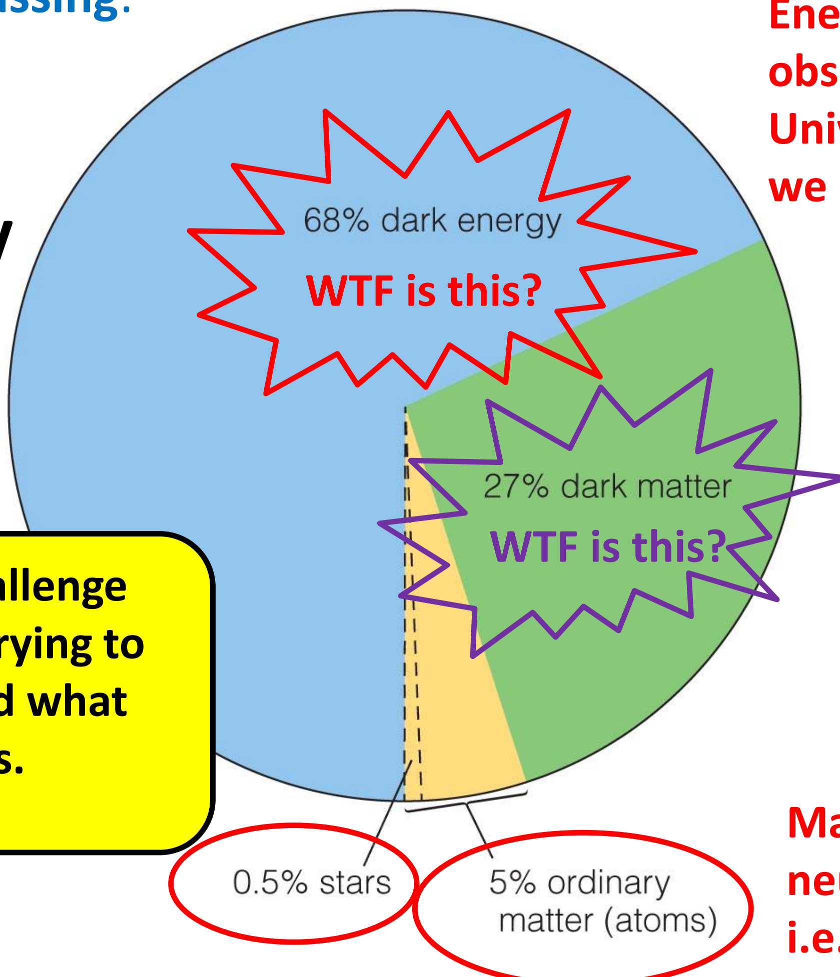
Dark Matter and Dark Energy

Now that we're almost at the end of Physics 111, you might think that we have come to a fair understanding of what the stuff in Universe is and how it works. **But an inventory of the composition of the Universe as we understand it today is rather embarrassing**:

Mass and Energy In the Universe



Energy that is causing the observed expansion of the Universe to accelerate; we have no idea what it is!

Matter that we can detect only by its gravity, we have no idea what it is!

Perhaps the biggest challenge in astronomy today is trying to identify and understand what ~ 95% of the Universe is.

Matter made of protons, neutrons, and electrons, i.e. stars, gas, planets, junk cars, people, etc.

The History of the Dark Matter Problem: Galaxy Clusters

In the 1930's, **Fritz Zwicky** (Swiss astronomer working at Cal Tech) was studying the Coma Cluster of Galaxies:

Fritz Zwicky

The Coma Cluster of Galaxies

For each galaxy in the cluster, he could measure:

- The Luminosity which gave him an estimate of the galaxy's mass
- The radial velocity toward or away from us from the Doppler effect.

Zwicky found that there was not enough matter in the cluster to keep it bound.

For the speeds that he measured, the cluster should just fly apart in about a billion years.

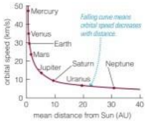
Zwicky proposed that there must be some unseen matter in the cluster that provides sufficient gravity to hold it together – he estimated that the amount of **"Dark Matter"** had to be about 100X that of luminous matter.

No one really took notice of Zwicky's work for many years!

The History of the Dark Matter Problem: Spiral Galaxy Rotation

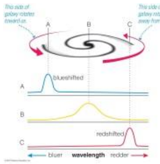
What is a Rotation Curve?

- For bodies in circular orbits, a rotation curve is a plot of the orbital speeds as a function of distance from the center; **e.g. the Solar System:**

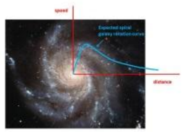


b The rotation curve for the planets in our solar system.

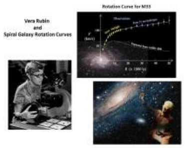
Rotation Curves for spiral galaxies can be found by measuring the speeds of stars (using visible light) and gas (using radio) using the Doppler Effect.



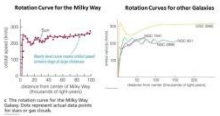
The rotation curve for a galaxy shouldn't be exactly like a solar system where the gravitating mass is concentrated at the center; **however, in the outer parts of the galaxy, the speeds should fall off like they do in the Solar System.**



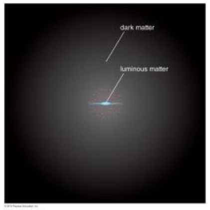
As we saw in the video, during the 1960's and 70's, Vera Rubin measured rotation curves for spiral galaxies (visible stars) and found that the curves were flat.
In the 1990's, radio measurements of gas extended the flat rotation curves well beyond where visible stars can be detected.



The History of the Dark Matter Problem: Flat Rotation Curves



What do the observed flat rotation curves of spiral galaxies tell us?



- The most accepted explanation to date is that galaxies are embedded in a large massive halo of matter that we can’t see, i.e. nonluminous or – **Dark Matter**.
- The extra gravity provided by the Dark Matter increases the speeds of the stars beyond what we expect based just on the matter that we can see.

How much Dark Matter is required to produce the observed rotation curves? (LC)

- **About ten times the mass that is in luminous matter!**

Exactly how would this Dark Matter be distributed? (LC)

- **No one really knows!**

The History of the Dark Matter Problem: Clusters again

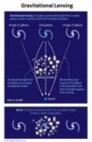
There are actually three ways to determine the mass of a cluster of galaxies:

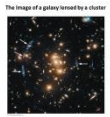
- As Zwicky did, measure the speeds of the galaxies by the Doppler effect, and calculate a mass from that.

- **X-ray observations** have detected that clusters are embedded in an **intracluster medium of hot gas** that contains much more mass than in stars (but not enough to account for the motion).

- The hot gas is in hydrostatic equilibrium (pressure balances gravity), so the temperature of the gas can be used to estimate the gravitating mass.

- **Gravitational Lensing**, where the gravity of the cluster bends the light of a more distant object, can be used to determine the mass of the cluster.

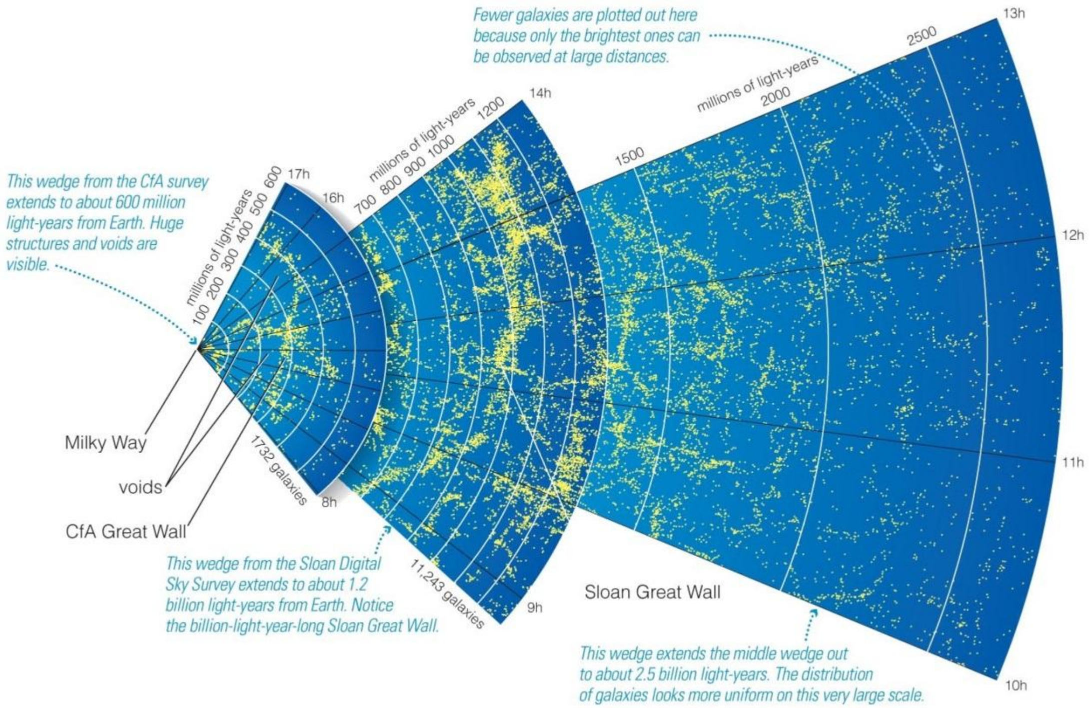




- All three of these methods reveal that there is ~40X more mass in clusters than can be accounted for in stars and the hot gas.

- **The Bullet Cluster** shows the three sources of matter.

Dark Matter and Cosmology

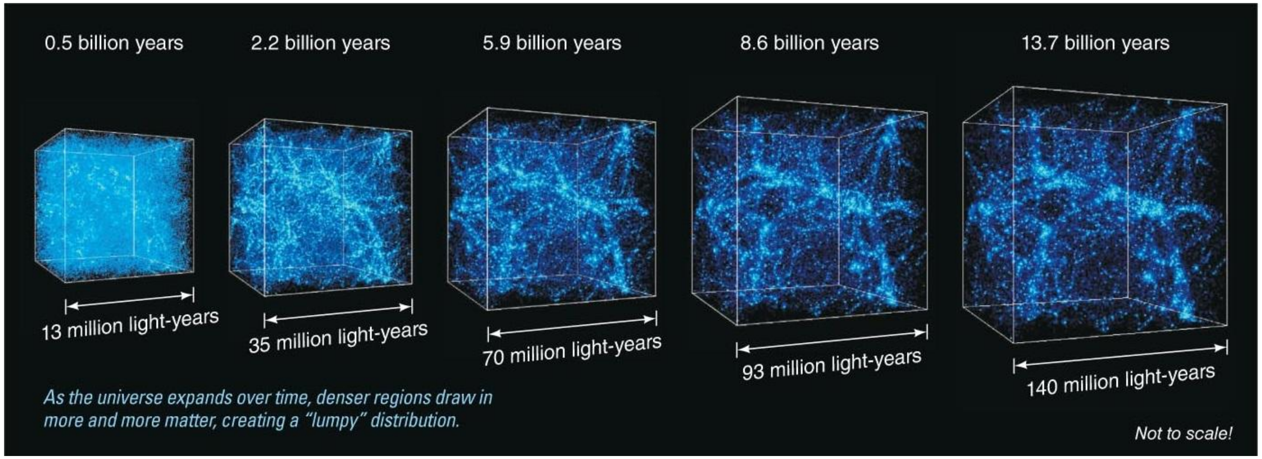


The observed distribution of galaxies out to about 3 billion light years.

Notice the galaxies cluster in filaments with large voids in between.

A computer simulation that includes dark matter. Normal matter collects along the filaments of dark matter and forms galaxies.

Compare the last block with the observations.



A simulation in motion

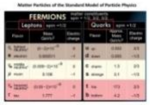
So What Could This Dark Matter Be?

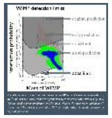
Observations indicate that Dark Matter is only detected by it's gravitational influence – we can't detect it by electromagnetic radiation.

Could it be ordinary matter that is just too faint for us to see?

- This could be in the form **baryonic matter** (made of baryons, i.e. protons and neutrons) in the form of cool gas, faint stars, neutron stars, black holes, i.e. Massive Compact Halo Objects (**MACHOS**).
  These have been looked for and found, but not nearly enough to account for the missing mass.
- **Big Bang Cosmology indicates that there could not have been this much matter in baryons** (normal matter composed of protons and neutrons).
- **Neutrinos**, since they have mass, interact only through the Weak Force and Gravity were proposed, but they have to move too fast to clump together on the scales of individual galaxies.

What does this leave us? Particles beyond the Standard Model of Particles.





- Several theories that go beyond the Standard Model allow for massive particles that interact only through the Weak Force and Gravity. These are called **WIMPs** (Weakly Interacting Massive Particles). None have been found after years of searching, and there's not much room for the WIMPs to hide!
- **Very low mass Axion-Like** particles with masses ~10^{-25} that of the electron have been proposed, but they will be almost impossible to independently detect.

So What Could This Dark Matter Be?

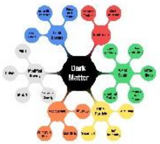
For the last few decades, searches for the Dark Matter particles has grown into into a huge industry. Here is a sampling of the major experiments:

Advanced This Ionization Calorimeter
Alpha Magnetic Spectrometer
ANAIS
ArDM
Axion Dark Matter Experiment
CERN Axion Solar Telescope
China Dark Matter Experiment
Cryogenic Dark Matter Search
Cryogenic Low Energy Astrophysics with Neon
Cryogenic Rare Even Search with Superconducting Thermometers
DAMA/LIBRA
DAMA/NaI
Dark Matter Time Projection Chamber
DarkSide
DEAP
Direct Recoil Identification From Tracks

EDELWEISS
European Underground Rare Event Calorimeter Array
Korea Invisible Mass Search
Large Underground Xenon experiment
Microlensing Observations in Astrophysics
MultiDark
Optical Gravitational Lensing Experiment
PAMELA detector
PandaX
PCASSO
PVLAS
SIMPLE (dark matter e experiment)
SNOLAB
UK Dark Matter Collaboration
WIMP Argon Programme
XENON
ZEPLIN III

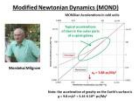
Wikipedia

- **As of late 2025, there has been no definitive detection of any Dark Matter particles.**
- **A pictorial summary of possible explanations for Dark Matter.**

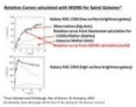


Maybe Dark Matter doesn't even exist

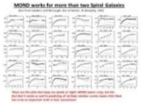
- The **Dark Matter Problem** is based on the fact that some objects under the the influence of Gravity are observed to move faster than they should. So, we assume there is unseen matter that provides more Gravity.
- **Perhaps our understanding of Gravity is in error?**
- In the early 1980's, the Israeli physicist, **Mordehai Milgrom**, proposed **Modified Newtonian Dynamics (MOND)** where Newtonian Gravity should be modified for <u>extremely low accelerations</u>, on the order of $a_0 \sim 10^{-10}$ m/s^2.



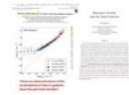
- **Is this an utterly absurd idea without precedent?**
  - No, there are many cases where Newtonian physics has to be modified: e.g. the very fast or very massive (Relativity) or the very small (Quantum), perhaps low acceleration is another case where Newton fails.



- **What does MOND predict for the rotation curves of spiral galaxies?**
- **Wait, there's even more!**



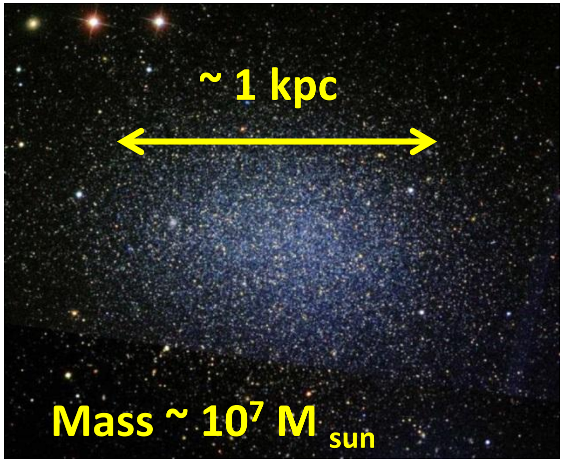
So, what are we to make of MOND - it won't go away?



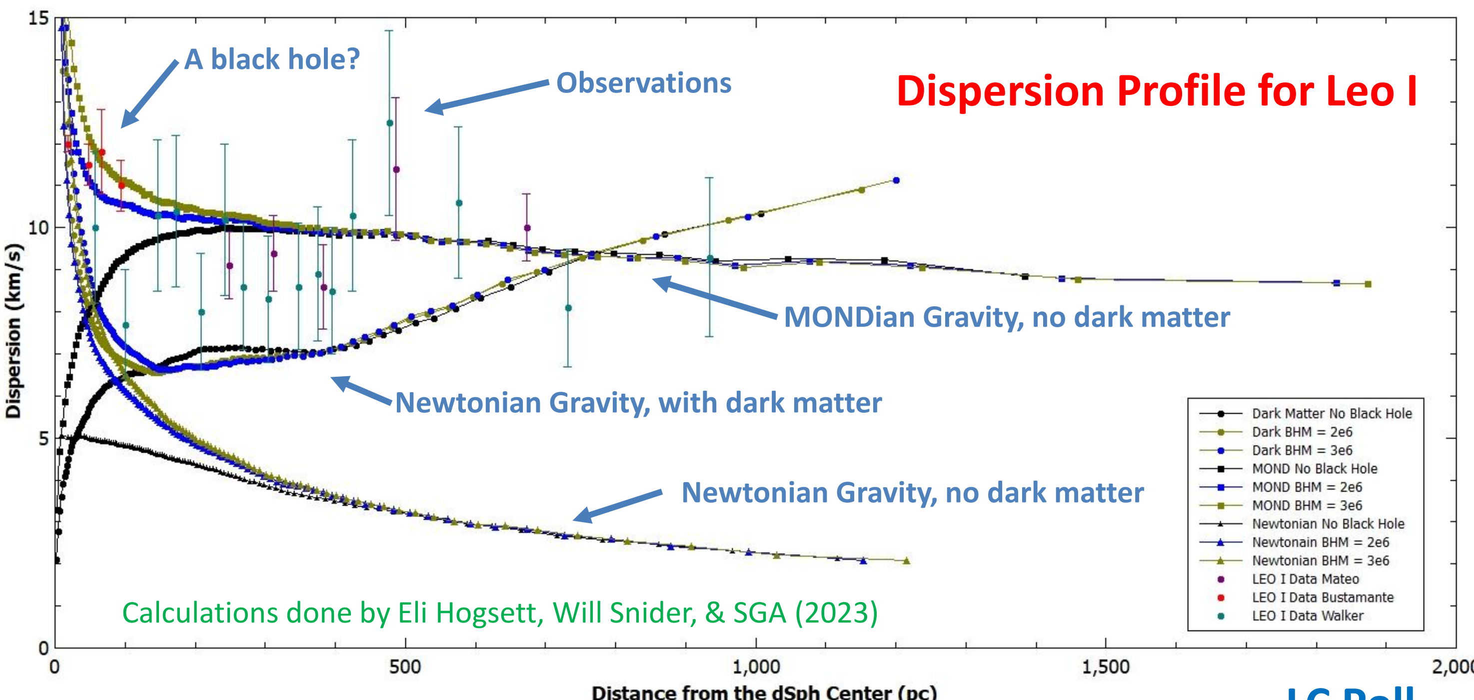
  - It works very well explaining galaxy rotation curves, not so well for clusters of galaxies, and says nothing about gravitational lensing.
  - **MOND is not a theory, but it may be a hint at a new theory of gravity.**
  - **Recently, MOND has been in the news.**

MOND Calculations for Dwarf Spheroidal (dSph) Galaxies at Miami:

Leo I dSph Galaxy

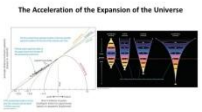


- Due to their low masses, dSphs are very loosely bound, and would fly apart unless they are dominated by Dark Matter.
- Or, if Dark Matter isn't real, dSphs are systems that have very low accelerations, i.e. deeply MONDian.
- Stars in a dSph don't have circular orbits, so a **dispersion profile** is observed instead of a rotation curve.



LC Poll

Dark Energy and the Acceleration of the Universe



- As we saw in the video, observations in the 1990's using White Dwarf Supernovae as standard candles to measure distance reveal that the **expansion of the Universe is accelerating**.

- **What is causing this acceleration? (LC)**

  Something, call it **Dark Energy**, is pushing the galaxies apart, but no one knows what it could be. It does seem to have been weaker in the past.

- **Are Dark Matter and Dark Energy related to each other? (LC)**

  There's no evidence that they are, but who knows.

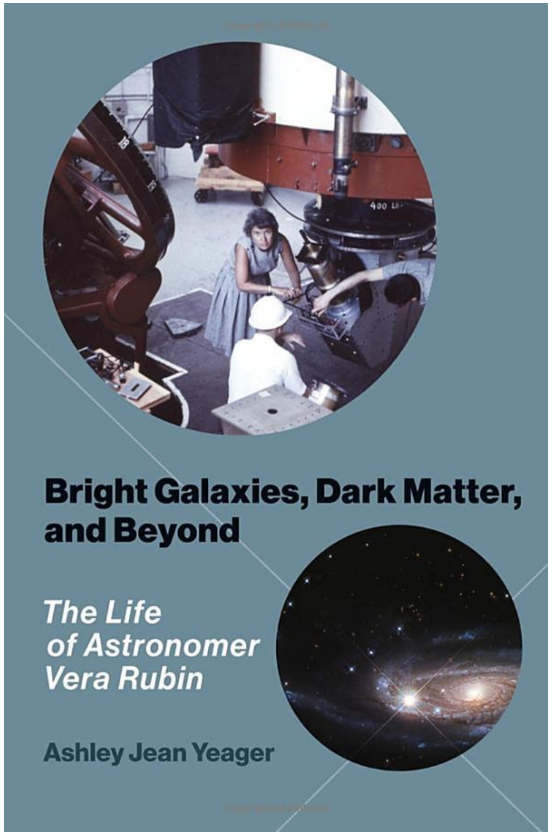
- **Where will this story go in the next 20 to 50 years? (My Forrest Gump Answer)**

  *It's hard to say, but I wouldn't be surprised if new forms of matter and energy **WILL** be discovered, **AND** our theories of Gravity **WILL** prove to be inadequate and have to be modified. There's so much we don't know!*

- **So, we're back to where we started.**

  WTF is the Universe made of anyway?

Vera Rubin (1928 – 2016)



Responding to a question about whether she thought her galaxy rotation data was best explained by dark matter or modified gravity, her response included:

"I'm sorry I know so little. I'm sorry we all know so little. But that's kind of the fun, isn't it".