A Little Astrophysics-From the Big Bang to Now

III Dark Matter and Dark Energy

Jim Rauf

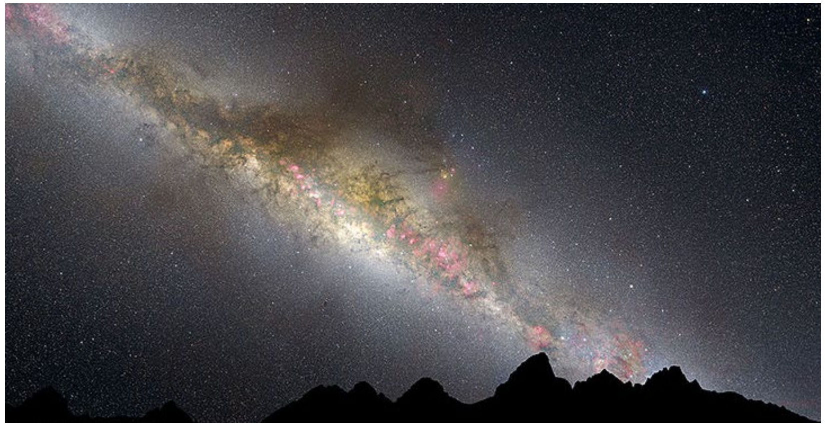
OLLI Fall 2022

What is Dark Matter?

Nobody knows!

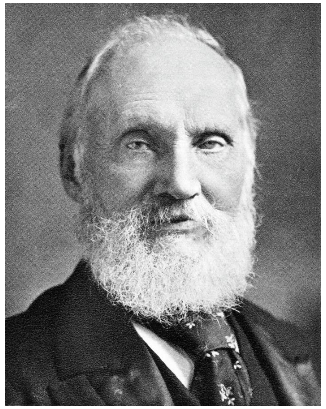
Dark Matter - Some History

- In 1884,**Lord Kelvin** estimated the number of *dark bodies* in the **Milky Way** from the observed **velocity dispersion** of the stars orbiting around the center of the galaxy



$$F = \frac{GM_{\odot}m}{r^2} = \frac{mv^2}{r}$$

$$v = \sqrt{\left(\frac{GM_{\odot}}{r}\right)}$$

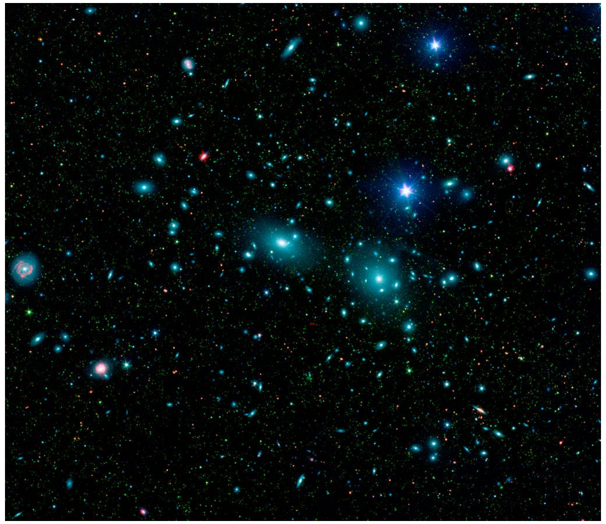


- He **estimated the mass** of the galaxy, which he determined is **different from the mass of visible stars**

- He concluded "Many of our supposed thousand million stars, perhaps a great majority of them, may be dark bodies"

Dark Matter - Some History

- 1937 **Fritz Zwicky** at Cal Tech studied the movement of individual galaxies within a huge cluster of galaxies called the **Coma Cluster**
- The cluster is about 300 million light years from earth and contains thousands of galaxies that orbit its center
- He used the motions of a few dozen galaxies as a tracer of the gravity field that binds the cluster together
- **Zwicky** discovered that their velocity had a shockingly high value
- He inferred an enormous mass for the **Coma Cluster**
- The **total mass** of the galaxies in the cluster was **not enough** to explain the **measured velocities**



- For the Coma cluster, Ve= 977 km/s and R = 3 Mpc
- Implies a mass of $3.3 \times 10^{15} M_o$
- The mass estimate from visual luminosity is about $5 \times 10^{12} L_o$, so the mass-to-light ratio is $M / L = 660 M_o / L_o$. This shows again the magnitude of the dark matter problem.
- Additional galaxy cluster observations show the same lack of visible mass to explain the galaxies' velocities

Dark Matter - Some History

- All the **Coma Cluster** galaxies are moving more rapidly then the “escape velocity” for the cluster
- **Escape velocity** is the speed required to overcome the gravitational attraction of a large mass (planet, star , galaxy or galaxy cluster)

$$v_e = \sqrt{\frac{2GM}{r}}$$

Ve = escape velocity

G = universal gravitational constant

M = mass of the body to be escaped from

R = distance from the center of the mass

Location	Relative to	V_e (km/s)[12]
On the Sun	The Sun's gravity	617.5
On Mercury	Mercury's gravity	4.25
On Venus	Venus's gravity	10.36
On Earth	Earth's gravity	11.186
On the Moon	The Moon's gravity	2.38
On Mars	Mars' gravity	5.03
On Ceres	Ceres's gravity	0.51
On Jupiter	Jupiter's gravity	60.20
On Io	Io's gravity	2.558
On Europa	Europa's gravity	2.025
On Ganymede	Ganymede's gravity	2.741
On Callisto	Callisto's gravity	2.440
On Saturn	Saturn's gravity	36.09
On Titan	Titan's gravity	2.639
On Uranus	Uranus' gravity	21.38
On Neptune	Neptune's gravity	23.56
On Triton	Triton's gravity	1.455
On Pluto	Pluto's gravity	1.23
At Solar System galactic radius	The Milky Way's gravity	492–594[13][14]
On the event horizon	A black hole's gravity	299,792.458 (speed of light)

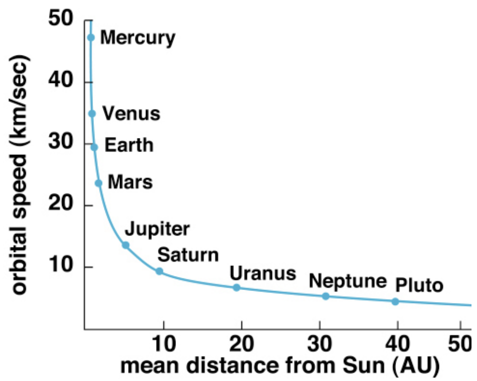
Dark Matter - Some History

- 1960s and 1970s **Vera Rubin, Kent Ford**, and **Ken Freeman** provided further strong evidence, also using galaxy rotation curves
- They worked with a **spectrograph** to measure the velocity curve of edge-on spiral galaxies with greater accuracy
- This result was confirmed in 1978
- An influential paper presented Rubin and Ford's results in 1980
- They showed most galaxies must **contain about six times as much dark as visible mass**
- By around 1980 the apparent need for **dark matter** was widely recognized as a major unsolved problem in astronomy

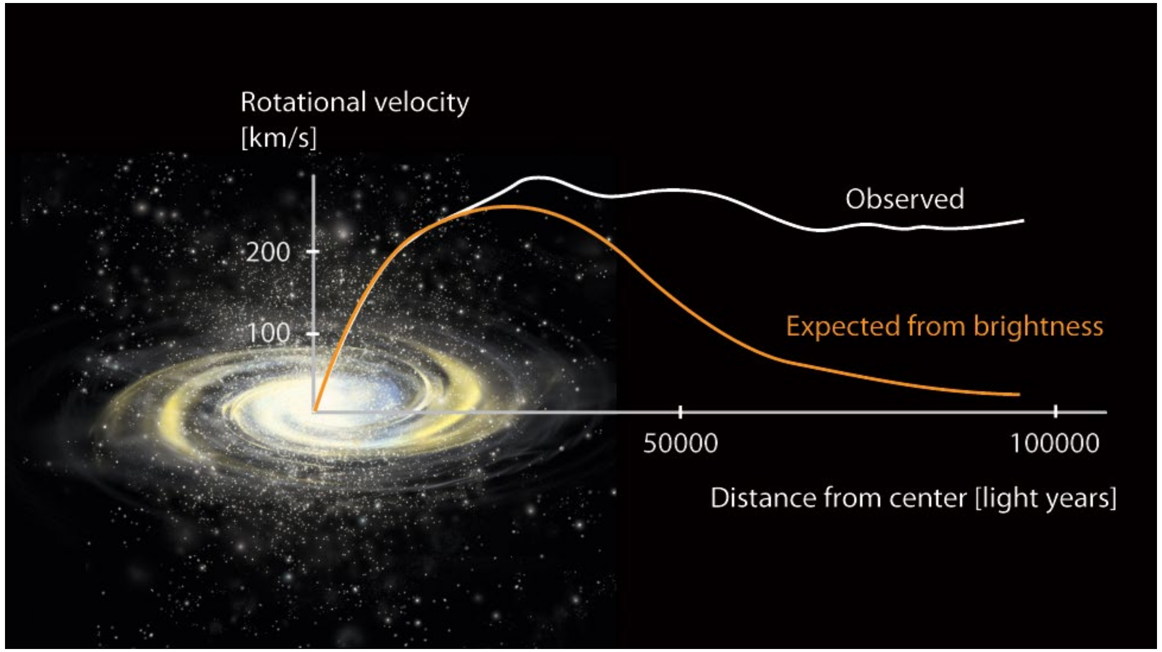
- **Vera Florence Cooper Rubin (** 1928 –2016) pioneered work on galaxy rotation rates
- She uncovered the discrepancy between the predicted and observed angular motion of galaxies by studying galactic rotation curves
- Identifying the galaxy rotation problem, her work provided evidence for the existence of dark matter
- These results were confirmed over subsequent decades

Dark Matter

- The **arms** of spiral galaxies rotate around the galactic center
- The **luminous mass density** of a spiral galaxy decreases as one goes from the center to the outskirts
- If luminous mass were all the matter, then we can model the galaxy as a point mass in the center and test masses orbiting around it
- **Kepler's Second Law -** it is expected that the **rotation velocities** will decrease with distance from the center
- The **galaxy rotation curve** remains flat as distance from the center increases
- The obvious way to resolve this discrepancy is to conclude the mass distribution in spiral galaxies is not similar to that of the Solar System
- In particular, there is a lot of non-luminous matter (**dark matter**) in the outskirts of the galaxy



$$v = \sqrt{\frac{GM}{r}} \qquad \textit{(circular orbit)}$$

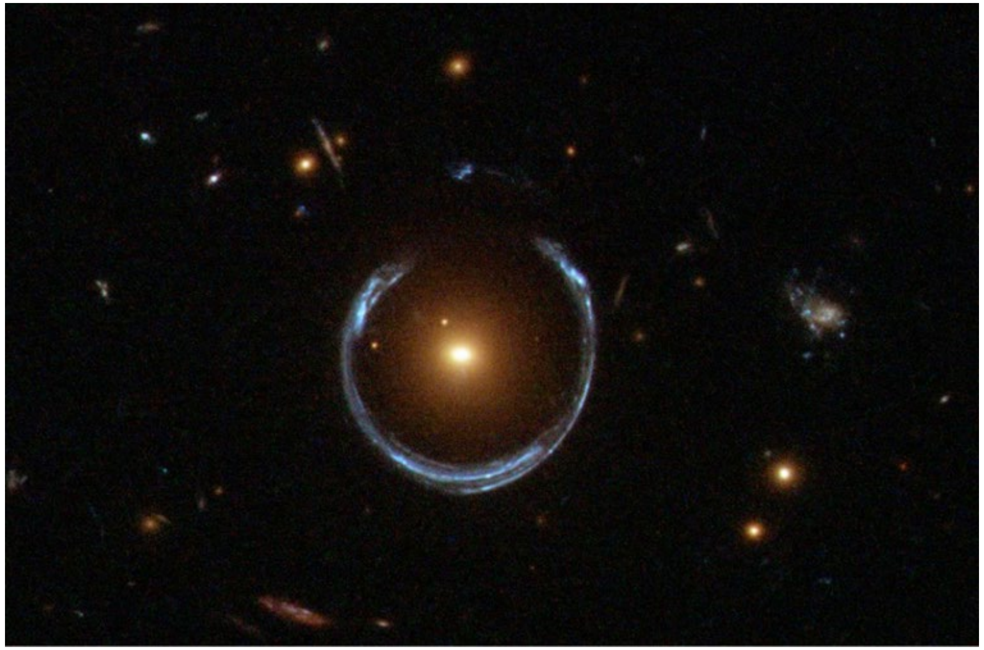


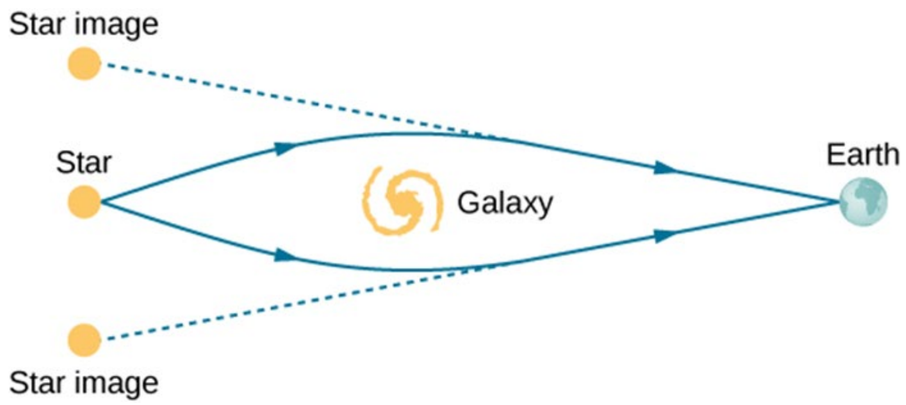
Dark Matter

Artist's impression shows the expected distribution of **dark matter** in the **Milky Way** galaxy as a blue halo of material surrounding the galaxy

Dark Matter

- We can **infer** its existence by the **deflection of distant starlight**
- If light from a distant galaxy is bent by the gravitational field of a clump of dark matter between us and the galaxy, it is possible that two images of the same galaxy can be produced The bending of light by the gravitational field of matter is called **gravitational lensing**
- In some cases, the starlight travels to an observer by multiple paths around the galaxy, producing a ring





- Light from a distant star is bent around a galaxy
- Under the right conditions, we can see a ring of light instead of a single star

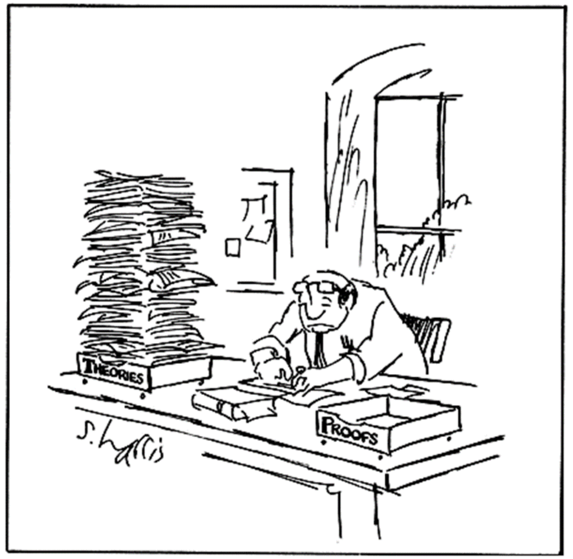
Dark Matter-NASA

- Combining **theoretical models** and **cosmological observations** scientists have come up with the composition of the universe :
- ~ 68% dark energy
- ~ 27% dark matter
- ~ 5% normal matter
- We are much more certain **what dark matter is not than we are what it is**
- It is **dark**, meaning that it is not in the form of stars and planets that we see
- Observations show that there is far **too little visible matter** in the universe to make up the 27% required by the observations
- **It is not in the form of dark clouds of normal matter**, matter made up of particles called baryons
- We know this because we would be able to detect baryonic clouds by their **absorption of radiation** passing through them
- It is is **not antimatter,** because we do not see the unique gamma rays that are produced when antimatter annihilates with matter
- We can rule out **large galaxy-sized black holes** on the basis of how many gravitational lenses we see
- High concentrations of matter bend light passing near them from objects further away, but we do not see enough lensing events to suggest that such objects to make up the required 27% dark matter contribution

Dark Matter

- There are still a few dark matter possibilities that are viable
- **Baryonic** matter could still make up the dark matter if it were all tied up in **brown dwarfs** or in small, dense chunks of heavy elements
- These possibilities are known as **massive compact halo objects**, or "**MACHO**s“
- The most common view is that **dark matter is not baryonic at all**
- But that it is made up of other, more exotic particles-
- Like **axions** (a hypothetical elementary particle postulated in 1977)
- **WIMPS (Weakly Interacting Massive Particles)**

- Dark matter candidates arise frequently in theories that suggest physics beyond the **Standard Model**, such as *supersymmetry* and *extra dimensions*
- One theory suggests the existence of a “*Hidden Valley*”, a parallel world made of dark matter having very little in common with matter we know

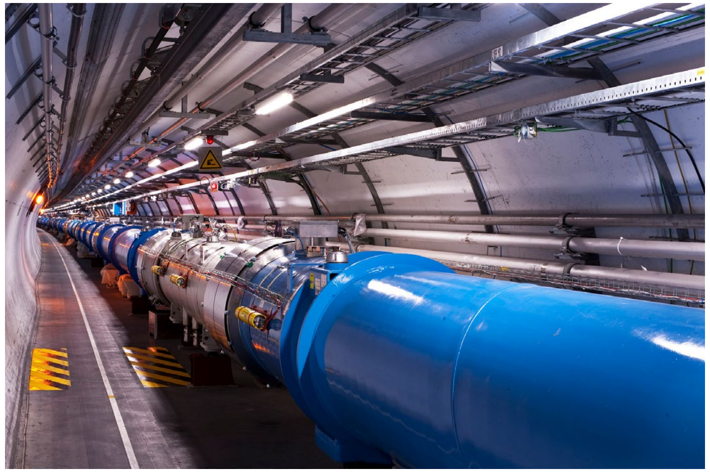


CERN Dark Matter and Dark Energy

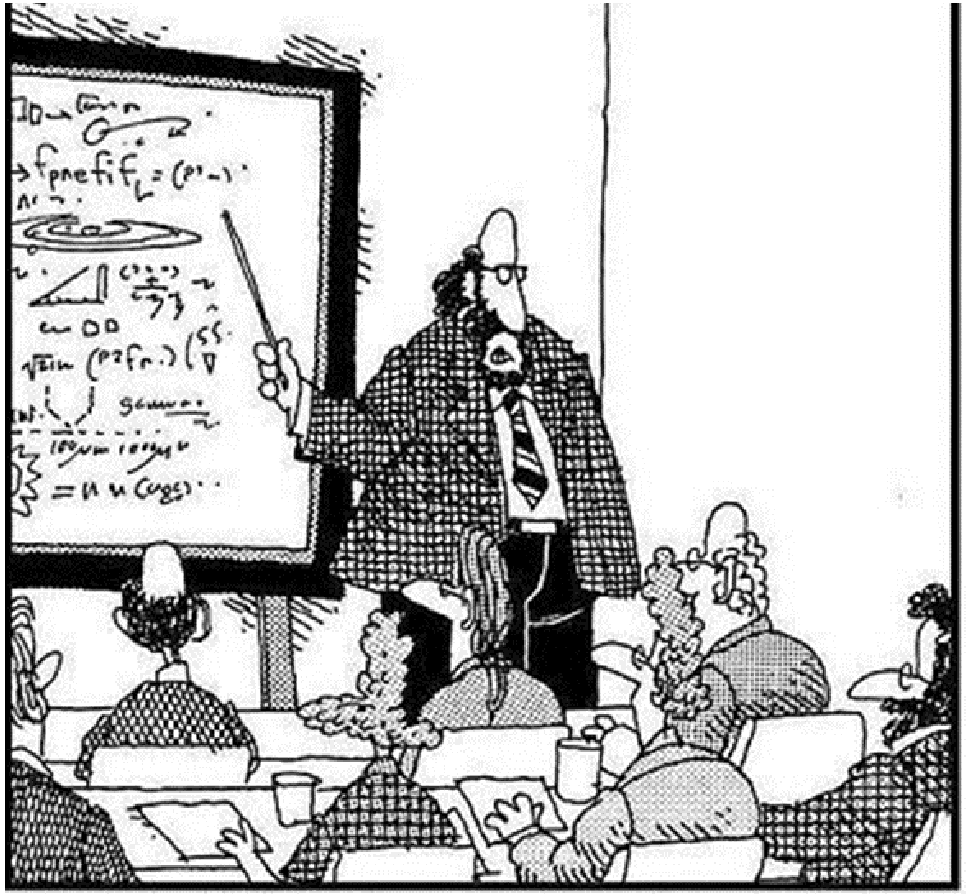
- **Dark matter**
- Unlike normal matter, **dark matter does not interact with the electromagnetic force**.
- This **means it does not absorb, reflect or emit light**, making it extremely hard to spot
- Researchers have been able to **infer** the existence of dark matter only from the gravitational effect it seems to have on visible matter
- But what is dark matter?
- One idea is that it could contain "**supersymmetric particles**" – hypothesized particles that are partners to those already known in the **Standard Model**
- Experiments at the **Large Hadron Collider (LHC**) may provide more direct clues about dark matter
- Many theories say the dark matter particles would be light enough to be produced at the **LHC**
- If they were created at the **LHC**, they would escape through the detectors unnoticed
- However, they would carry away energy and momentum, so physicists could **infer** their existence from the amount of energy and momentum “missing” after a collision

Dark Matter - Large Hadron Collider (LHC) at CERN

- The term *hadron* refers to subatomic composite particles composed of quarks held together by the strong force
- The best-known hadrons are the baryons such as protons and neutrons
- A *collider* (LHC at CERN in Europe) is a type of a particle accelerator which brings two opposing particle beams together such that the particles collide
- In particle physics, colliders, though harder to construct, are a powerful research tool because they reach a much higher center of mass energy than fixed target setups
- Analysis of the byproducts of these collisions gives scientists good evidence of the structure of the subatomic world and the laws of nature governing it
- Many of these byproducts are produced only by high-energy collisions, and they decay after very short periods of time
- Many of them are hard or nearly impossible to study in other ways



Matter in the Universe



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

What is Dark Energy?

Nobody knows!

Dark Energy

- Dark energy is the **repulsive force** that is the dominant component of the universe
- The rest of the universe consists of **ordinary matter** and **dark matter**
- Dark energy is relatively uniform in time and space and is repulsive within the volume it occupies
- It is not well understood
- A kind of repulsive force was hypothesized by Einstein in 1916 and was represented by his cosmological constant in his general theory of relativity in order to counteract the attractive force of gravity
- The **cosmological constant** Λ was required to describe a **static universe** -neither contracting or expanding

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- In the 1920s after **Hubble** discovered that the universe was expanding , Einstein discarded his cosmological constant-”his greatest blunder”
- The measured amount of matter in the mass-energy of the universe was low so some unknown missing component , like the cosmological constant , was required to make up the deficit
- Direct evidence for the existence of this “**dark energy**” was first presented in 1998

CERN Dark Matter and Dark Energy

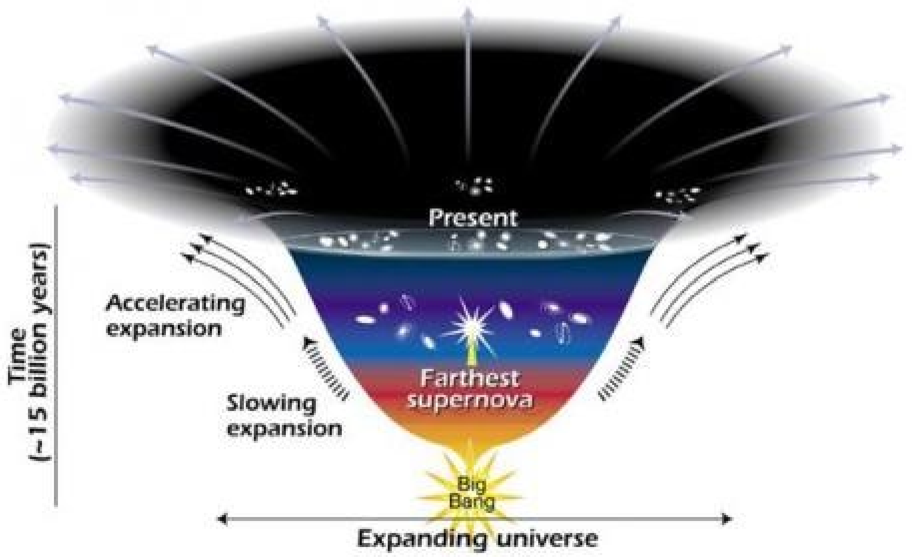
- **Dark energy**
- Dark energy makes up about 68% of the universe and appears to be associated with the vacuum in space
- It is distributed evenly throughout the universe, not only in space but also in time – in other words, its **effect is not diluted** as the universe expands
- The even distribution means that dark energy does not have any local gravitational effects, but rather a global effect on the universe as a whole
- This leads to a **repulsive force**, which tends to **accelerate the expansion** of the universe
- The rate of expansion and its acceleration can be measured by observations based on the Hubble law
- These measurements, together with other scientific data, have confirmed the existence of dark energy and provide an estimate of just how much of this mysterious substance exists

- In the early 1990s, one thing was fairly certain about the expansion of the universe
- It might have enough **energy density** to stop its expansion and recollapse
- It might have **so little energy density** that it would never stop expanding
- But **gravity** was certain to **slow the expansion** as time went on
- The slowing had **not been observed**, but, *theoretically*, the universe had to slow
- The universe is full of matter and the attractive force of gravity pulls all matter together

$$F = G\frac{m_1 m_2}{r^2}$$

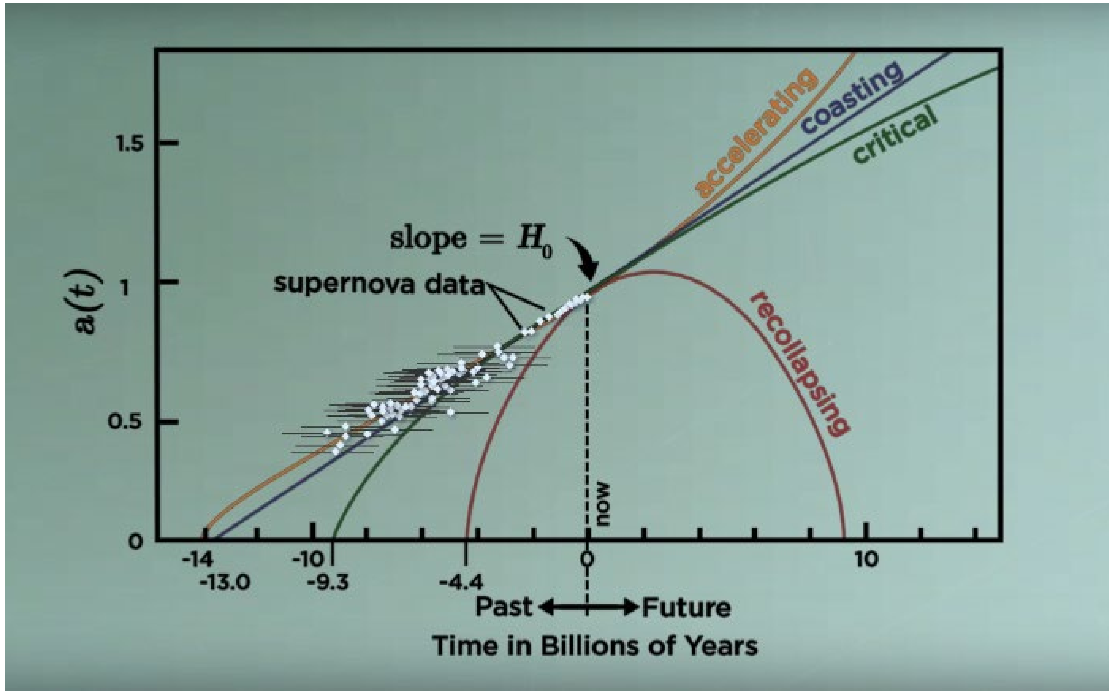
Dark Energy

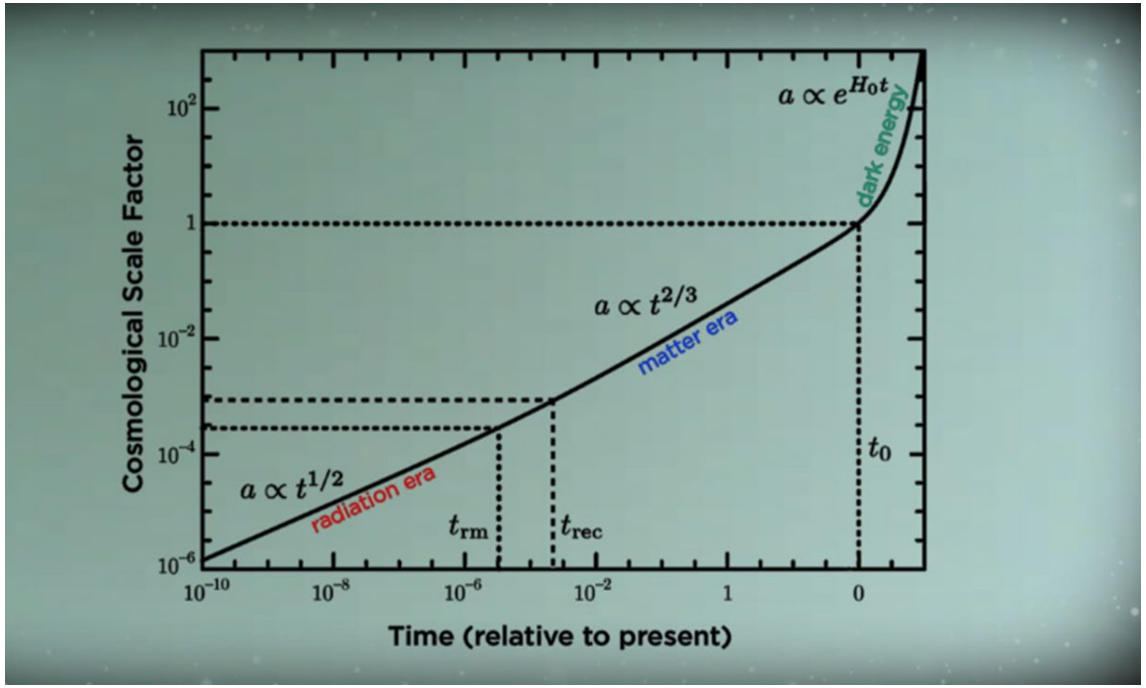
- In 1998 the **Hubble Space Telescope** (**HST**) observations of very distant **supernovae** that showed that, a long time ago, the universe was actually expanding more slowly than it is today
  - Observations at great distances are observations of the past
- So the **expansion of the universe** has **not been slowing** due to gravity, as everyone thought, **it has been accelerating**
- This was unexpected
- No one knew how to explain it



- This diagram depicts changes in the rate of expansion since the Big Bang
- *The more shallow the curve, the faster the rate of expansion*
- The curve changes noticeably about 7.5 billion years ago,

Cosmological Scale Factor Versus Time





Dark Energy

- Eventually theorists came up with three sorts of explanations
- **Maybe** it was a result of a long-discarded version of Einstein's theory of gravity, one that contained what was called a "**cosmological constant**"
- **Maybe** there was some strange kind of *energy-fluid* that filled space
- **Maybe** there is something wrong with Einstein's theory of gravity and a new theory could include some kind of field that creates this cosmic acceleration
- Theorists still don't know what the correct explanation is, but they have given the solution a name
- It is called **dark energy**

- More is unknown than is known
- We know how much dark energy there is because we know how it affects the universe's expansion
- Other than that, it is a complete mystery
- It turns out that roughly 68% of the universe is **dark energy**
- **Dark matter** makes up about 27%
- The rest - everything on Earth, everything ever observed with all of our instruments, all **normal matter** - adds up to less than 5% of the universe

Dark Energy

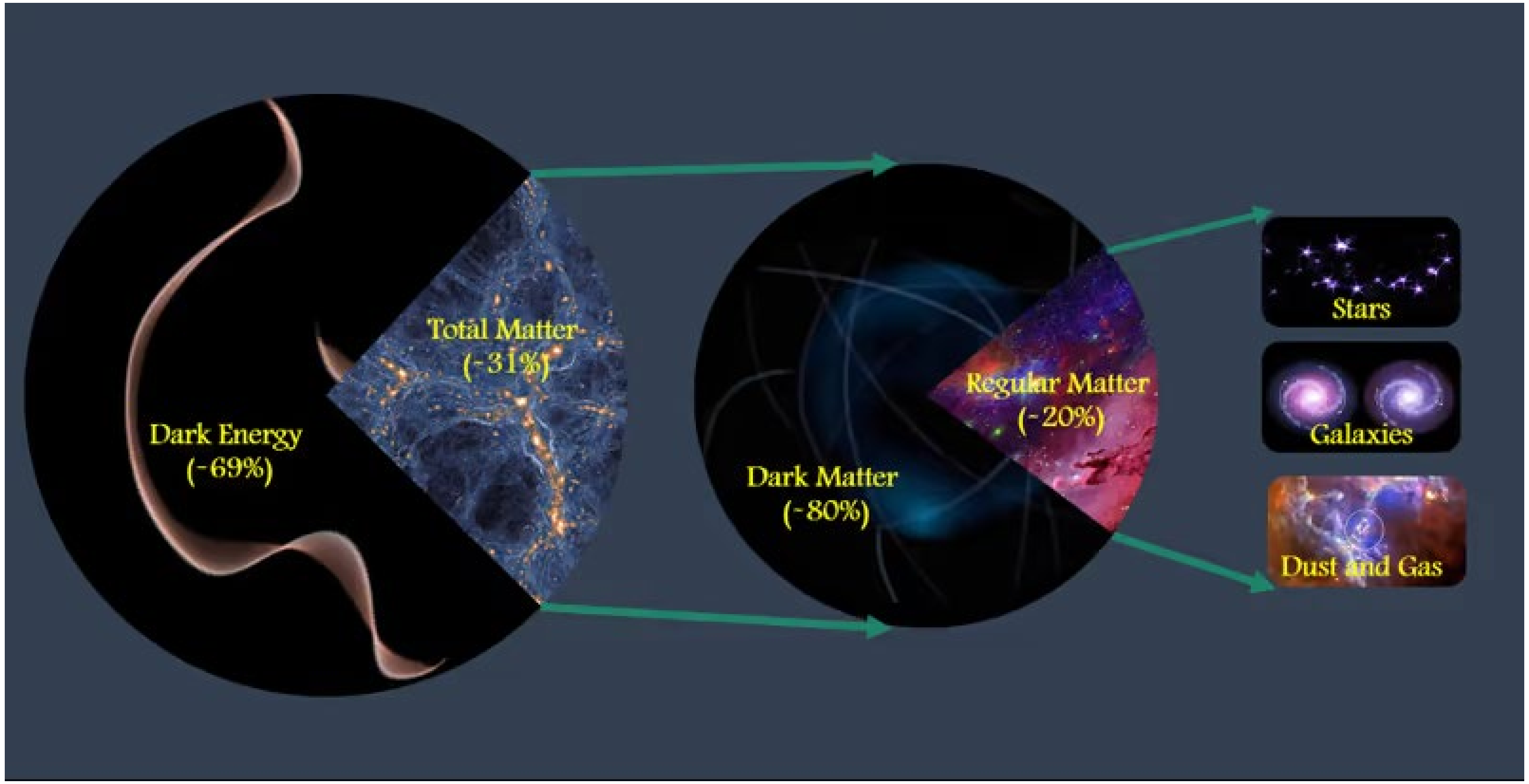
- One explanation for **dark energy** is that it is a *property of space*
- **Albert Einstein** was the first person to realize that *empty space is not nothing*
- Space has amazing properties, many of which are just beginning to be understood
- The first property that Einstein discovered is that *it is possible for more space to come into existence*
- Then one version of Einstein's gravity theory, the version that contains a cosmological constant, makes a second prediction: "**empty space" can possess its own energy**
- Because this energy is a property of space itself, it would not be diluted as space expands
- *As more space comes into existence, more of this energy-of-space would appear*
- As a result, this form of energy would cause the universe to expand faster and faster
- Another explanation for how space acquires energy comes from the **quantum theory** of matter
- In this theory, "empty space" is actually full of **temporary ("virtual") particles that continually form and then disappear**
- But when physicists tried to calculate how much energy this would give empty space, the answer came out wrong - wrong by a lot
- The number came out 10e120 times too big
  - That's a 1 with 120 zeros after it
- So the mystery continues

Dark Energy

- Another explanation for dark energy is that it is a *new kind of dynamical energy fluid or field*
- *S*omething that fills all of space but something whose effect on the expansion of the universe is the opposite of that of matter and normal energy
- Some theorists have named this "**quintessence**," after the fifth element of the Greek philosophers
- But, if quintessence is the answer, we still don't know what it is like, what it interacts with, or why it exists
- So the mystery continues

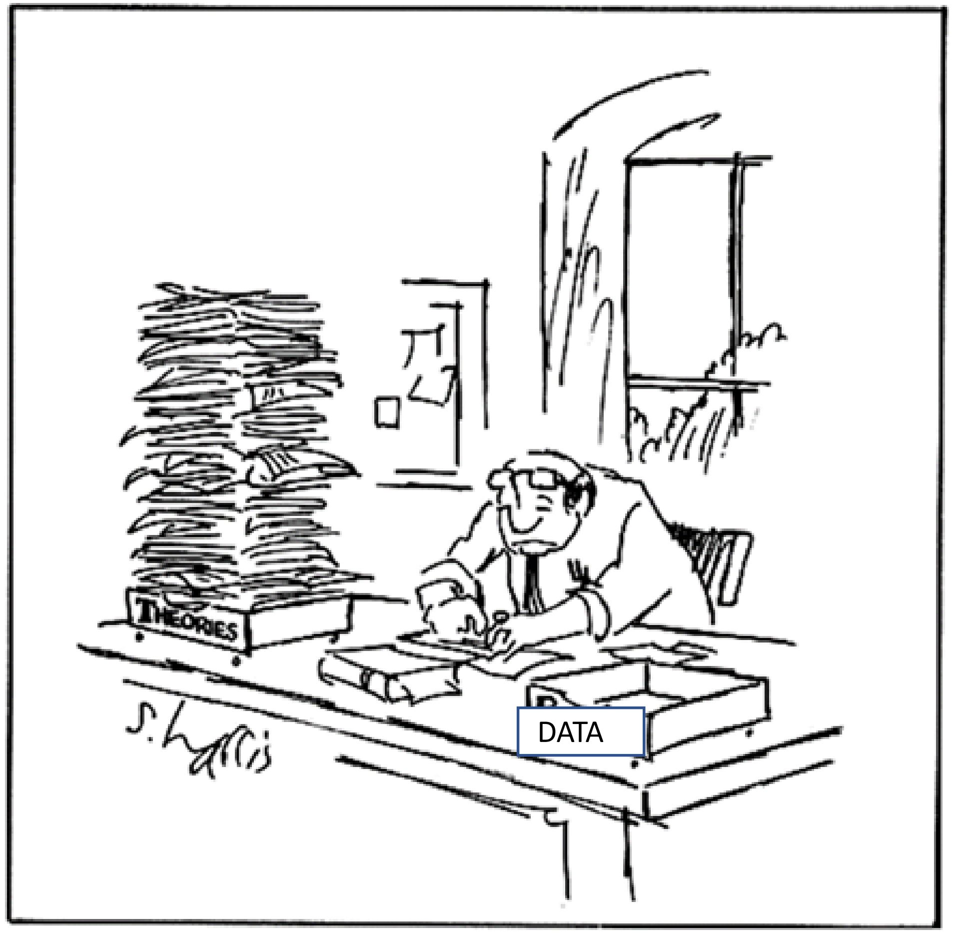
- A last possibility is that ***Einstein's theory of gravity is not correct***
- That would also affect the way that normal matter in galaxies and clusters of galaxies behaved
- This fact would provide a way to decide if the solution to the dark energy problem is a new gravity theory or not: we could observe how galaxies come together in clusters
- If a new theory of gravity is needed, what kind of theory would it be?
- How could it correctly describe the motion of the bodies in the Solar System, as Einstein's theory is known to do, and still give us the different prediction for the universe that we need?
- There are some candidate theories, but none are compelling
- So the mystery continues.

Constituents of the Universe –Most Not Understood



Dark Energy

- What is needed to decide among **dark energy possibilities** –
  - A property of space
  - A new dynamic fluid
  - A new theory of gravity
- **More data** and **better data**



Next Session

Stars