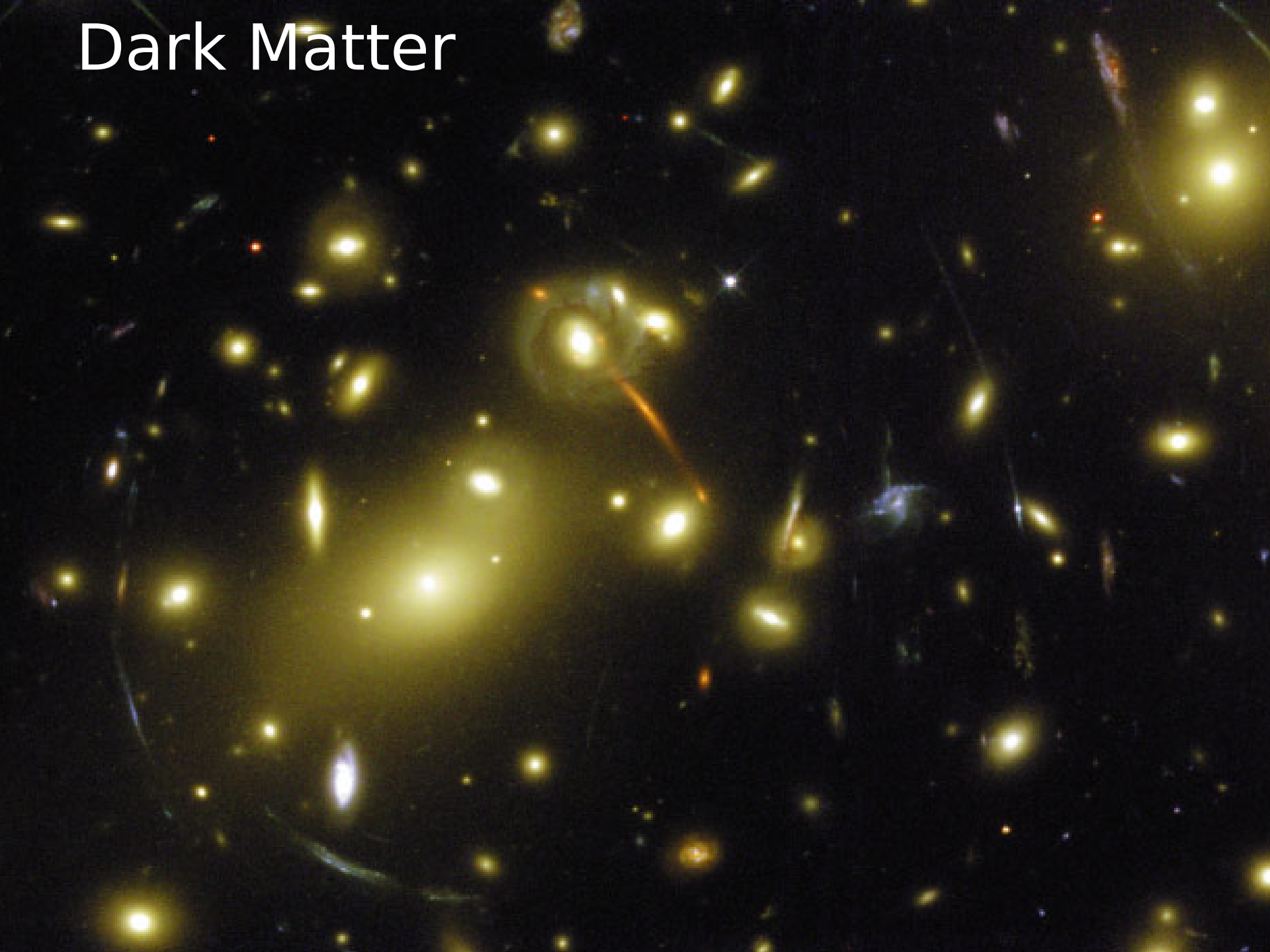
# Dark Matter



# Orbits, mass, and radius

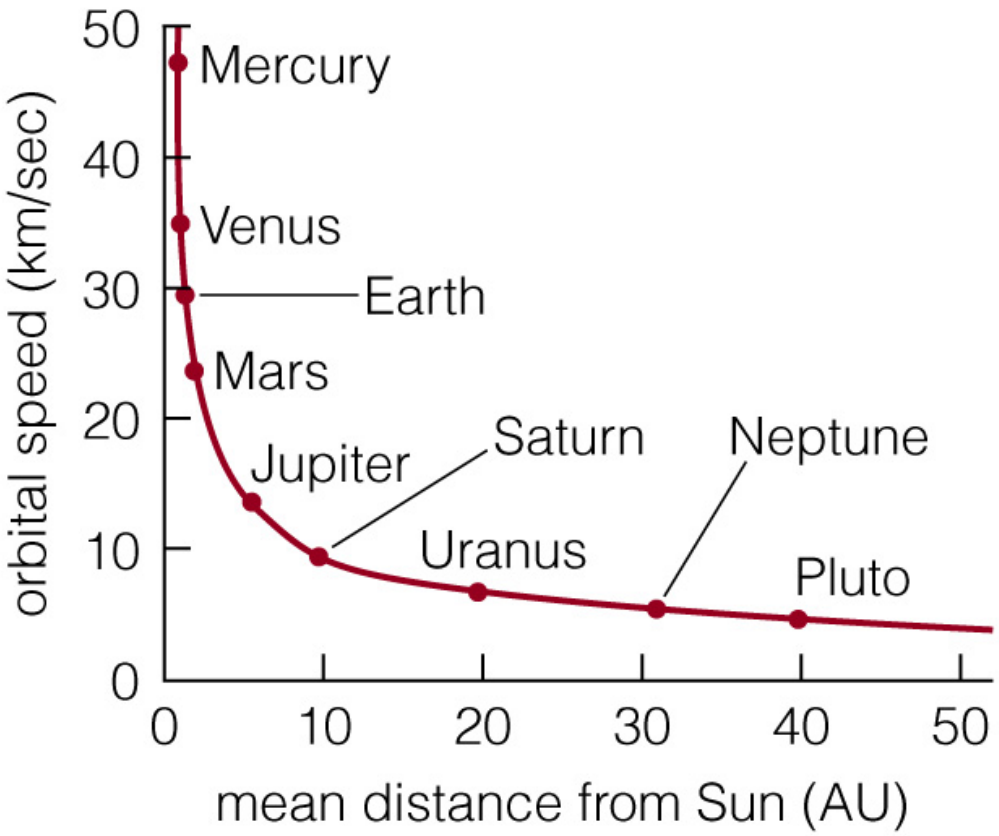
Orbital speed is related to the mass interior to the orbit, and the orbital radius

http://boojum.as.arizona.edu/~jill/NS102_2004/Lectures/SystemFiles/ToolBrowser/Tutorial_15/orbital_velocity_mass_and_r.swf

# LT Book

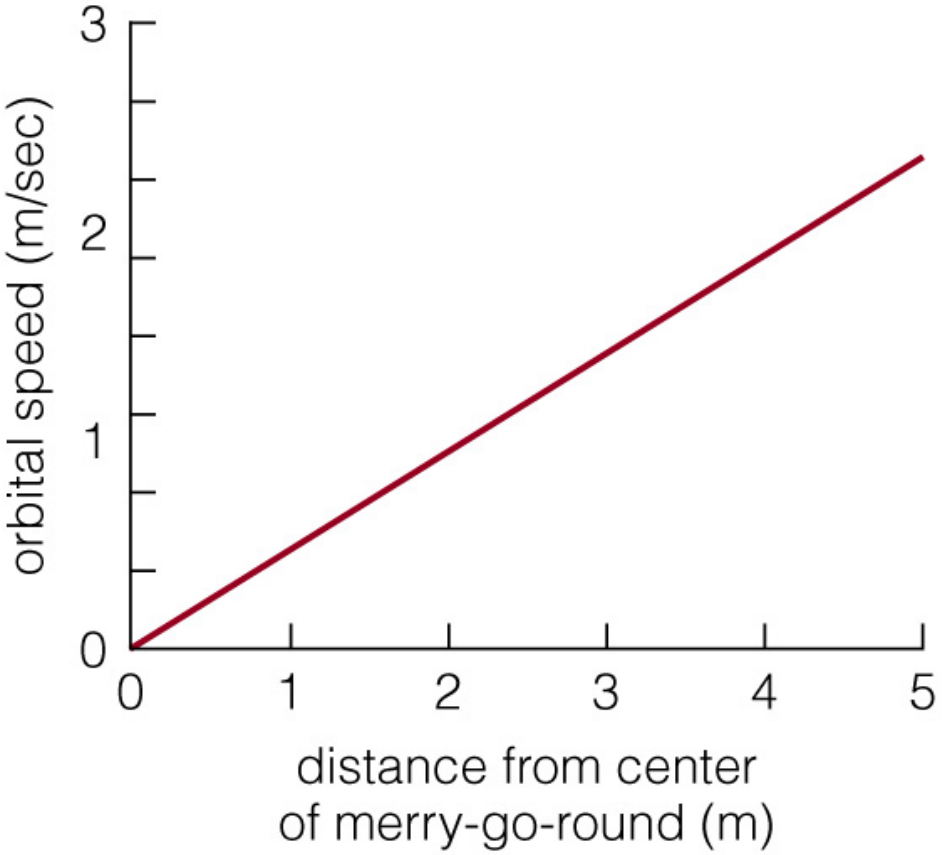
“Dark Matter,” 143, #1-9

# Solar System Rotation Curve




- Solar system's rotation curve declines because Sun has almost all the mass
- This is what is expected from Kepler's 3rd law

# Merry-go-round Rotation Curve



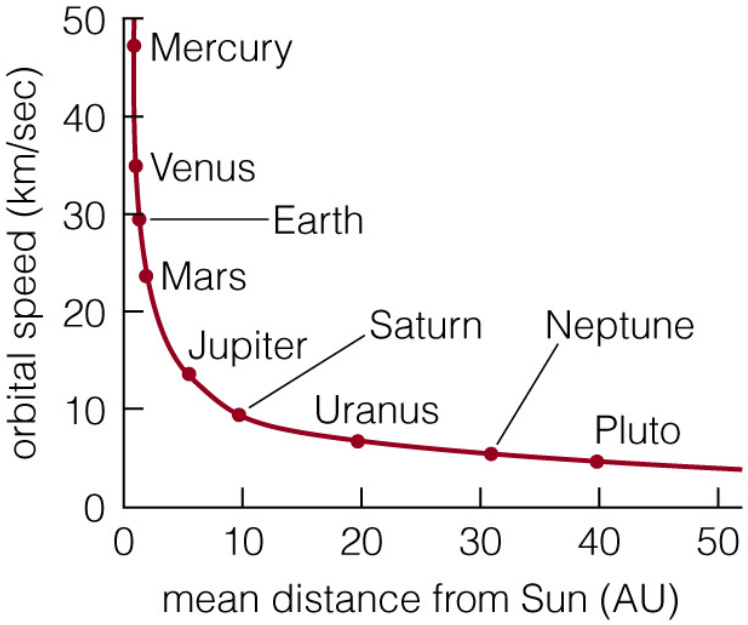

Rotation curve of merry-go-round rises with radius because mass is spread out with radius

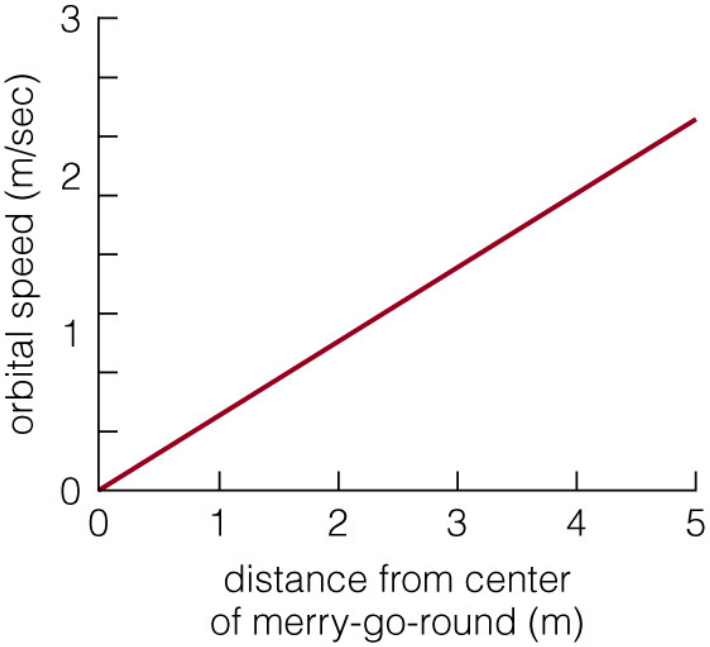
# Concept Quiz

What will the rotation curve of our Galaxy look like?

A) Like that of the Solar System

B) Like that of the Merry-go-round



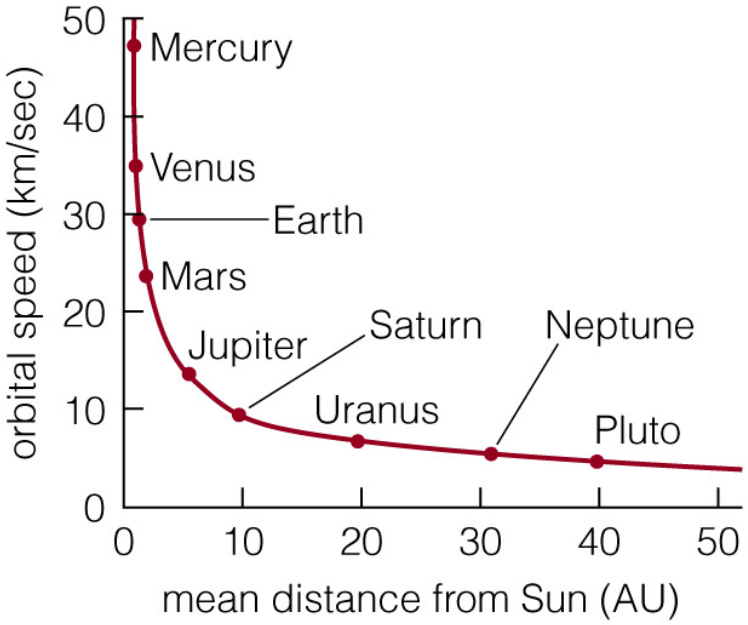
# Concept Quiz

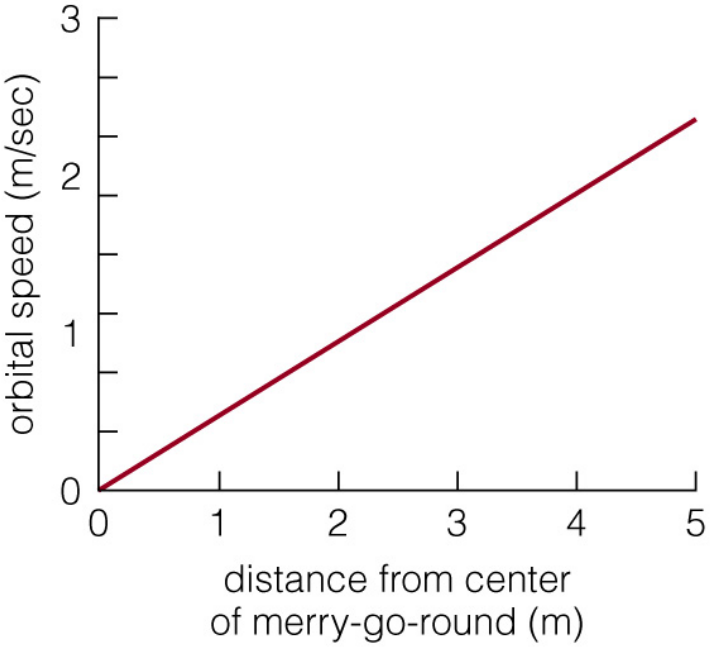
What will the rotation curve of our Galaxy look like?

A) Like that of the Solar System

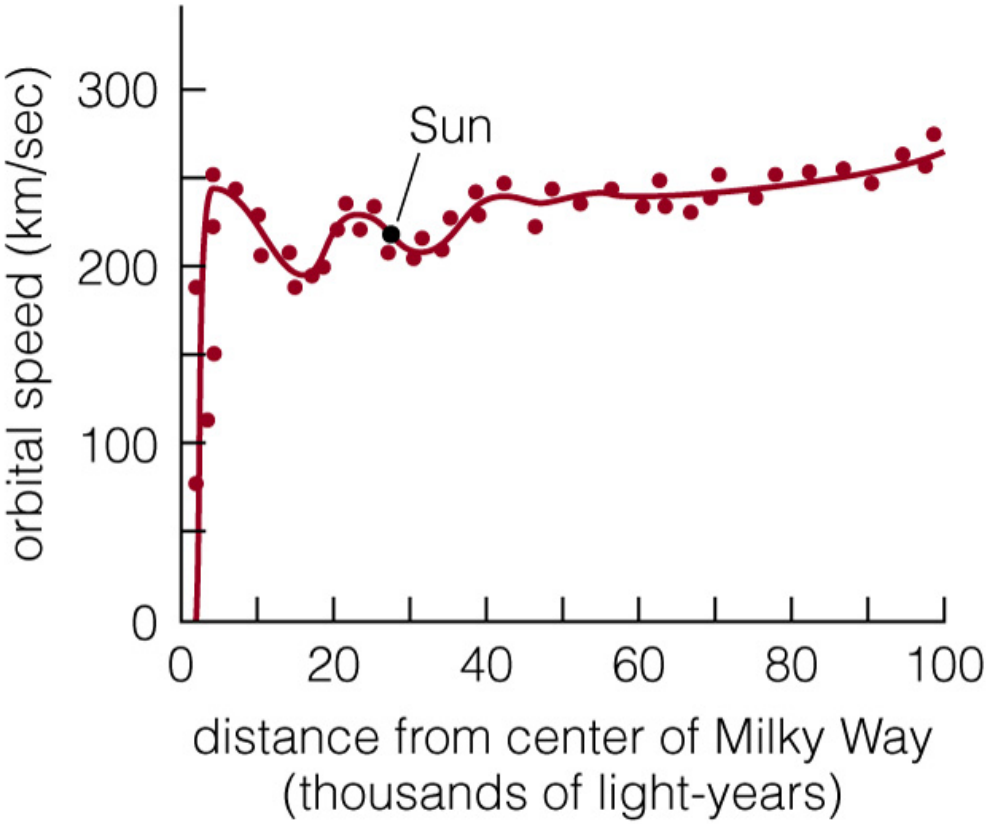
B) Like that of the Merry-go-round

C) Neither! Ha!



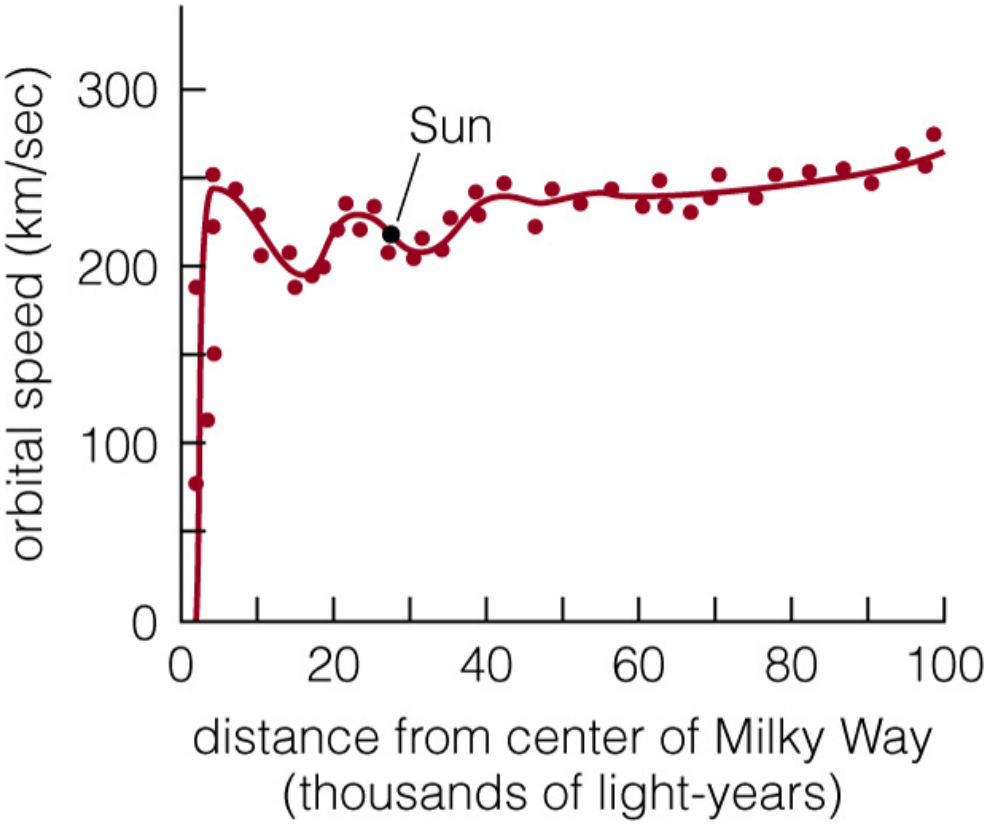



# Milky Way Rotation Curve



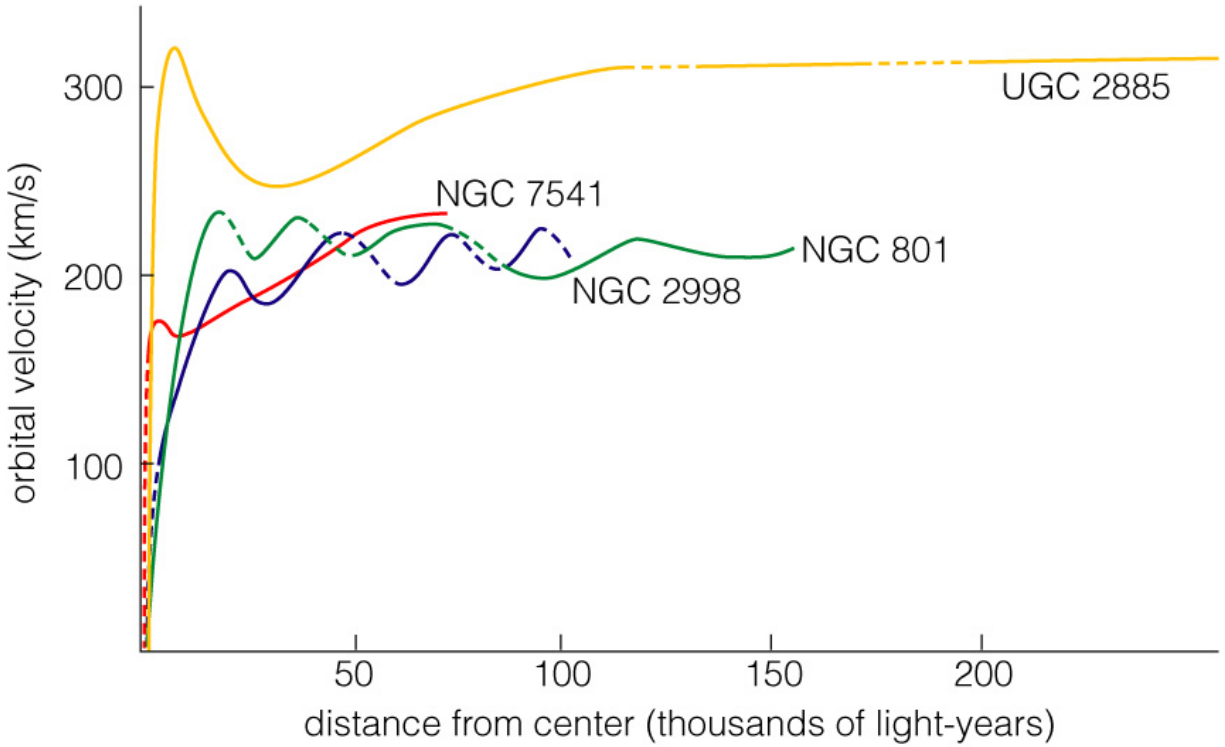

Mass must be more spread out than in solar system, but not as much as for a merry-go-round

# Milky Way Rotation Curve




But from visible matter, we would expect something more like what we see in the Solar System because most of the mass is in the center of the Galaxy.

# Dark Matter in Spirals



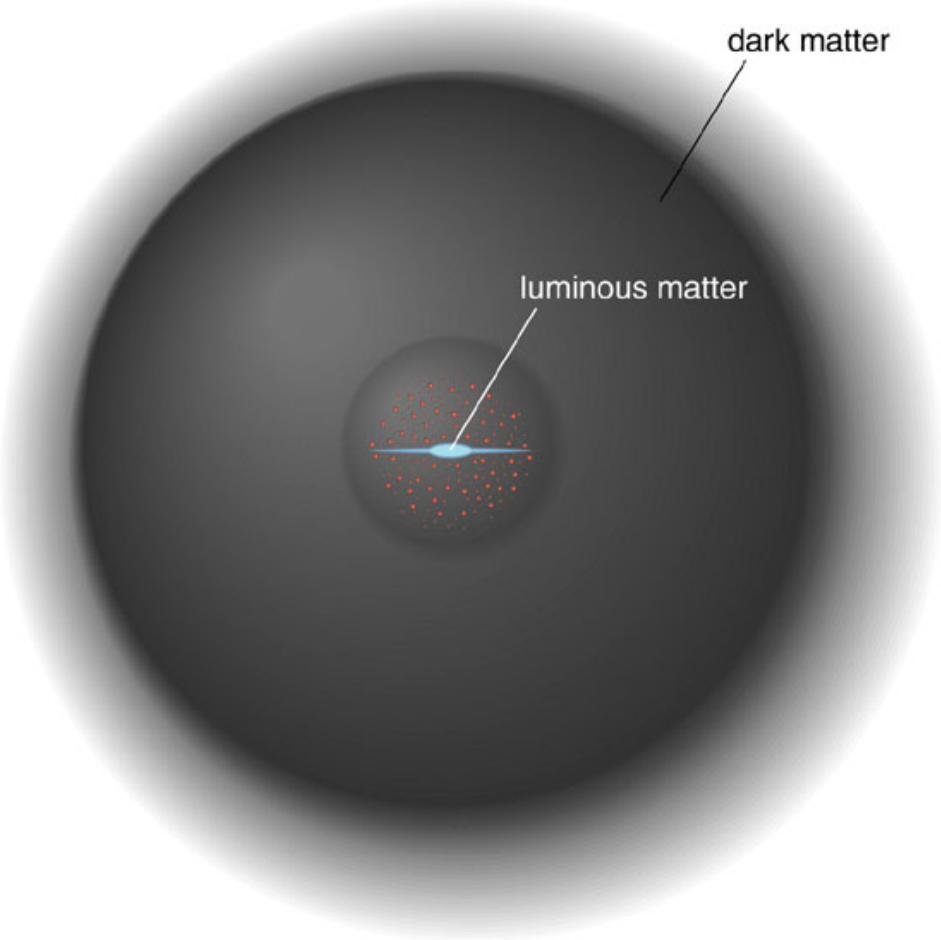

- Spiral galaxies all tend to have flat rotation curves
- ->Lots of Dark Matter!
- Ellipticals have dark matter too, but they don’t have rotation curves

# Evidence for Dark Matter

We hypothesize that dark matter exists from comparisons between the mass of the matter we can see and the mass calculated from gravity

We'll see two forms of evidence for dark matter – in galaxies and in clusters

# Dark Matter




The visible portion of a galaxy lies deep in the heart of a large halo of dark matter

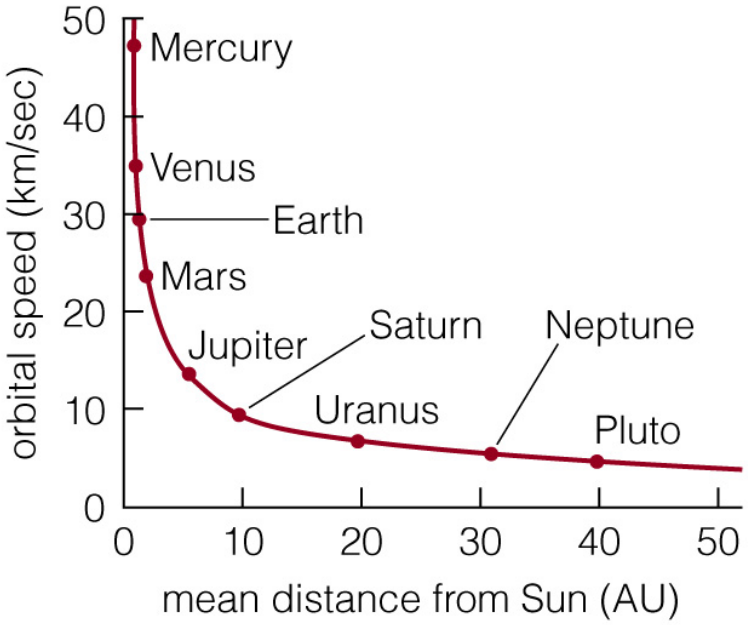
Dark Matter provides the missing mass

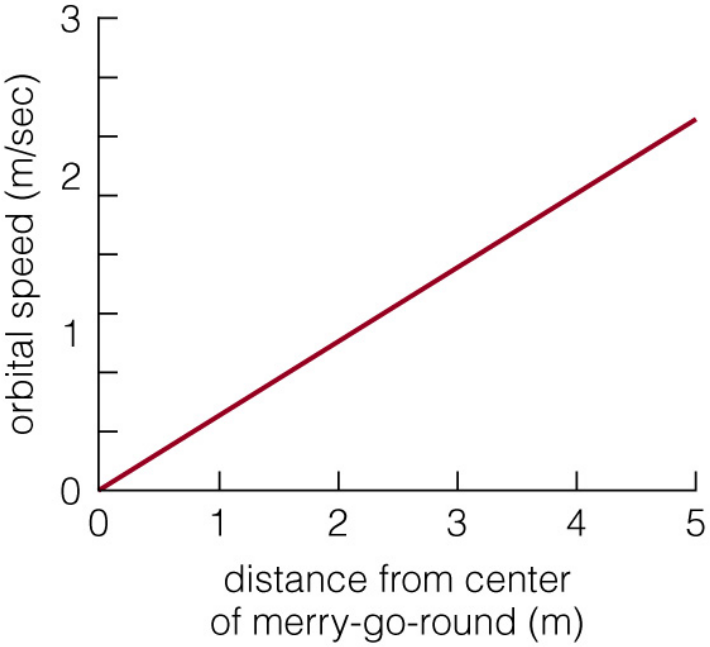
# Concept Quiz

What will the rotation curve of our Galaxy look like?

A) Like that of the Solar System

B) Like that of the Merry-go-round



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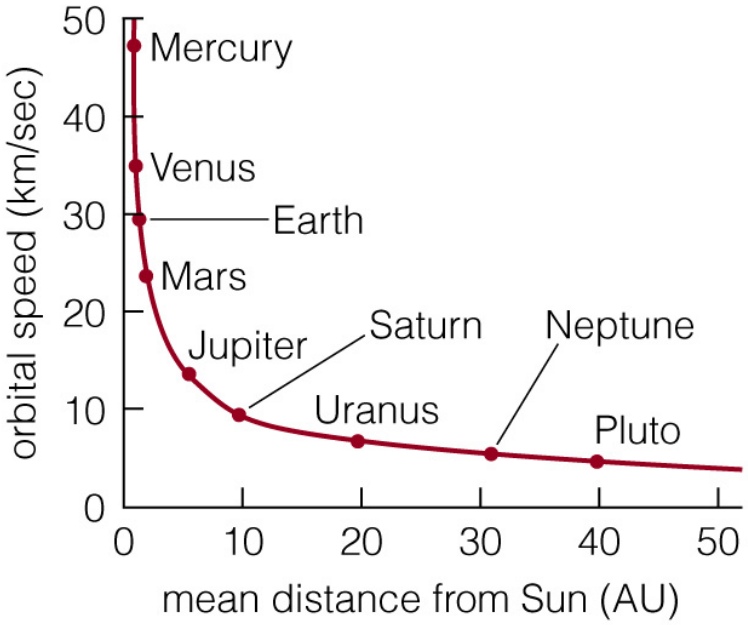
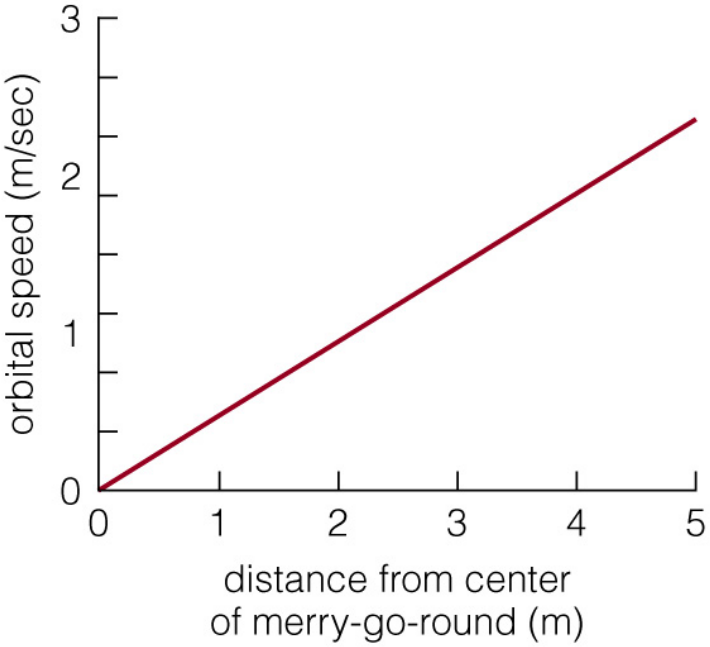
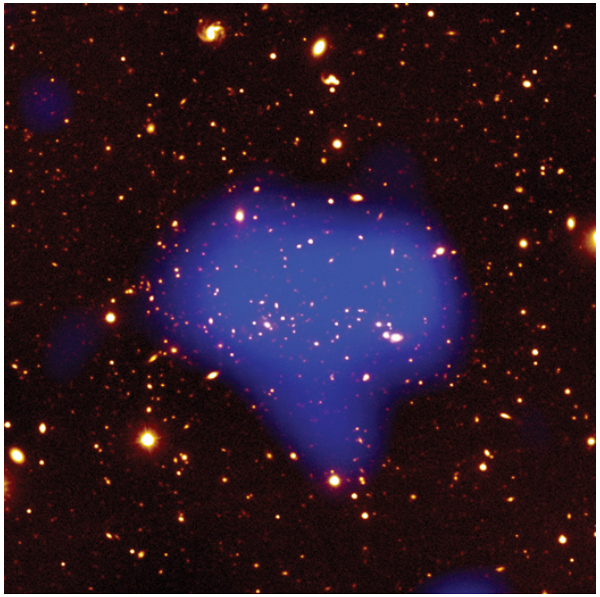


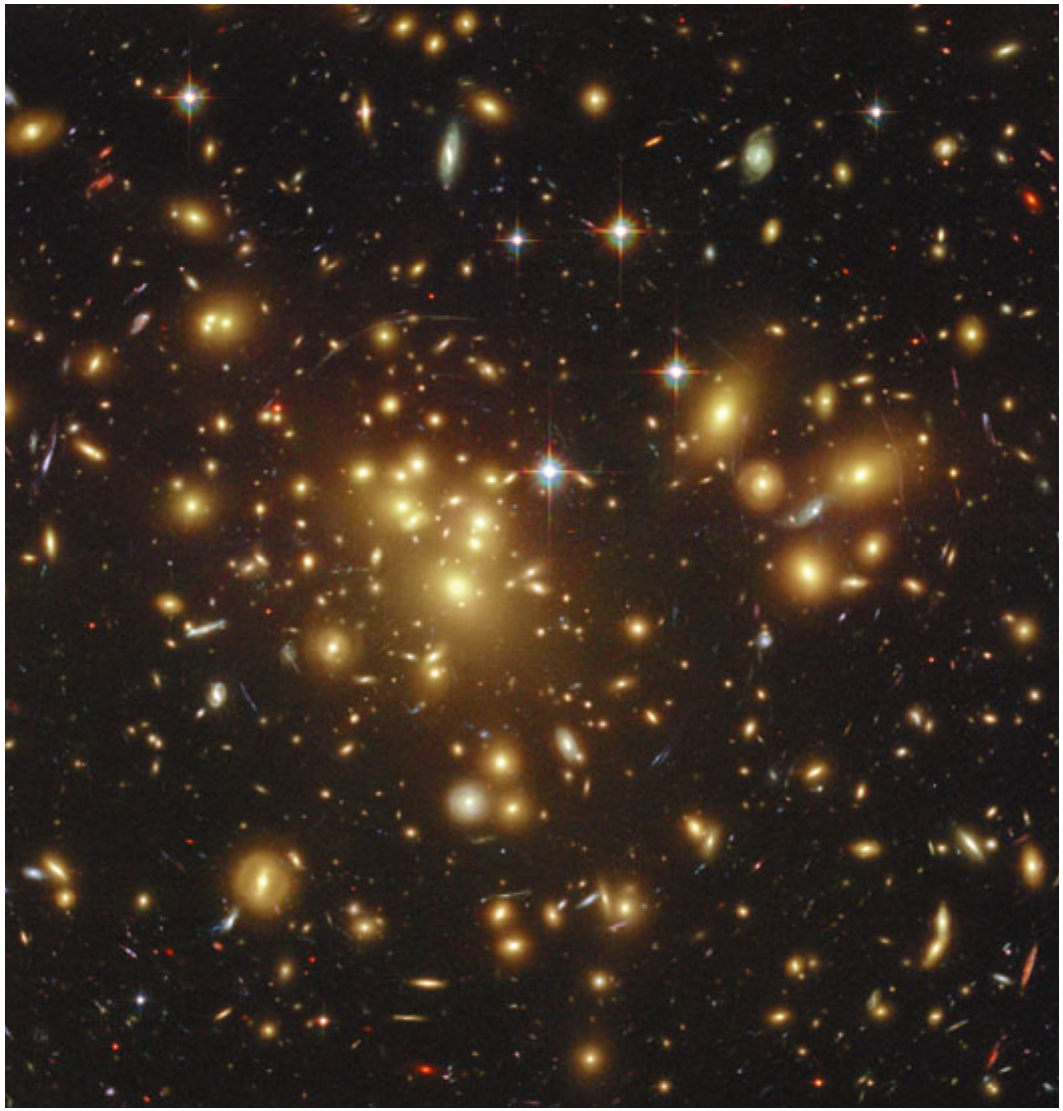



# Dark Matter in Clusters


Clusters are large groups of galaxies
There are three ways to find cluster mass

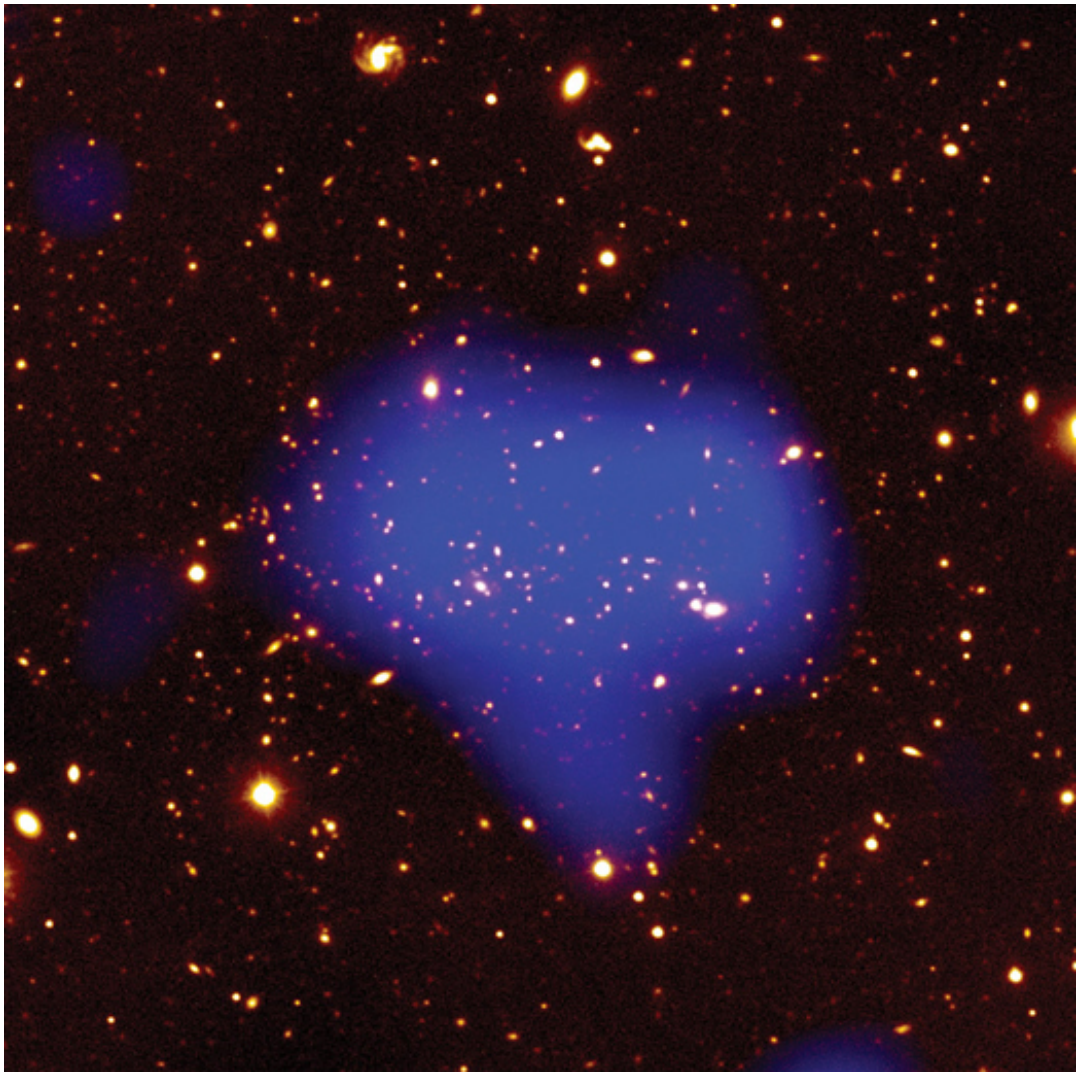
# 1) Velocities of galaxies



The galaxies are moving too fast, indicating unseen mass

The mass we calculate from galaxy motions in a cluster is about ***50 times*** larger than the mass in stars!

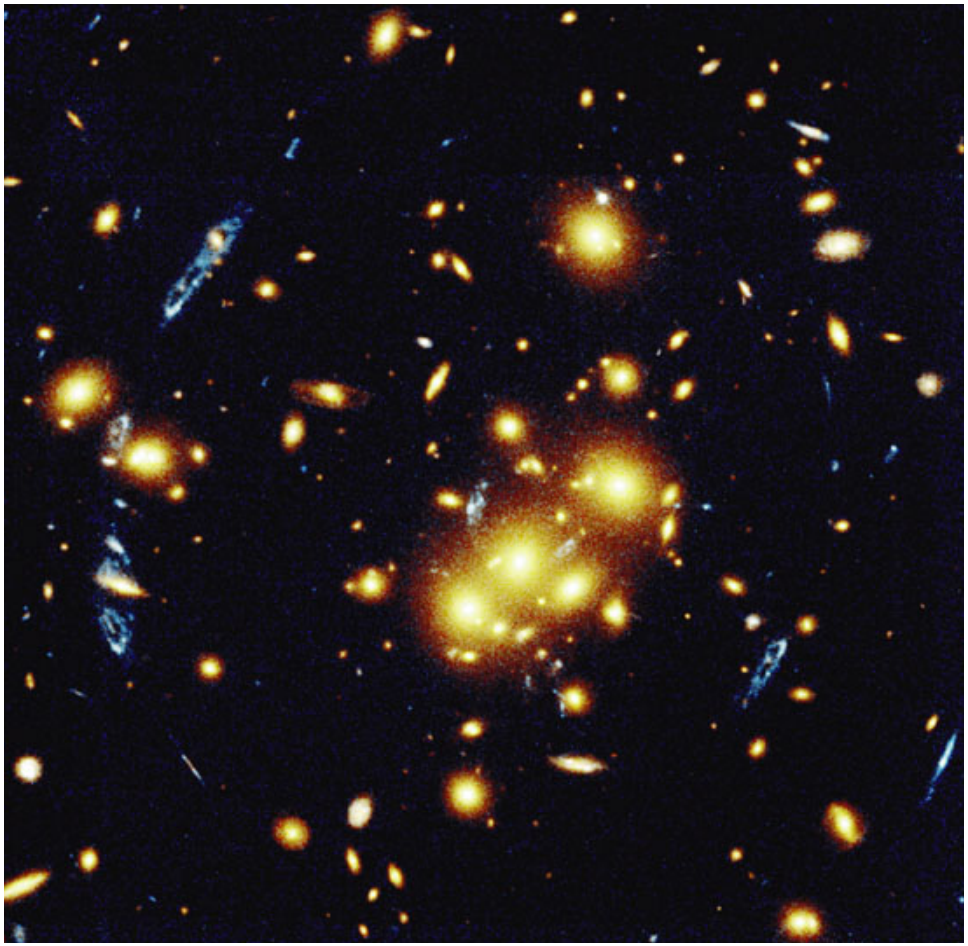
# 2) Mass traced through X-rays

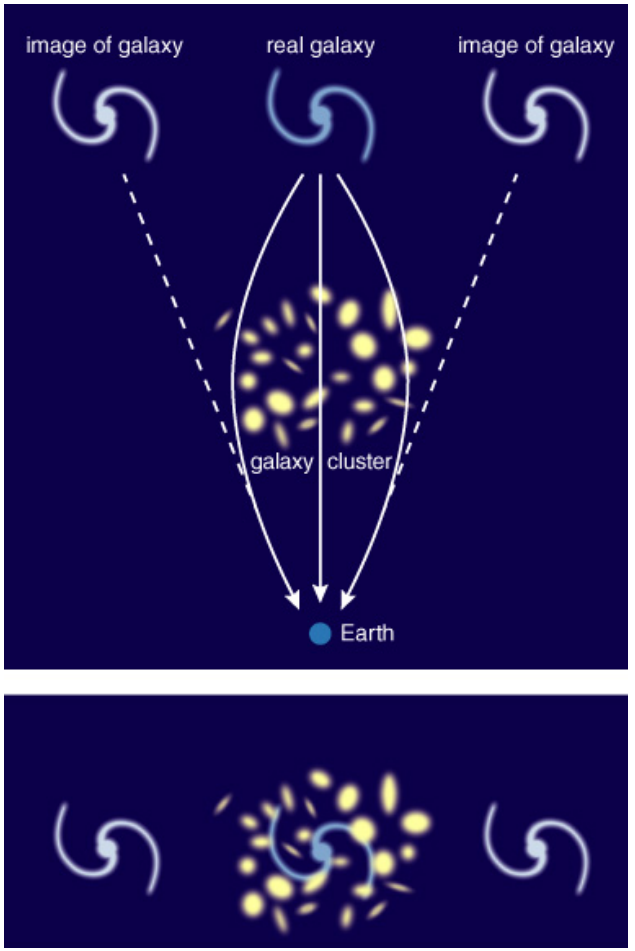


Clusters contain large amounts of X-ray emitting hot gas

Temperature of hot gas (particle motions) tells us cluster mass. The gas is hotter than it would be if there was no dark matter.

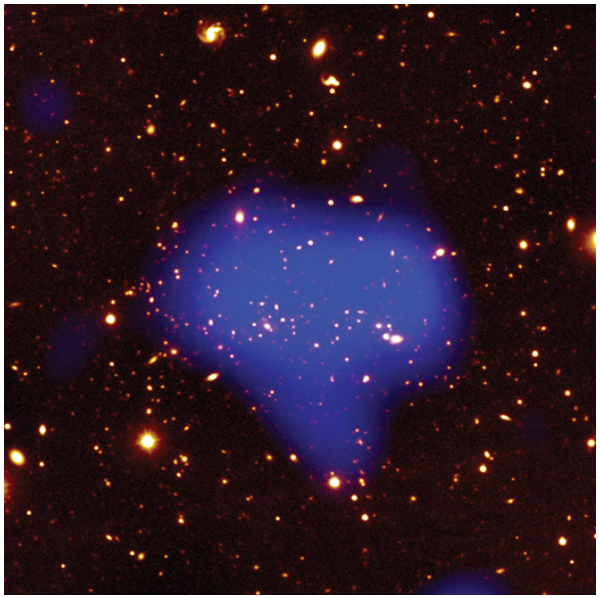
# 3) Gravitational Lensing






***Gravitational lensing,*** the bending of light rays by gravity, can also tell us a cluster's mass

# Cluster Masses


All three methods of measuring cluster mass indicate similar amounts of dark matter

# But Does Dark Matter Really Exist???

Something is needed to explain the discrepancy between the mass measured through gravity and the mass directly observed.

1) Dark matter really exists, and we are observing the effects of its gravitational attraction
2) Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

Because gravity is so well tested, most (but not all!) astronomers prefer option #1

# How dark is dark matter?

... not as bright as a star.

# Two Basic Options

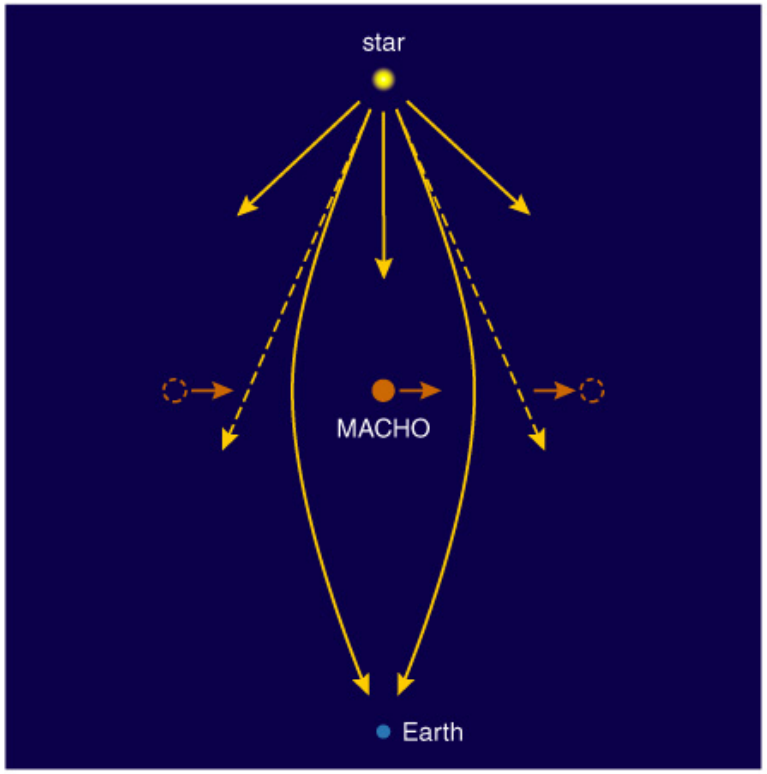
- Ordinary Dark Matter (MACHOS)
  - Massive Compact Halo Objects:

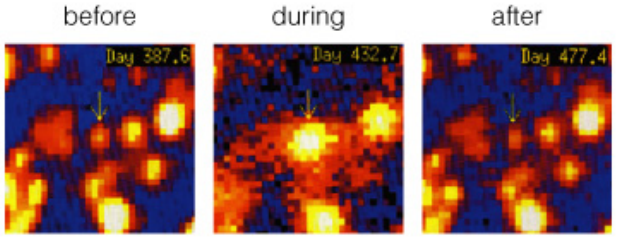
    dead or failed stars in halos of galaxies – basically brown dwarfs

- Extraordinary Dark Matter (WIMPS)
  - Weakly Interacting Massive Particles:

    a new type of particle – possibly similar to a neutrino

# Evidence for MACHOS




MACHOs occasionally make other stars appear brighter through lensing

… but there are not enough lensing events to explain all the dark matter

# Evidence for WIMPs

- There’s not enough ordinary matter
- WIMPs could be left over from Big Bang
- Models involving WIMPs explain how galaxy formation works

# Unseen Influences

***Dark Matter:*** An undetected form of mass that does not emit light but whose existence we infer from its gravitational influence

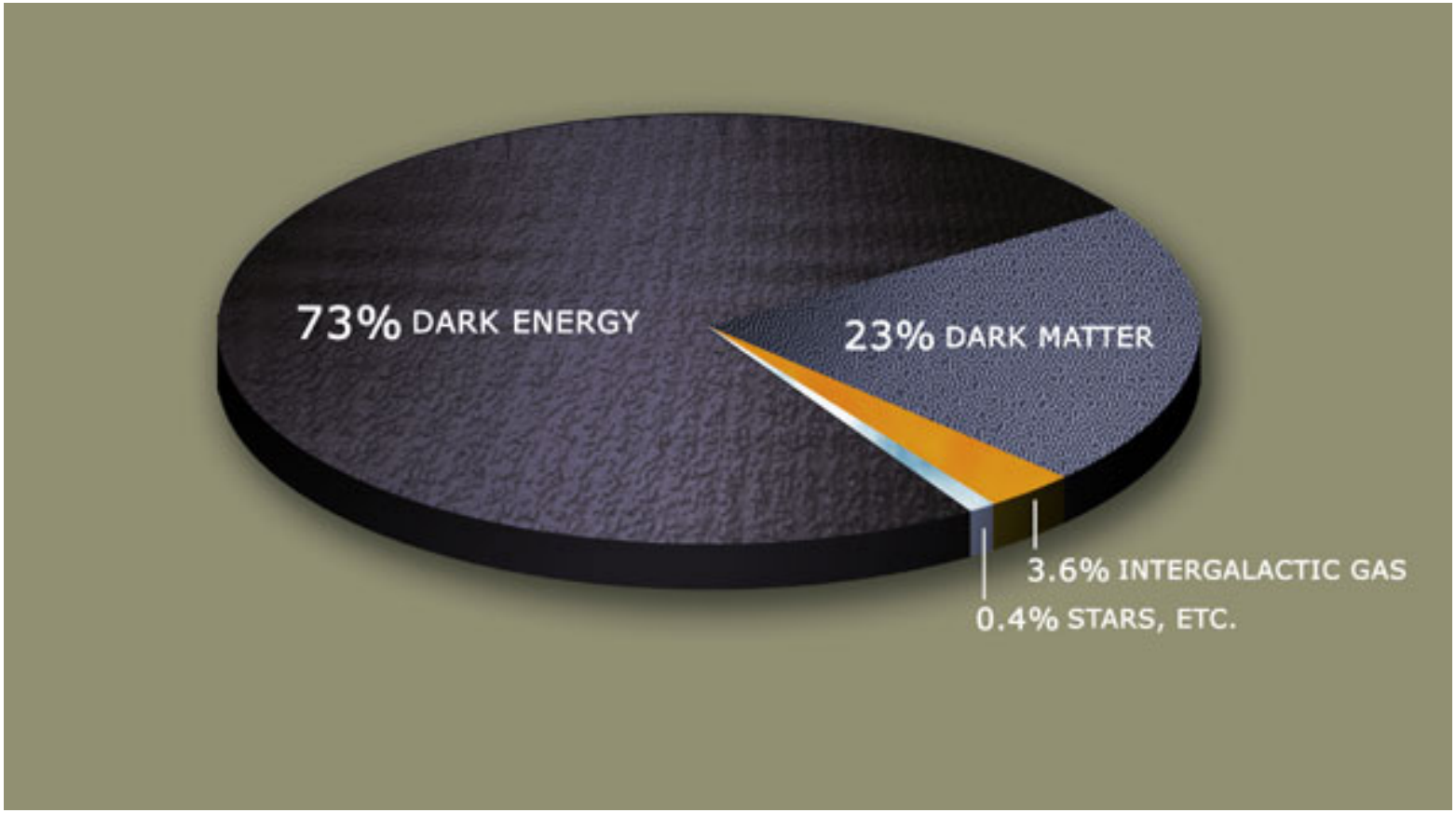
***Dark Energy:*** An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate

# Contents of Universe

"Normal" Matter: ~ 4%

Dark Matter: ~ 23%

Dark Energy ~ 73%



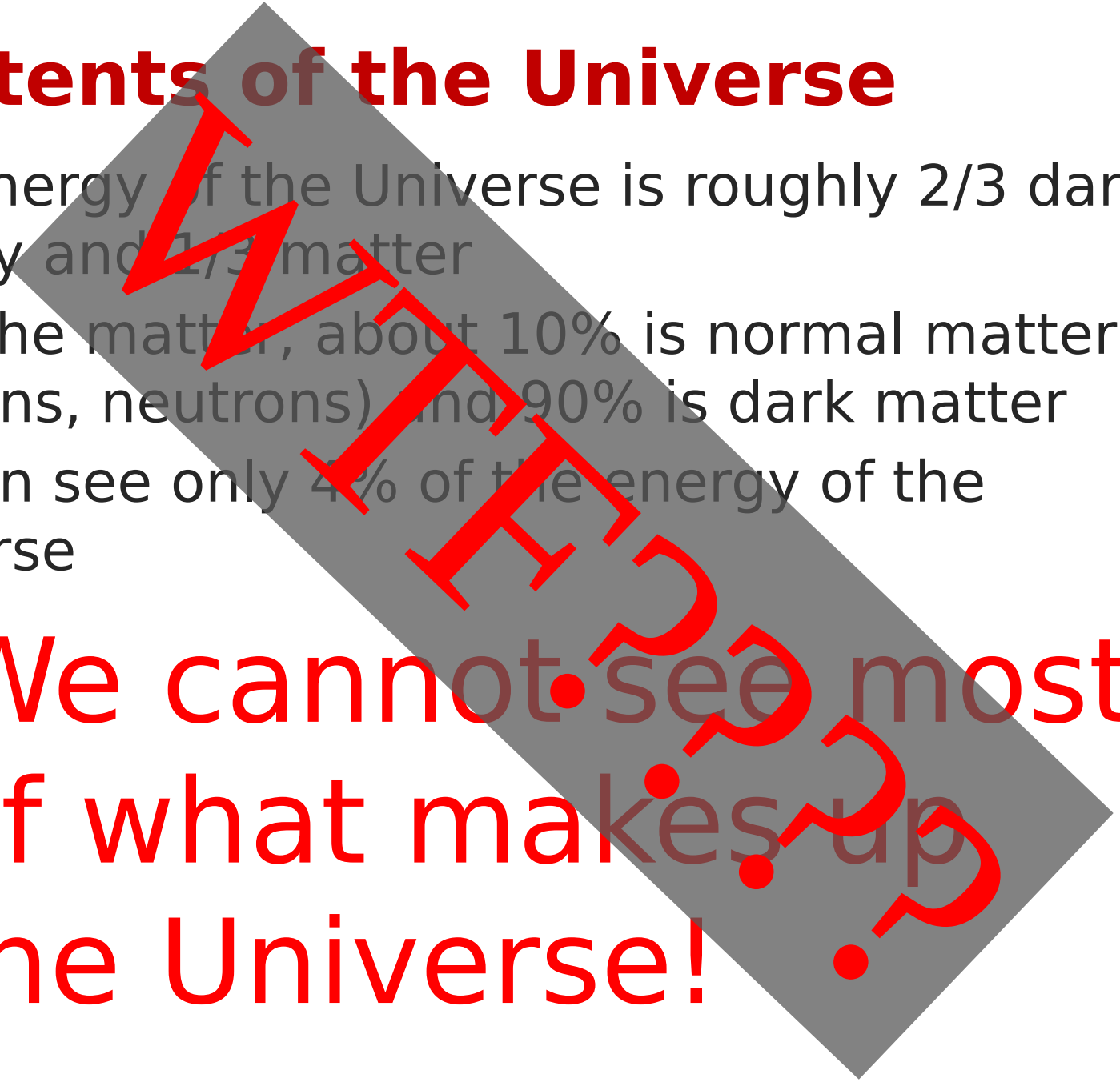
# Contents of the Universe

The energy of the Universe is roughly 2/3 dark energy and 1/3 matter

Of the matter, about 10% is normal matter (protons, neutrons) and 90% is dark matter

We can see only 4% of the energy of the Universe

– We cannot see most of what makes up the Universe!



# What have we learned?

1) What are dark matter and dark energy?
   - "Dark matter" is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds
   - "Dark energy" is the name given to whatever might be causing the expansion of the universe to accelerate

2) What is the evidence for dark matter in galaxies?

   - Rotation curves of galaxies are flat, indicating that most of their matter lies outside their visible regions

3) What is the evidence for dark matter in clusters of galaxies?

Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark

4) What might dark matter be made of?

There does not seem to be enough normal matter to account for all the dark matter, so most astronomers suspect that dark matter is made of particles that have not yet been discovered