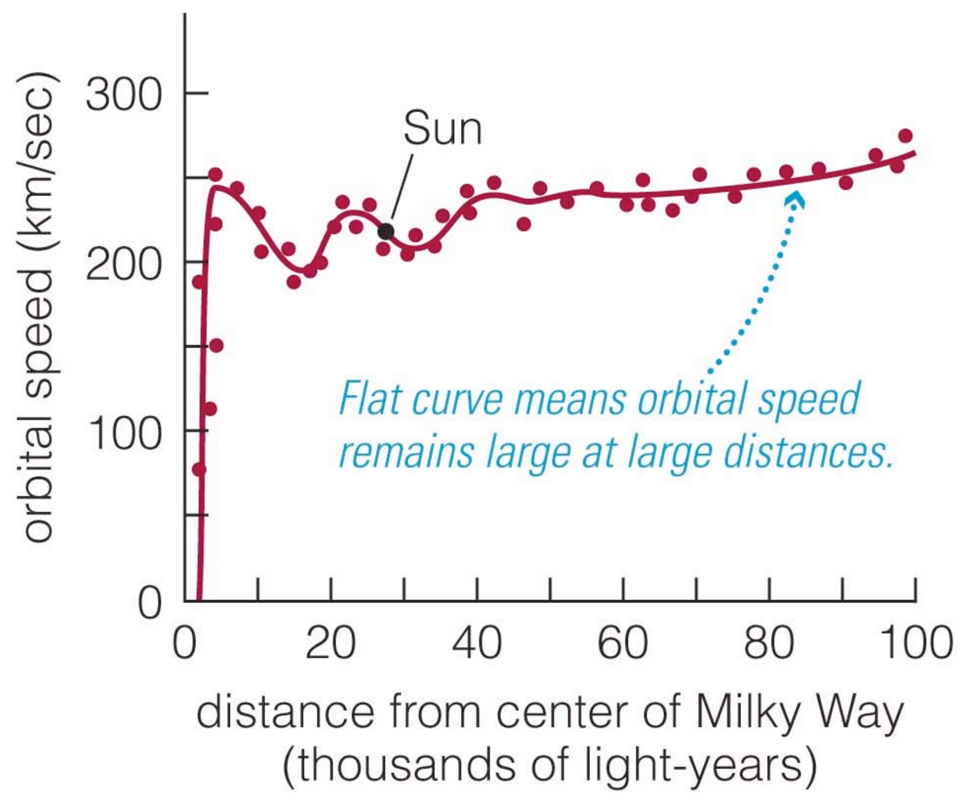
She found that as much as 90% of the masses of galaxies is in something other than the stars we see.

# Rotation curves for solar system and Milky Way



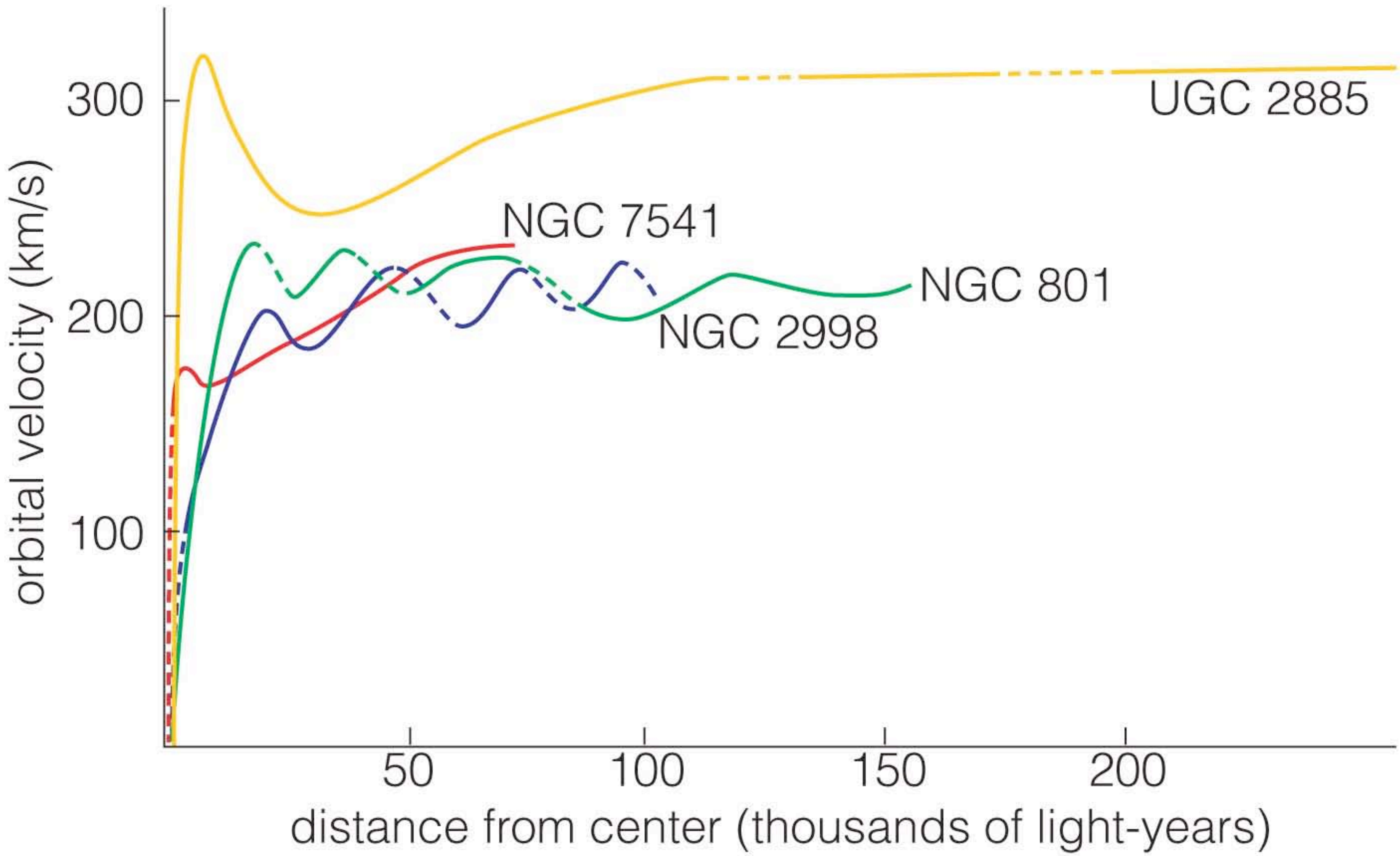

**b** The rotation curve for the planets in our solar system.






**c** The rotation curve for the Milky Way Galaxy. Dots represent stars or gas clouds whose rotational speeds have been measured.

# Rotation curves for other galaxies



# Meaning of flat rotation curves

The fact that rotation curves are flat means that stars orbit around galaxies at about the same speed at all distances from the center.

Kepler's 3rd law says that this means that there is as much mass in a 1000 pc wide ring at the outer edge of a galaxy as within 1000 pc of the center, even though there are many fewer stars near the outer edge.

Especially in the outskirts of galaxies, most of the mass in galaxies must be in something other than stars.

Fritz Zwicky's measurements indicate that even more dark matter is found in clusters of galaxies, in between the galaxies.

# Dark Matter in galaxies and galaxy clusters

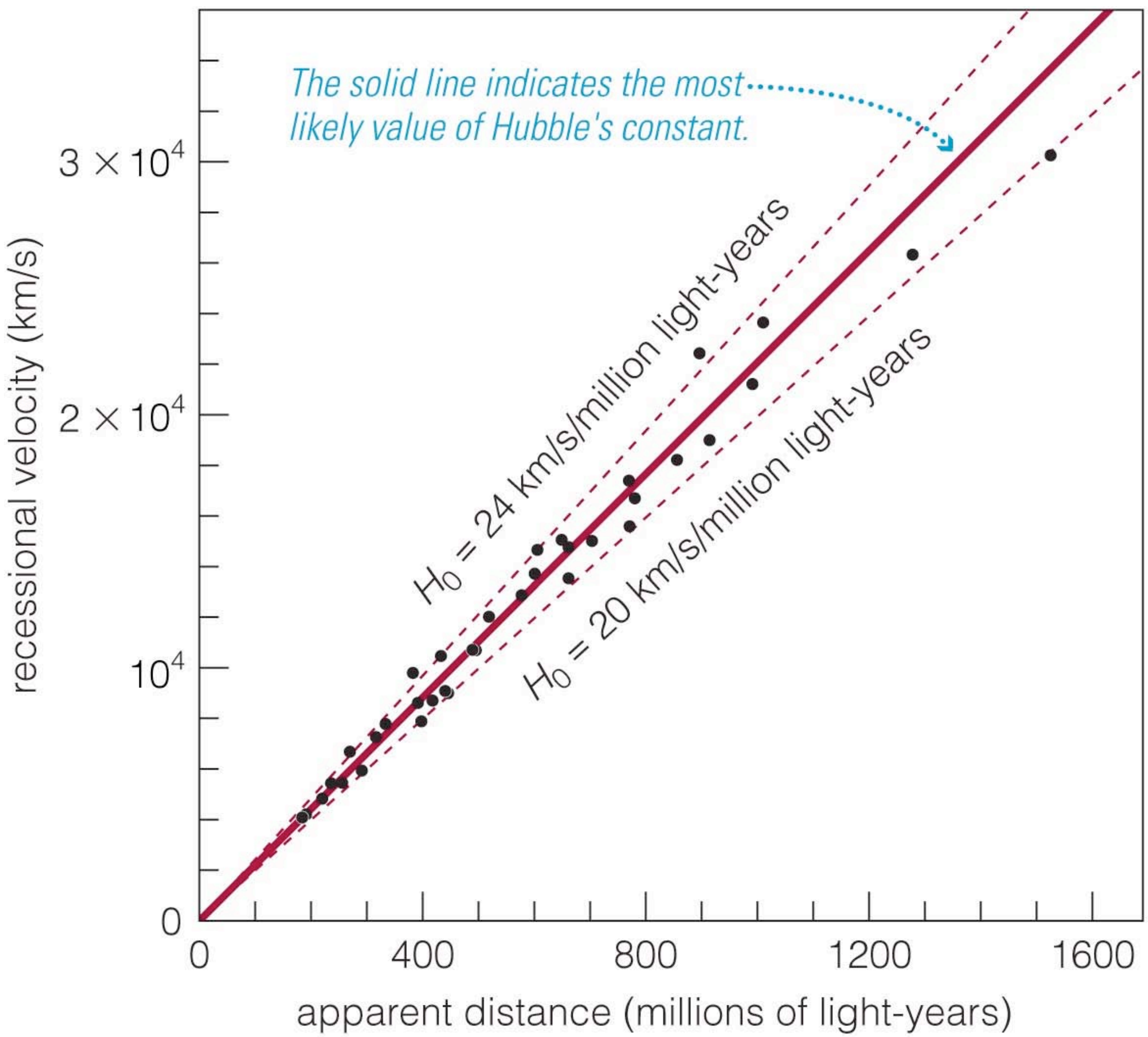
The dark matter could be in many small black holes, or conceivably even in rocks in space, but we now think it is in some unknown form of matter which doesn’t respond to either the electromagnetic force or the strong force.

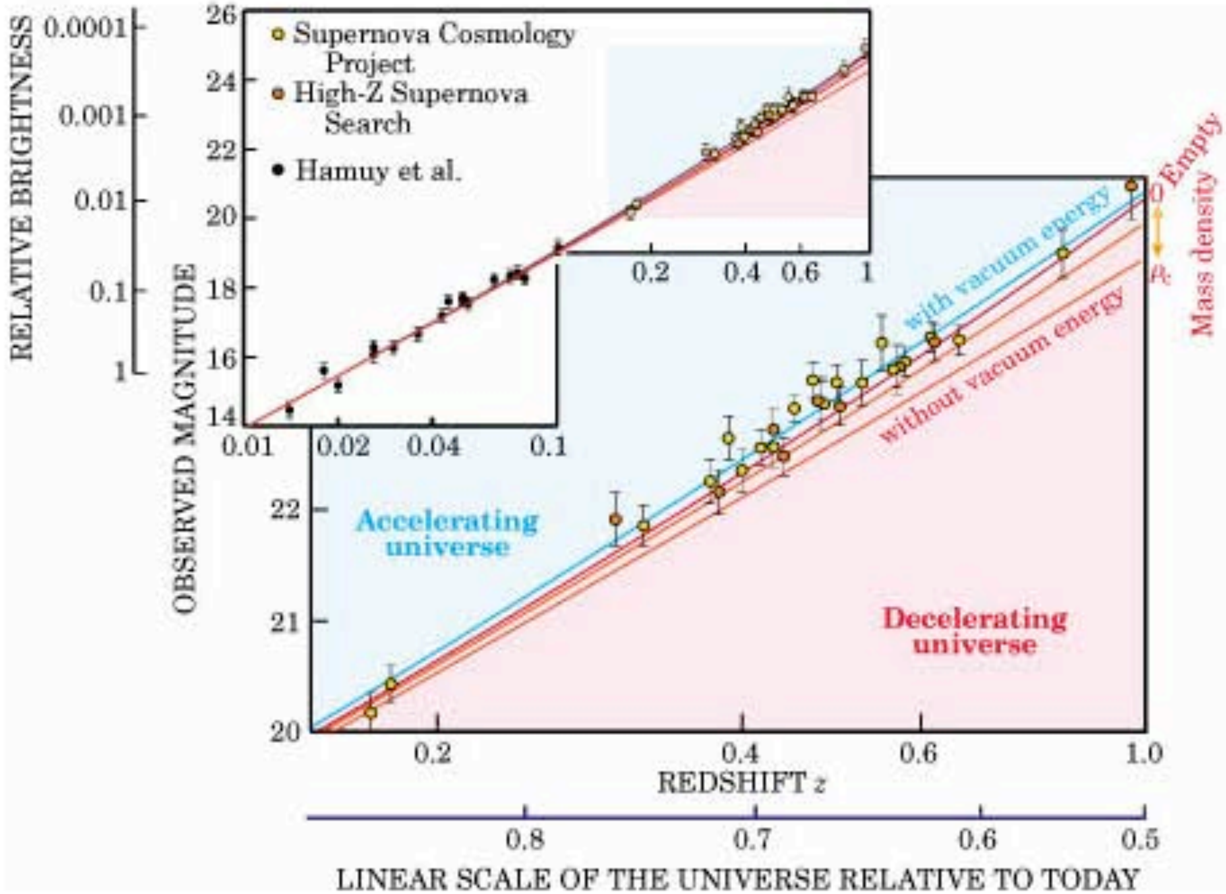
Neutrinos fit this description, but we don’t think they have enough mass to be the dark matter.

Maybe there is some kind of a particle like the neutrino, but with much more mass.

These hypothesized particles are often called WIMPs, or weakly interacting massive particles.

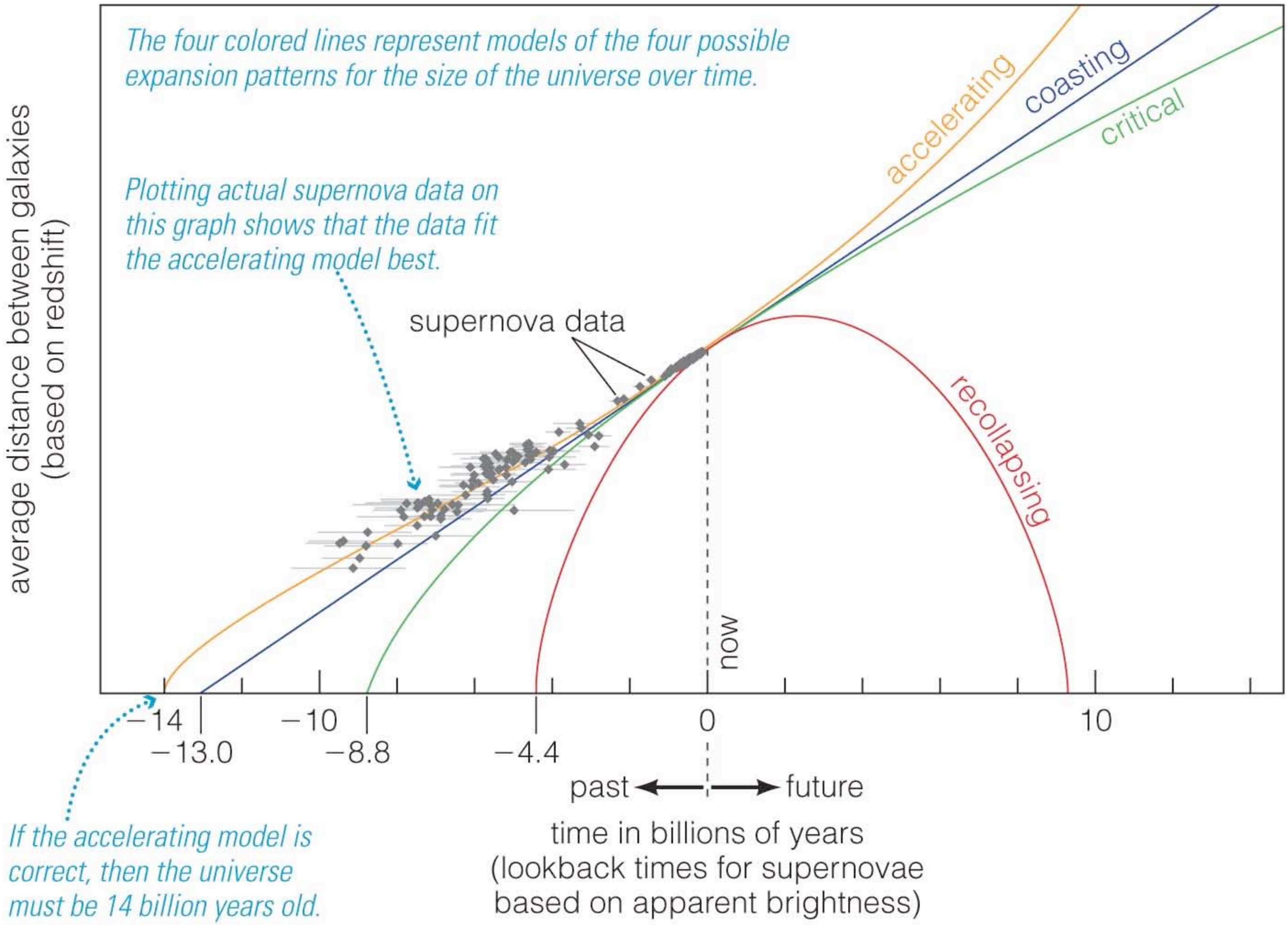
# Hubble diagram for not too distant galaxies






Observed magnitude versus redshift is plotted for well-measured distant[12,13] and (in the inset) nearby[7] type Ia supernovae. For clarity, measurements at the same redshift are combined. At redshifts beyond $z = 0.1$ (distances greater than about $10^9$ light-years), the cosmological predictions (indicated by the curves) begin to diverge, depending on the assumed cosmic densities of mass and vacuum energy. The red curves represent models with zero vacuum energy and mass densities ranging from the critical density $\rho_c$ down to zero (an empty cosmos). The best fit (blue line) assumes a mass density of about $\rho_c/3$ plus a vacuum energy density twice that large--implying an accelerating cosmic expansion.

# Expansion of Universe vs. time



# The measured acceleration

Instead of greater speeds in the past, as would be expected if gravity is causing the expansion of the Universe to decelerate, smaller speed were observed.

Apparently the expansion is accelerating.

There seems to be some sort of negative gravity affecting the expansion of the Universe.

According to general relativity this could happen if creation and destruction of particles in a vacuum gives the vacuum a negative pressure (like a stretched piece of rubber).

# The inventory

As a fraction of the critical density, which would have enough gravity to stop the expansion:

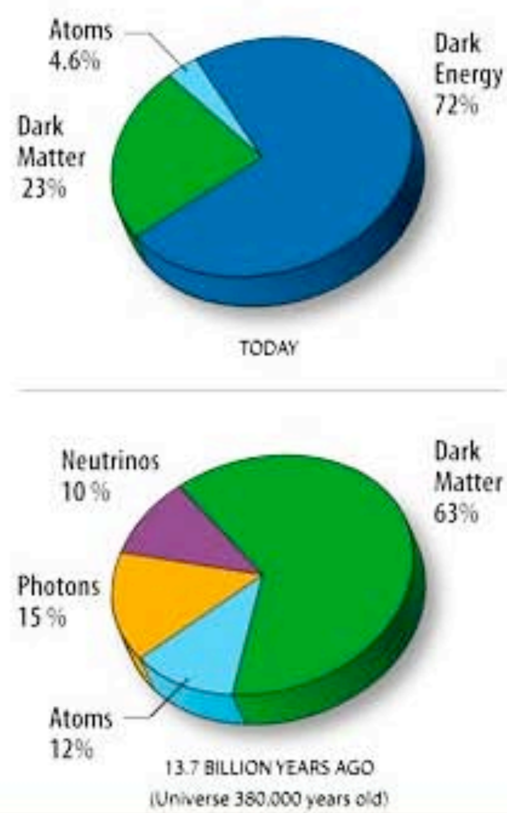
| | |
|---|---|
| visible stars: | 1% |
| unseen normal matter: | 2% |
| dark matter: | 24% |
| vacuum energy | 73% |

(Note: vacuum energy accelerates, rather than slows the expansion, but we include it in the inventory since the sum of these four stays constant as the Universe expands.)

# What is the Universe made of?

**Content of the Universe**

WMAP measures the composition of the universe. The top chart shows a pie chart of the relative constituents today. A similar chart (bottom) shows the composition at 380,000 years old (13.7 billion years ago) when the light WMAP observes emanated. The composition varies as the universe expands: the dark matter and atoms become less dense as the universe expands, like an ordinary gas, but the photon and neutrino particles also lose energy as the universe expands, so their energy density decreases faster than the matter. They formed a larger fraction of the universe 13.7 billion years ago. It appears that the dark energy density does not decrease at all, so it now dominates the universe even though it was a tiny contributor 13.7 billion years ago.

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