Earth 101
Introduction to Astronomy

Cosmology
&
Dark Matter

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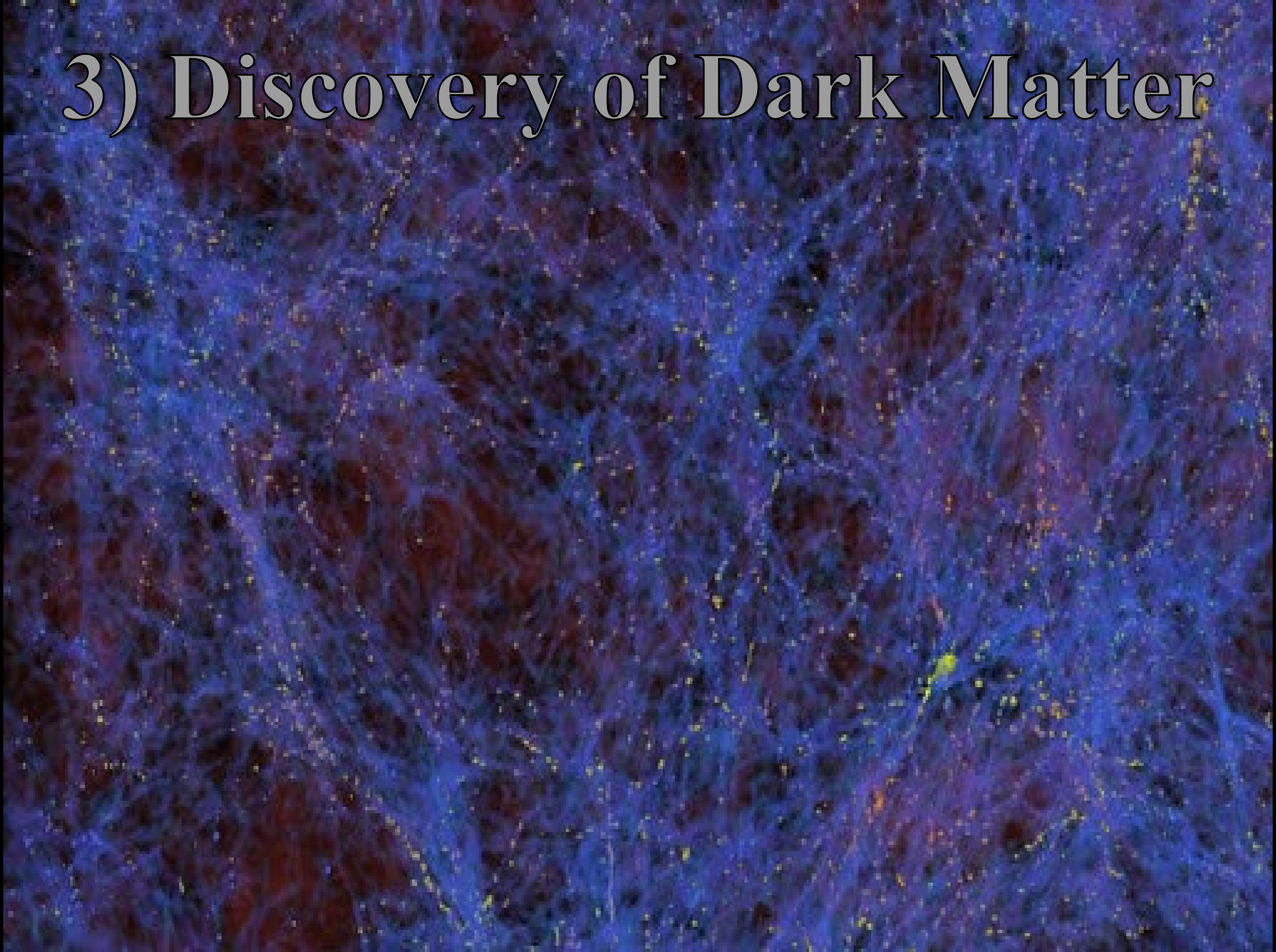
NGC 2359 Thor's Helmet © 2022 Hector Jimenez

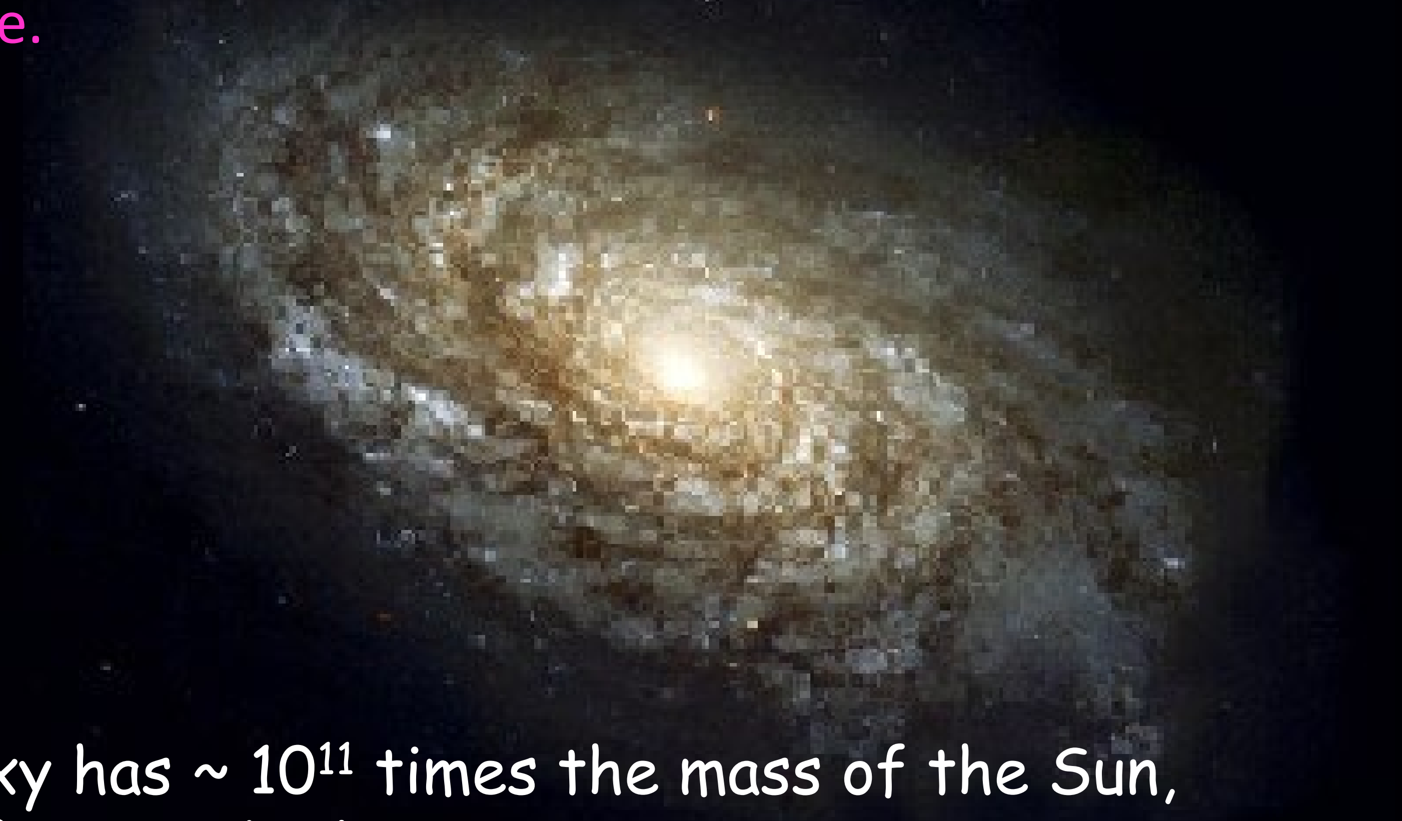
OpenStax Ch 29
--Dark Matter
--Gravitational Lensing
--Dark Energy

Photo/Material Credit:
- Fred Marschak
- Dr. Jatila van der Veen
- Erin O'Connor + others

3) Discovery of Dark Matter



First clue that some unseen mass must be present in galaxies was that there appears to be more mass in galaxies, calculated from gravitational effects, than there is when calculated from the luminosity alone.



A typical galaxy has ~ 10^{11} times the mass of the Sun, but only ~ 10^{10} times the luminosity.
We conclude that there is 10 times more mass in a galaxy than we can see.

Measuring the amount of mass in a galaxy:

The motions of stars and clouds of hydrogen in a galaxy can only be caused by gravitational forces.

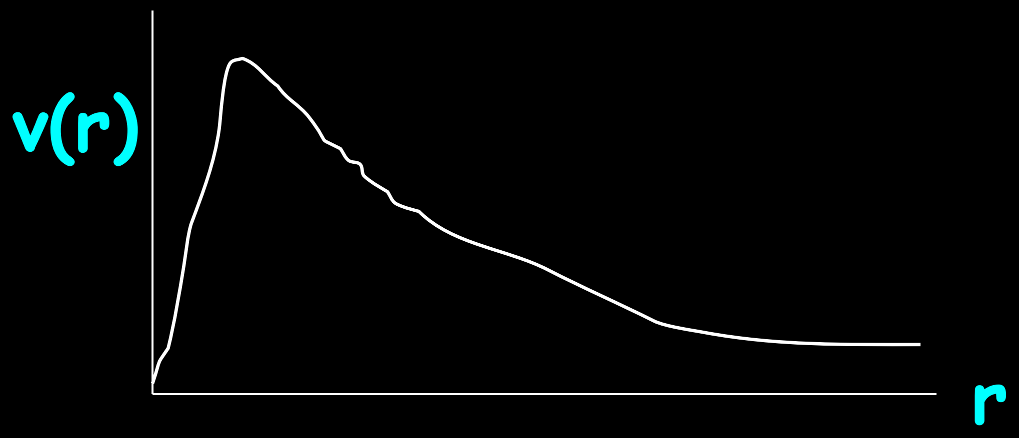
Recall Kepler's 3rd Law! $R^3 / P^2 = \text{Mass}$

By measuring the DOPPLER SHIFTS of stars at different distances from the center of a galaxy, moving towards us (blue shifted) and away from us (red shifted), we can determine how fast the stars are moving, and then calculate, using Kepler's Third Law, how much mass is contained in the galaxy, ASSUMING that most of the mass of a galaxy is contained in its central bulge.

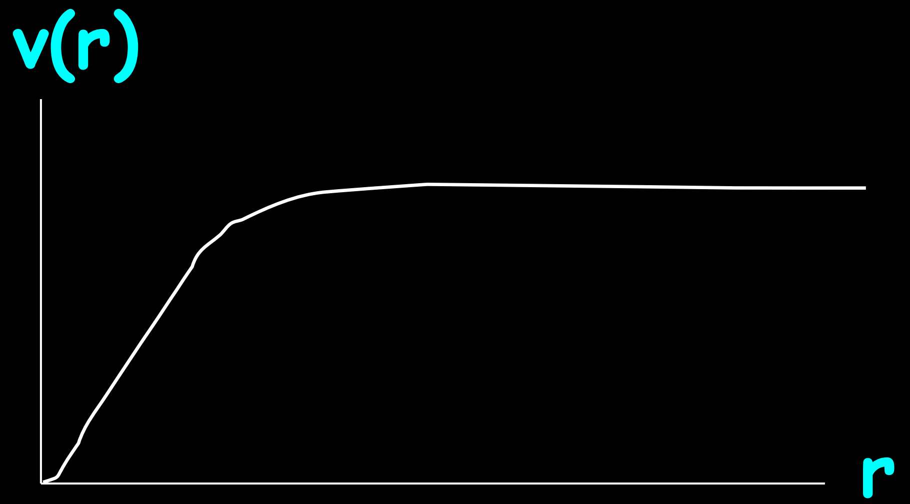
The underlying assumption in this approach is that galaxy rotation is similar to the rotation of planets in orbit around the Sun – most of the mass of the system is concentrated at its center.

If the rotation of galaxies about their centers followed Kepler's Third Law, we should see the stars and hydrogen clouds at the outer edges of galaxies move more slowly than stars closer to the center, just as the outer planets in our solar system move more slowly than the inner ones.

Here's an approximate graph of what we would expect to measure for galaxy rotation speed as a function of distance from the center, if galaxies followed Kepler's Third Law, and most of the mass were concentrated in the galactic center:



But this is what was found: galaxy rotation curves do not follow Kepler's Third Law!

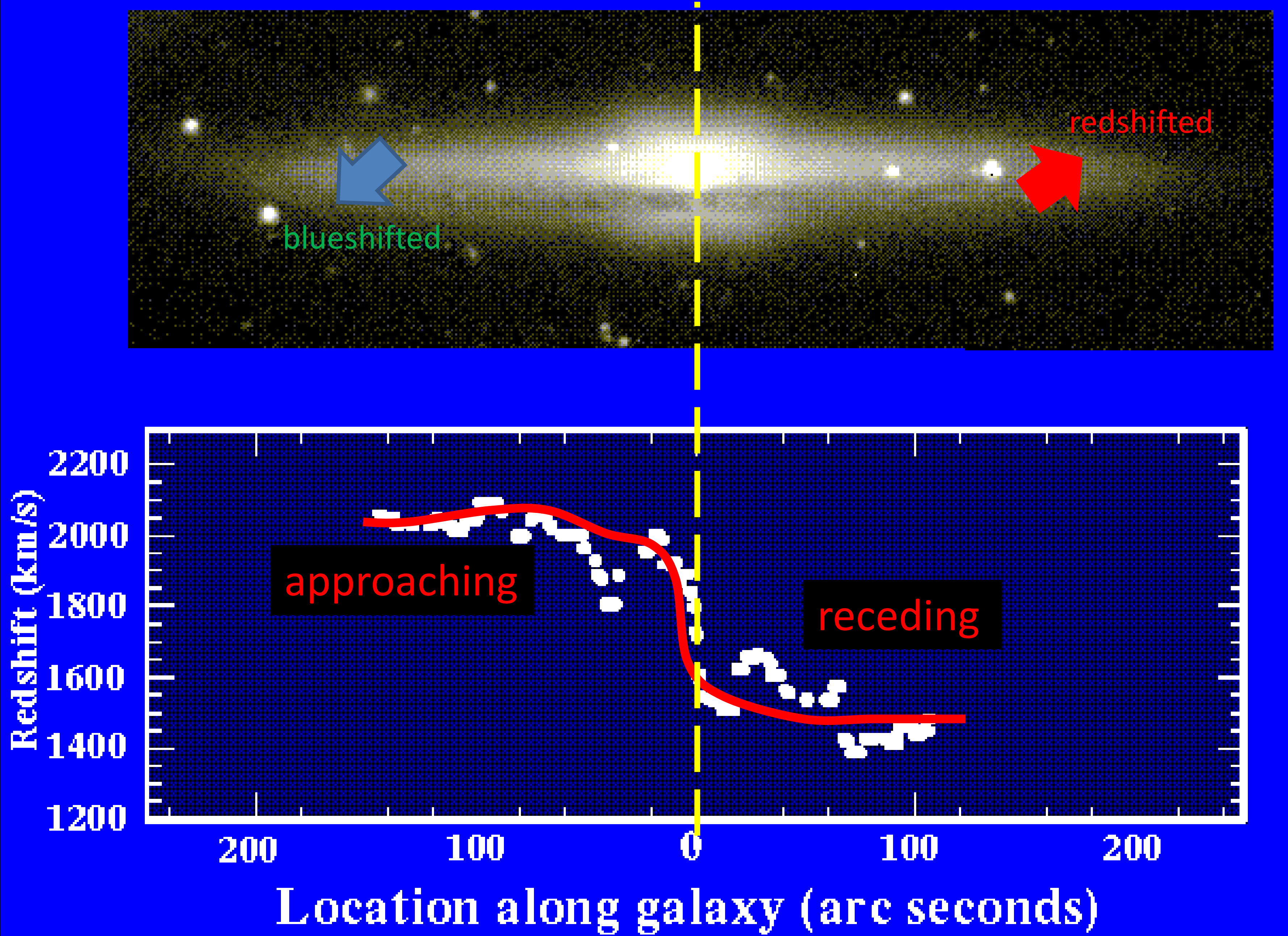


This was the first clue that there is some unseen mass surrounding galaxies that does not interact electromagnetically, but only gravitationally.

Vera Rubin was the first to discover that galaxies did not follow Keplerian rotation curves.

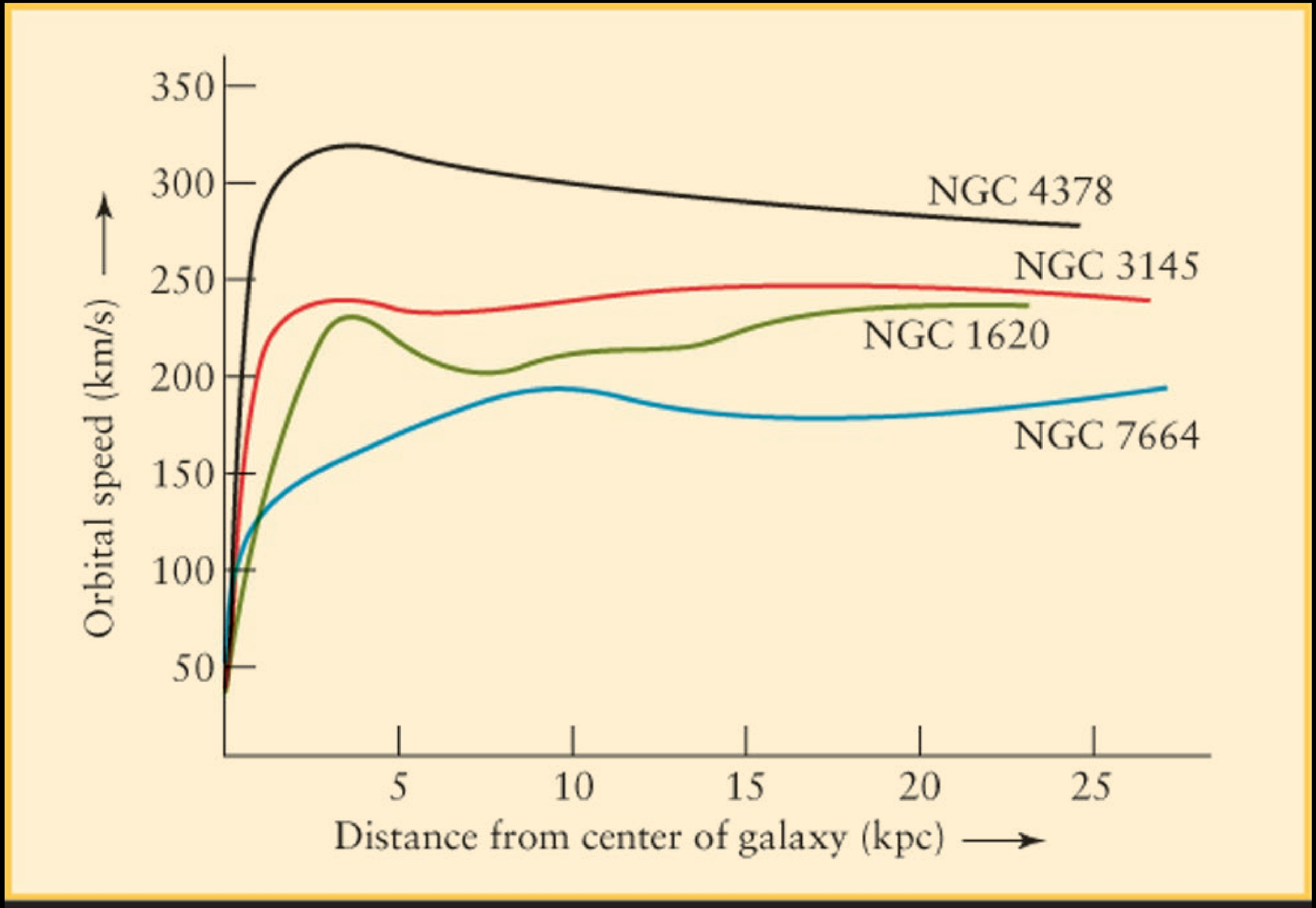
Some of her data are shown on the next slide...

NGC 5746

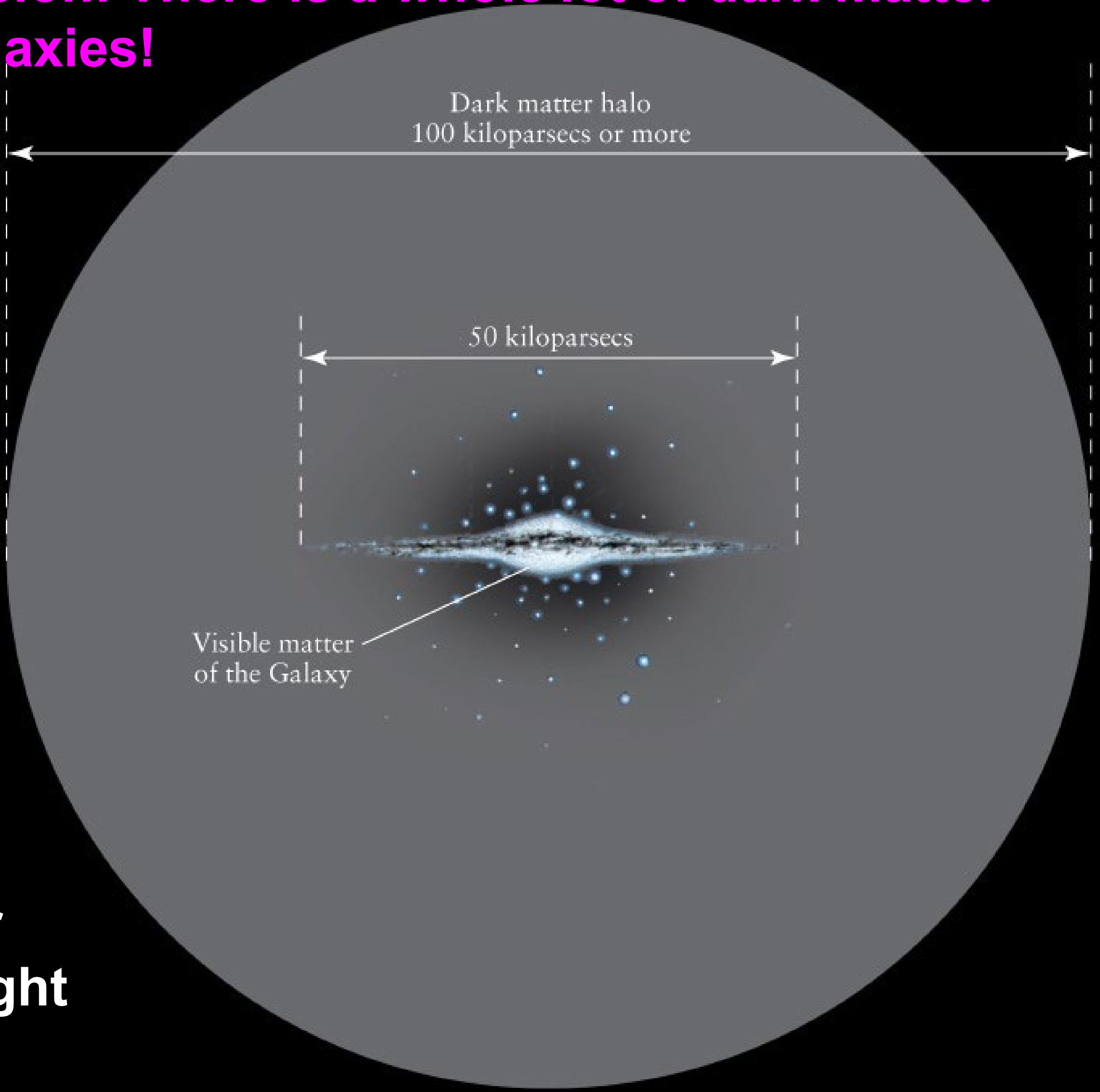


redshifted
blueshifted
approaching
receding
Redshift (km/s)
2200
2000
1800
1600
1400
1200
200
100
0
100
200
Location along galaxy (arc seconds)

Many galaxies show similar results!!
The only possible explanation is that the actual mass of any galaxy must extend well *beyond* the visible matter (stars and hydrogen clouds) that we can see.



General conclusion: There is a whole lot of dark matter surrounding galaxies!



The unseen Milky Way Galaxy:
90% dark matter

90% of our galactic matter doesn't emit light

Pause to reflect...

Most astronomers think that there is dark matter in our Galaxy because

A. matter in the outer edges of our Galaxy moves faster than expected.
B. matter in the outer edges of our Galaxy moves slower than expected.
C. large amounts of matter can be seen at infrared wavelengths.
D. large amounts of matter can be seen at radio wavelengths.
E. large amounts of matter can be seen at x-ray wavelengths.

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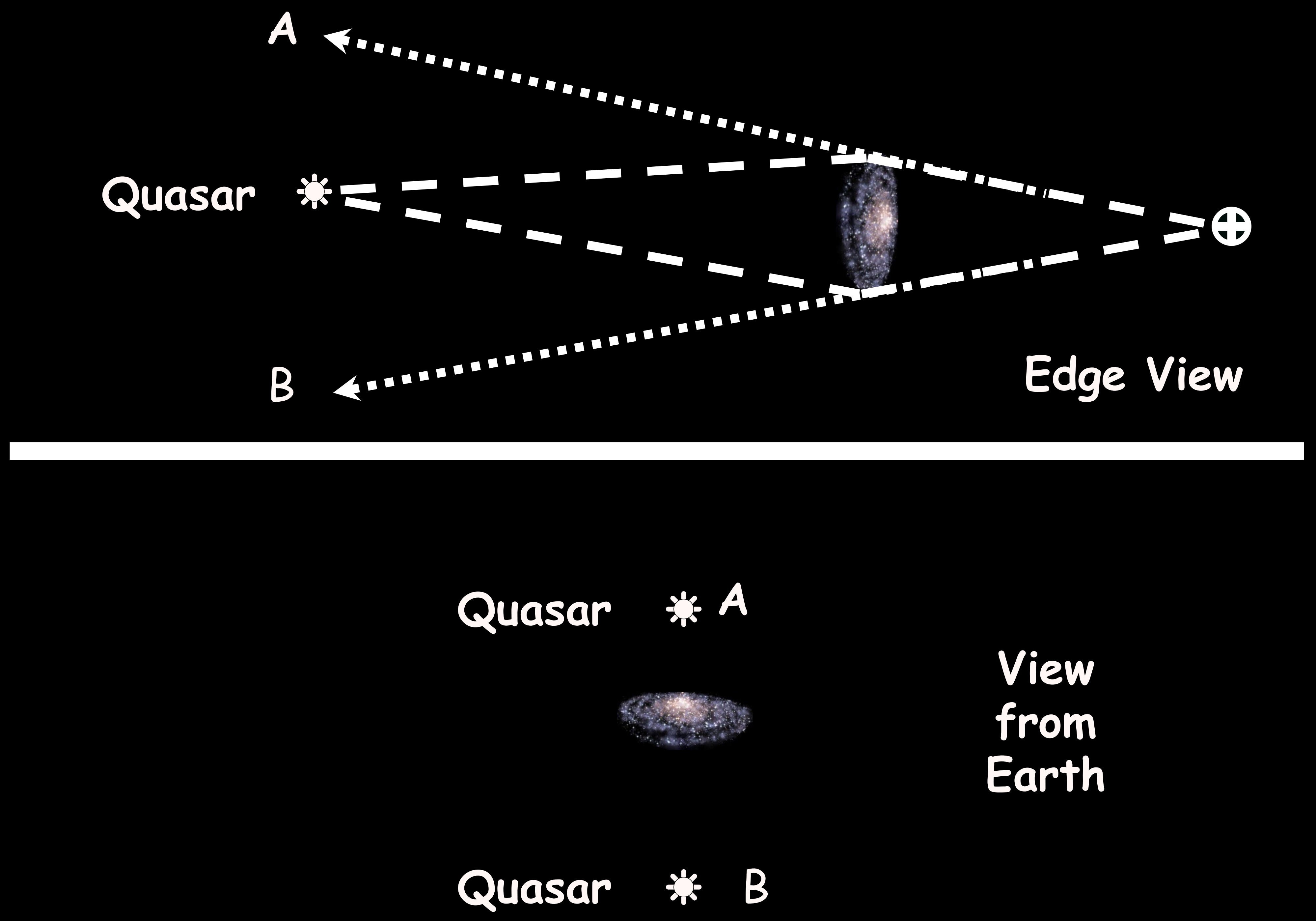
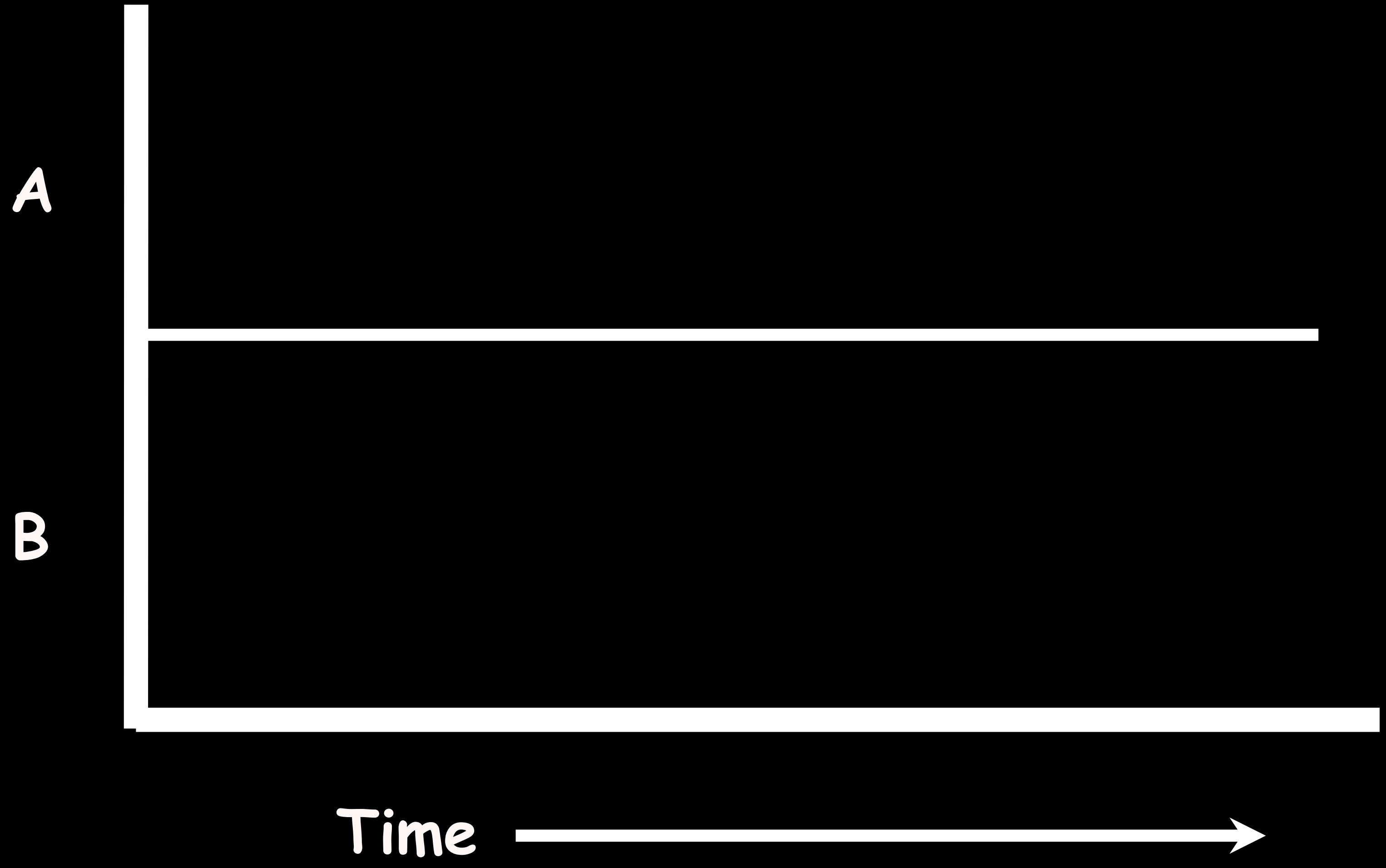
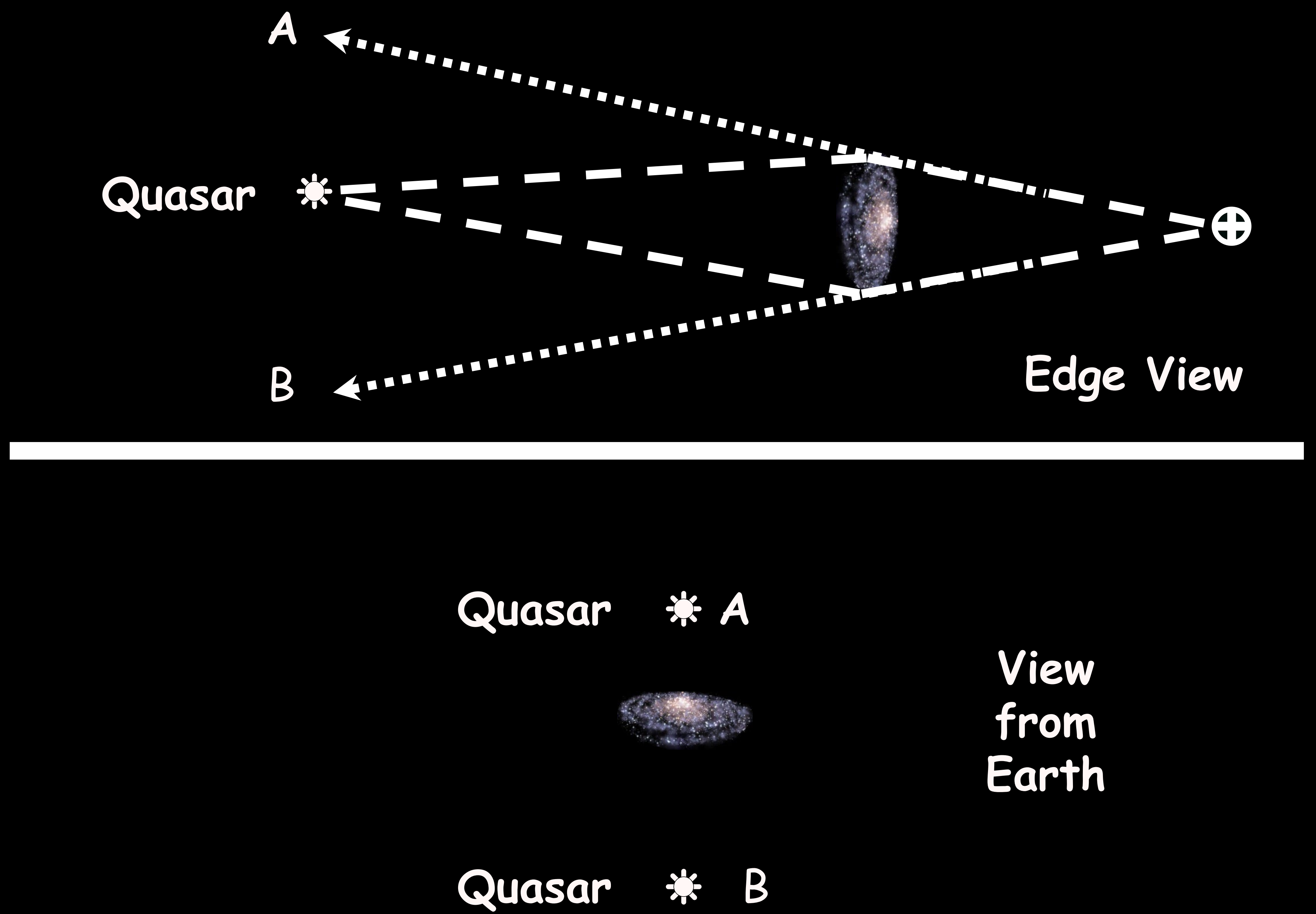
Gravitational Lenses - more evidence for dark matter


A
Quasar
B
Edge View
Quasar
A
View
from
Earth
Quasar
B

Quasar Radio Signal over time ...




A
Quasar
B
Edge View
Quasar A
View
from
Earth
Quasar B

Quasar Radio Signal over time ...

We know from General Relativity that mass bends spacetime, and that light follows the curvature of space. So when we see distorted images of distant galaxies, we know there is some unseen mass in between us and the distant galaxies that is causing the distortion.

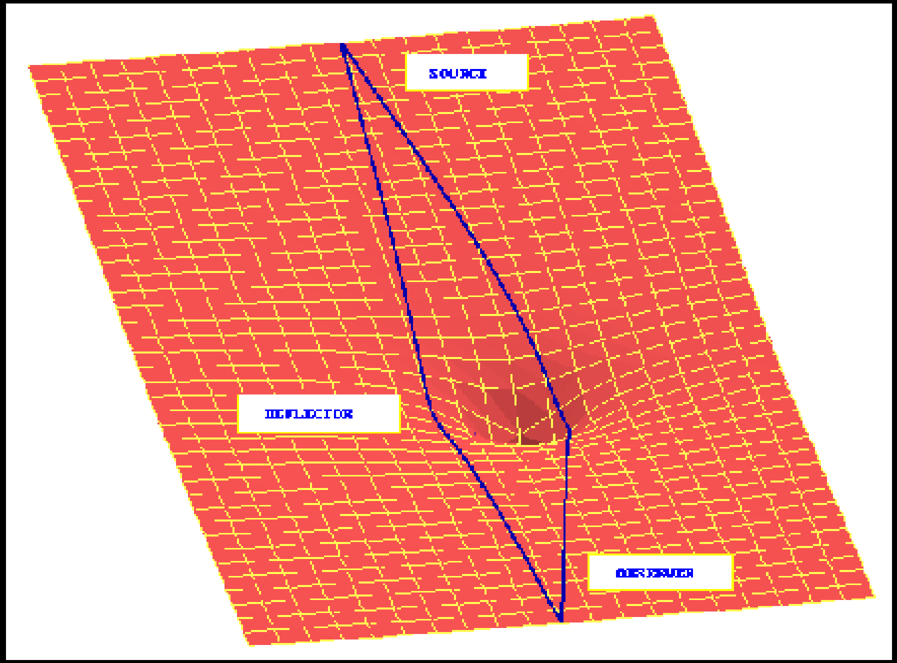
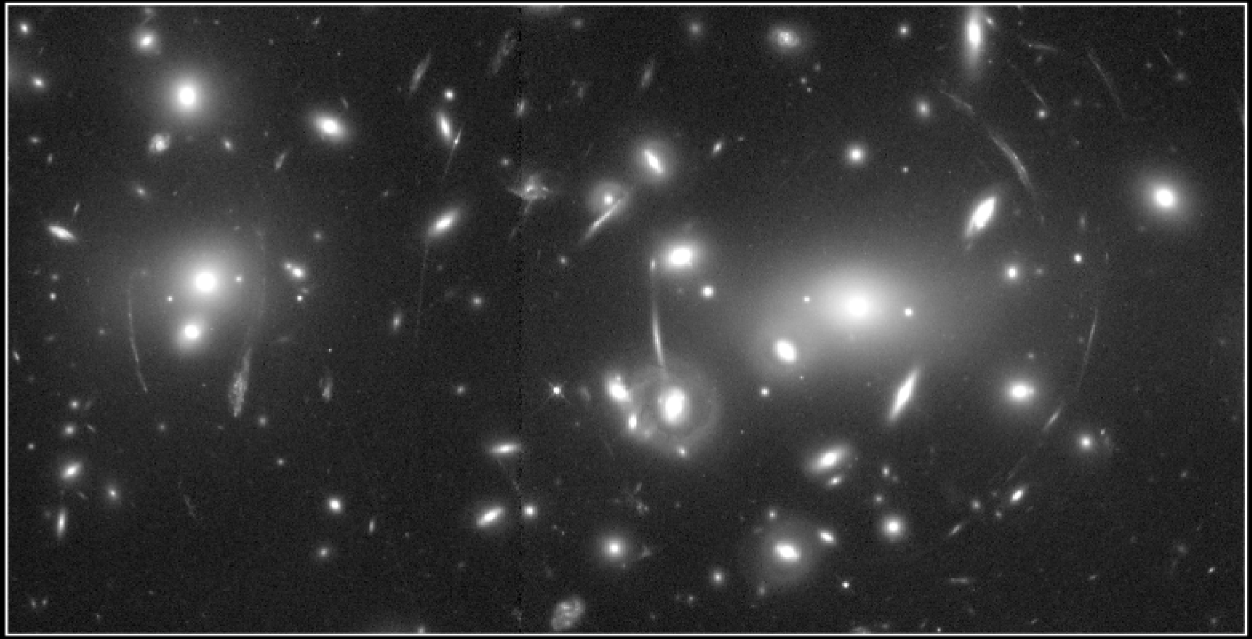


Diagram of light rays being bent around mass that lies between the source and the observer

A gravitational lens: the blue arc is the image of a distant galaxy, distorted by the gravitational lens effect produced by the dark matter surrounding the elliptical galaxies in the foreground.

Just as looking through a wine glass distorts images, looking through a gravitational lens distorts the images of background galaxies.



Gravitational Lens in Abell 2218 HST · WFPC2

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

What matter makes up Dark Matter?

Hypothesis #1: MACHOs

“Massive Compact Halo Objects”

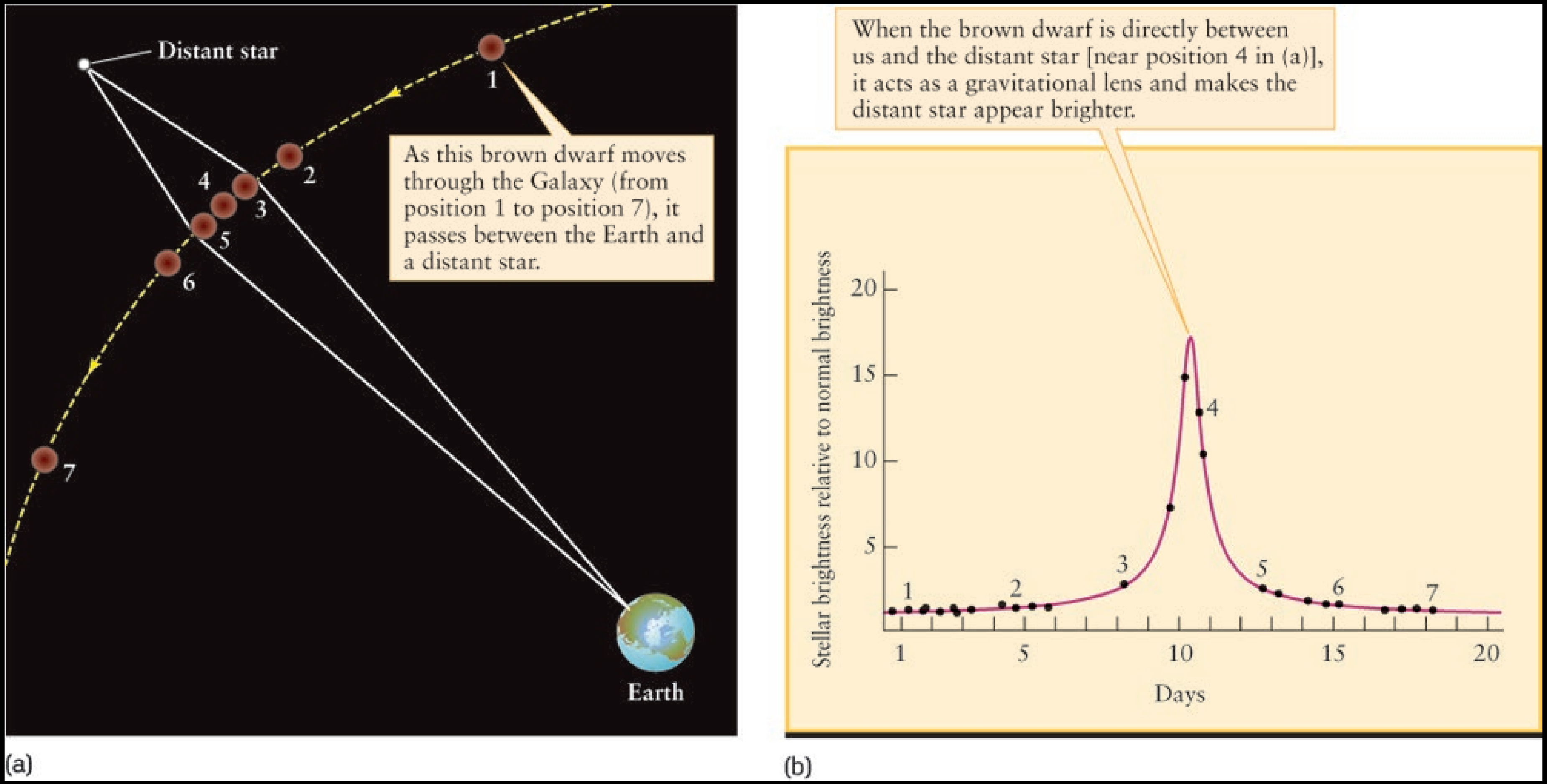
Black holes, white dwarfs, or Brown Dwarfs

Brown Dwarfs are bigger than Jupiter, BUT not big enough to become nuclear-powered stars, and thus, “dark”.)

Massive Compact
Halo Objects

One type of dark matter candidate that has been searched for over the past few decades are the *MACHOs*.

Two groups began searching for MACHOS in the early 1990's – one group looked toward the center of our galaxy, the other toward the Large Magellenic Cloud.



HUGE effort to find MACHOs by "gravitational microlensing" has failed to find enough to account for galactic Dark Matter.

What matter makes up Dark Matter?

Hypothesis #2: Neutrinos

→Neutrinos have some small amount of mass, and there are a great many of them.

(masses, uncertain, but there could be enough…)

What matter makes up Dark Matter?

Hypothesis #2: Neutrinos

→Neutrinos have some small amount of mass, and there's zillions of them.

BUT they have no way to "clump up" to form galactic Dark Matter. They can only be very smoothly distributed throughout the universe.

MAYBE they play a role in Dark Matter found elsewhere, but neutrinos clearly don't solve the whole mystery.

What matter makes up Dark Matter?

Hypothesis #3: WIMPs

→Weakly Interacting Massive Particles

These are NEW, proposed particles, with properties fine-tuned to solve the Dark Matter problem.

There are many efforts to detect these by their occasional collisions with massive nuclei in huge underground pools of liquid, deep inside mines, deep underground.

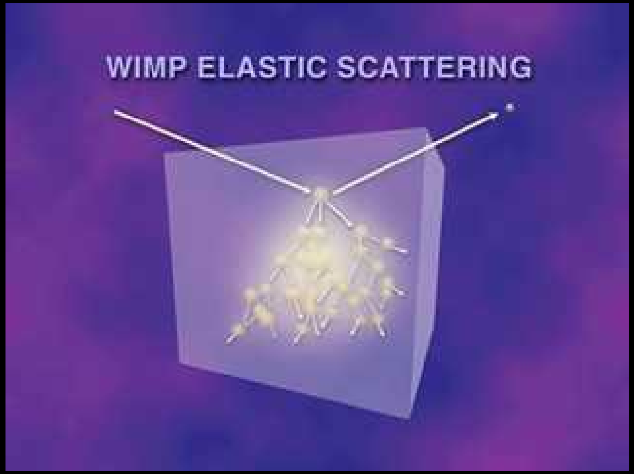
What matter makes up Dark Matter?

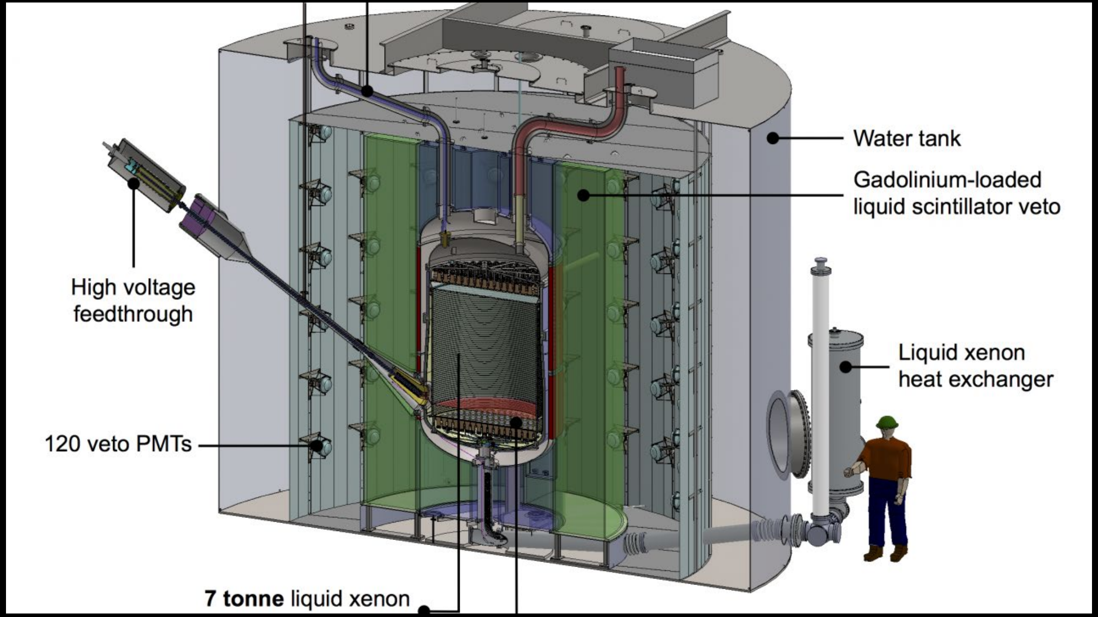
There are other STRONG reasons to think that Dark Matter can't possibly be made of "ordinary" matter. (DM can't be made of protons and neutrons.)

That means most of the matter in the Universe is made of some new, "exotic" unknown type of matter!

People are searching for a particle that has a mass between 30 and 200 GeV, interacts by rare collisions with heavy nuclei, and represents an extension of our current understanding of particle physics!

Weakly-Interacting Massive Particles are the other dark-matter candidates, thought to be a new type of subatomic particle. People hope to detect it by its scattering products, when it occasionally scatters off a heavy nucleus, causing recoil and releasing sound and low energy Xrays.





Underground searches underway in the US, Canada, & Japan

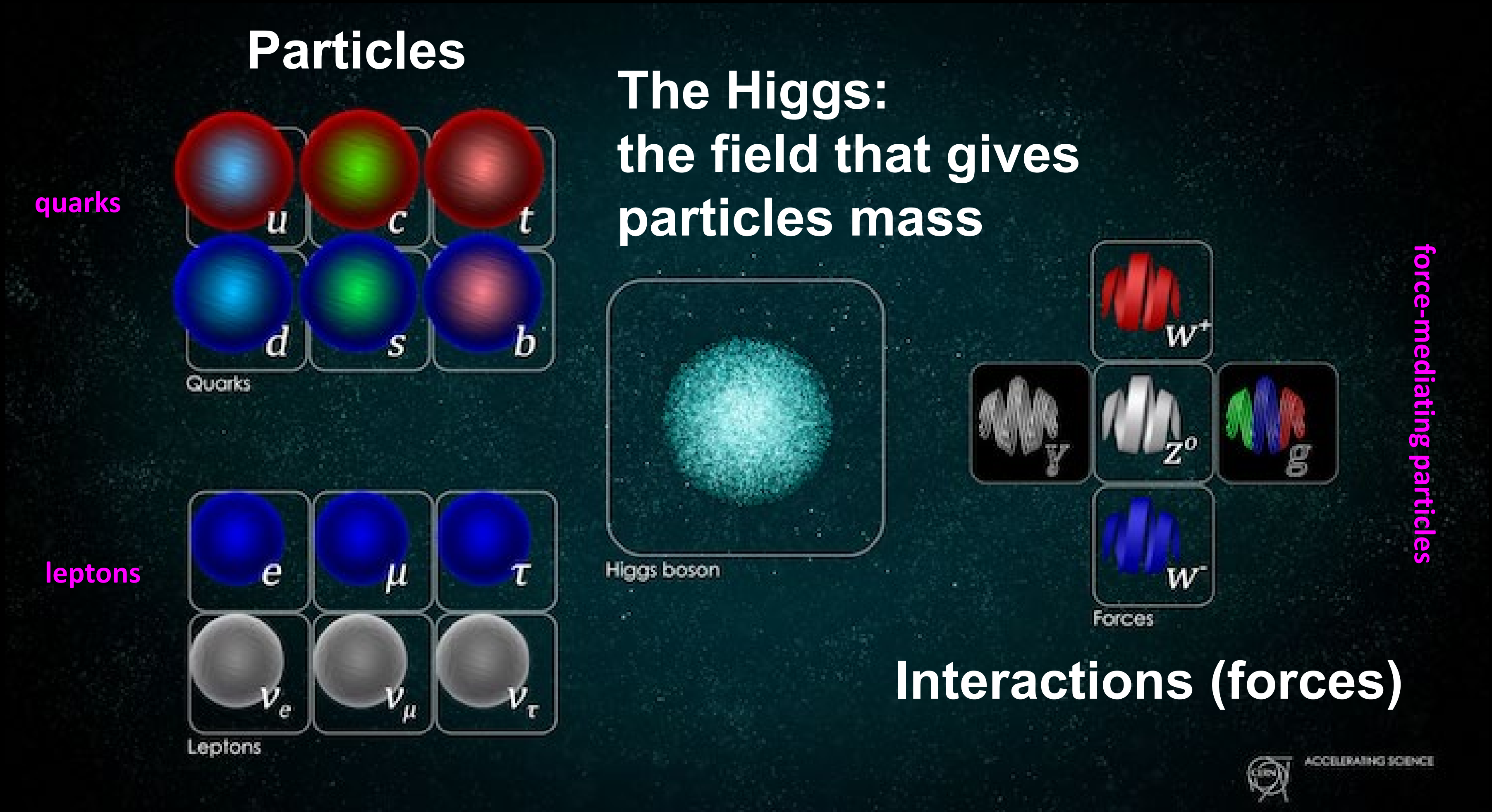
What we know: Standard Model of Particles and Interactions

Particles

quarks

leptons

The Higgs: the field that gives particles mass



force-mediating particles

Interactions (forces)

Review the last lecture on modern physics relevant to cosmology.

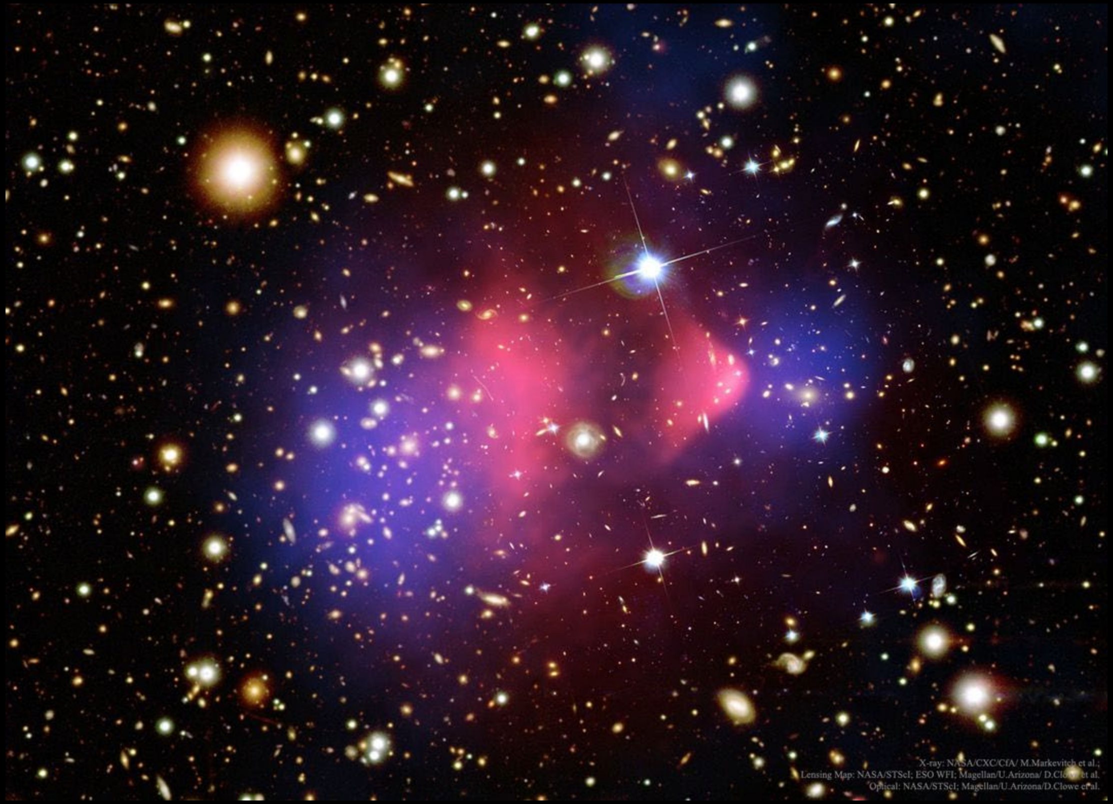
We still don't know what dark matter is!

The most favored models are for cold dark matter made up of as-yet-undiscovered particles: axions, wimps, and sterile neutrinos, with axions being the most popular.

Dark matter candidates

		axion	WIMP	sterile ν
mass	m	$10^{-5}\ \frac{\mathrm{eV}}{c^2}$	$100\frac{\mathrm{GeV}}{c^2}$	$10\frac{\mathrm{keV}}{c^2}$
velocity dispersion	δv	$10^{-17}c$	$10^{-12}c$	$10^{-8}c$
coherence length	$\ell = \frac{\hbar}{m\ \delta v}$	$10^{17}\mathrm{cm}$	$10^{-5}\mathrm{cm}$	$10^{-1}\mathrm{cm}$

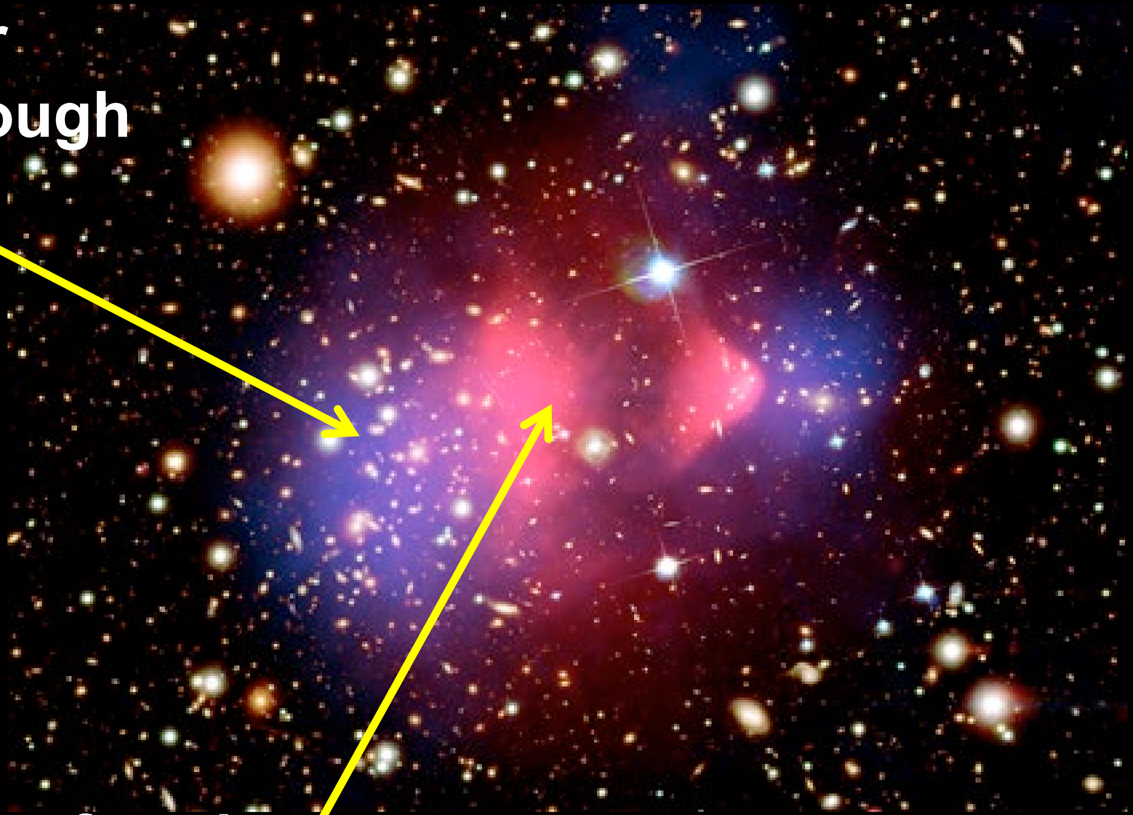
Dark matter interacts ONLY by gravity. Evidence for dark matter has been found in galaxy clusters such as the Bullet Cluster – two galaxy clusters that are colliding with each other.



The stars of the cluster seem to pass by each other with little interaction. The hot gas within each cluster, shown in pink, is so hot that it is only detected in X-rays. The intracluster gases interact electromagnetically, and slow down, thus lagging behind the stars of the galaxies.

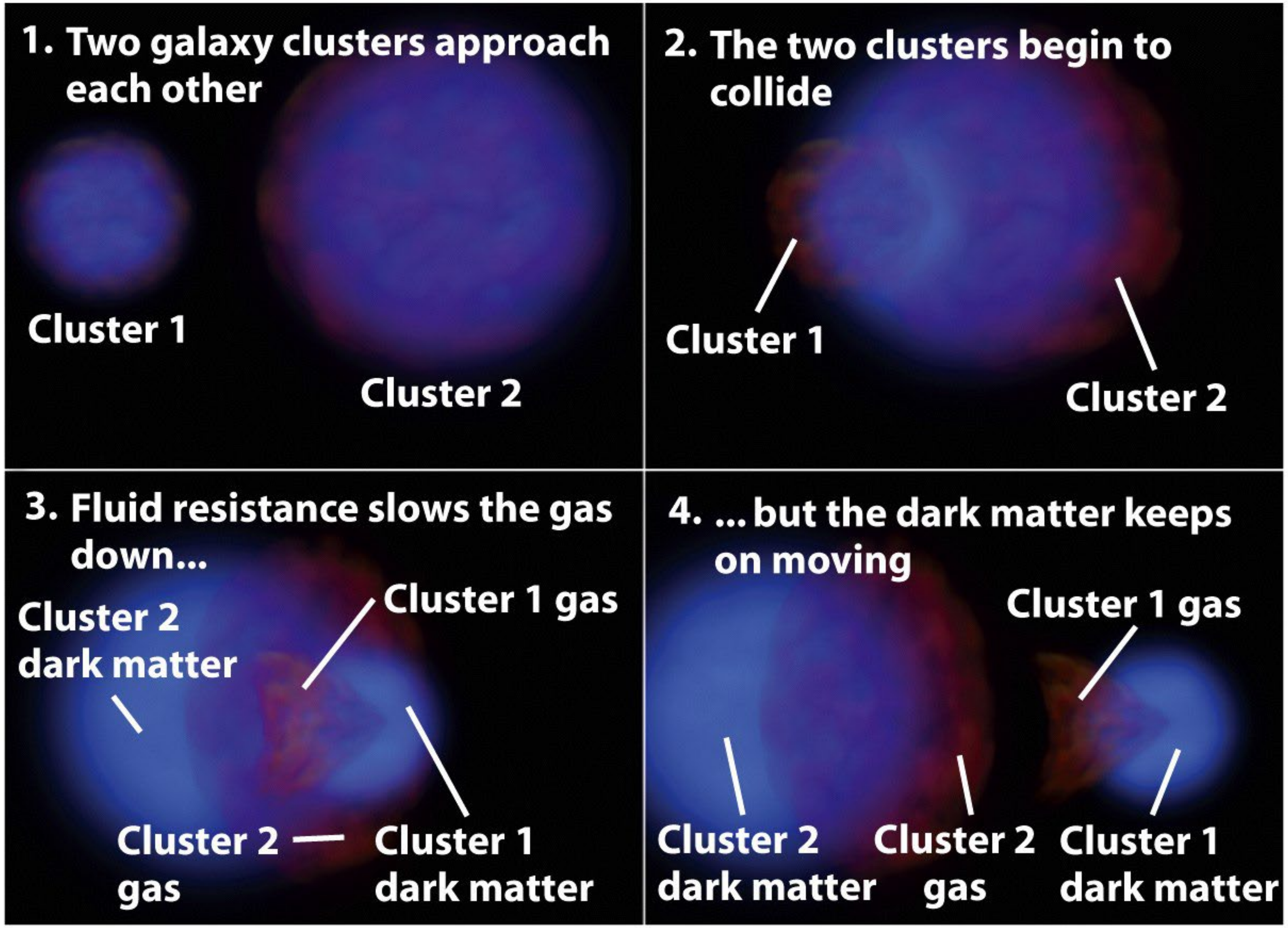
The dark matter, shown in blue, was detected only by its gravitational lensing effects on background galaxies. The dark matter appears to lead the collision, passing right through the rest of the matter, since it is only weakly interacting, and only via gravitational interaction.

Dark Matter passes through



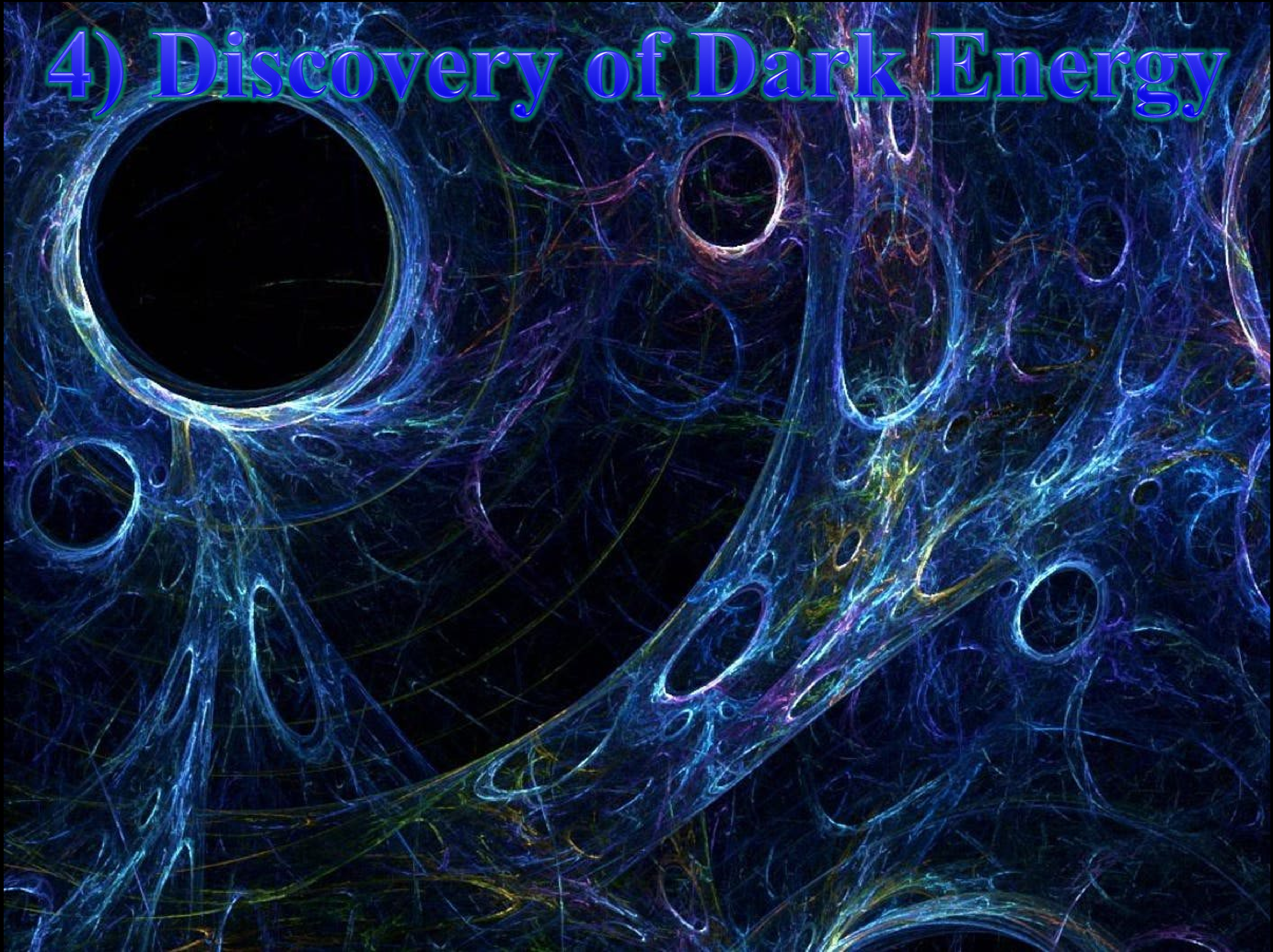
Hot gases of each cluster interact with each other electromagnetically

Bullet Cluster, aka 1E 0657-56



A model of how the gas and dark matter in 1E0657-56 could have become separated

4) Discovery of Dark Energy



The search for an Energy Field that would provide a more-or-less Anti-gravity force began with Einstein.

1. Recall from Einstein's General Relativity Theory that Mass and Energy curve spacetime; and

2. Recall from Newton's Universal Theory of Gravity that gravity is a force by which every particle in space attracts every other particle.

So, in order to make his equations match the fact that the universe has NOT collapsed under its own weight, Einstein postulated that there must be a 'cosmological constant' which he called λ (lambda). He inserted this constant into his GR equation in keeping with the observation that something must be holding the universe "up" against the force of its own gravitational attraction.

So Einstein modified his equations of General Relativity to include a cosmological constant, the antigravity factor which he postulated would keep the universe from collapsing under its own weight.

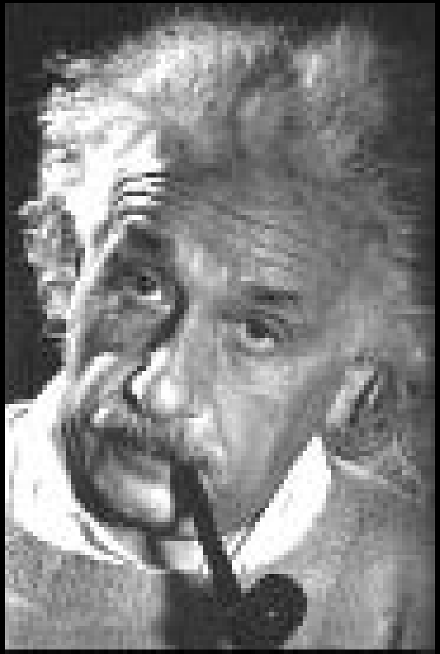
THE EINSTEIN FIELD EQUATION

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \lambda$$

Left hand side = geometry of spacetime

Right hand side = the matter and energy contained in the Universe, where “T” is the “stress-energy tensor” which describes the distribution of matter and energy in spacetime

λ is the assumed cosmological constant which counteracts gravity



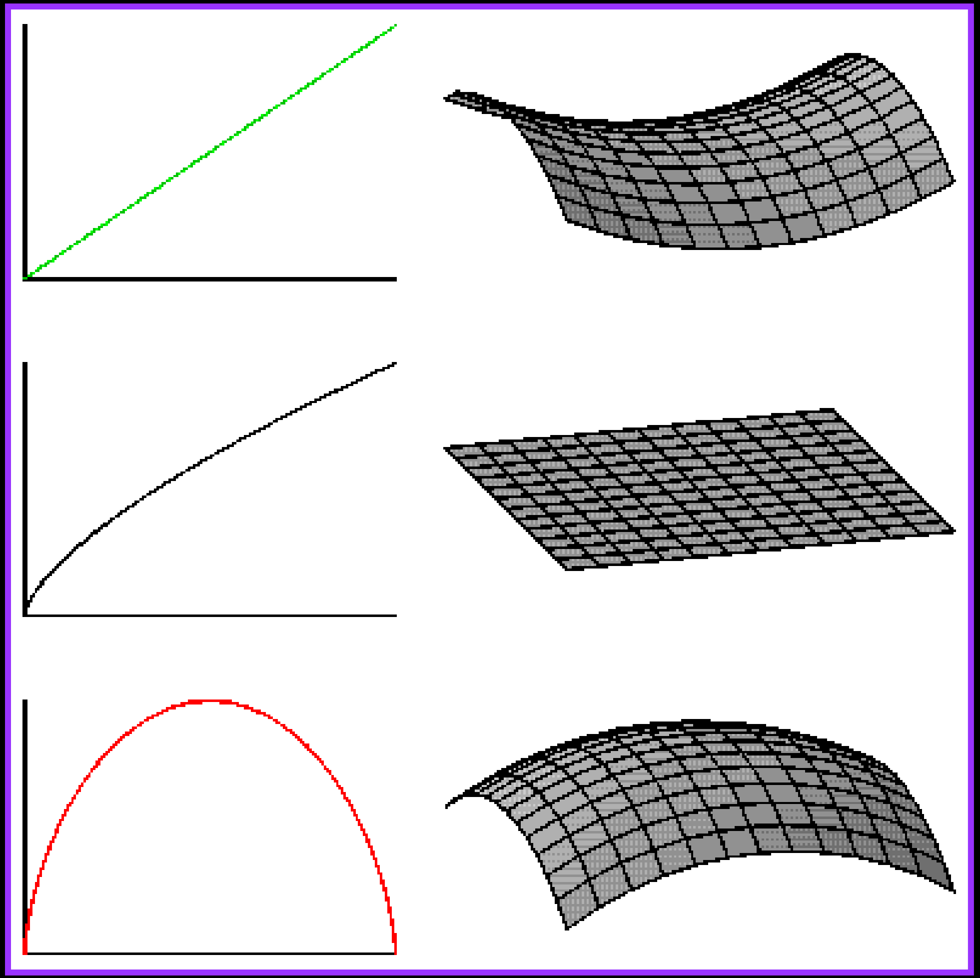
When Edwin Hubble announced is results in 1929, and it was apparent that the universe was expanding, Einstein retracted his cosmological constant, calling it “the biggest blunder of his life.”

The question then was, What is the geometry of spacetime? Given that Einstein's equations of General Relativity (GR) plus the Newtonian model of conservation of energy, was the kinetic energy of expansion from the Big Bang greater than, equal to, or less than the total gravitational potential energy of the universe?

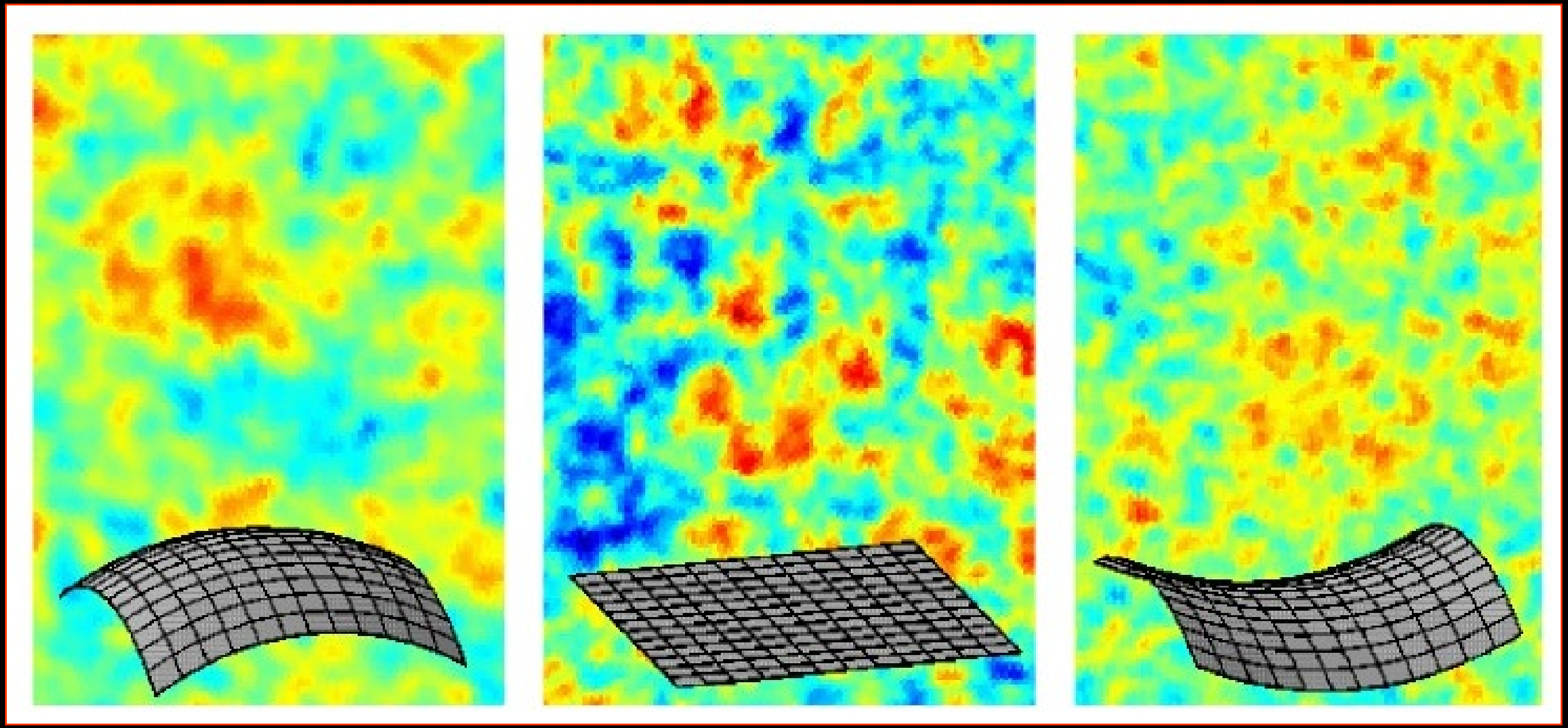
negative curvature: more expansion energy than gravity? Universe expansion accelerates

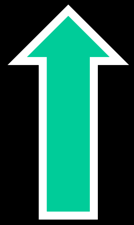
zero curvature: expansion energy is just barely balanced by gravity?
Universe expansion asymptotically approaches 0

positive curvature: more gravity than expansion energy?
Universe will eventually reach its limit and fall back into a Big Crunch



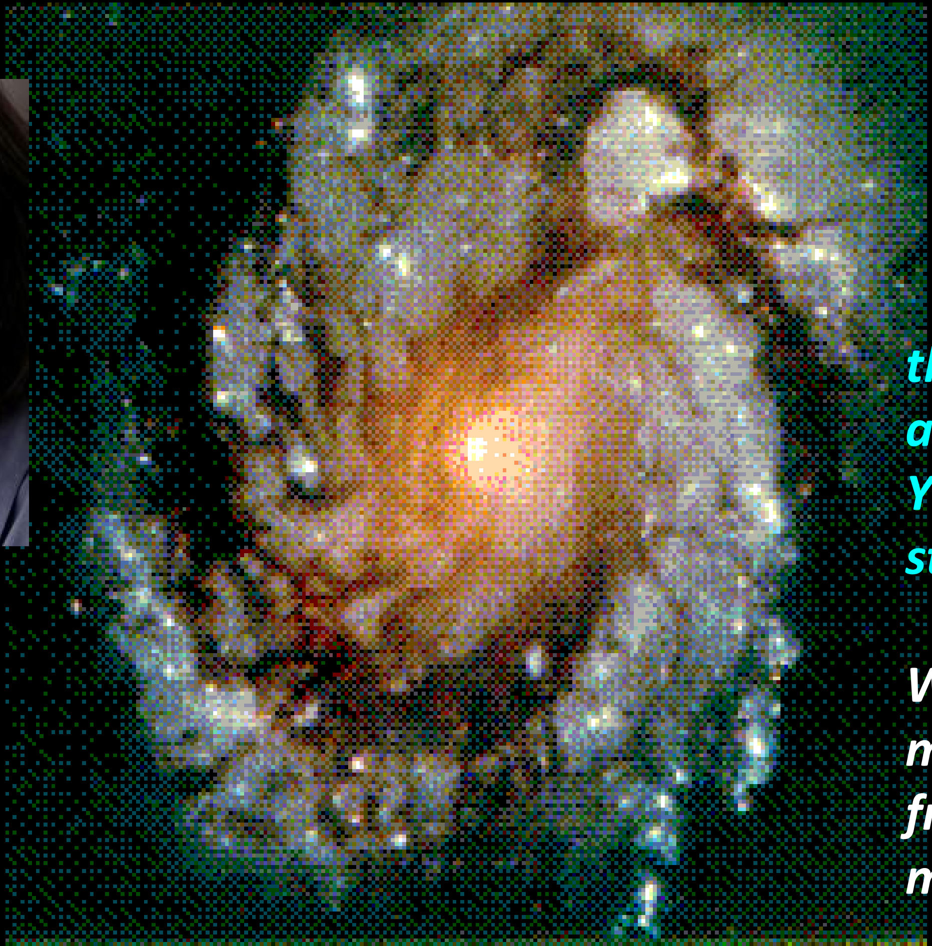
Increasingly accurate measurements of the CMB have led us to conclude that the geometry of the Universe is FLAT as far as we can see, back to the CMB (which will be explained in the last section).





H_0 was measured from the red shifts of the light from distant galaxies. The first clue that there might be something like Einstein's cosmological constant adding extra expansion to the already-expanding universe came unexpectedly.

In the mid 1990's, Professor Wendy Freedman of the University of Chicago and her team used the newly-repaired Hubble Space Telescope to measure H_0, using Cepheid variables (see Lab 11) in galaxies of the Virgo Cluster to measure the distance to Virgo Cluster galaxies independently of the redshift of the galaxies in the cluster.



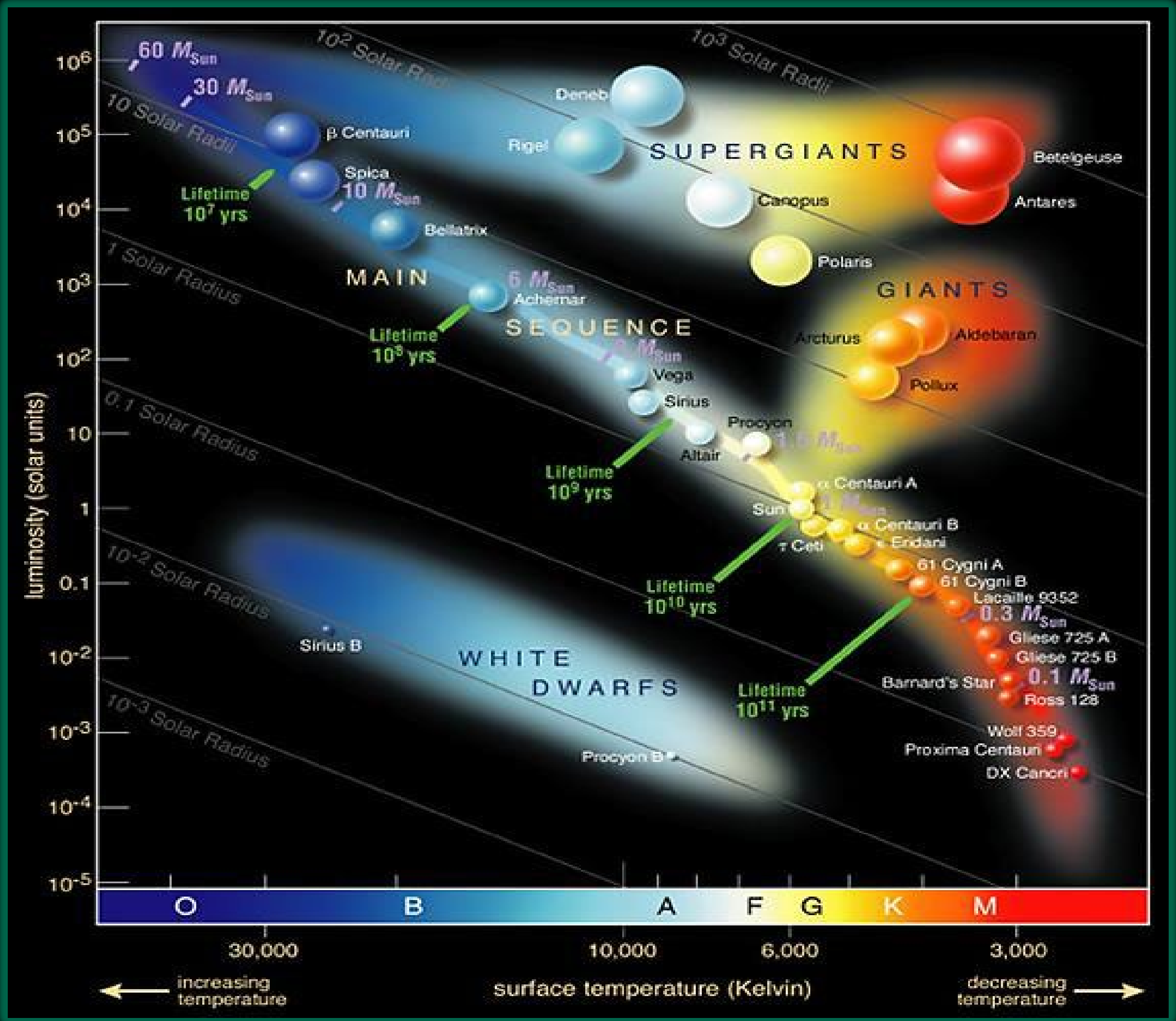
Freedman and her team reported a value for H_0 of more than 70 km/sec/Mpc…

thus making the Universe appear to be YOUNGER than the oldest stars!

What??? Let us digress a moment to ages of stars from their time on the main sequence.

Recall:

Where a star begins its life on the Main Sequence, and how it 'lives' and 'dies' is determined by how much mass it has to start with.



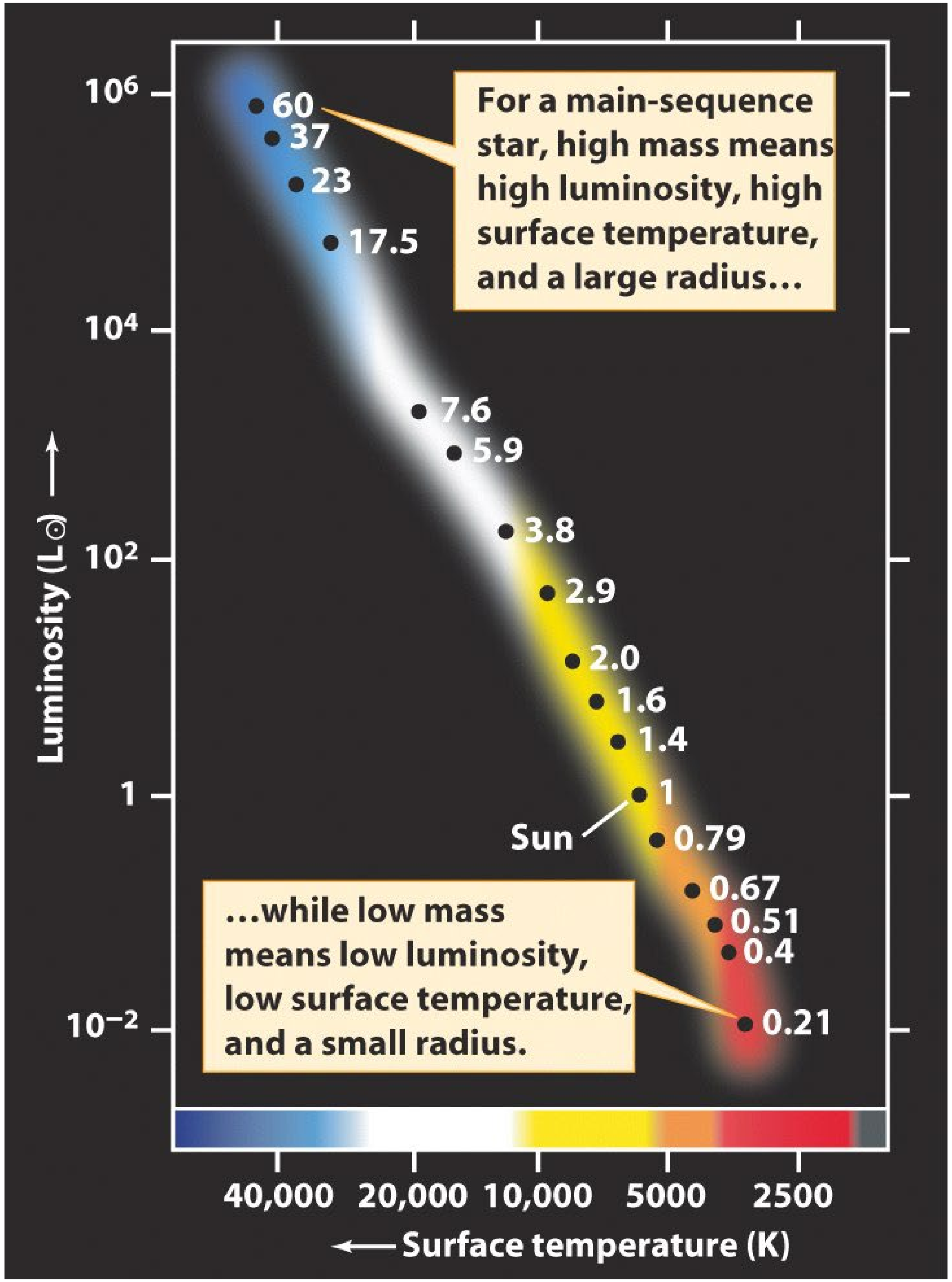
More mass

↓

faster rate of nuclear fusion

↓

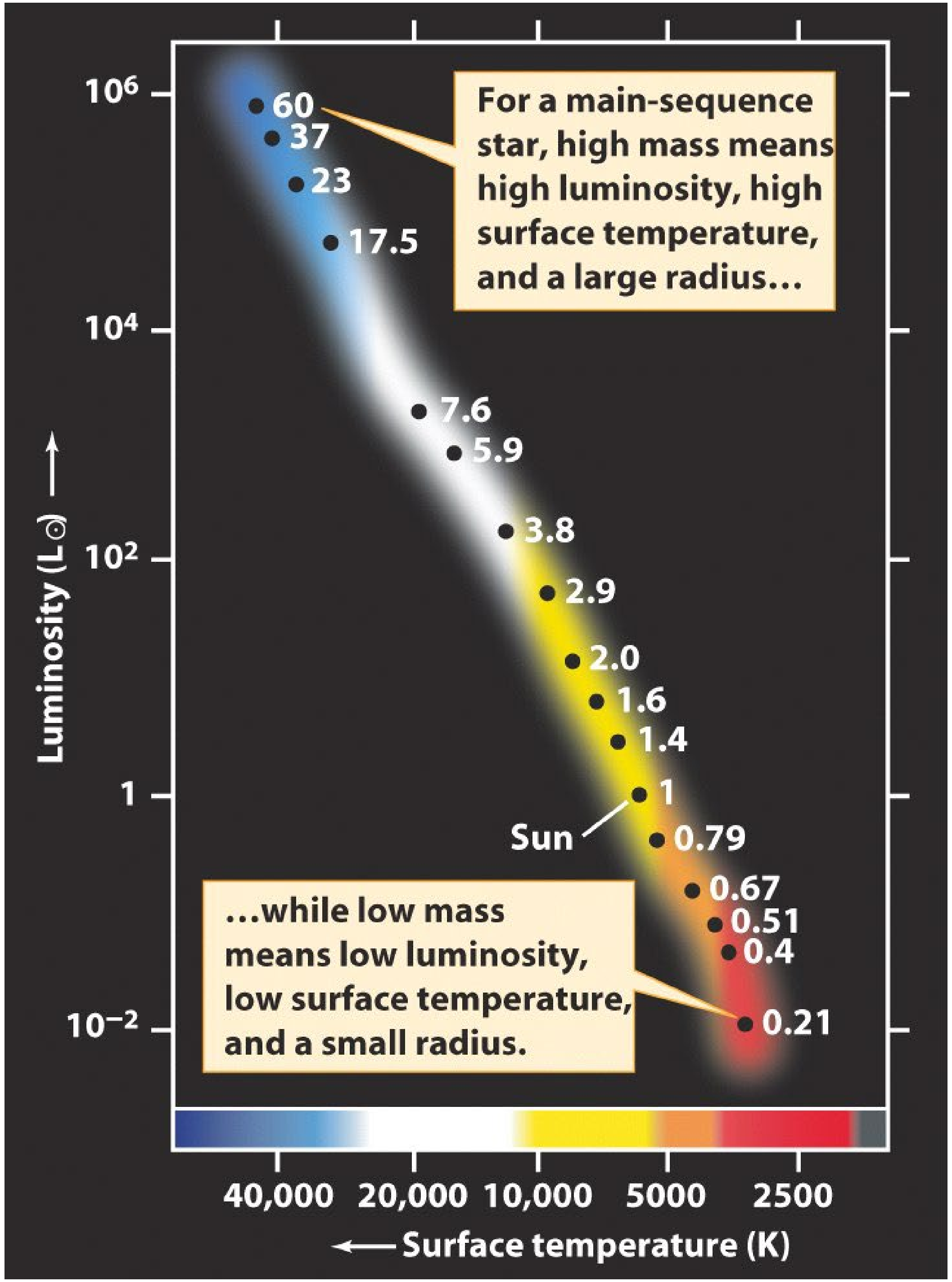
shorter lifetime



Recall:
You can calculate a star's PREDICTED lifetime on the main sequence by its luminosity.

$$T = \frac{1}{L^{.7143}}$$

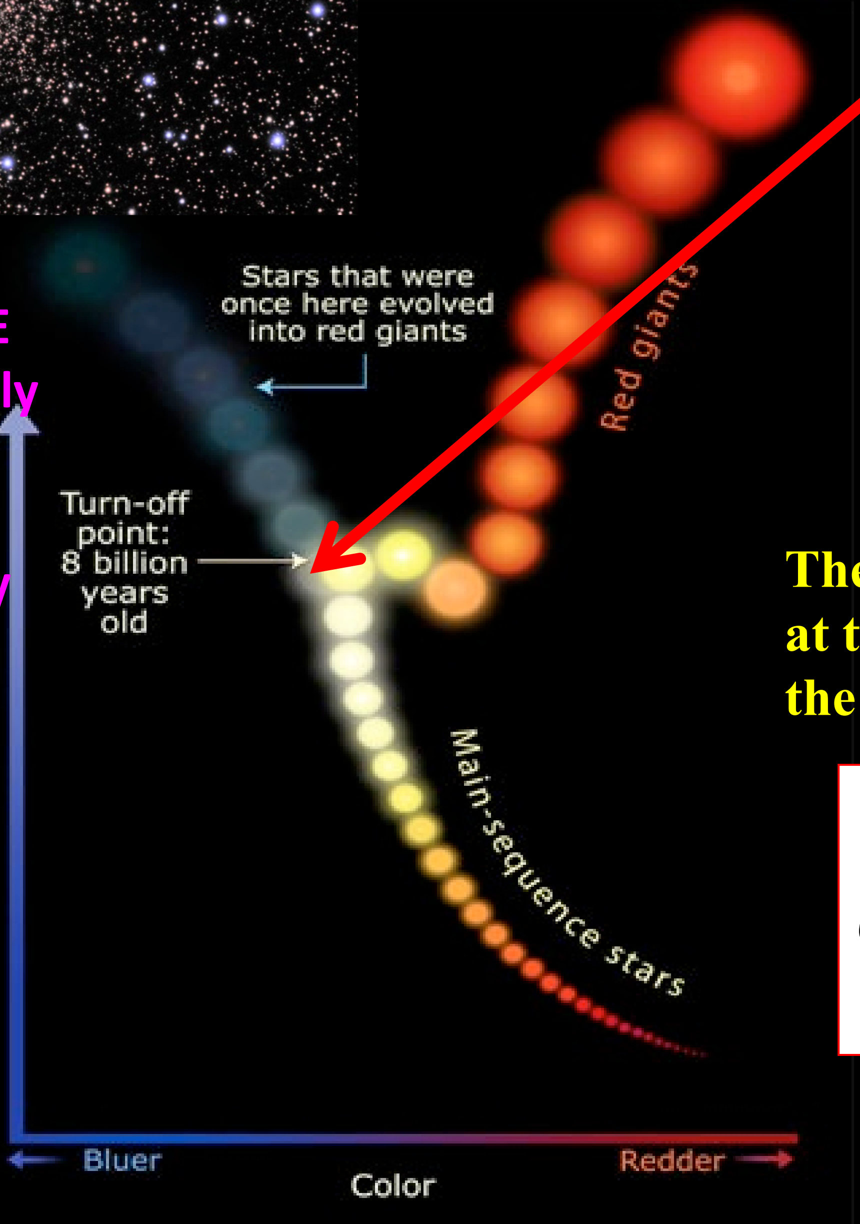
This is the predicted age when the star will run out of hydrogen in its core and turn off the main sequence, towards the red giant branch.



NGC 6791

HR diagram of a very old, metal-rich open cluster

Similarly, we can calculate the AGE of a gravitationally bound cluster of stars by the luminosity of the stars that are just leaving the main sequence, on their way to becoming red giants.



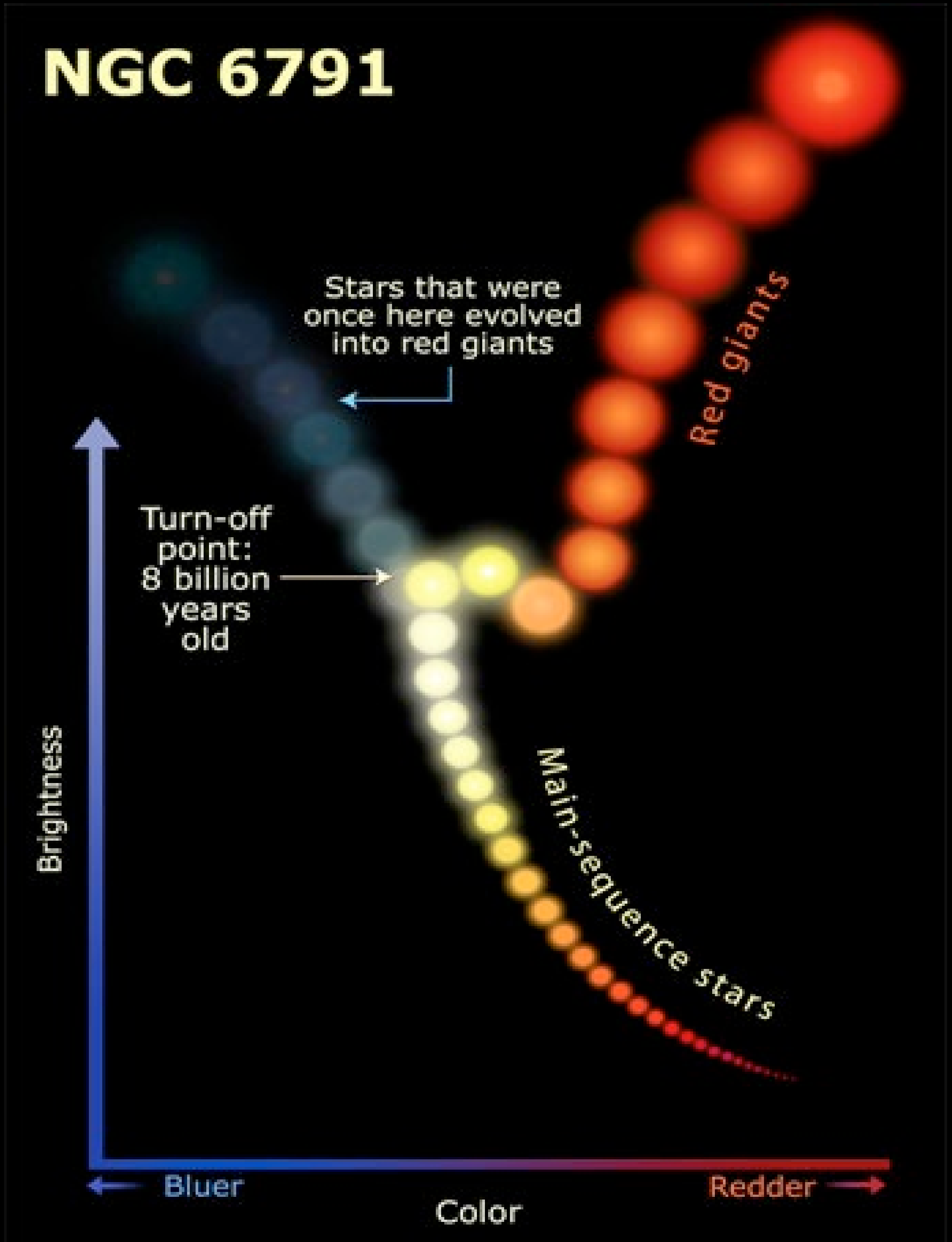
Turn off point: where stars in a cluster leave the main sequence, having exhausted their hydrogen fuel, and become red giants.

The luminosity of the stars at the turn off point tells the age of the cluster.

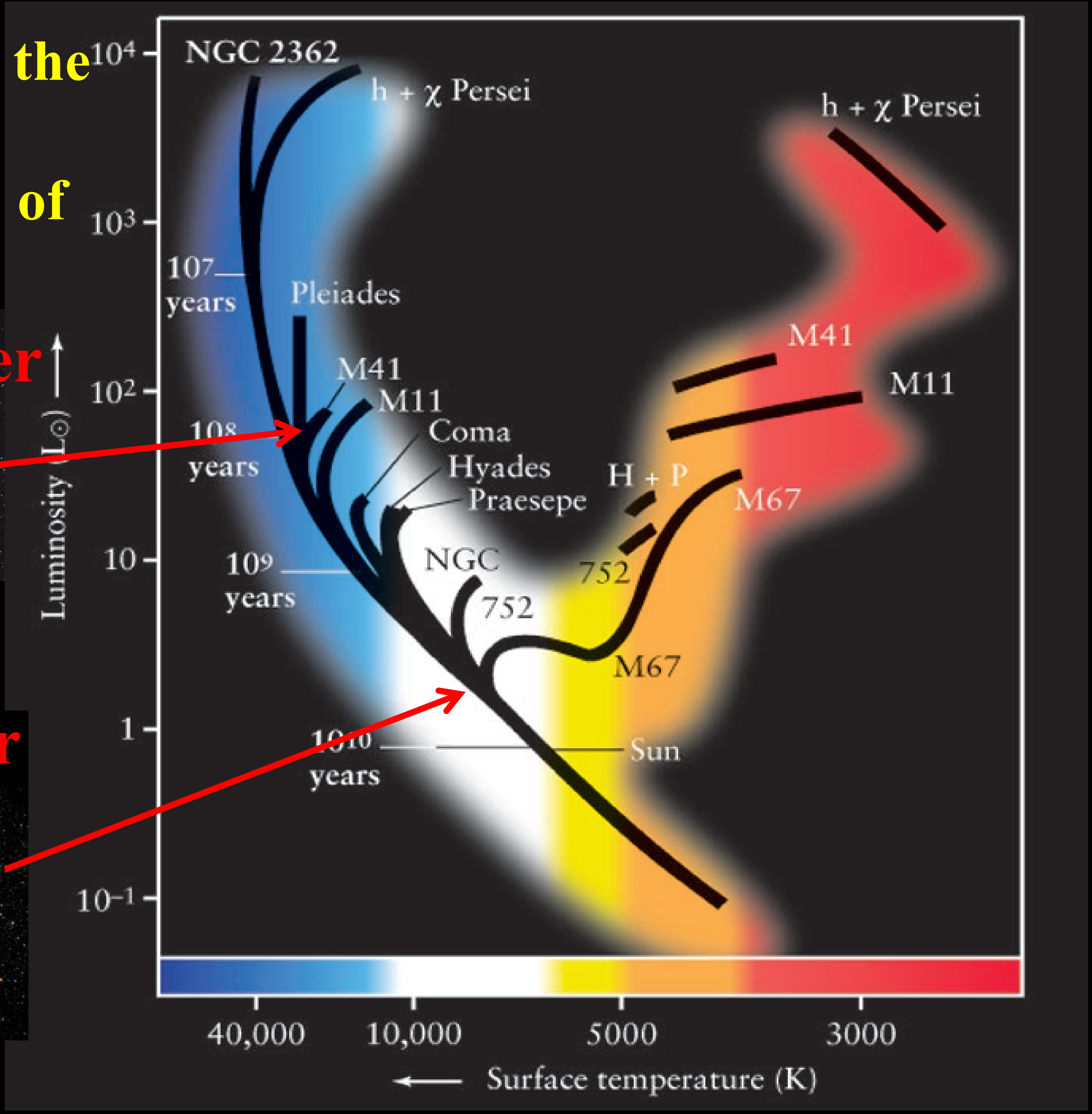
$$age = \frac{1}{L^{.7143}}$$

Since we know
how long a star of a
certain MASS will
stay on Main sequence, we can
tell how old the cluster is in
terms of the predicted
lifetime of the Sun,
from the turnoff point of the
stars that are just at the
point of becoming
red giants.

$$age = \frac{1}{L^{.7143}}$$

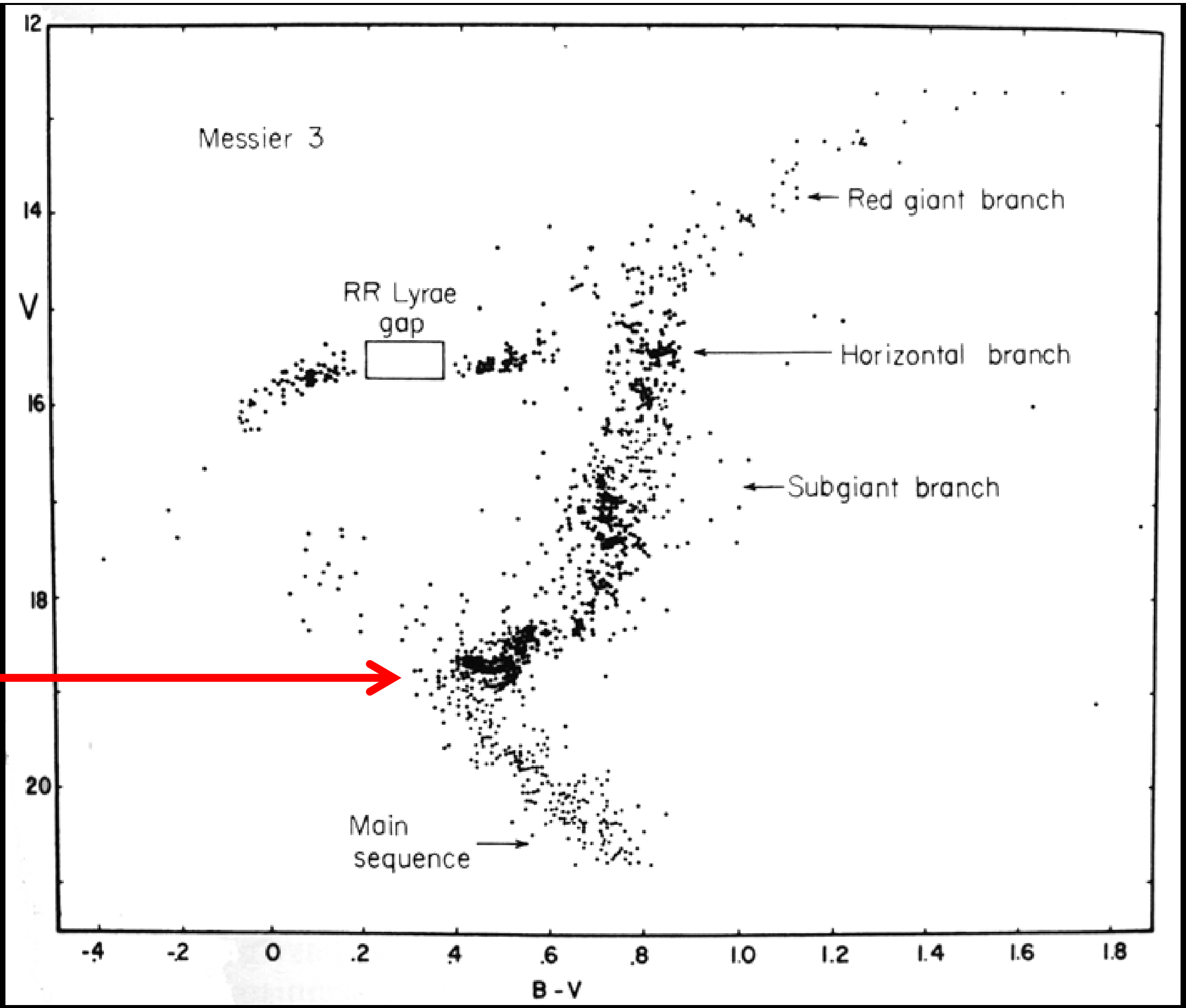


Luminosity at the turn-off point gives the AGE of the cluster!



Back to our story of the discovery of dark energy:
At the time Prof. Freedman calculated the expansion rate of the universe from the distance to Cepheid variables in Andromeda, it was well known that the oldest stars are around 11 billion years old, just from basic stellar evolution.

M3 – an old globular cluster



turn off point
$L \sim 0.8\ L_{sun}$
$T = 1/.8^{.7143} = 1.1 T_{Sun}$
~11 Gyr for M3.

Freedman's observations which led her to estimate H_0 as 70 km/sec/Mpc, as opposed to the generally accepted value at that time of 50 km/sec/Mpc, presented a paradox. Many said, at the time, that her data must be wrong. She has since refined her measurements many times, and they are NOT wrong!

So theoretical physicists, notably Lawrence Krauss (left) and Michael Turner (right) proposed bringing back Einstein's cosmological constant to make all the observations make sense. In other words, they suggested that there is a COSMOLOGICAL CONSTANT which acts like an ANTIGRAVITY force, and thus the expansion rate of the universe may not be slowing down, as was believed in the mid-1990's

Meanwhile, around the same time (late 1990s), two groups of researchers – one at UC Berkeley and the other at Harvard – who were each looking for Type Ia Supernovae at high redshifts found something unexpected.

The also found a contradiction in their data: If they calculated the distances to high red shift supernovae (High z Sne) from their absolute magnitudes at their brightest, they found a distance that is much greater than it should be from their theoretical light curves.

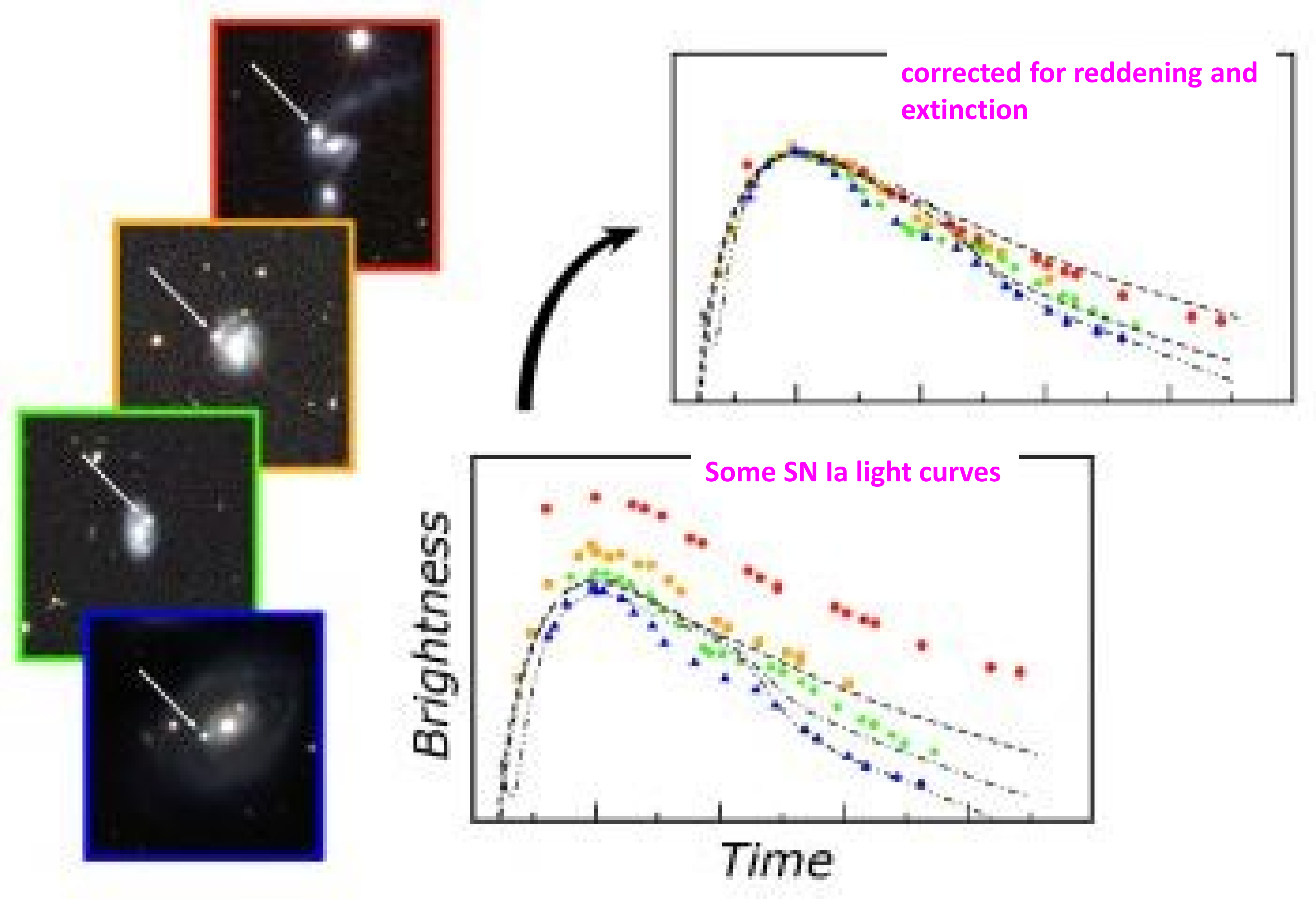
They were able to make their calculations match their data IF they also included a cosmological constant (anti gravity) force indicating that the universe began *accelerating in its expansion rate around 5 billion years ago.*

In 1997 new data from distant Type Ia Supernovae gave confirmation that supported Freedman's measurements for a higher than expected expansion rate of the universe.

First – a closer look at Type Ia SNe light curves as a means of measuring distances:

Light curves of Sne Ia are used as standard candles.

See p. 356 in your text.



These light curves are powered by radioactive decay in two stages:

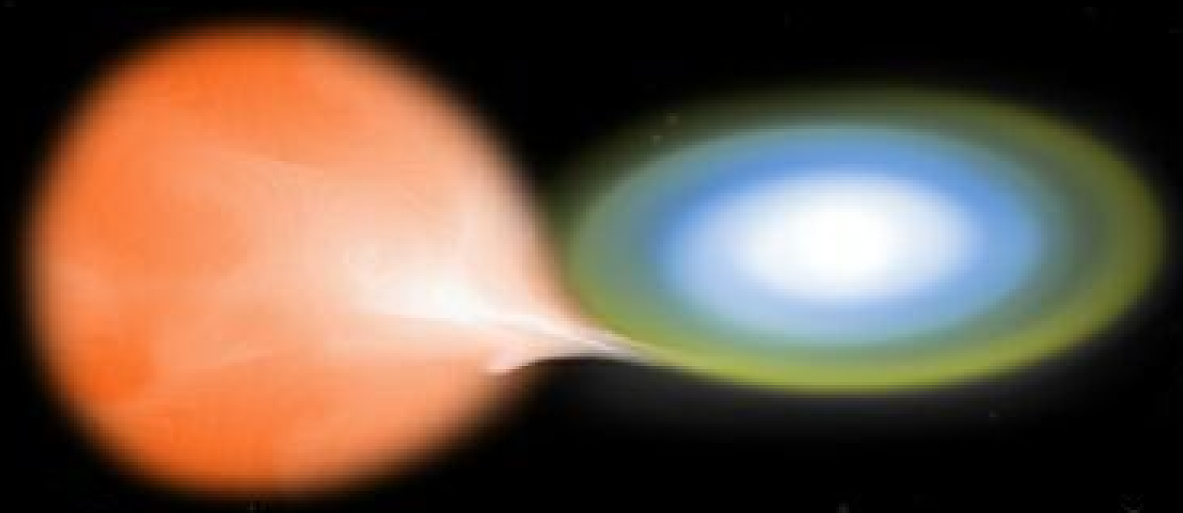
Stage 1 is the decay of ^{56}Ni to ^{56}Co This has a 1/2 life of 6.1 days and predicts that the SN luminosity decays at the rate of 11% per day.

$$^{56}_{28}\mathrm{Ni} \rightarrow \; ^{56}_{27}\mathrm{Co} + e^{+} + \nu_e + \gamma$$

Stage 2 is the decay of ^{56}Co to ^{56}Fe.   This has a 1/2 life of 77 days and predicts that the SN luminosity decays at the rate of 1% per day.

$$^{56}_{27}\mathrm{Co} \rightarrow \; ^{56}_{26}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$

Recall that all Type Ia supernovae are the nuclear detonations of a white dwarf in a binary relationship with a main sequence star. The denser white dwarf pulls gas and dust off the companion star.



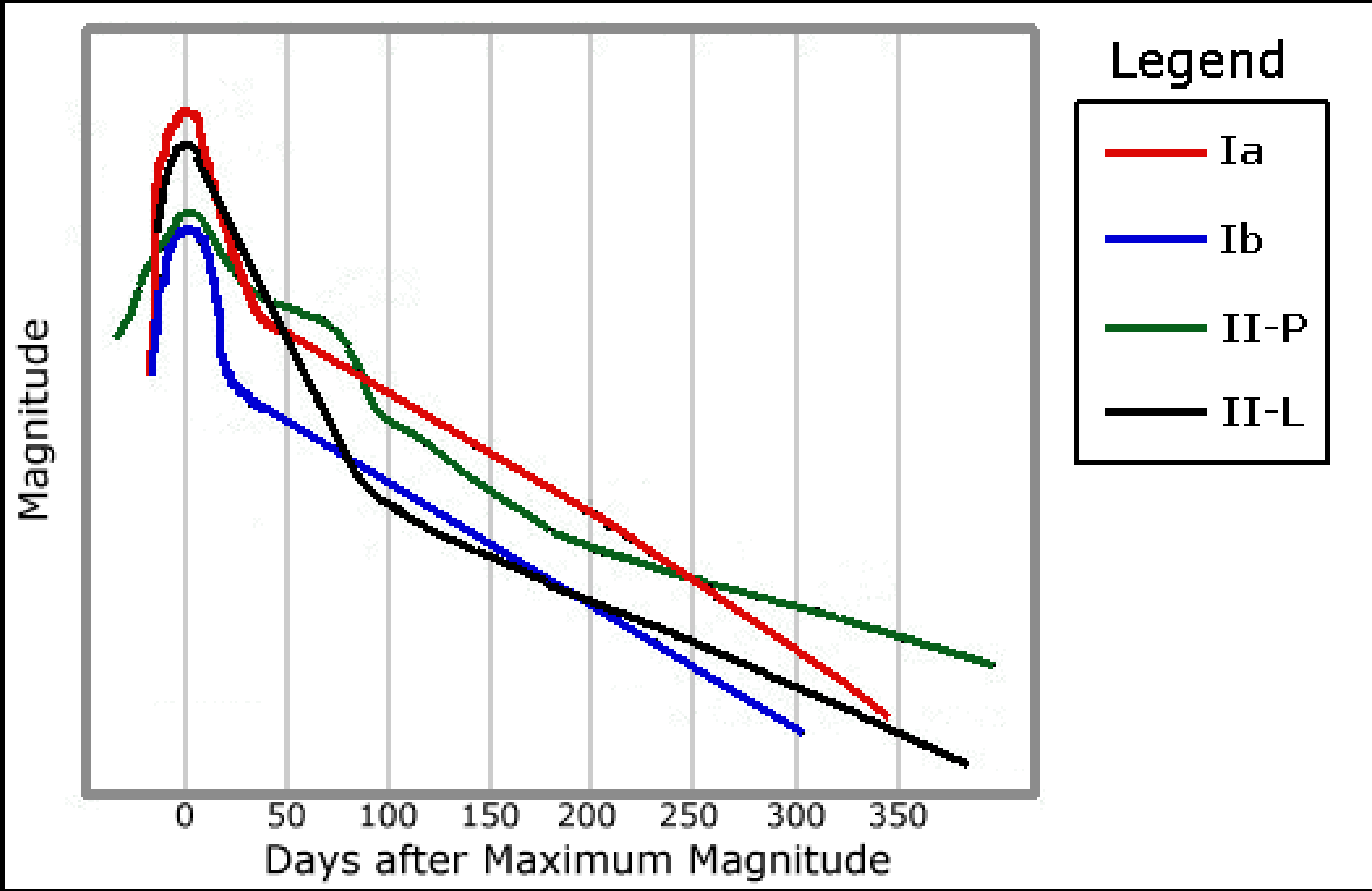
Remember the CHANDRASEKHAR LIMIT: that the MAXIMUM mass that a white dwarf can have is 1.44 solar masses before it collapses into a neutron star.

So, if the mass of the white dwarf, after pulling gas and dust off its binary companion, exceeds the Chandrasekhar Limit, then it detonates in a huge nuclear explosion as a Type Ia supernova.

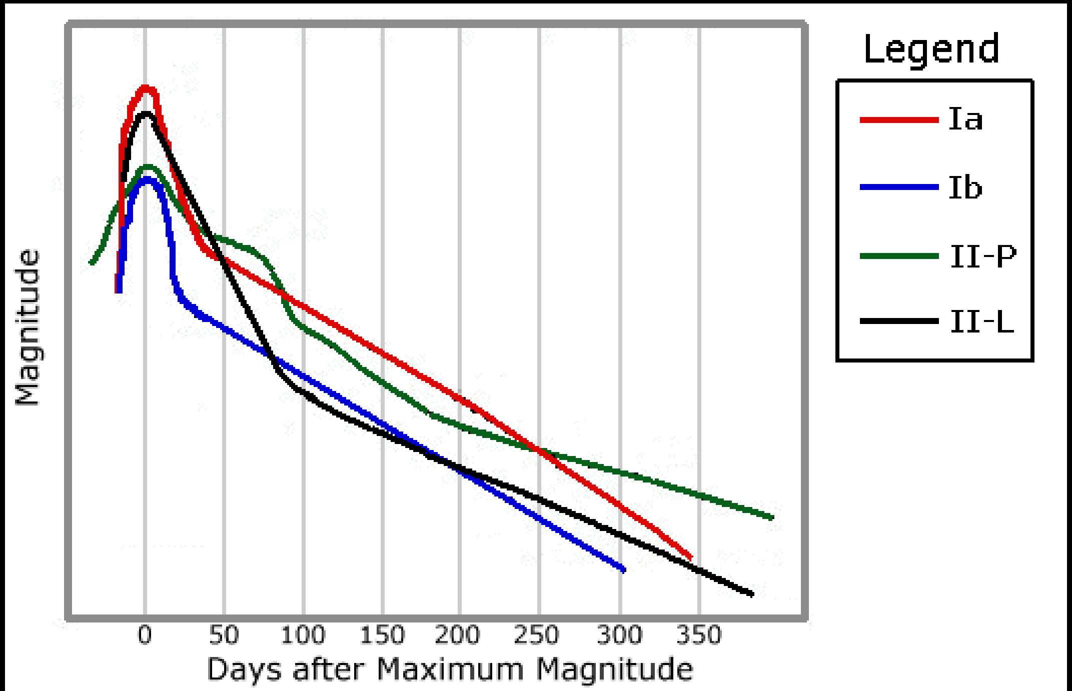
Thus we know an upper limit for the mass of this star just before it exploded.

All type Ia supernovae reach nearly the same brightness at the peak of their outburst, with an absolute magnitude of a whopping

-19.5, + or – a bit. Remember: The more negative the number, the brighter the object. Review Stars01, slides 8 – 15.



With a known absolute magnitude (M) at maximum brightness, it is possible to calculate their distance by measuring their apparent magnitudes (m) at maximum brightness, correcting for the expected reddening and extinction due to the InterStellar Medium (ISM- refer back to Lecture 12a), and using the distance formula.



$$d = 10^{(m-M+5)/5}$$

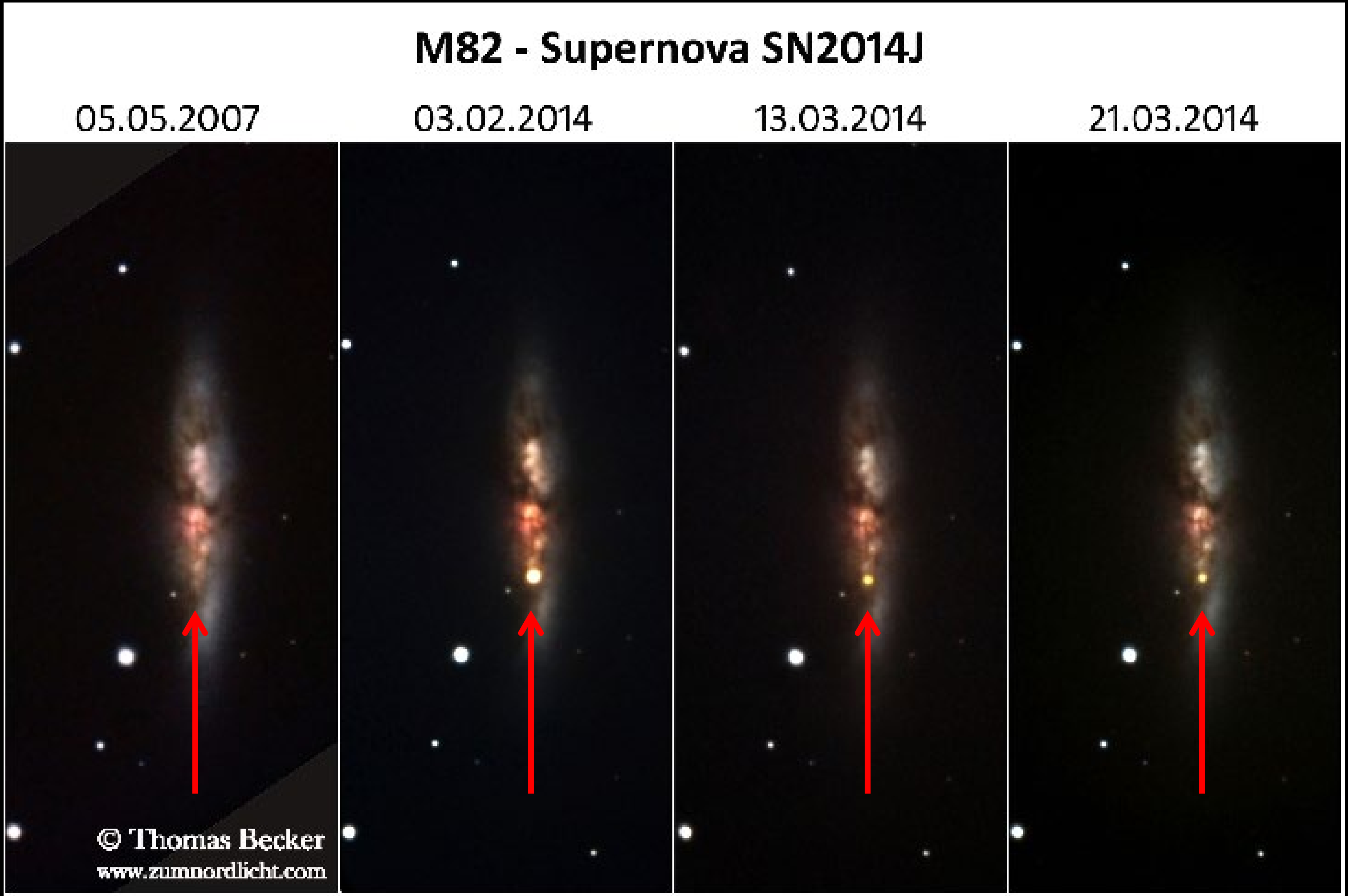
units of d are parsecs

1 pc = 3.26 ly

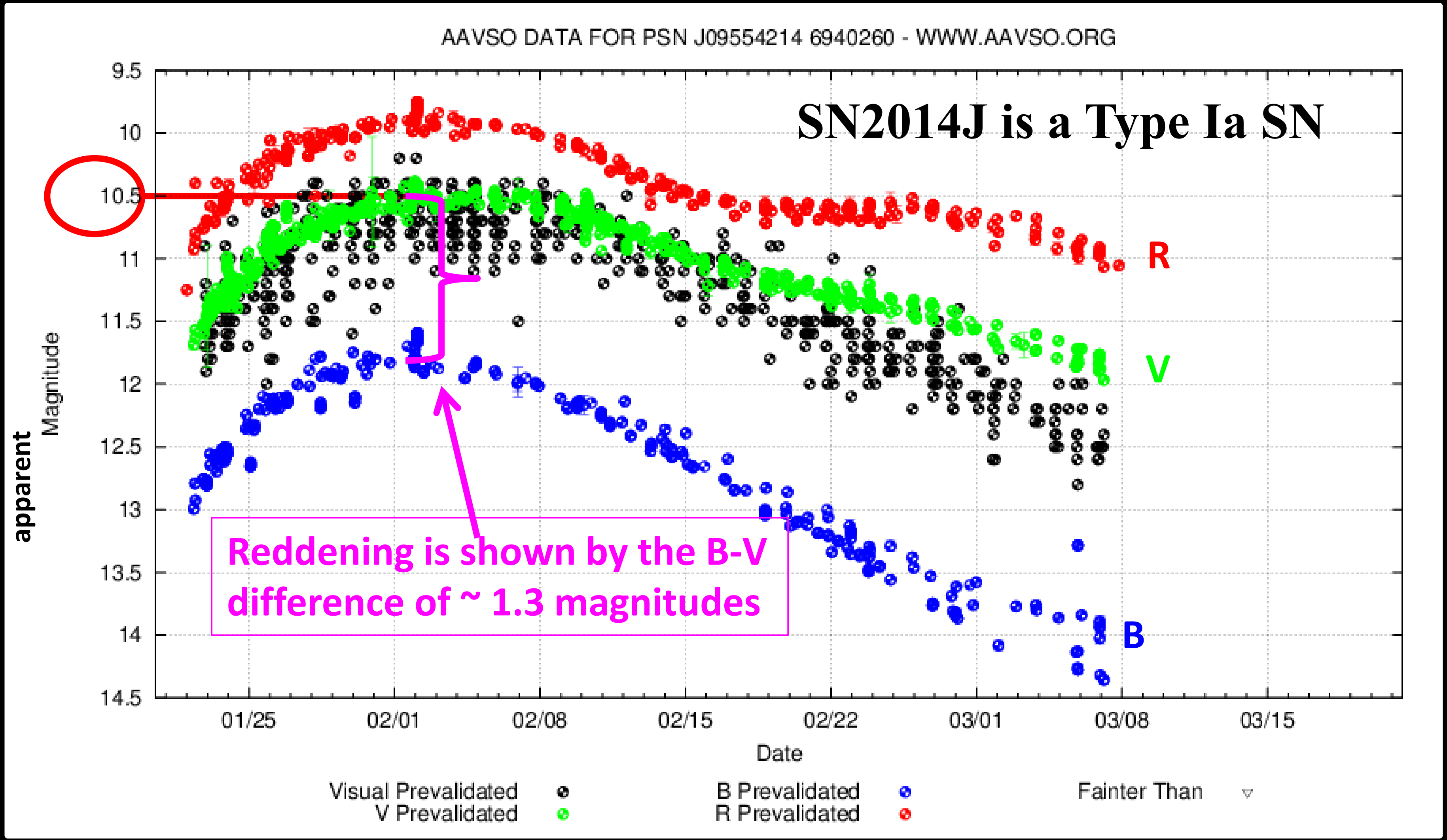
Thus, if you can measure the apparent magnitude of a type Ia Sn, you can calculate how far away its host galaxy is.

Supernova 2014J in Galaxy M82 *HST* ▪ WFC3/UVIS ▪ ACS/WFC

NASA and ESA STScI-PRC14-13a



Series of images of M82. First image on the left is M82 before the supernova.



Numerous studies have been done on this supernova because it is relatively close. It has been determined that it has quite a bit of REDDENING due to dust, since M82 is a very dusty galaxy. Dust affects different wavelengths differently (review Lecture 12a, slides 6 – 11!) and makes stars appear both redder AND dimmer than they otherwise would appear. This is an important idea pertaining to the next piece of the dark energy puzzle, starting on the next slide.

Back to our discussion of dark energy.

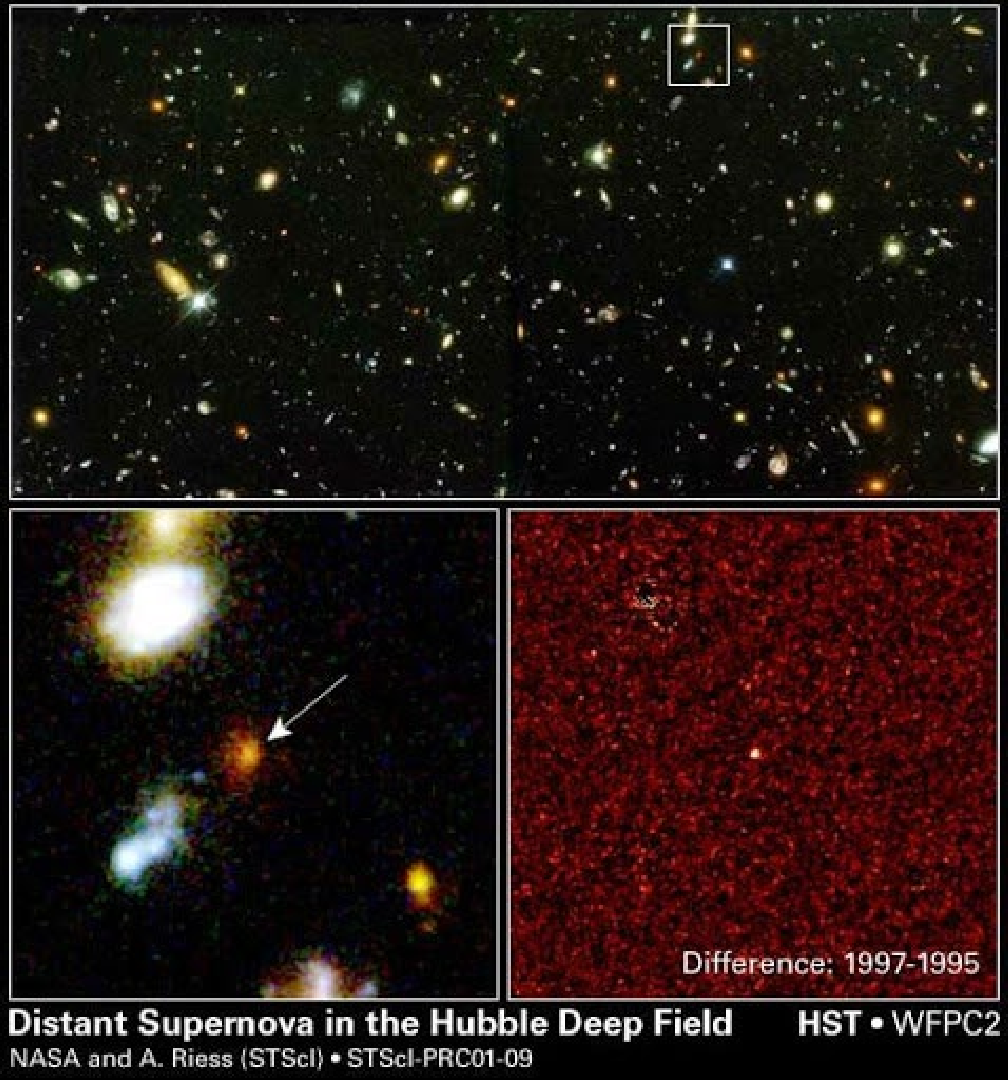
In 1997 two groups of astronomers, one from UC Berkeley and the other from Harvard, found a supernova in a galaxy at a red shift of 1.7 using an image of very distant, very ancient galaxies known as the Hubble Deep Field.

They compared an image of this region of the sky from 1995 with one taken in 1997.

Top: Part of the Hubble Deep Field (HDF). Square: location of SN1997ff.

Lower left: magnification of the square in the HDF showing the location of SN1997ff.

Lower right: Image from 1995 subtracted from image taken in 1997, in infrared light. What's left: SN1997ff!



Refer back to slide 13: For a redshift of 1.7, the universe has stretched by a factor of 2.7 since the light left that galaxy. $R_{then}/R_{now} = 2.7$.

This redshift corresponds to an age of around 10-11 billion years since the light left the galaxy and SN1997ff, and the galaxies in the Hubble Deep Field are thus some of the very oldest galaxies.

The DISTANCE calculated from the measured redshift depends on the model used for the expansion of the universe, and in particular on the value of H_0.

The distance calculated from the light curve depends on accurately measuring the apparent magnitude at peak brightness.

In principle, these two independent measurements should agree. In the case of SN1997ff they did not, and so – as in all scientific discoveries, as you have seen throughout this course! – when the data don't match predictions, a new theoretical model must be developed.

The equations are shown on the next slide...

$$H_0 d = cz$$

Hubble's Law, c = speed of light, z = red shift, d = distance, and H_0 = the Hubble constant, i.e. the expansion rate of the universe per Megaparsec.

$$\frac{\Delta\lambda}{\lambda} = z$$

z = red shift, measured from spectra (see slide 4)

$$d = \frac{cz}{H_0}$$

Distance calculated from measuring the red shift and assuming a value of H_0.

These two independent measurements for distance should agree.... unless there is something unexpected!

$$d = 10^{(m-M+5)/5}$$

Distance calculated from knowing the apparent magnitude (m) and absolute magnitude (M).

The distance calculated from red shift and the assumption that the universe must be slowing down in its expansion since the big bang, was too large compared to the distance calculated using the distance formula from (m-M).

Options: Either H_0 is wrong or not constant, or there is more dust than expected, making the peak brightness less than expected. The result was surprising!

The problem with assuming too much dust:
Remember – dust makes starlight REDDER. Go back to slide 83 – notice the difference between the V (green) and B (blue) curves – that difference is due to the REDDENING by dust in that dusty galaxy, M82.

There was no similar reddening of the light from SN1997ff! It was just altogether too dim for its distance.

That left only the alternative explanation: The expansion rate of the universe is speeding up, putting SN1997ff farther away than expected from its distance calculated just from its redshift!

If it is assumed to be DIMMER (m larger, because remember the larger m, the dimmer the star, the more negative m, the brighter the star) then the two distance measurements can agree.

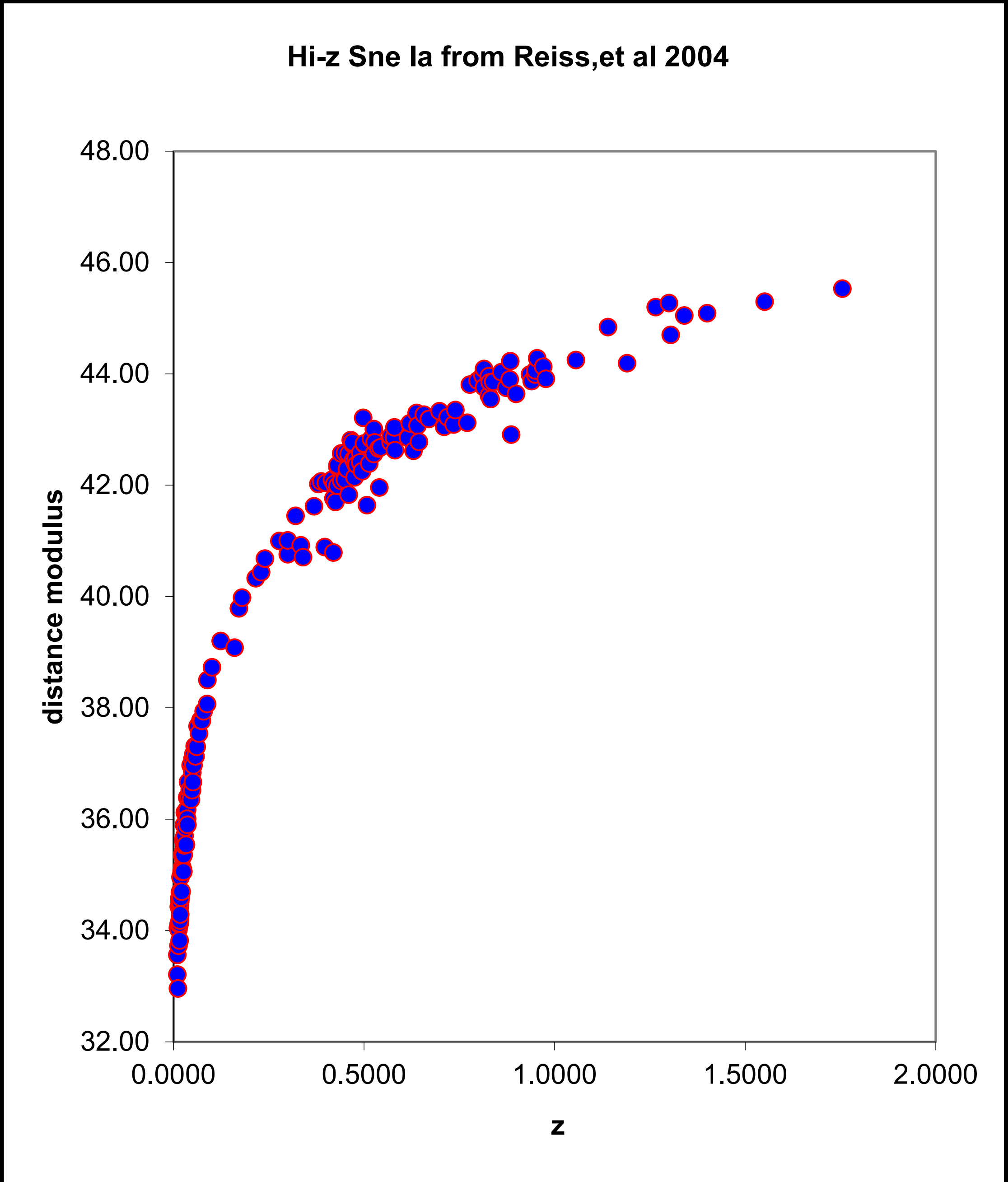
Actual data from 187 high redshift supernovae from Adam Reiss and the UCB team are shown on the next slide.

Data:
Distance modulus μ = m-M
as a function of z, red shift.

Recall: M = -19.5. m's are large positive numbers because the supernovae are far away. To get an idea of the visual magnitudes, subtract 19.5 from the values on the y-axis.

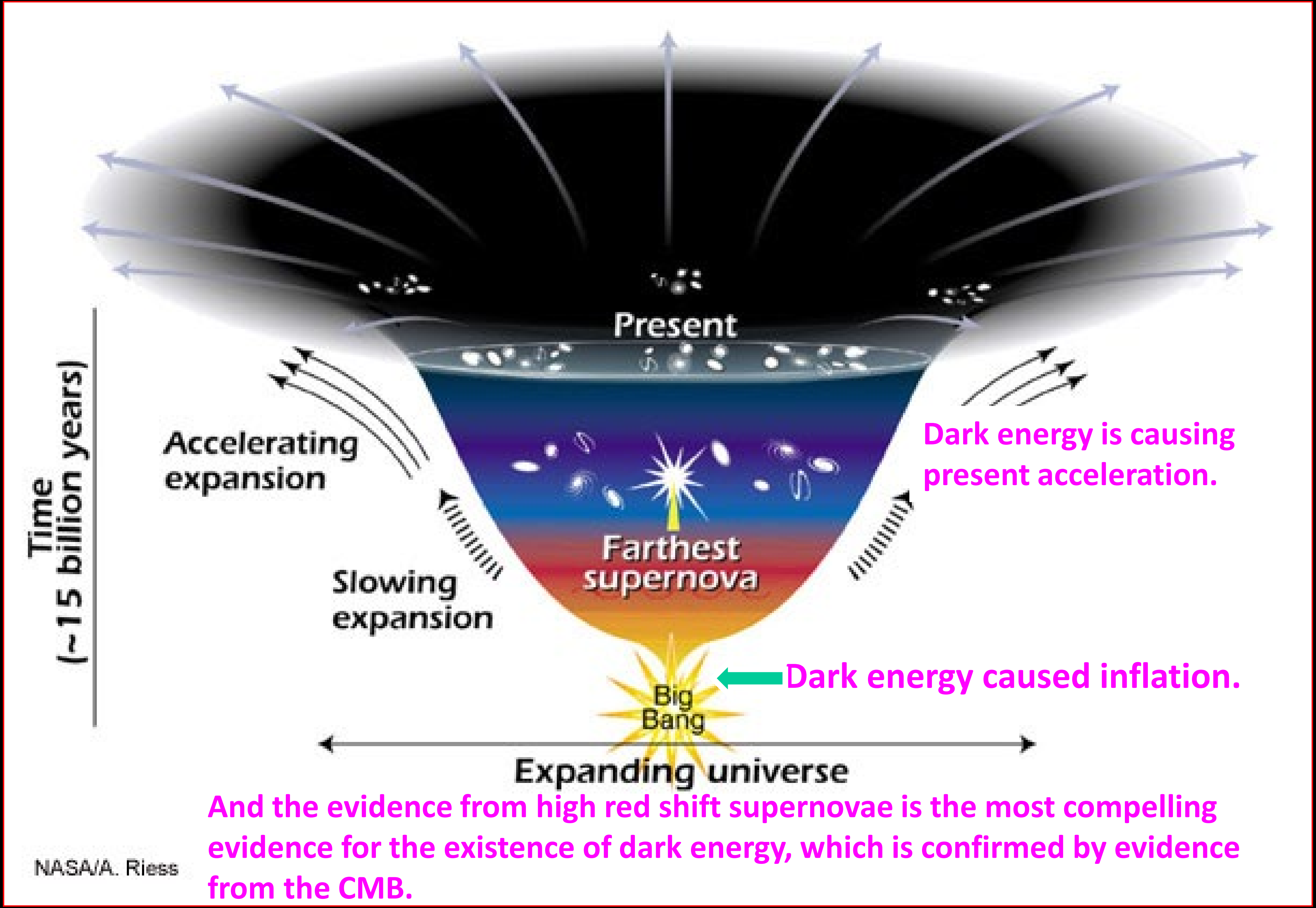
Finding the equation that fits a curve to these data points was the challenge that led to the conclusion that the universe began accelerating around 5 billion years ago.

If there was no change in H_0 over time, this graph should be a straight, diagonal line like Hubble's graph for close-by galaxies.
Look back at slide 5.



Graph from van der Veen & Lubin (2009)

To make a long story short, we now understand that the universe is accelerating in its expansion rate, and that this acceleration began approximately 5 billion years ago.



Dark energy is causing present acceleration.

Dark energy caused inflation.

And the evidence from high red shift supernovae is the most compelling evidence for the existence of dark energy, which is confirmed by evidence from the CMB.

Contents of the universe:

< 5% Atoms – regular matter

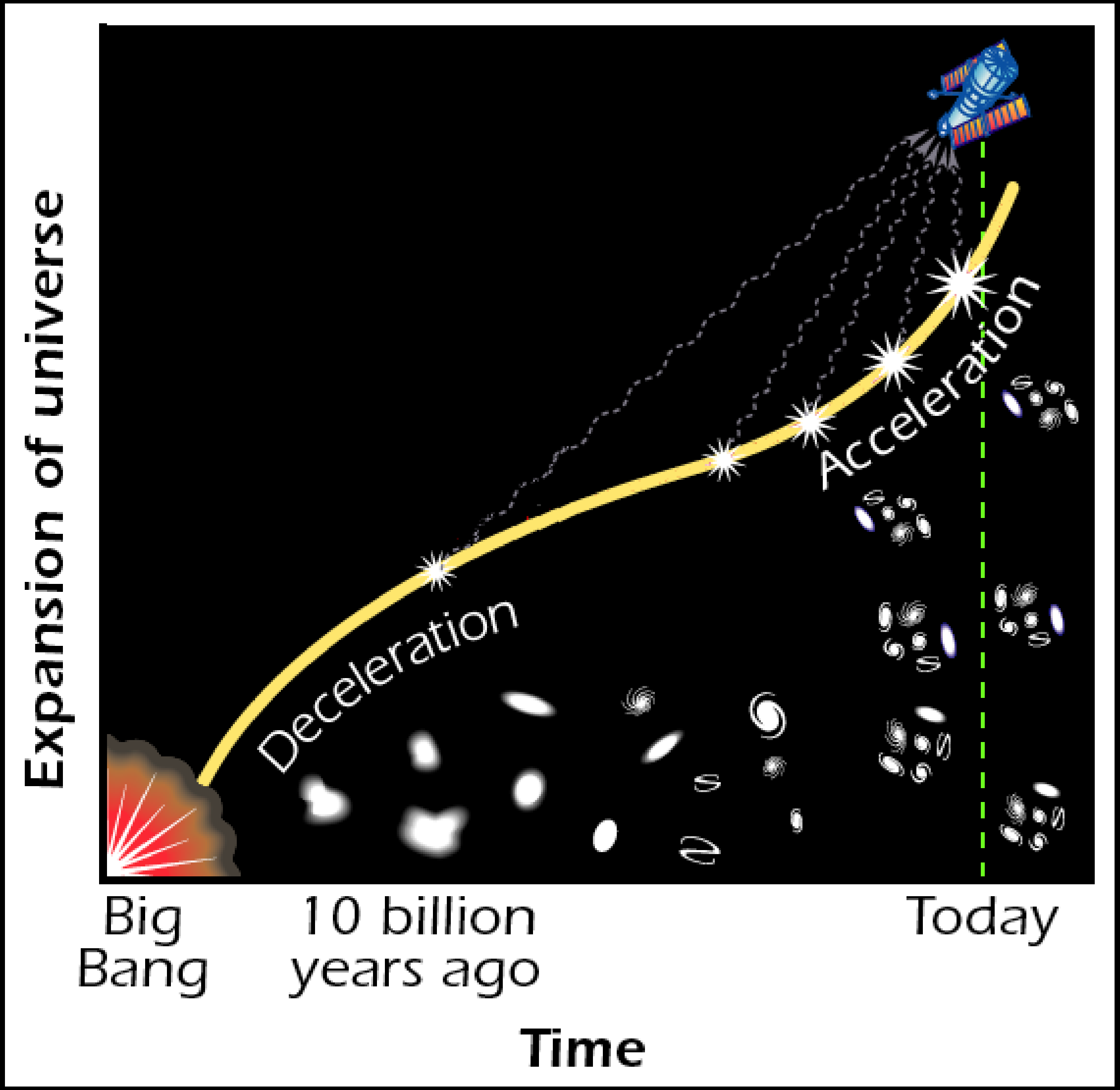
> 95% unknown!!!!

We need new physics
to figure out the 95%

Conclusions:

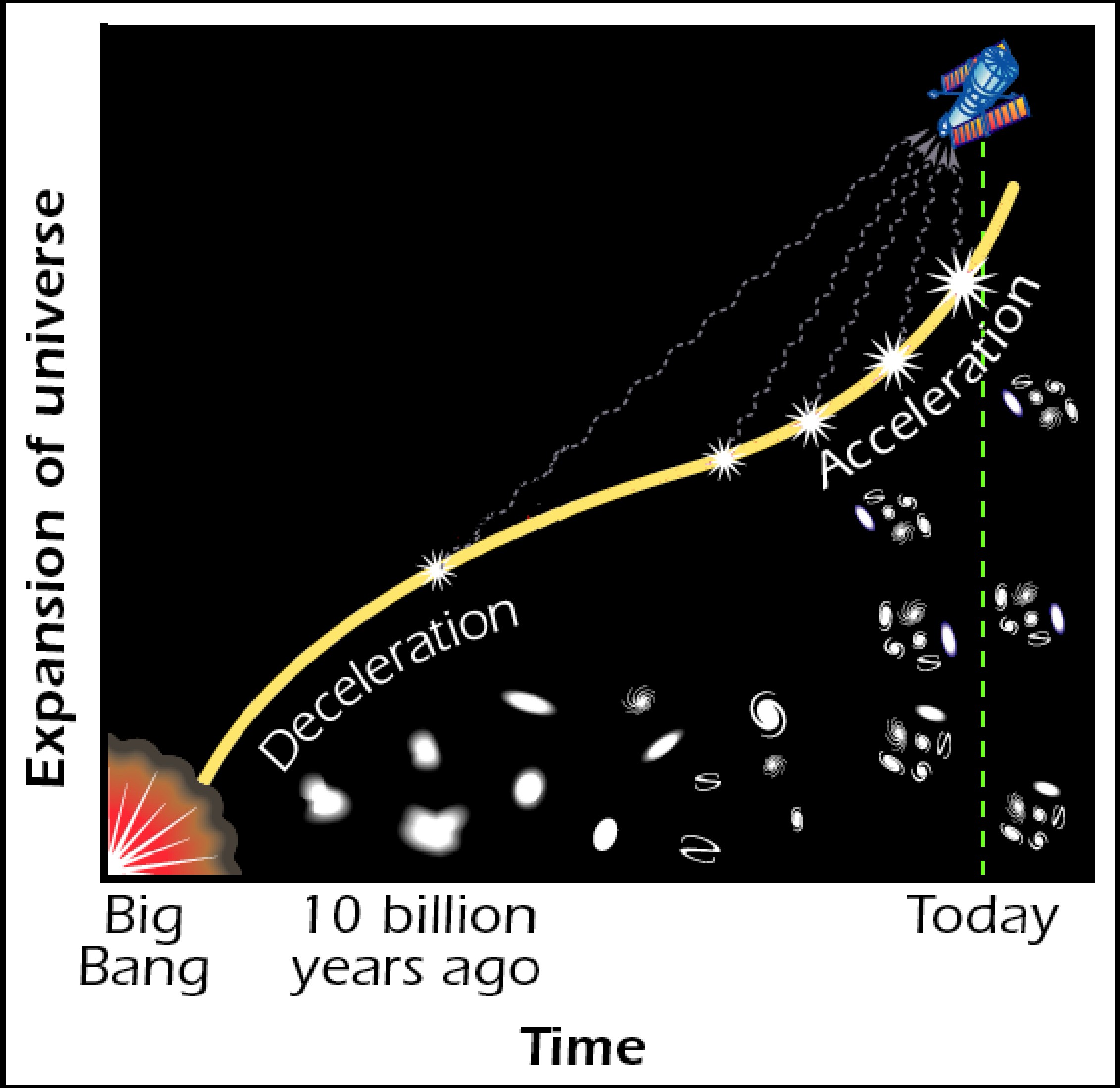
• Until about 5 billion years ago, the expansion of the universe was *slowing down*.

• Since then, the expansion has been *speeding up.*



Our best explanation:

- The universe is suffused with a kind of "antigravity" called **DARK ENERGY.**



- For the past 5 billion years, *dark energy has been the dominant form of energy in the universe.*

What is the Source of Dark Energy?

(weird particles, mysterious fields, properties of space itself, modifying Einstein’s equations, the existence of hidden extra dimensions that we can’t see???)

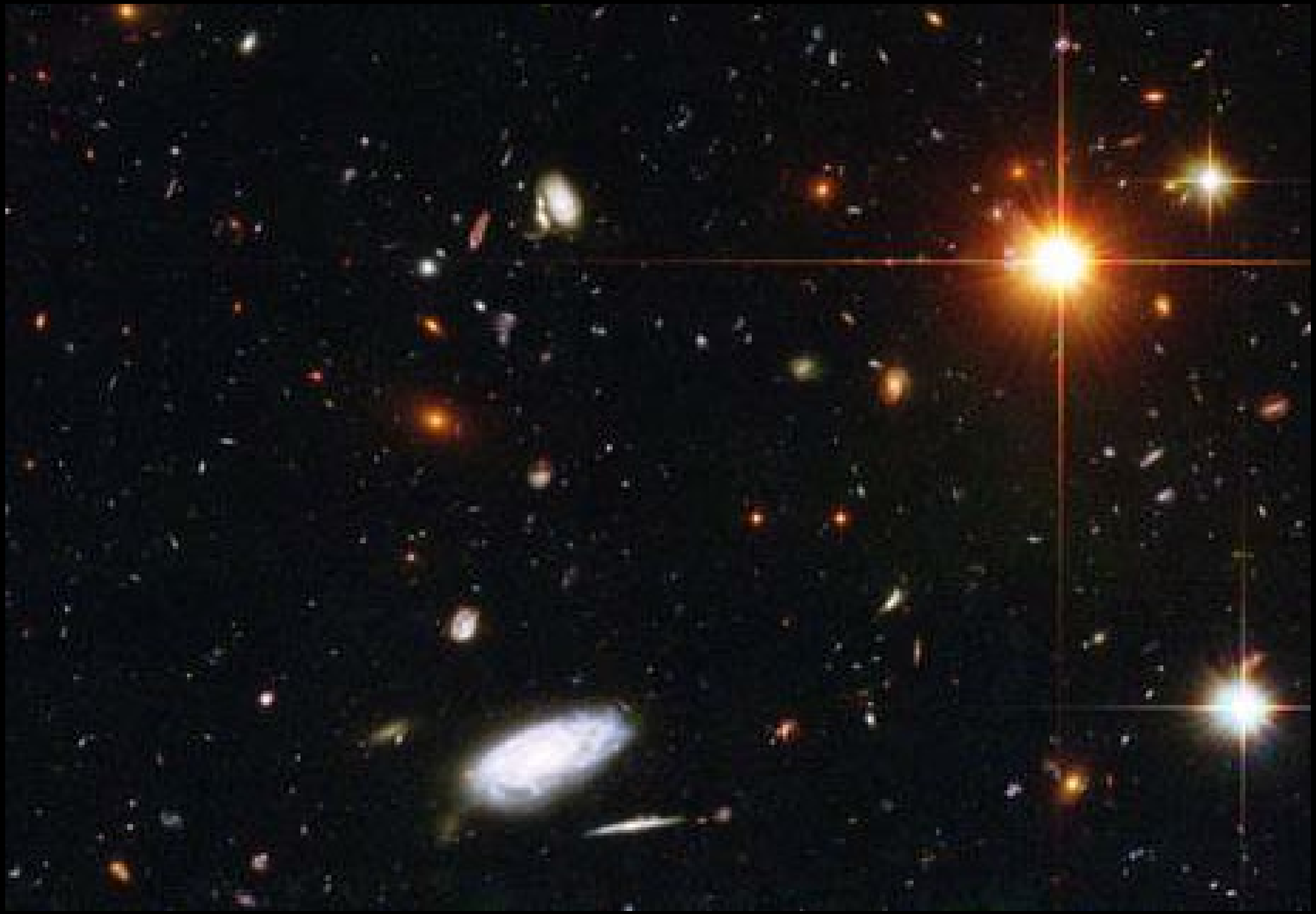
We don’t know…

There are ideas, but none have worked out so far.

Other ideas require more observations to test.

Because dark energy is dominant,
at the present time, the expansion of the universe will continue forever at an ever-increasing rate.

…eventually receding away faster than the speed of light!



Tens of billions of years from now, other galaxies will be so far away as to be invisible…

...and a future observer in our Milky Way galaxy will think they are the only galaxy in a vast universe of darkness.