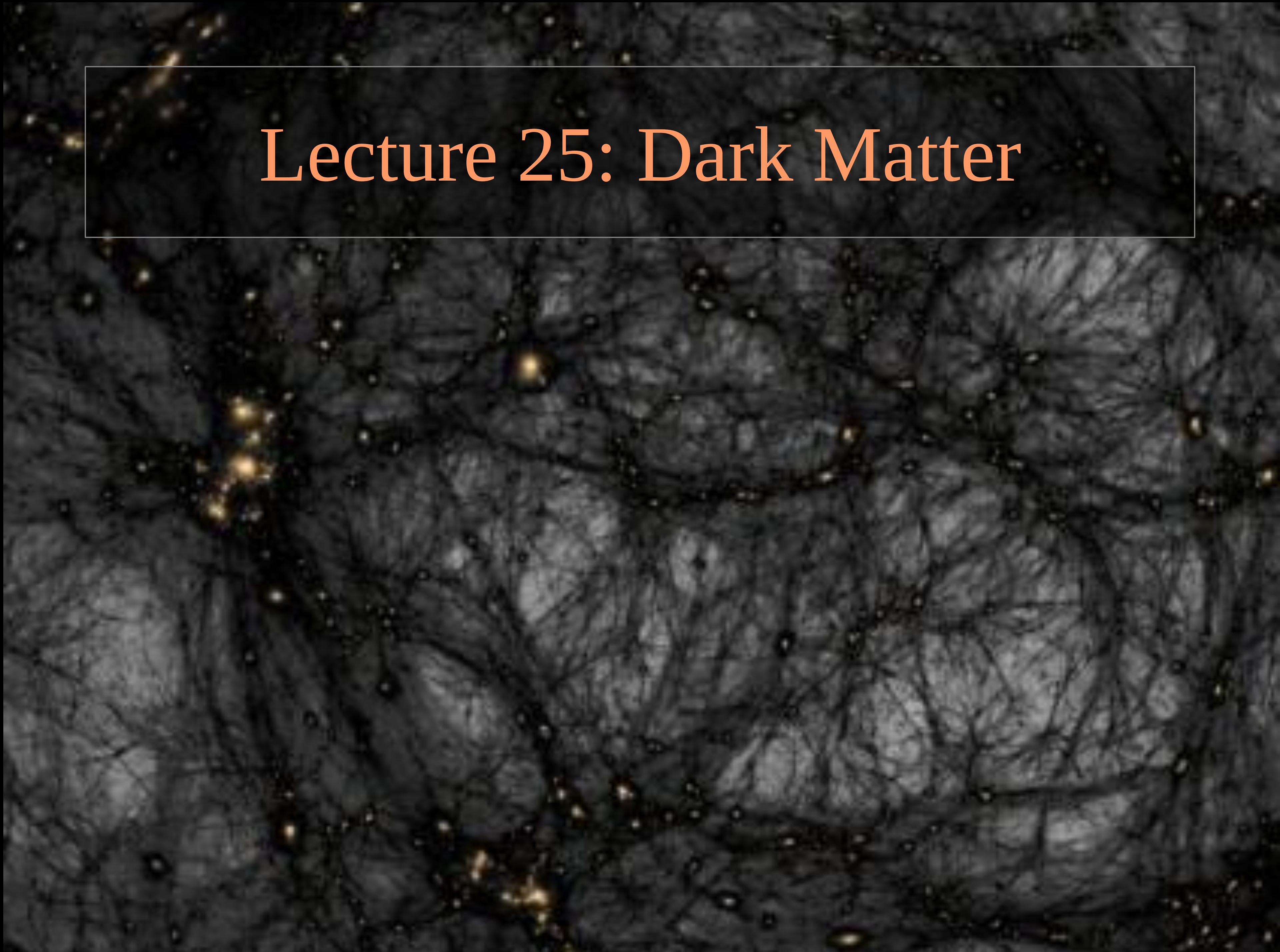
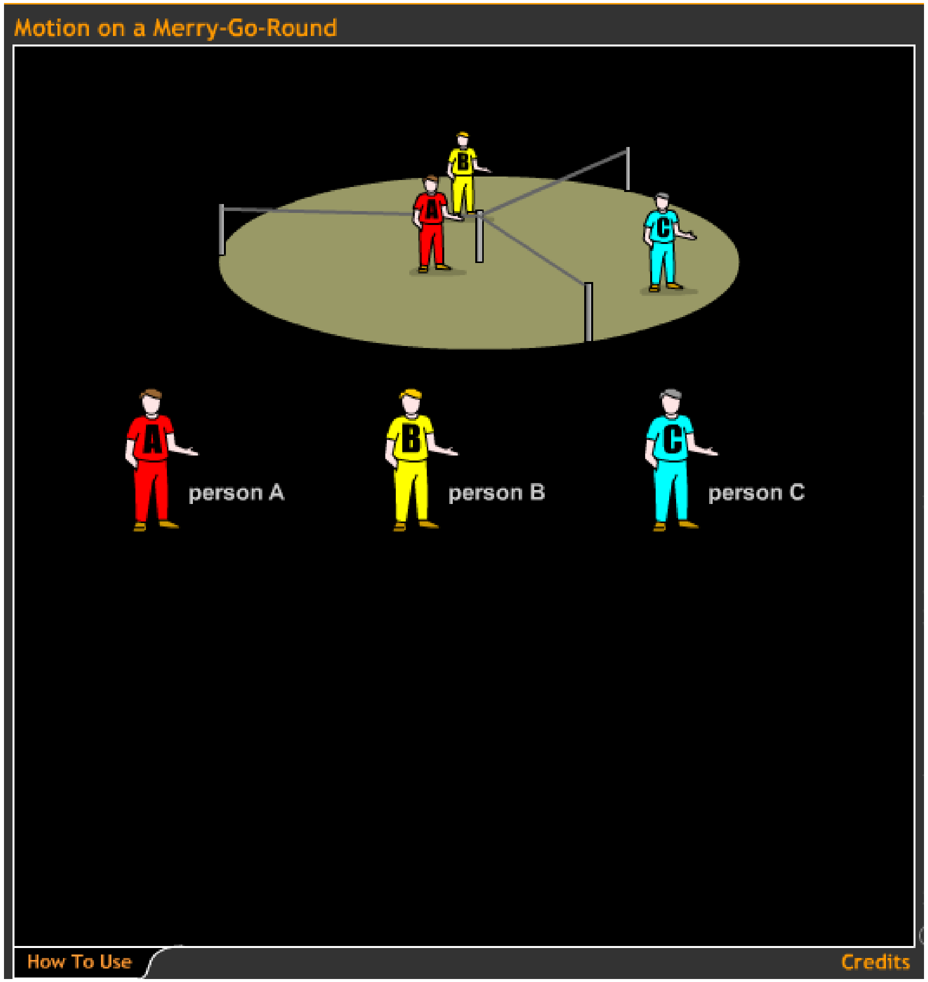
Lecture 25: Dark Matter



The mass of the Milky Way

Detailed study of the Milky Way's rotation reveals one of the greatest mysteries in astronomy…

Rotation curve

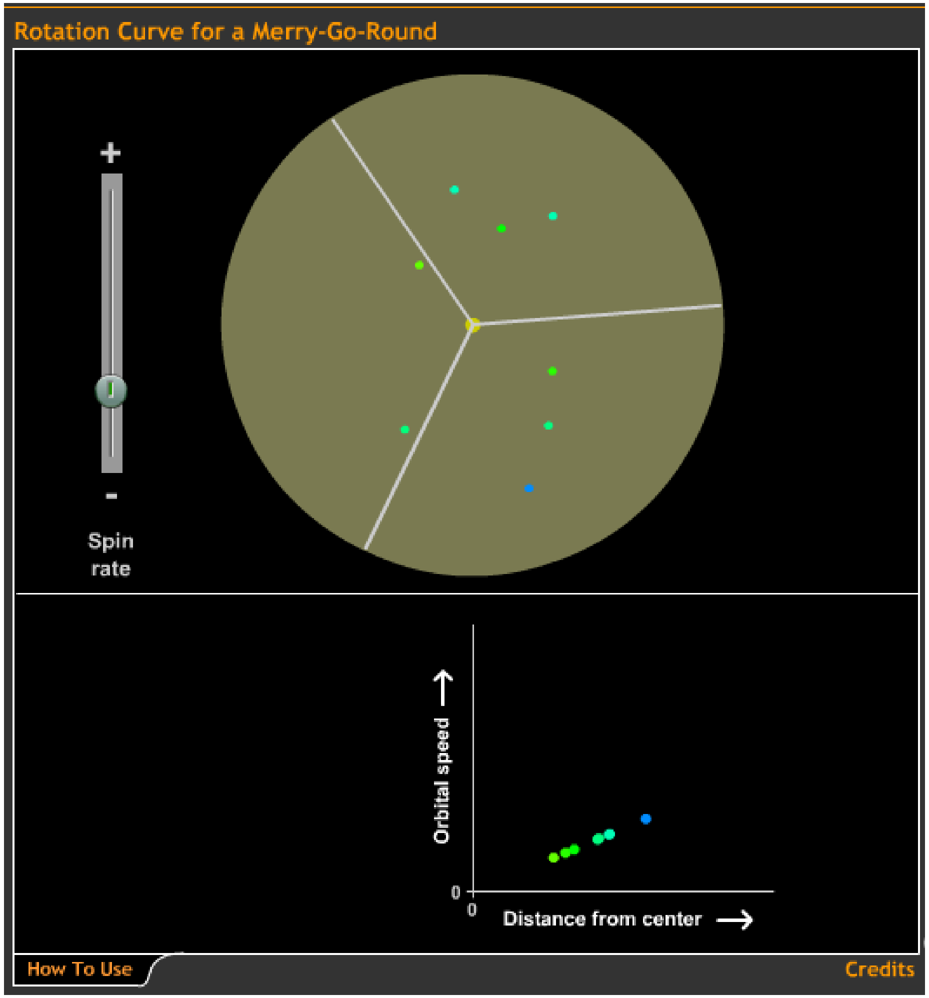


Who has the largest orbital velocity?

A, B, or C?

PLAY Motion on a Merry-Go-Round

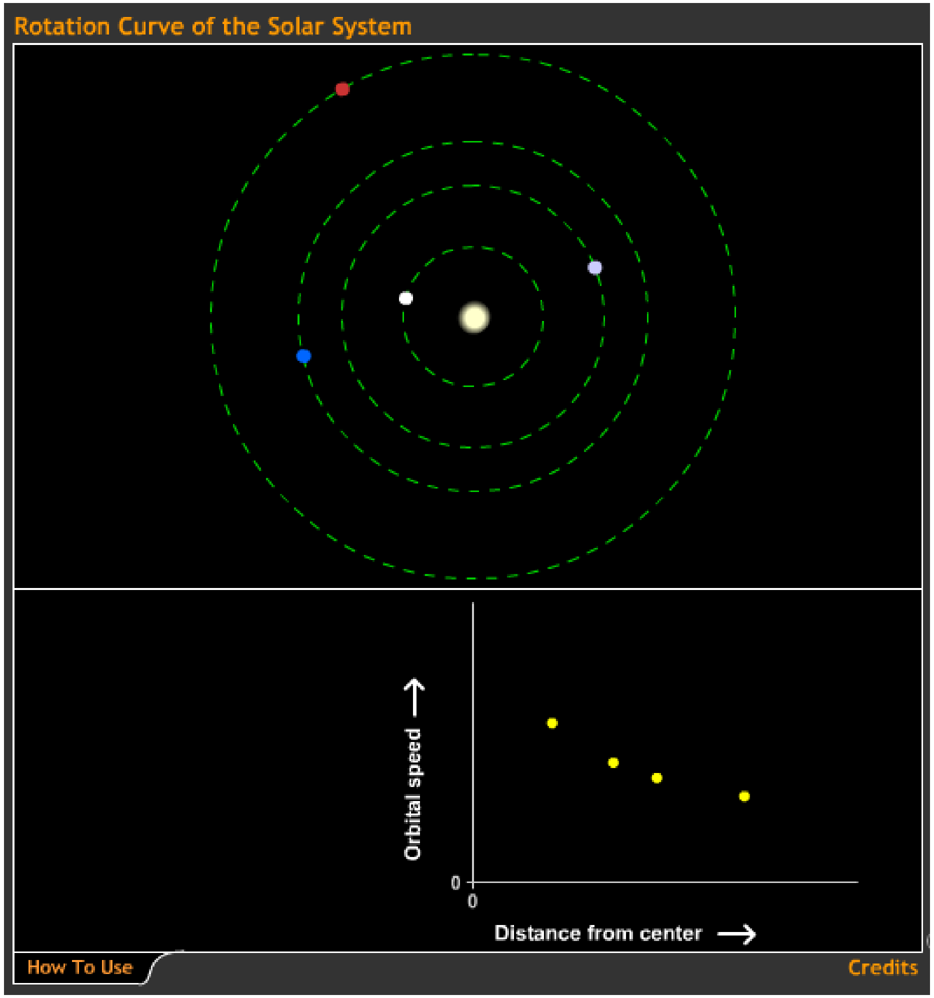
Rotation curve



Rotation curve of merry-go-round (*solid body*) **rises** with radius

PLAY Rotation Curve for a Merry-Go-Round

Measuring mass with rotation

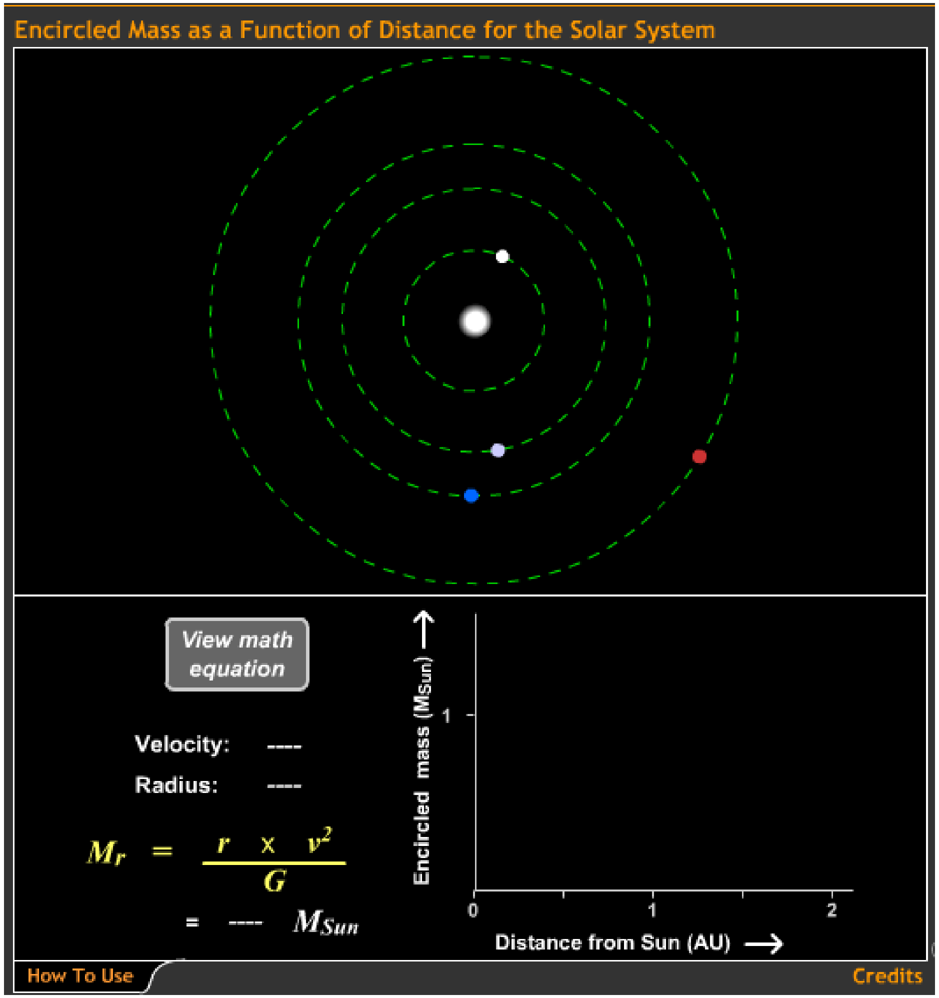


Rotation curve of solar system

A plot of orbital velocity versus orbital radius indicates that the solar system's rotation speed **declines** with distance from center because the *Sun has almost all the mass.*

PLAY Rotation Curve of the Solar System

Measuring mass with rotation



We measure mass of the solar system (~Sun) using the orbits of planets and Kepler's Law

- Orbital period
- Average distance

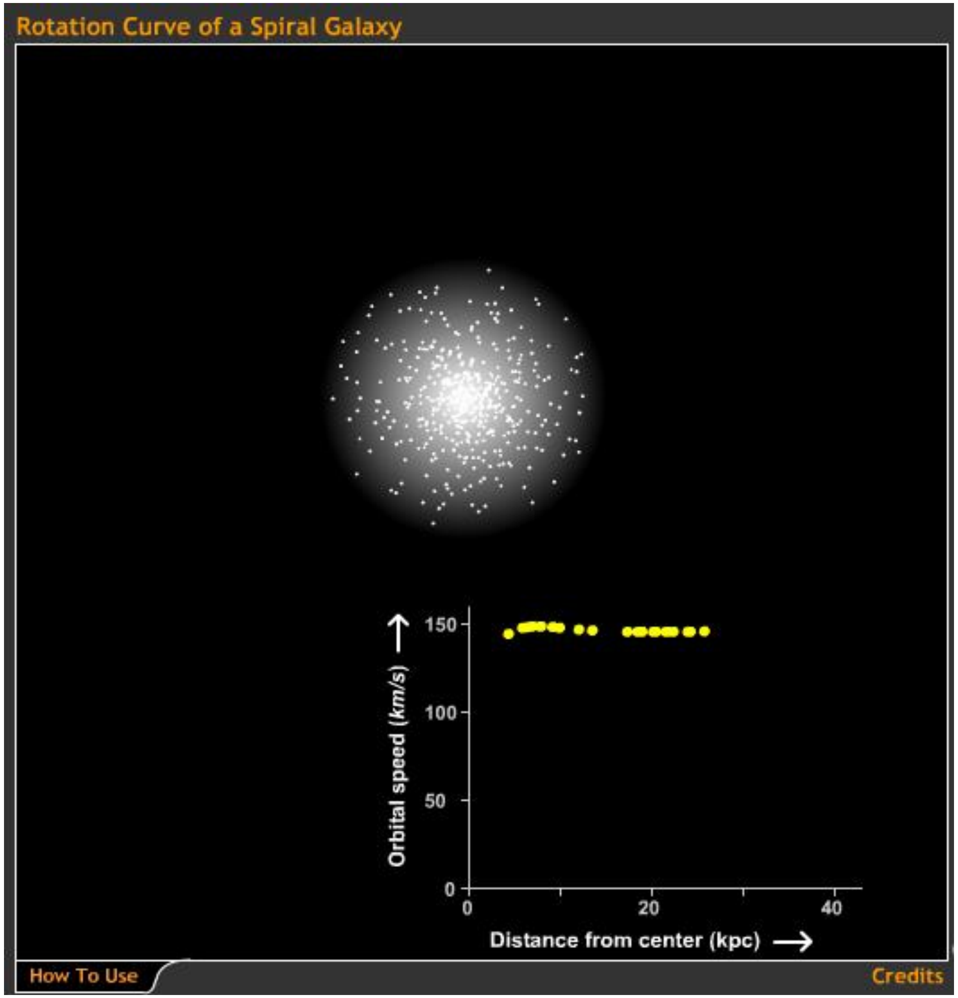
Or for circular orbits:

- Orbital velocity
- Orbital radius

Mass = rv^2 / G

PLAY Encircled Mass as a Function of Distance for the Solar System

Measuring mass with rotation

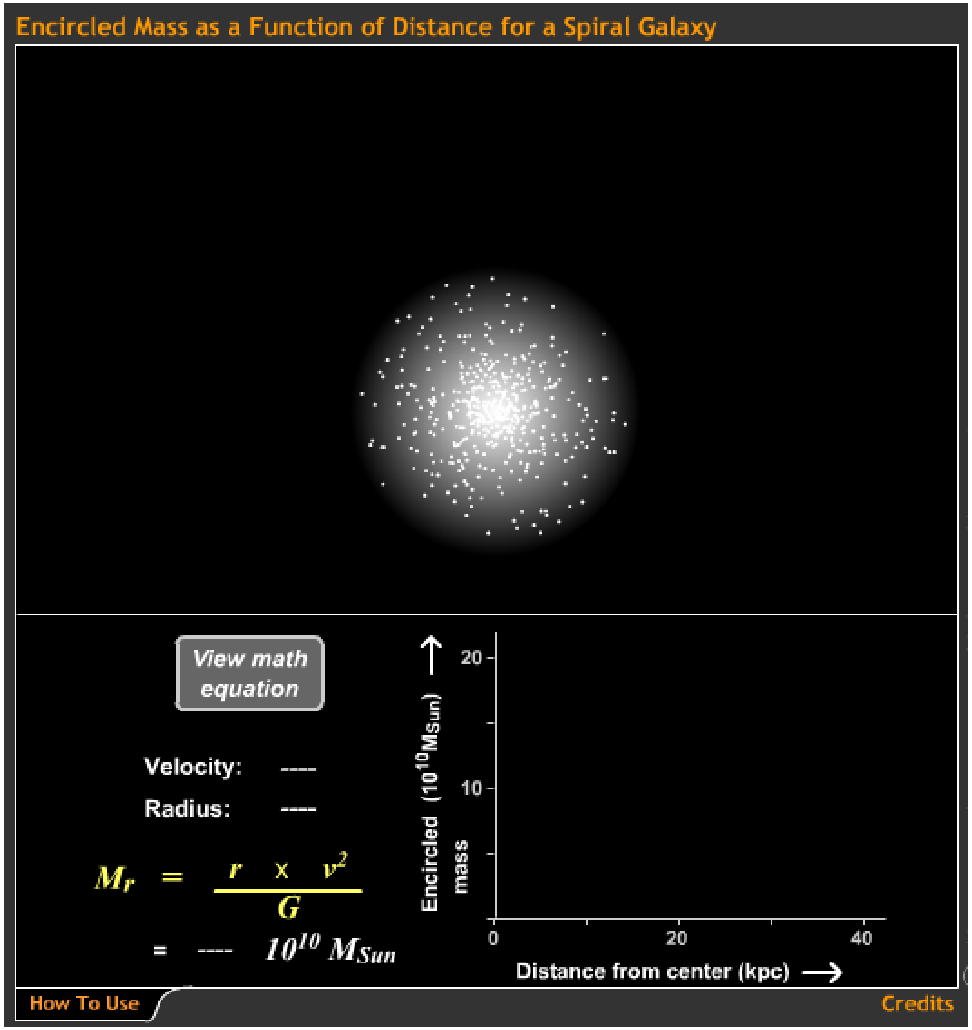


- The rotation speed of the Milky Way **stays flat** with distance.

- *Mass must be more spread out than in the solar system.*

PLAY Rotation Curve of a Spiral Galaxy

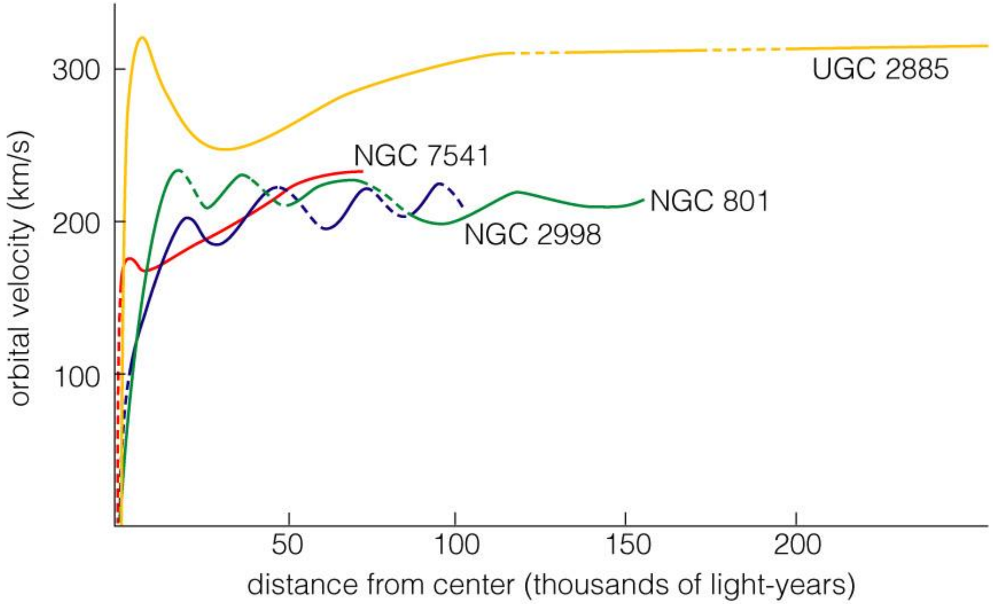
Measuring mass with rotation

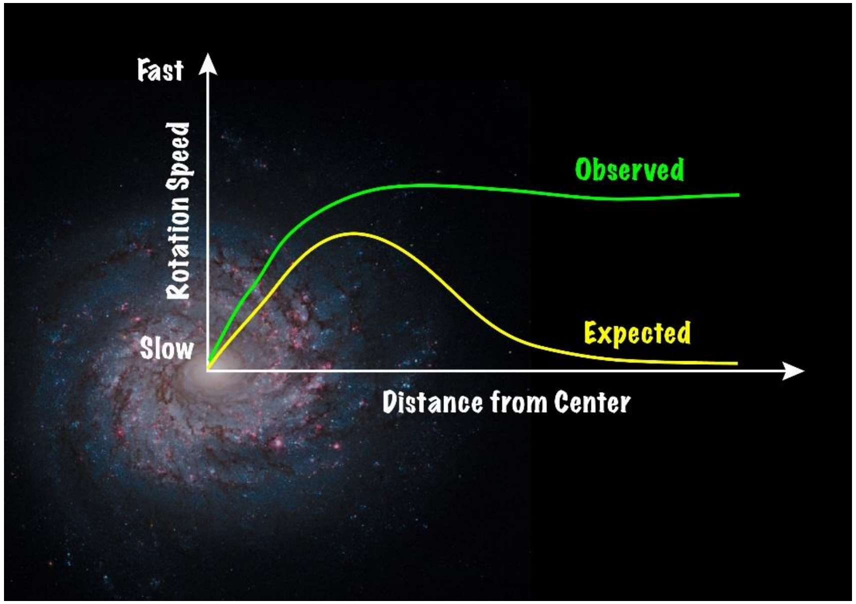


- The mass in the Milky Way is spread out over a larger region than the stars.
- Most of the Milky Way's mass seems to be unseen, ***dark** matter!*

PLAY Encircled Mass as a Function of Distance for a Spiral Galaxy

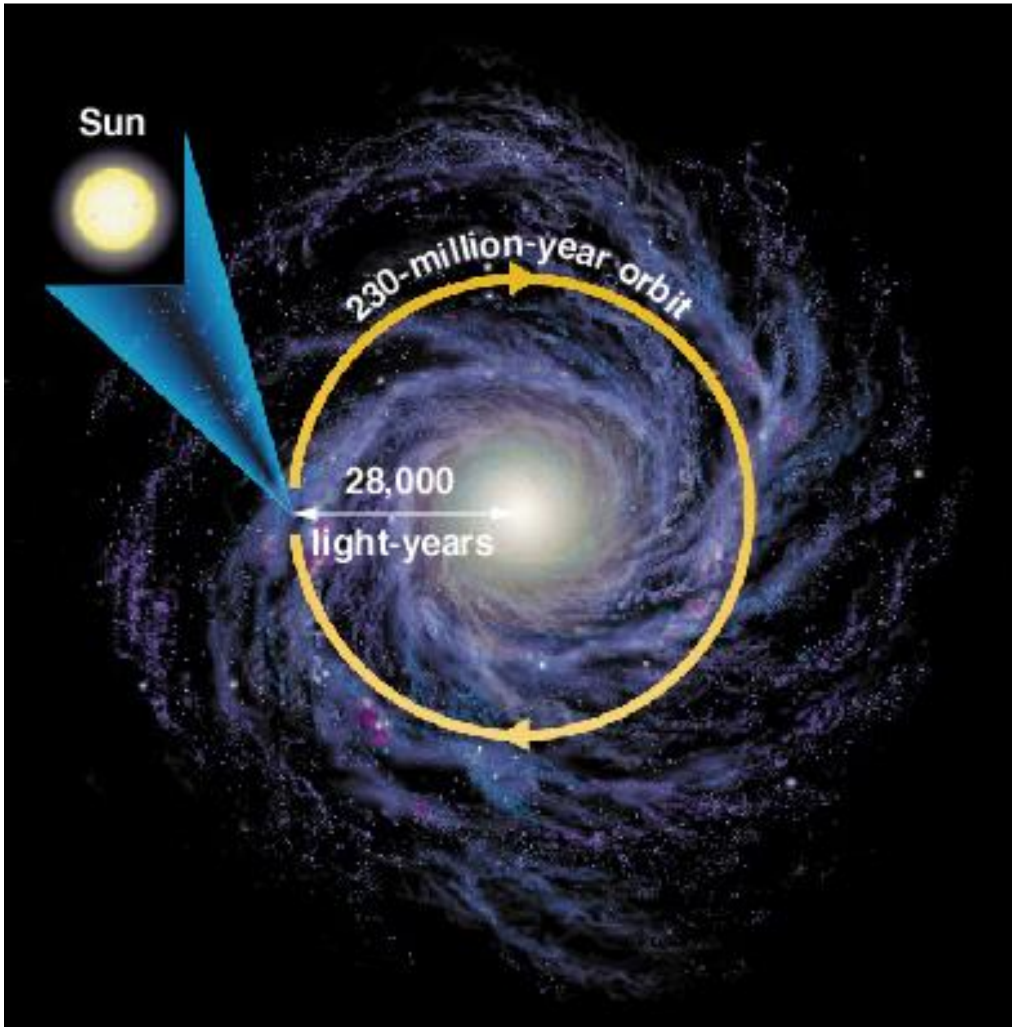
Evidence for dark matter





Vera Rubin found that almost all spiral galaxies have flat rotation curves indicating large amounts of dark matter.

Evidence for dark matter



Mass within Sun's orbit:

$10^{11}\ M_{\text{Sun}}$

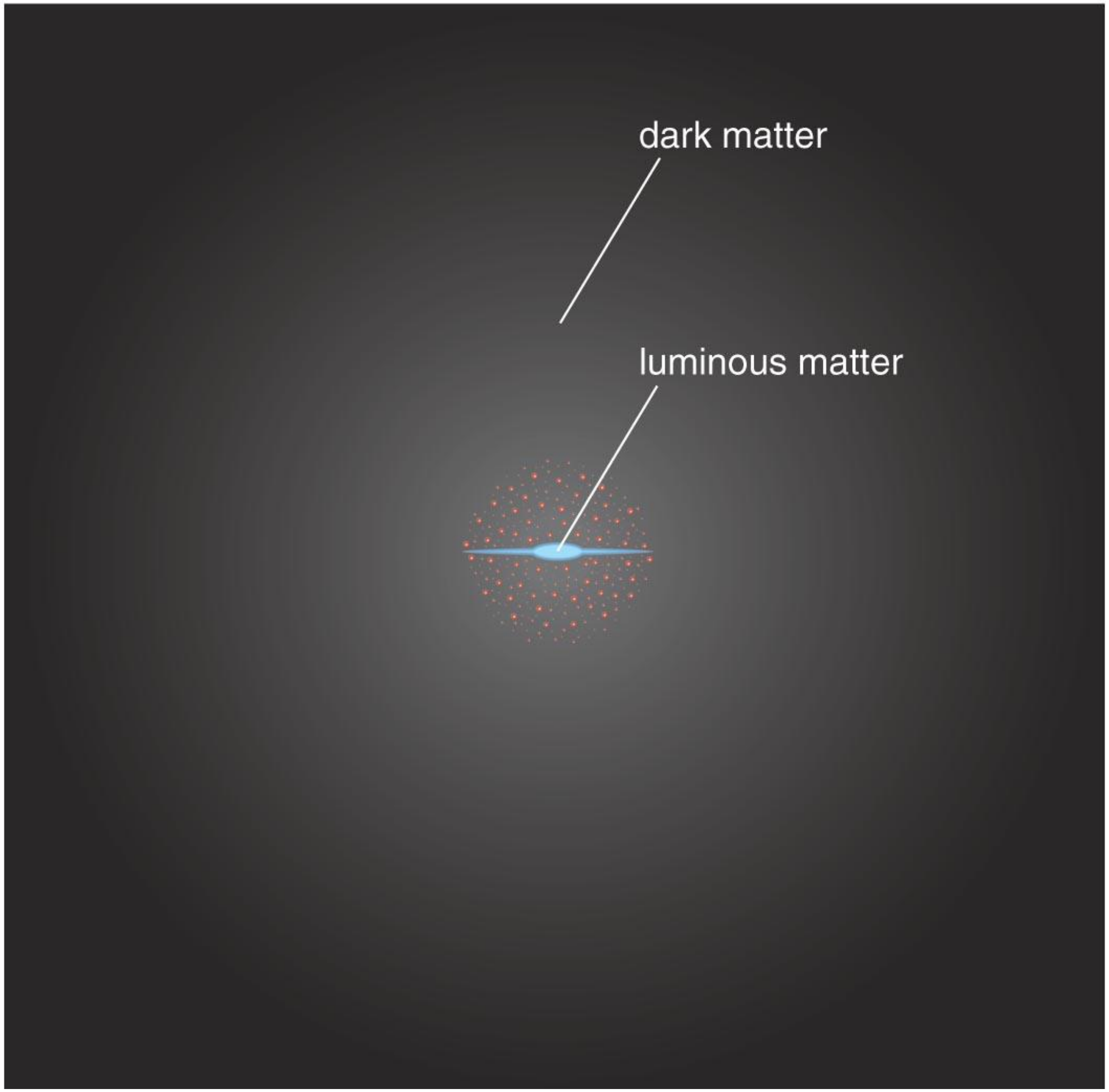
Total mass:

$10^{12}\ M_{\text{Sun}}$

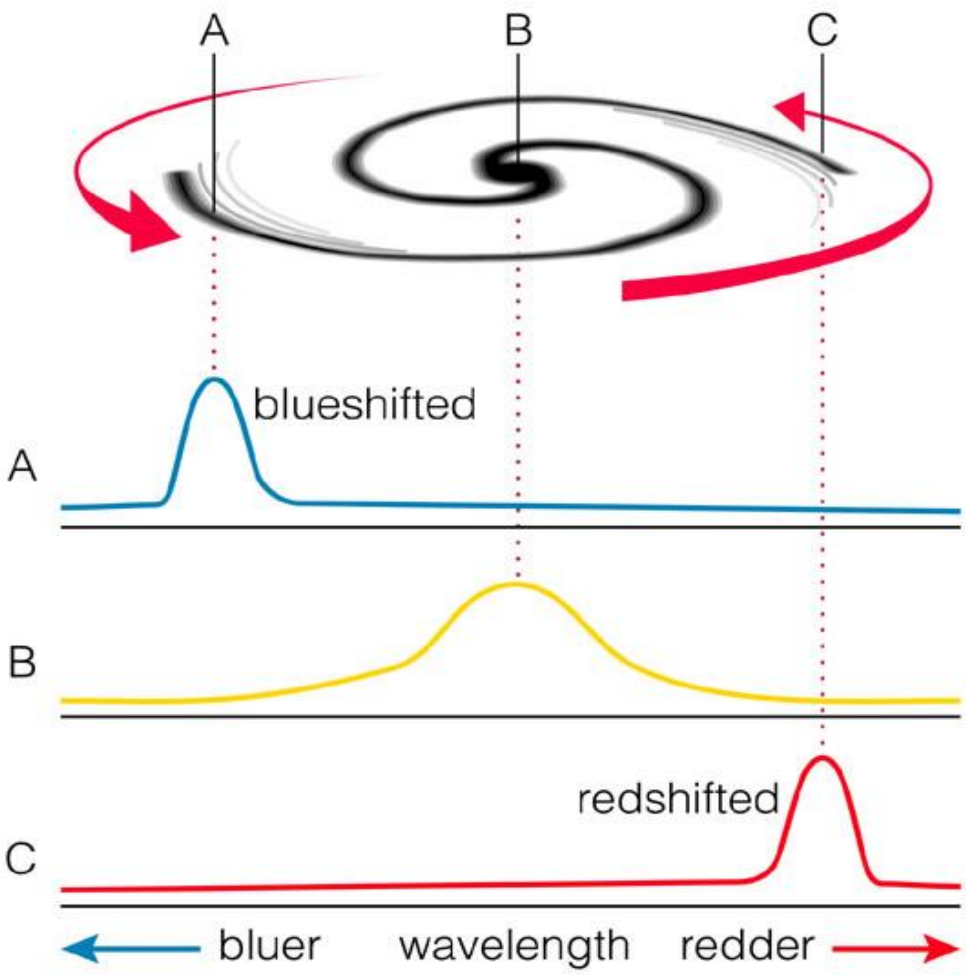
There is 10x as much total matter as within Sun's orbit!

Evidence for dark matter

- The visible portion of a galaxy lies deep in a large halo of dark matter.
- Density of dark matter increases moderately towards center



Evidence for dark matter

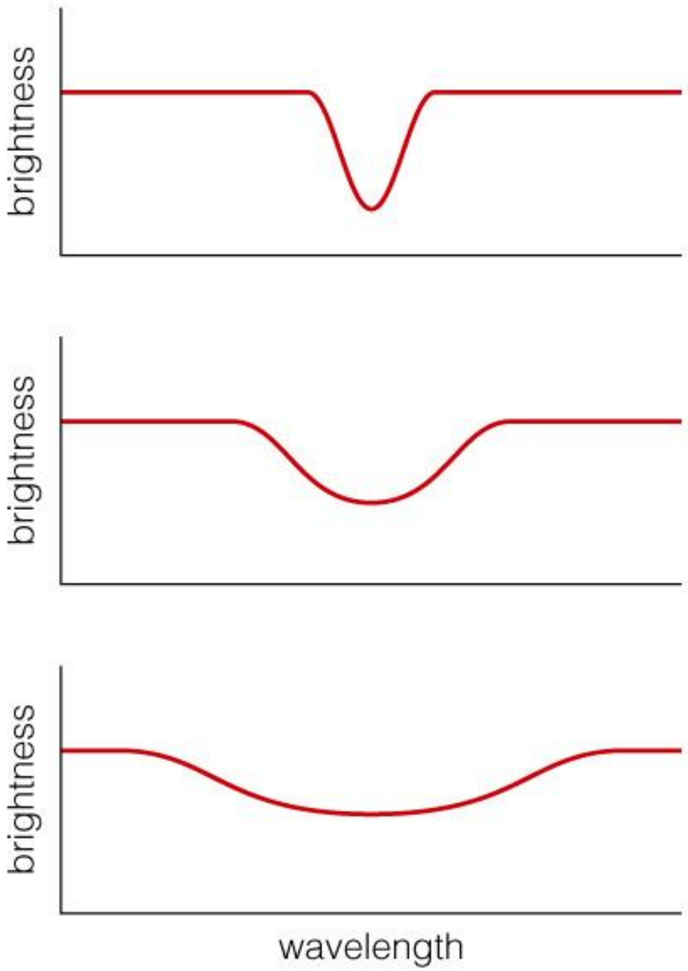


- We measure the **rotation curves** of other spiral galaxies using the Doppler shift of H gas clouds.
- Their rapid rotation requires strong gravity to keep them from flying apart.

Evidence for dark matter

• Since **elliptical** galaxies have little gas we must use another method to measure rotation

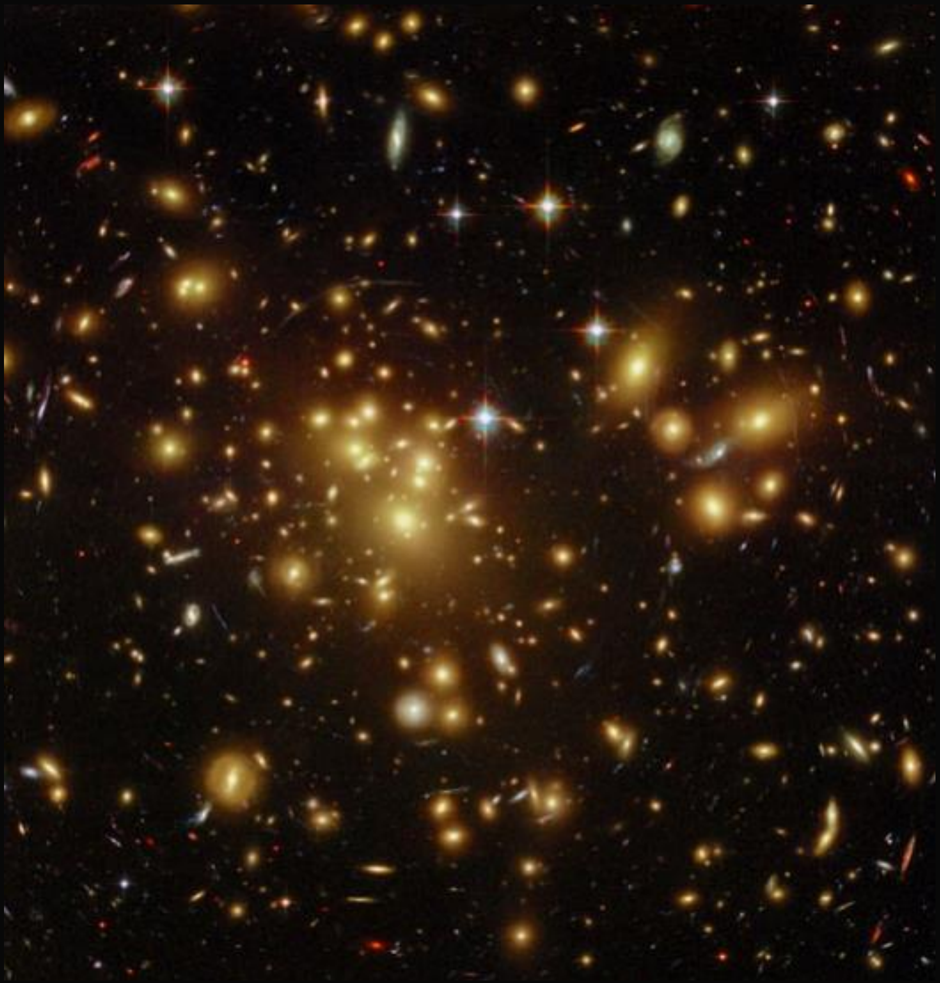
• The **broadening of spectral lines** in elliptical galaxies tells us stars are orbiting fast – evidence these galaxies also have dark matter.



Dark matter

Dark matter: An unseen form of matter that emits no light but whose existence we infer from its gravitational influence. *It causes galaxies to rotate faster than expected*.

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



More evidence for dark matter

1) We measure *overall* velocities of galaxies in a cluster from Doppler shifts. This gives *average* velocity of the cluster as a whole.
2) We subtract average cluster velocity from individual galaxy velocities to find galaxies' velocities *within* cluster. These give cluster mass.
3) Comparing cluster mass to luminosity shows ***many times*** more mass than visible mass in stars!

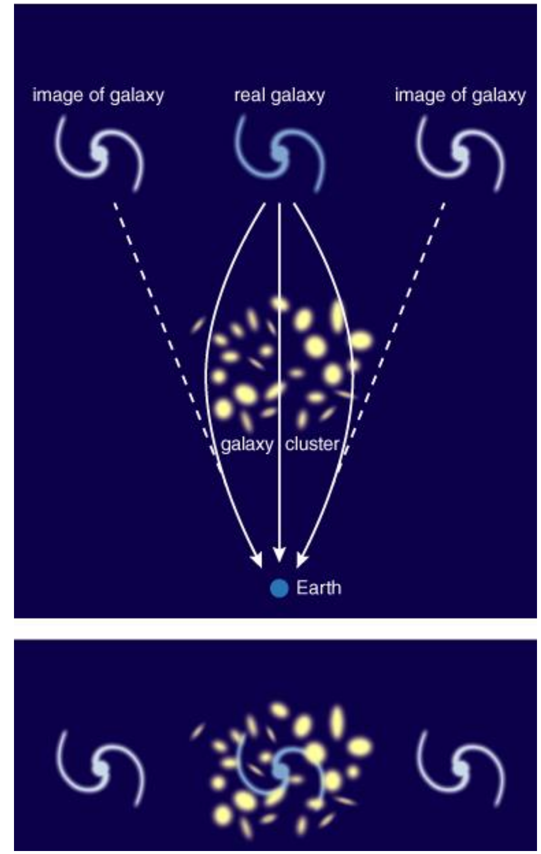
More evidence for dark matter

- Clusters contain large amounts of X-ray emitting hot gas.
- The *temperature* of hot gas (particle velocity) depends on total mass and tells us cluster's mass:
  - 80% dark matter
  - 15% hot gas
  - 5% stars

$$v_H = 140\text{m/s} \times \sqrt{\text{Temp}}$$
$$= 140\text{m/s} \times \sqrt{9\text{x}10^7}$$
$$= 1.3 \times 10^7 \text{ m/s}$$

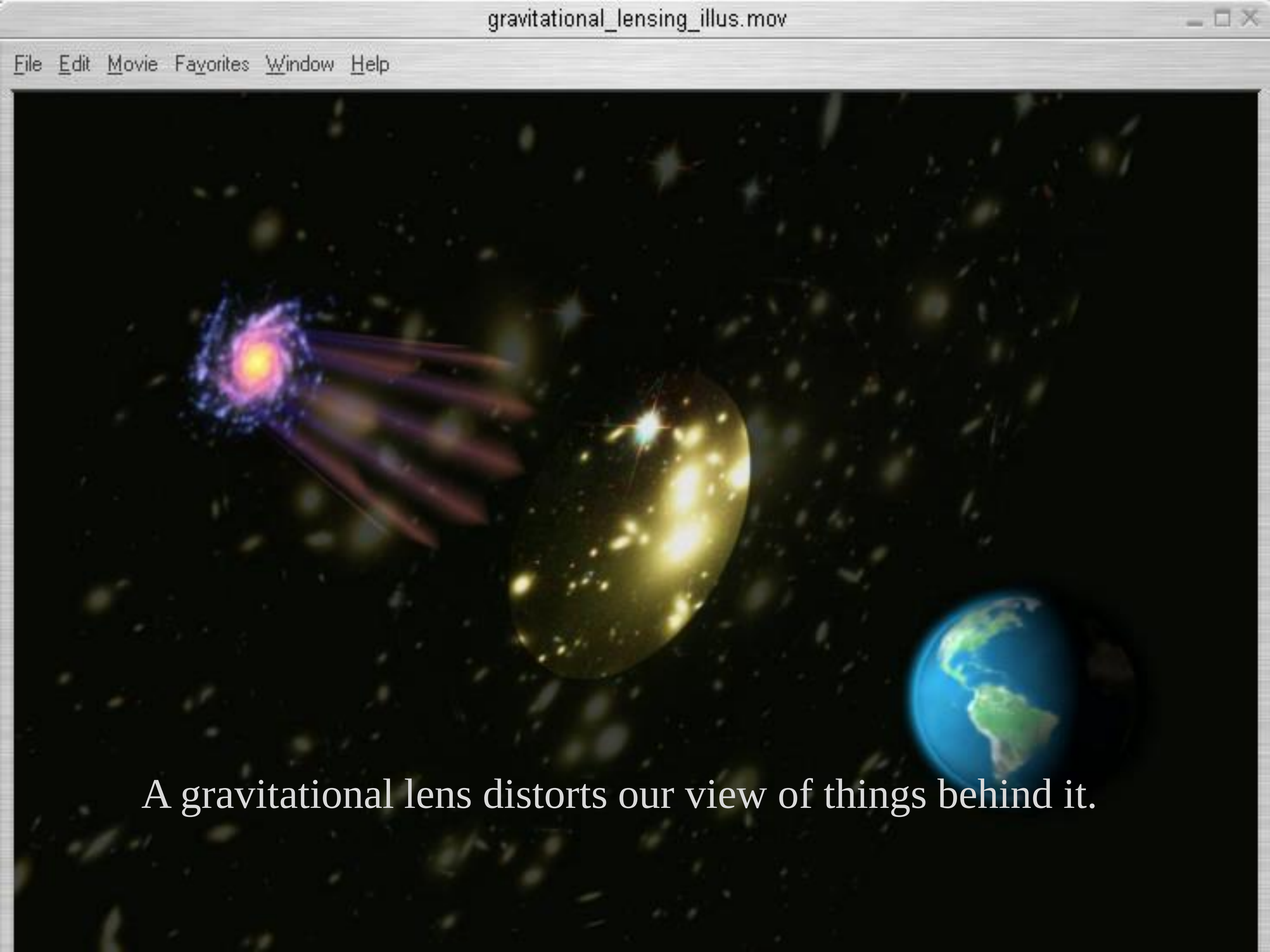
$$M_r = \frac{\text{radius x velocity}^2}{G}$$
$$= 1.5 \times 10^{45} \text{ kg!}$$

More evidence for dark matter



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

• Mass of the cluster is proportional to amount of bending


gravitational_lensing_illus.mov
File Edit Movie Favorites Window Help
A gravitational lens distorts our view of things behind it.

More evidence for dark matter

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

Think/Pair/Share

What kind of measurement does not tell us the true mass of a cluster of galaxies?

A. Measuring velocities of cluster galaxies.
B. Measuring total mass of cluster’s stars.
C. Measuring temperature of its hot gas.
D. Measuring distorted images of background galaxies

Think/Pair/Share

What kind of measurement does not tell us the true mass of a cluster of galaxies?

A. Measuring velocities of cluster galaxies
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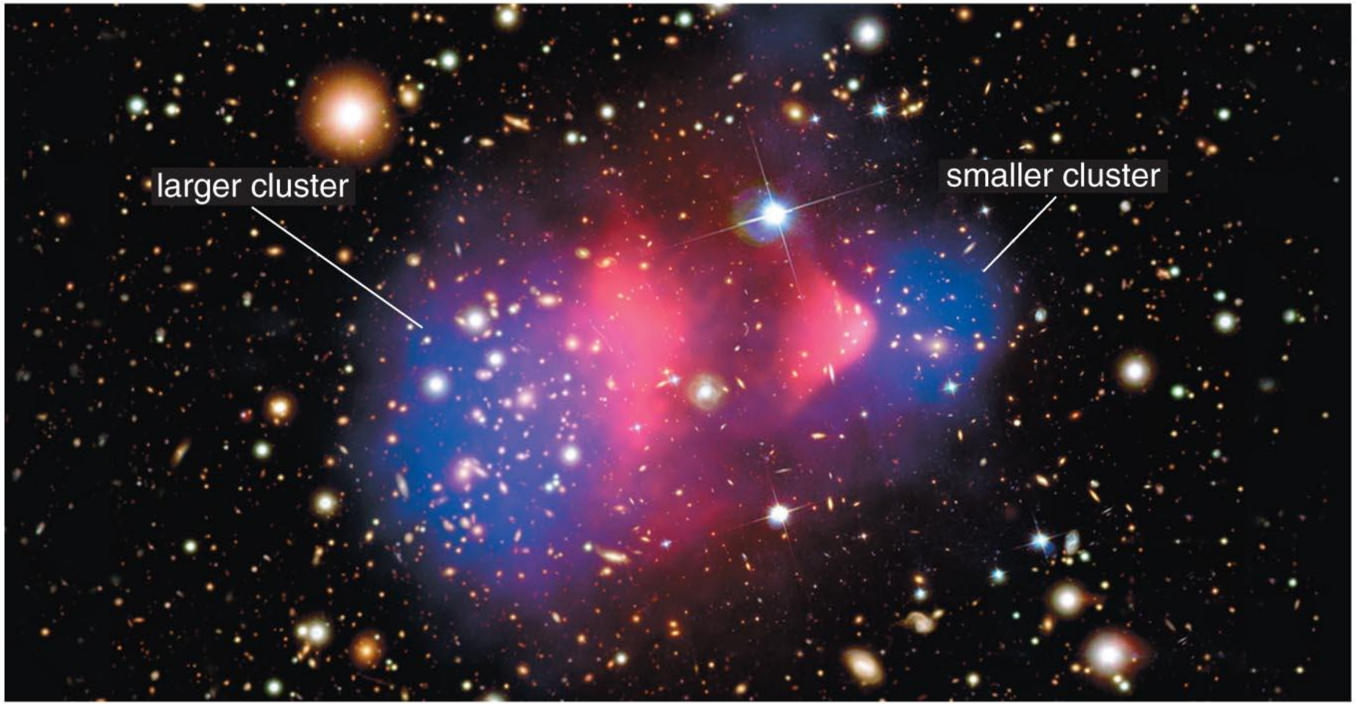
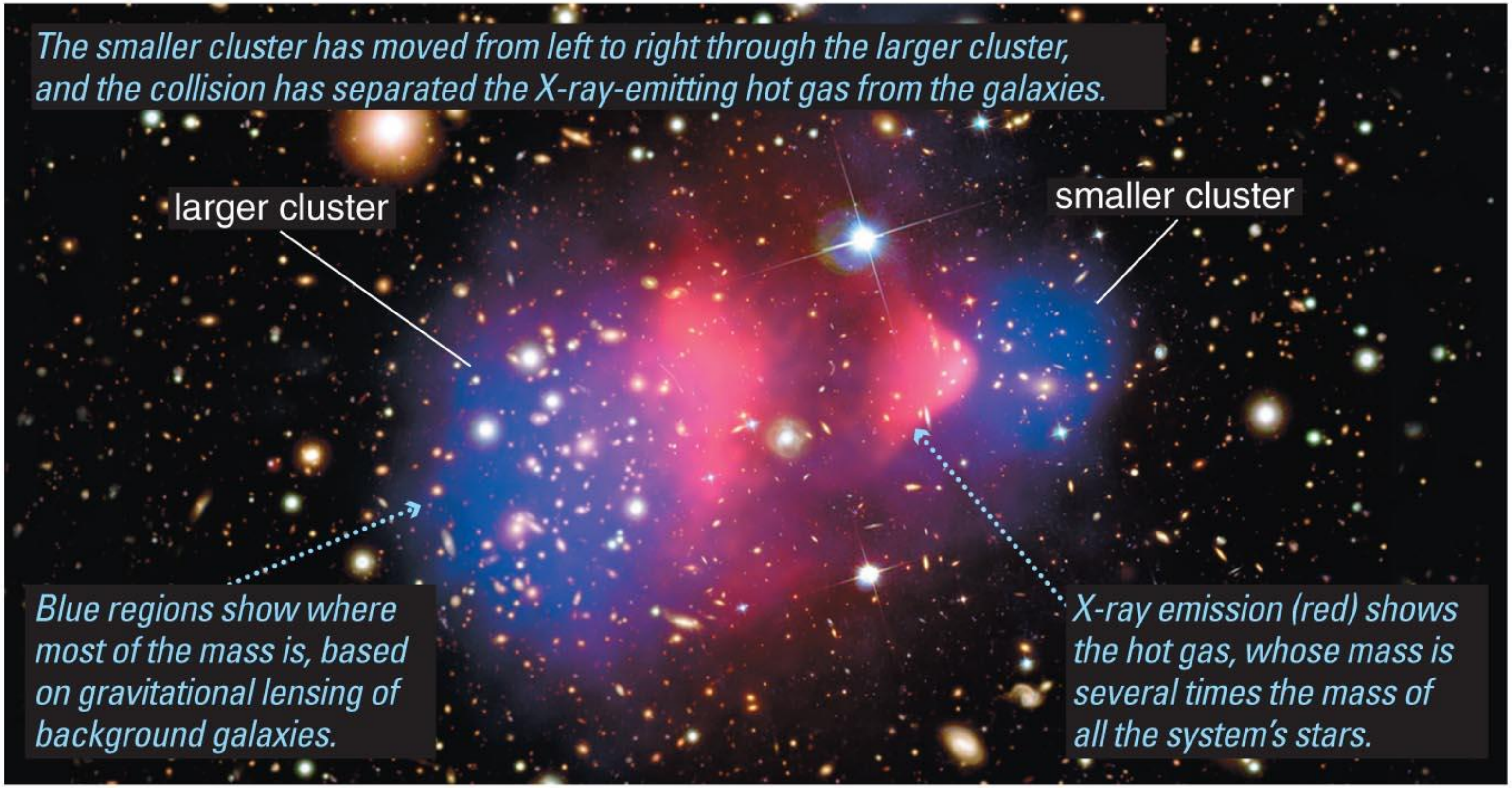
C. Measuring temperature of its hot gas
D. Measuring distorted images of background galaxies

Does dark matter really exist?



1. Something is wrong with our understanding of gravity, causing us to infer the existence of dark matter – *unlikely*.
2. Dark matter really exists, and we are observing the effects of its gravitational attraction – *most likely*.

Recent evidence for dark matter



- Most of the **visible mass** is hot gas (shown in red)
- Most of the **actual mass** is found using gravitational lensing (shown in blue) - *where no visible mass appears!*

Interactive Figure

What “dark matter” is *not*

MACHOS (**M**assive **C**ompact **H**alo **O**bjects)

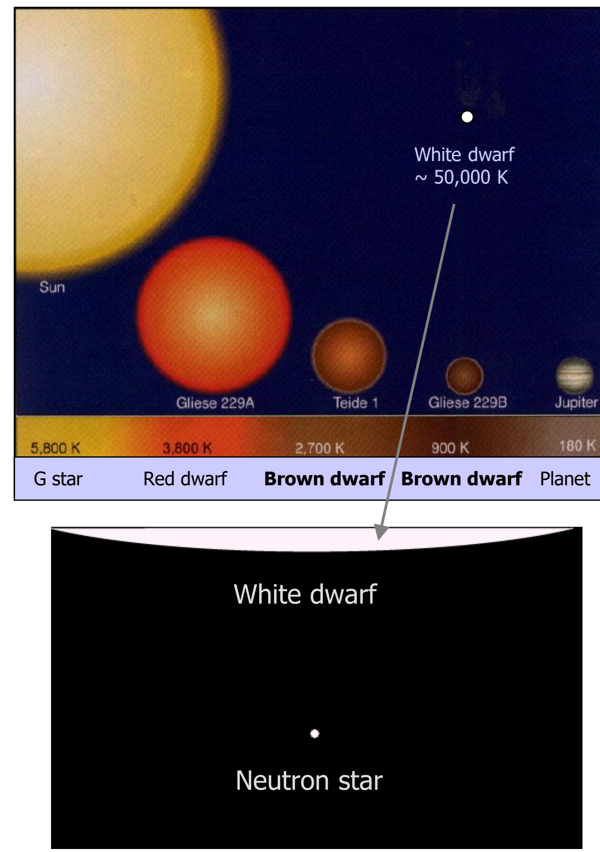
Examples: *brown dwarfs, white dwarfs, neutron stars, black holes*.

Brown Dwarfs’ low mass and temperature produce little visible light but some infrared light. They are nowhere near as abundant enough to account for dark matter.

White Dwarfs are the remains of small to medium sized stars. and haven't had enough time to cool enough to be invisible.

Neutron Stars or **Black Holes** are the remains of rare massive stars but are very dim, especially black holes.

It seems unlikely that dark matter is composed of MACHOS.



What “dark matter” *may be*

WIMPS (**W**eakly **I**nteracting **M**assive **P**articles)

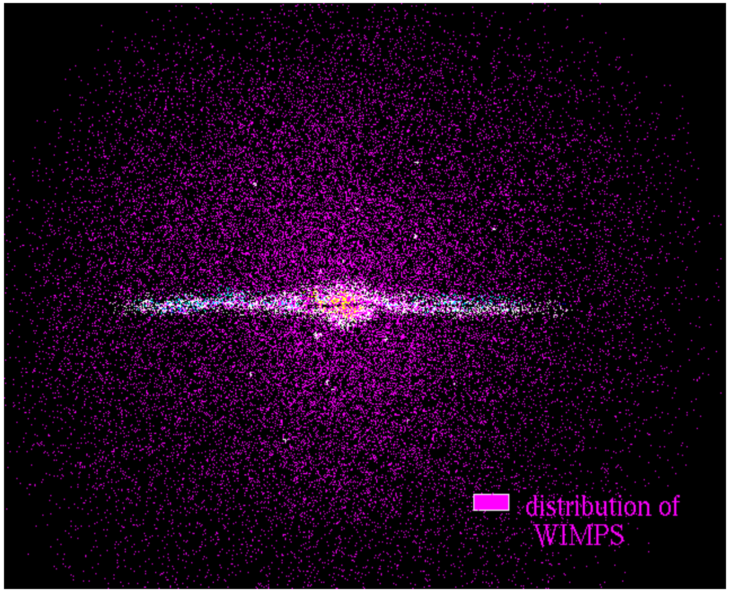
Exotic subatomic particles; likely an unknown new particle.

Axions

Lighter than WIMPs, axions must be even more abundant to make up the same mass of the universe.

Heavy sterile neutrinos

A new type of neutrino would interact even less than the three types already known.



- **Dark matter** interacts <u>very</u> weakly with matter - extremely difficult to detect!
- It doesn't feel electromagnetic or nuclear forces, only gravity.
- It could have been produced at the beginning of the universe with the right properties to explain dark matter.
- Could there be more than one type of dark matter particle?

Why believe in WIMPs?

- There's simply not enough ordinary matter to explain many observations.
- WIMPs could be left over from Big Bang.
- Models involving WIMPs explain how galaxy formation works.

What have we learned?

Begin 3 minute review

What have we learned?

What do we mean by dark matter?

"Dark matter" is the name given to the *unseen mass* whose gravity governs the observed motions of stars and gas clouds.

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.

What is the evidence for dark matter in galaxy clusters?

Masses measured from (1) **galaxy motions**, (2) **temperature of hot gas**, and (3) **gravitational lensing** all indicate that the vast majority of matter in clusters is dark.

What have we learned?

Does dark matter really exist?

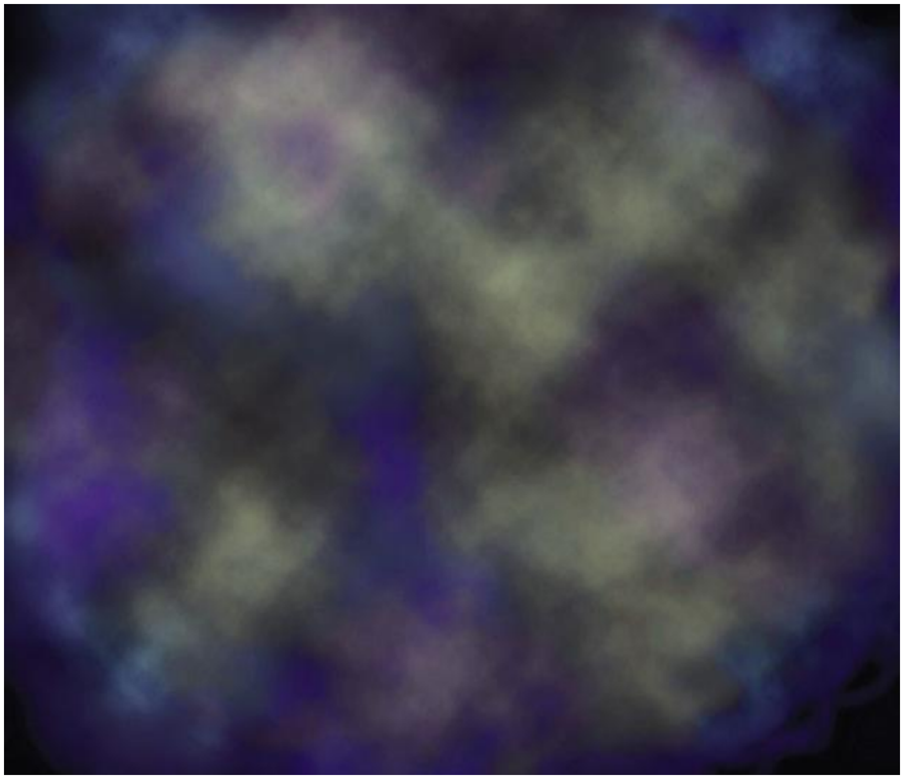
Either our understanding of gravity is wrong (very unlikely) or dark matter does actually exist (very likely).

What might dark matter be made of?

MACHOS (unlikely)

WIMPS (likely)

What is the role of dark matter in galaxy formation?



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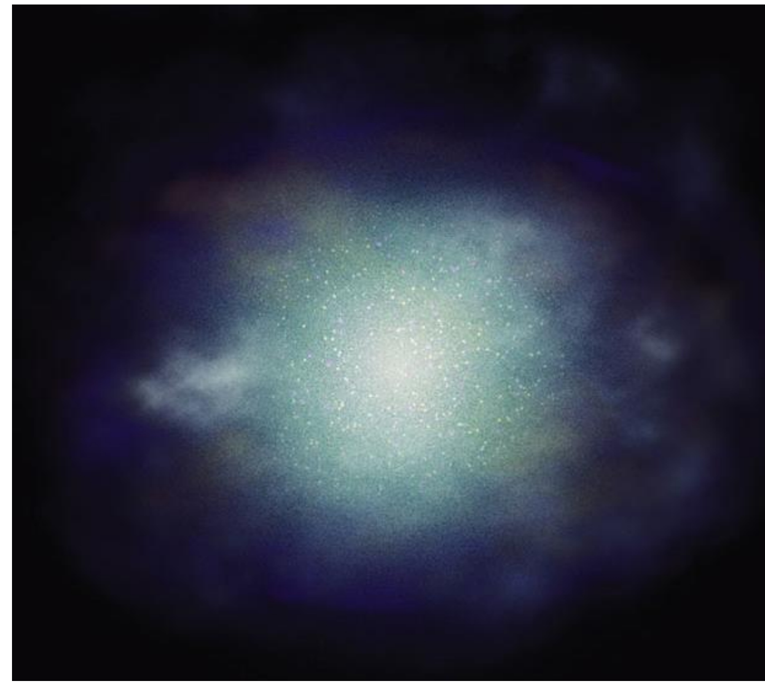
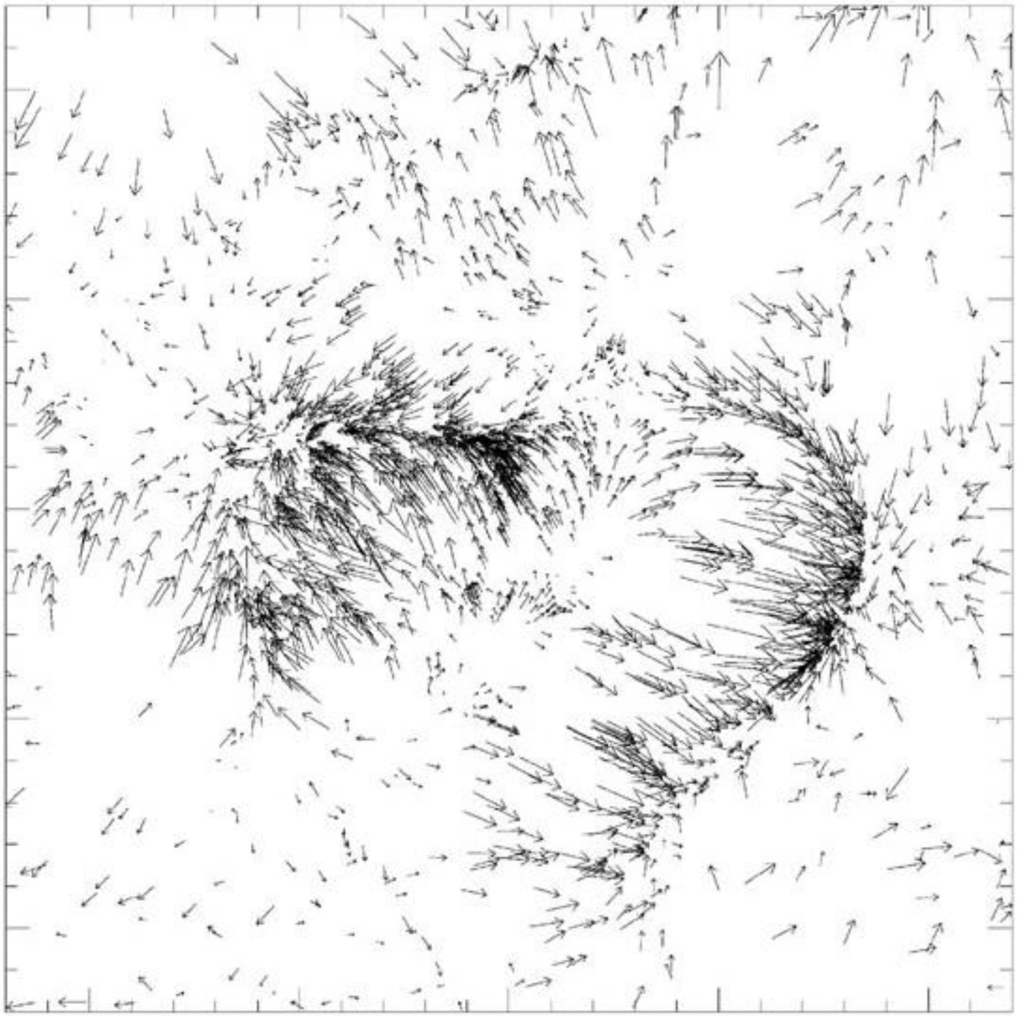


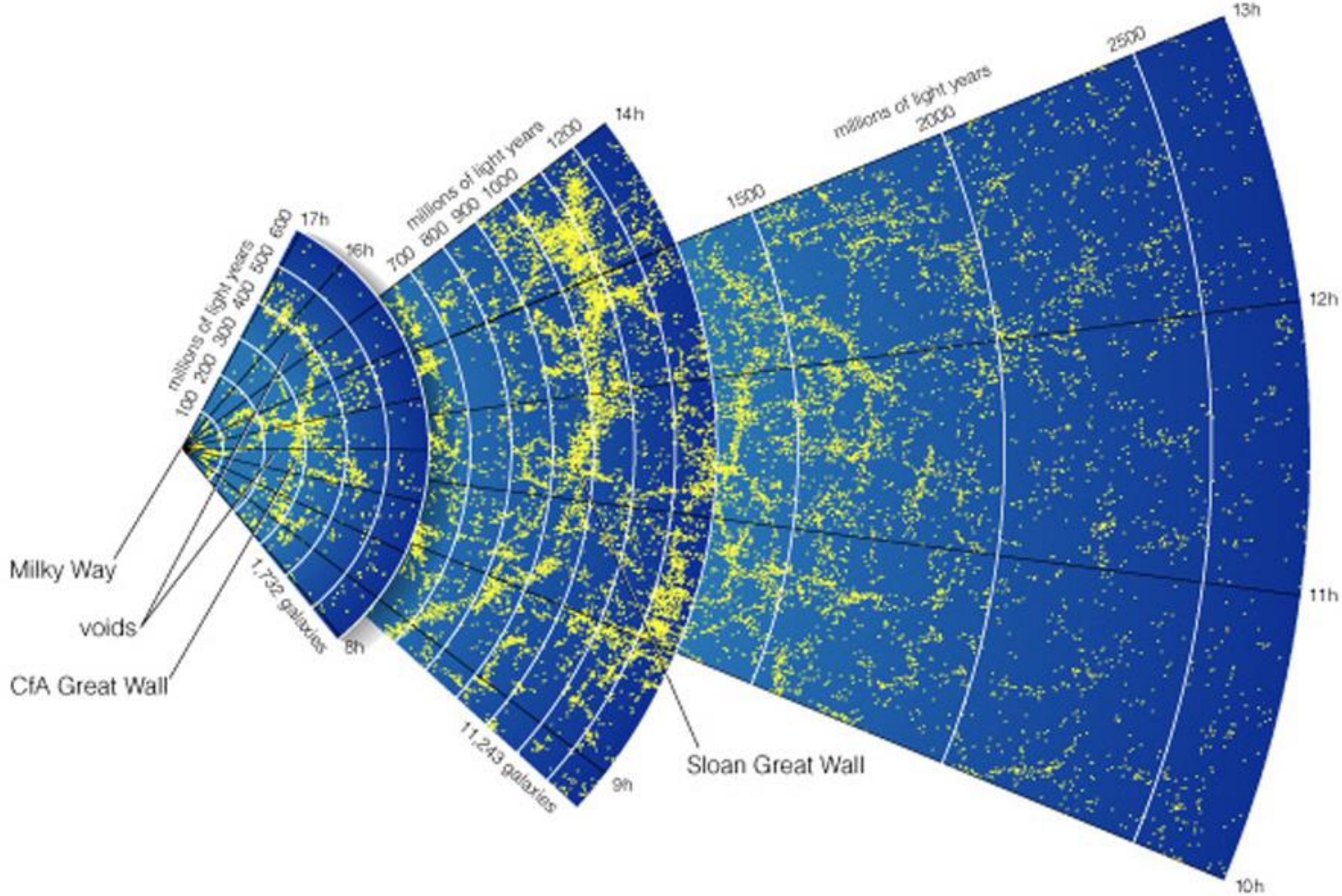
- Gravity of dark matter is what primarily caused protogalactic clouds to contract early in time.
- Without dark matter it is difficult to model galaxy formation

What is the role of dark matter in galaxy formation?



- Dark matter is still pulling things together.
- After removing velocity of Hubble’s law, we can see galaxies are flowing toward the densest regions of space.

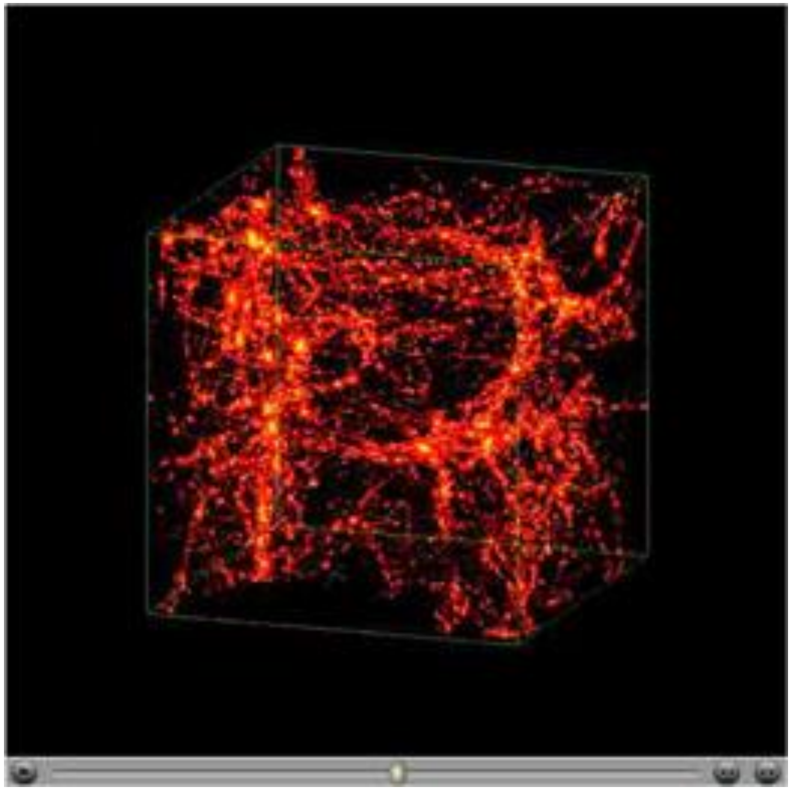
What are the largest structures in the universe?



Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids.***

Where does this structure come from?

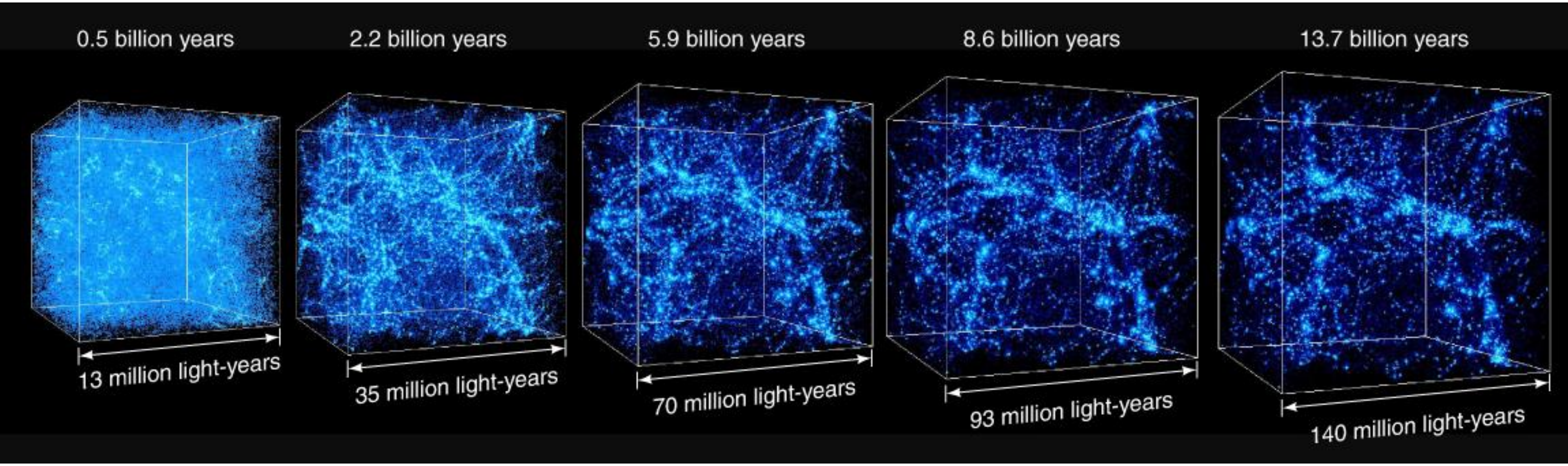
Models show that gravity of dark matter pulls mass into denser regions — universe grows lumpier with time.



PLAY Large-Scale Structure of the Universe

Time in billions of years

0.5 2.2 5.9 8.6 13.7

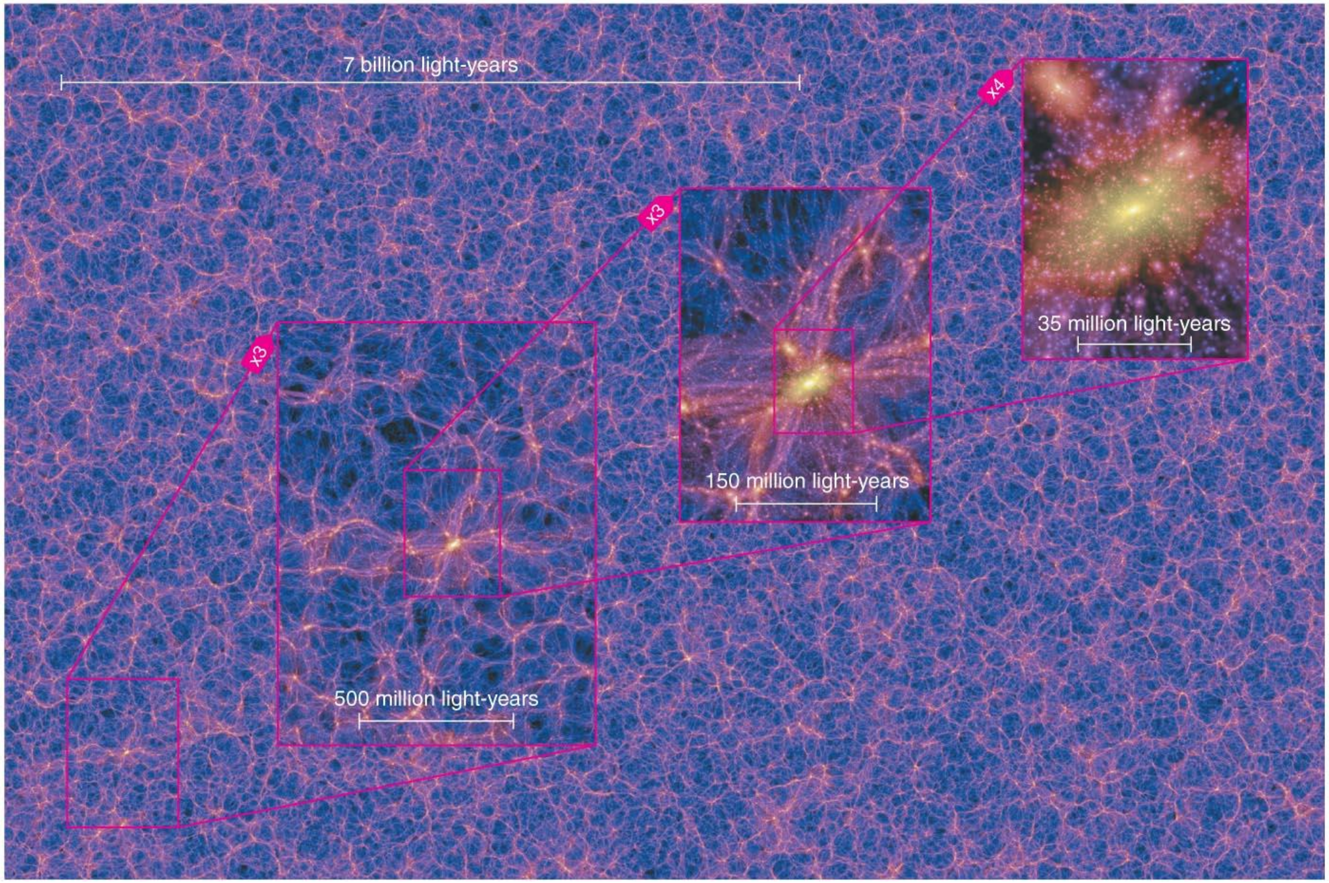


13 35 70 93 140

Size of expanding box in millions of light-years

Structures in galaxy maps look very similar to the ones found in models with dark matter made of WIMPs.

What is the large-scale structure of the universe?



Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs.

What have we learned?

Begin 3 minute review

What have we learned?

What is the role of dark matter in galaxy formation?

The gravity of dark matter seems to be what drew gas together into protogalactic clouds, initiating the process of galaxy formation.

What are the largest structures in the universe?

Galaxies appear to be distributed in gigantic chains and sheets that surround great voids.

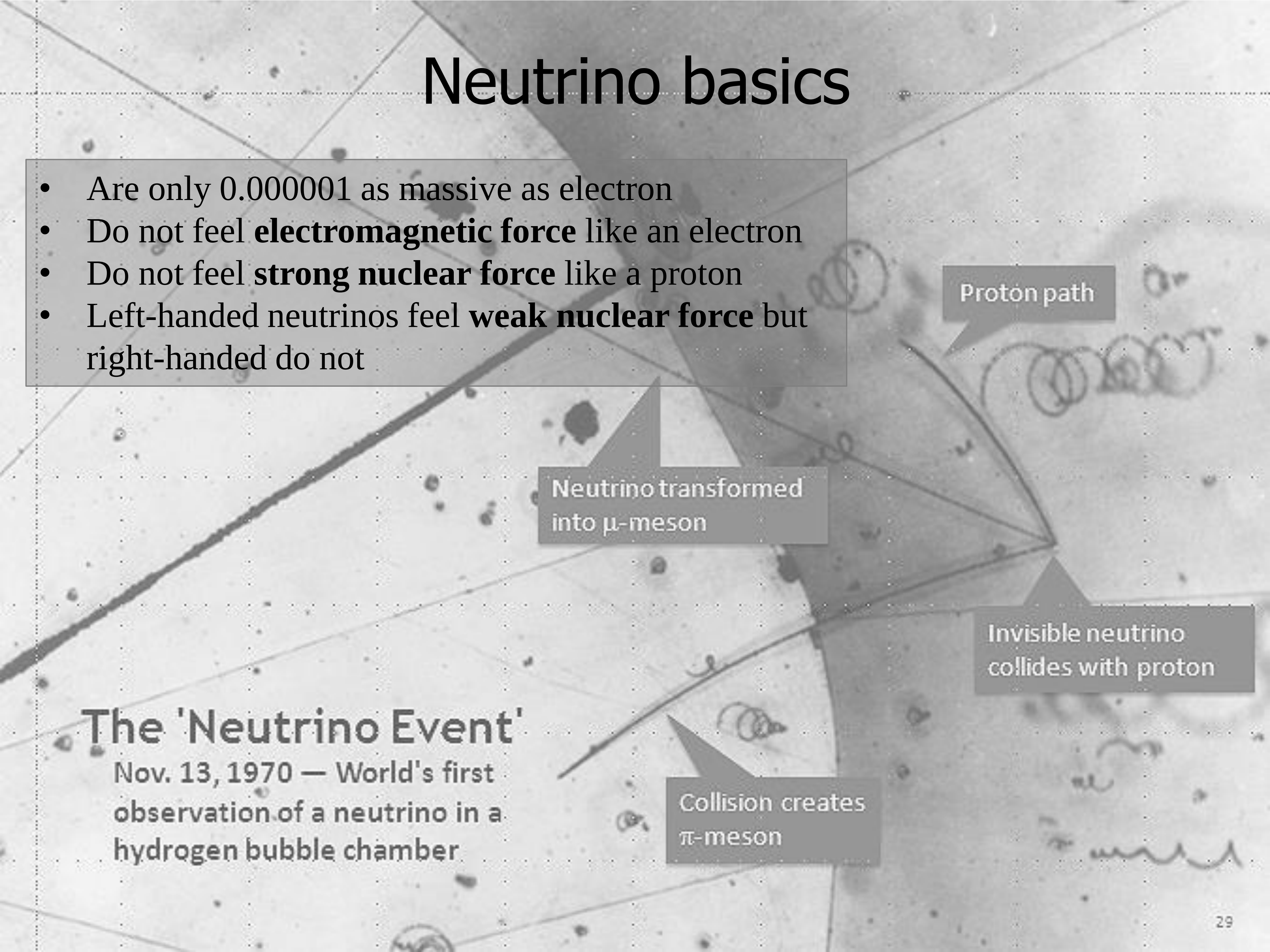
Just FYI…

The following 3 slides describe some basic about neutrinos.

Review if you wish. It is not required.

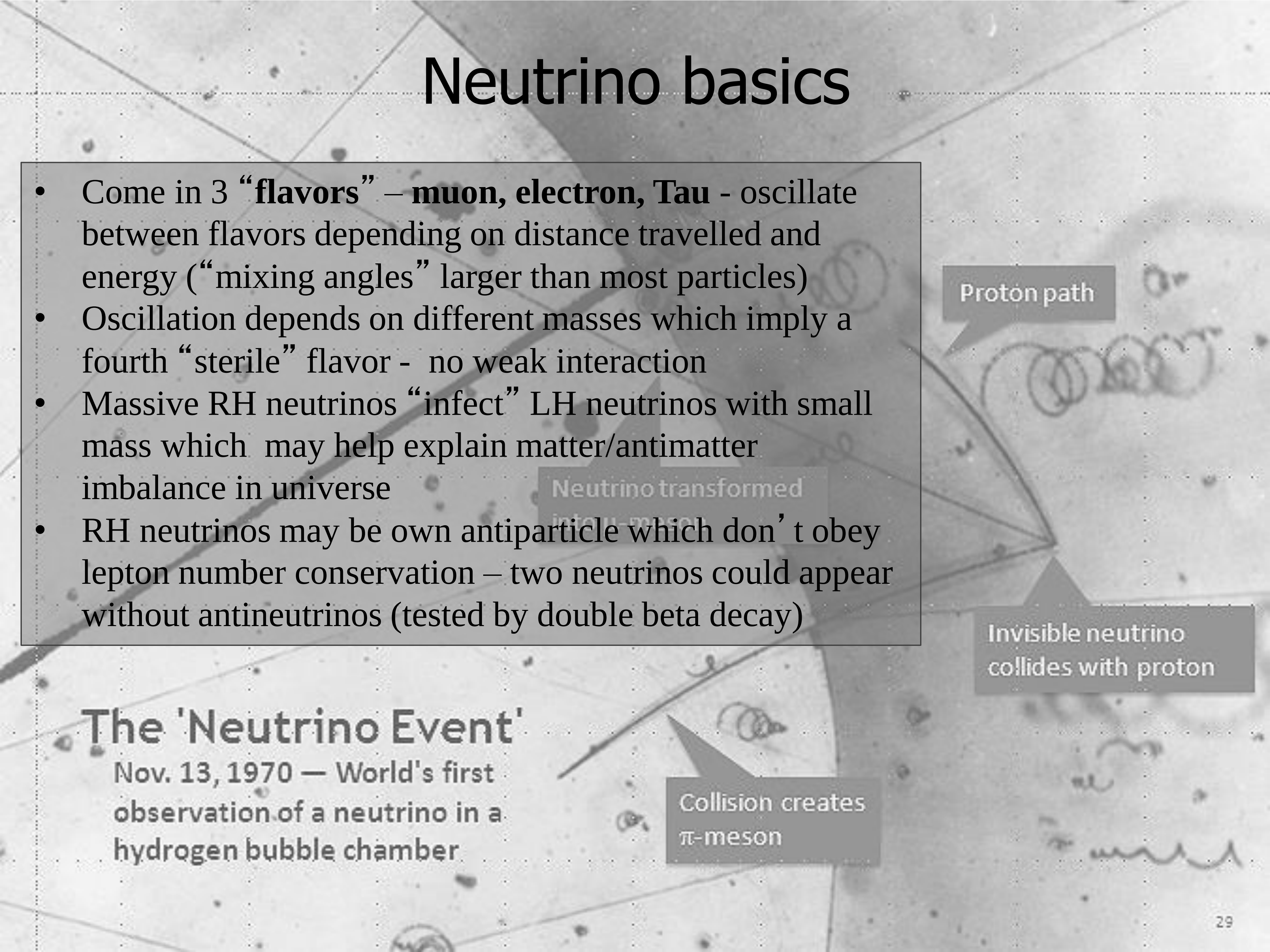
Neutrino basics

- Are only 0.000001 as massive as electron
- Do not feel **electromagnetic force** like an electron
- Do not feel **strong nuclear force** like a proton
- Left-handed neutrinos feel **weak nuclear force** but right-handed do not

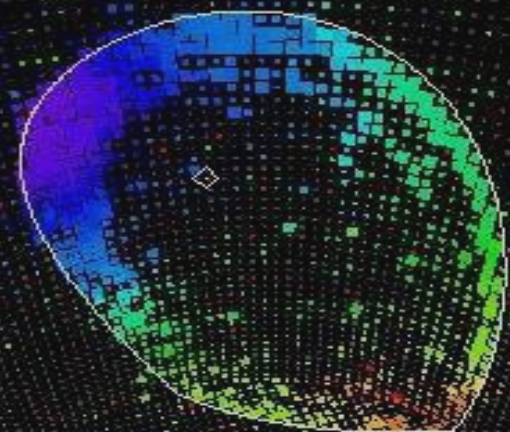


Neutrino basics

- Come in 3 "**flavors**" – **muon, electron, Tau** - oscillate between flavors depending on distance travelled and energy ("mixing angles" larger than most particles)
- Oscillation depends on different masses which imply a fourth "sterile" flavor - no weak interaction
- Massive RH neutrinos "infect" LH neutrinos with small mass which may help explain matter/antimatter imbalance in universe
- RH neutrinos may be own antiparticle which don't obey lepton number conservation – two neutrinos could appear without antineutrinos (tested by double beta decay)



How can we confirm neutrino masses?



A neutrino interaction with the electrons or nuclei of water can produce a particle that moves faster than the speed of light *in water* (but slower than the speed of light in vacuum). This creates a flash of light (**Cherenkov radiation**), the optical equivalent to a sonic boom.

- Neutrino masses may be best measured using CMB
  - Early helium fusion generated perhaps 10^89 neutrinos!
  - Dark matter collapsed into clumps first, seeding galaxies
  - Neutrinos clumped later – *hindering clumping* of dark matter
  - The more massive neutrinos are, the more they hinder clumping of dark matter – *blurring edges of early structures*
- Gravitational lensing of DM between us and CMB measures its distribution
- High precision CMB measurements “map” dark matter
  - Sharp-edged DM structure implies small neutrino mass
  - Blurry, fuzzy DM structure implies higher neutrino mass