Galaxy Interactions
Dark Matter

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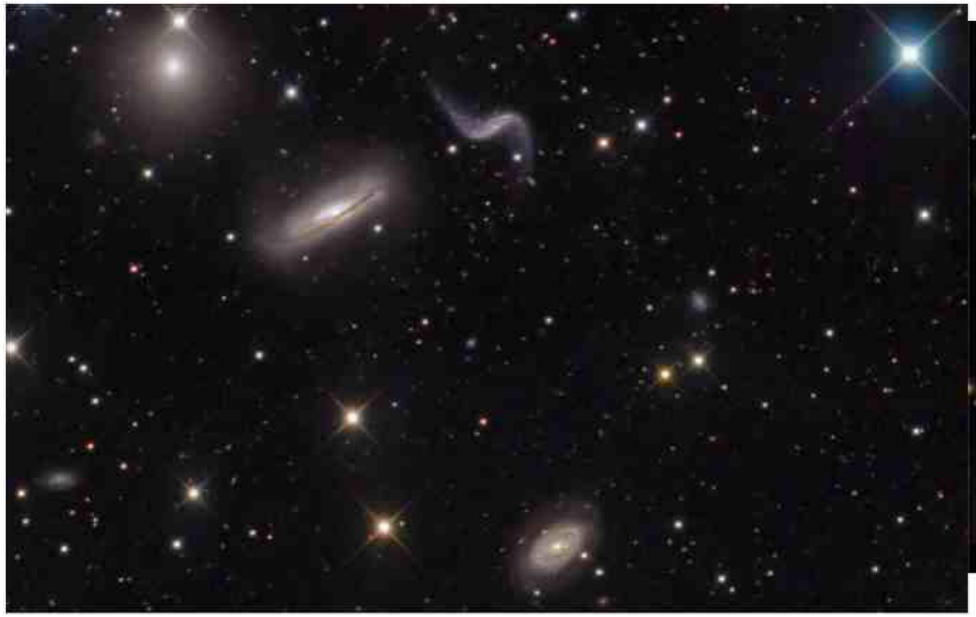
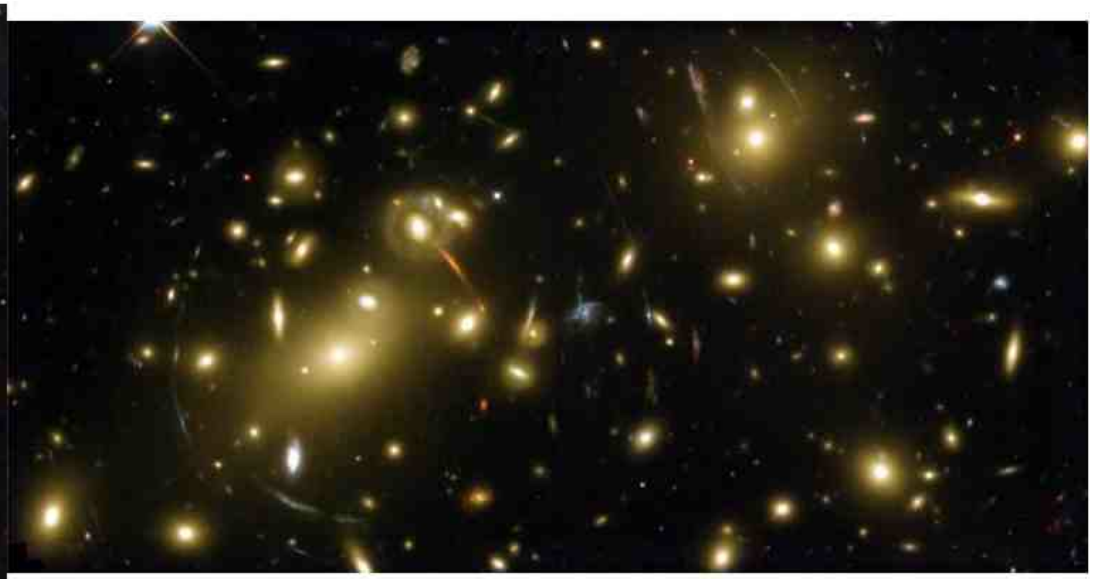
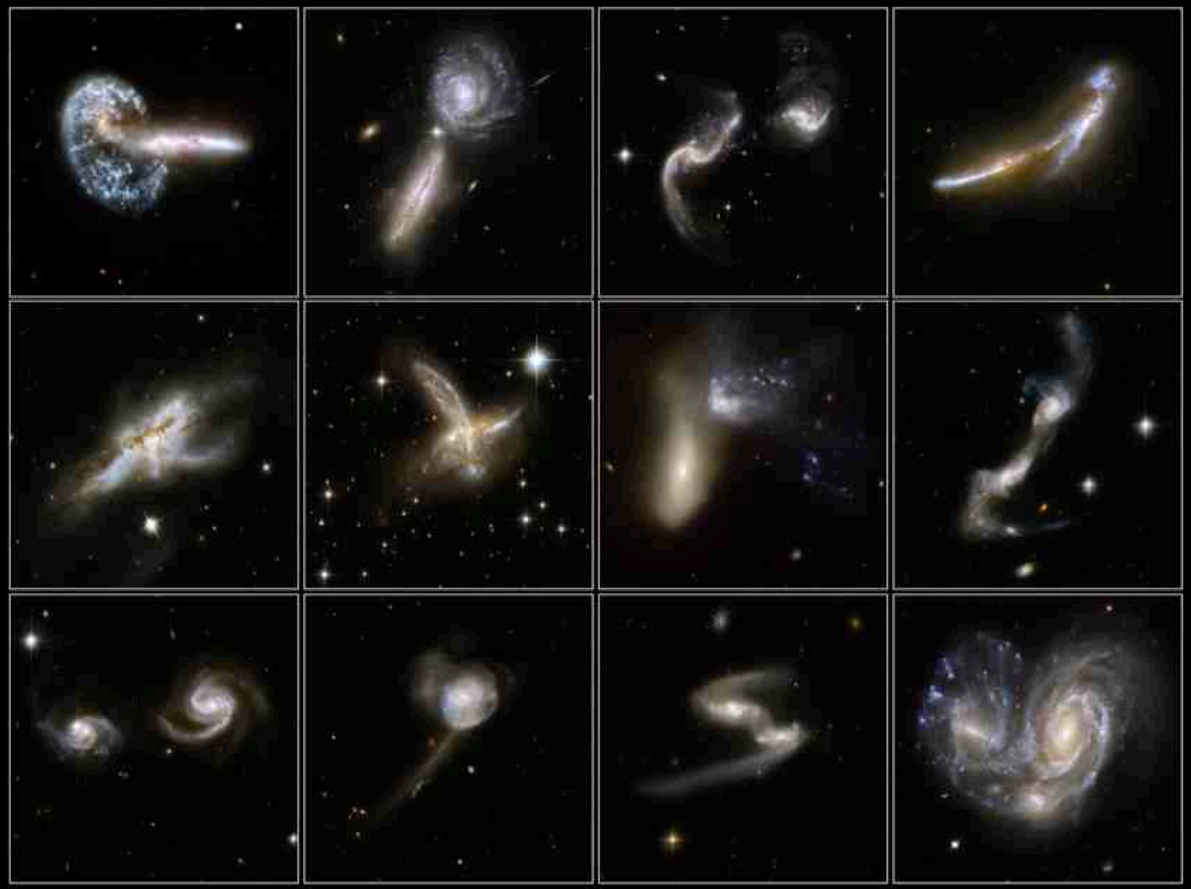
Groups and Clusters

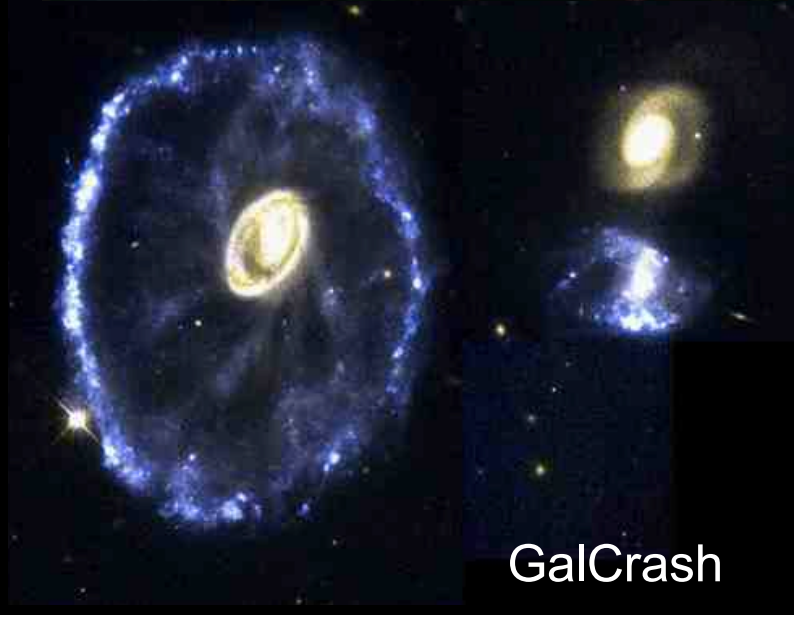




- Galaxies are very social and typically reside in small groups or large clusters.
- Galaxies may be separated by only a couple times their size.
- Large clusters have masses ≥ 10^{14} $M_{\odot}$, large enough to bend light (**gravitational lensing**). Groups and clusters span about 1 million parsecs (1 Mpc).
- The Milky Way resides in the Local Group, a collection of ~ 50 galaxies.

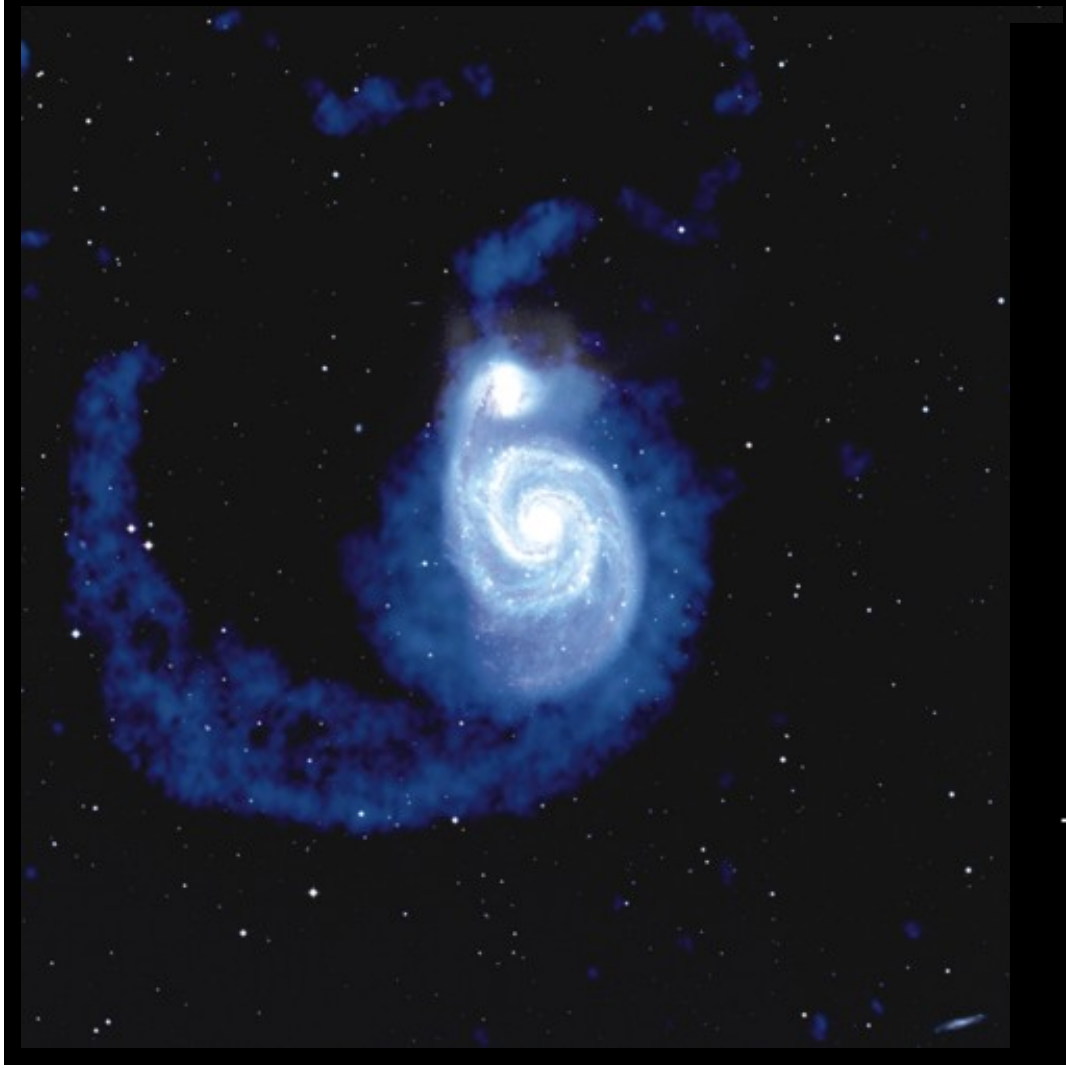
Interacting Galaxies

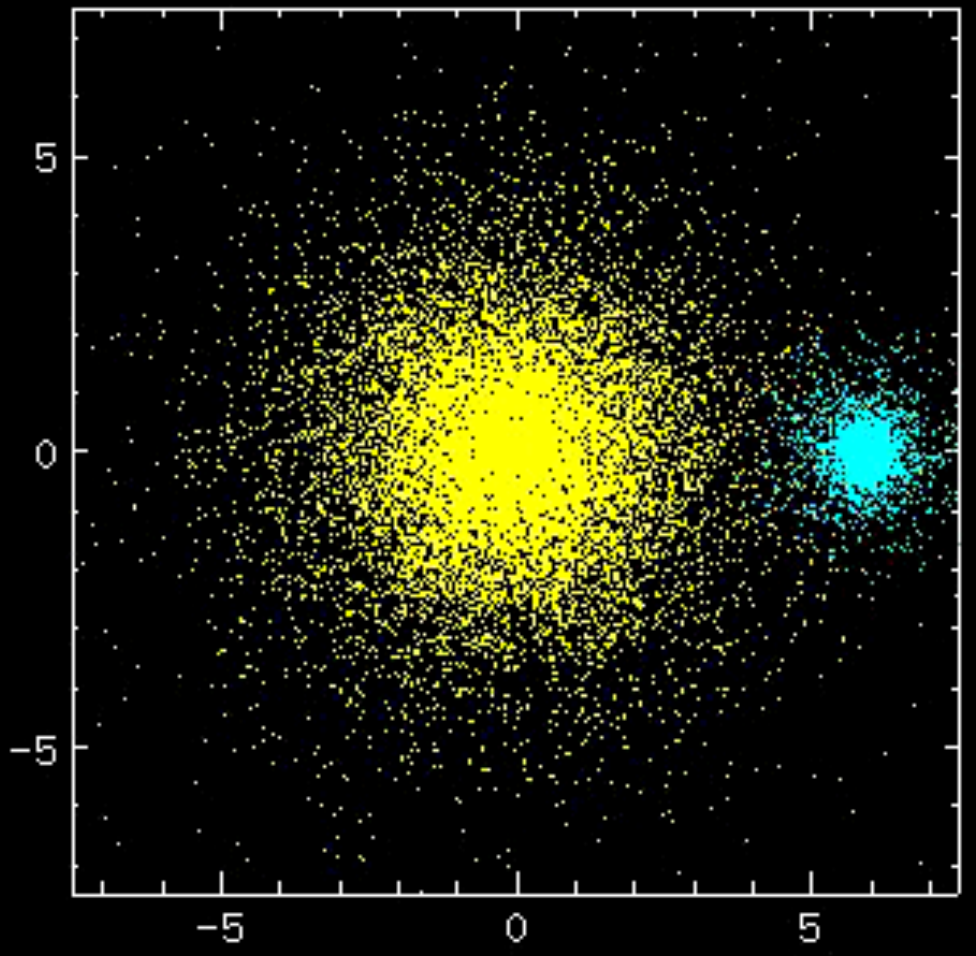




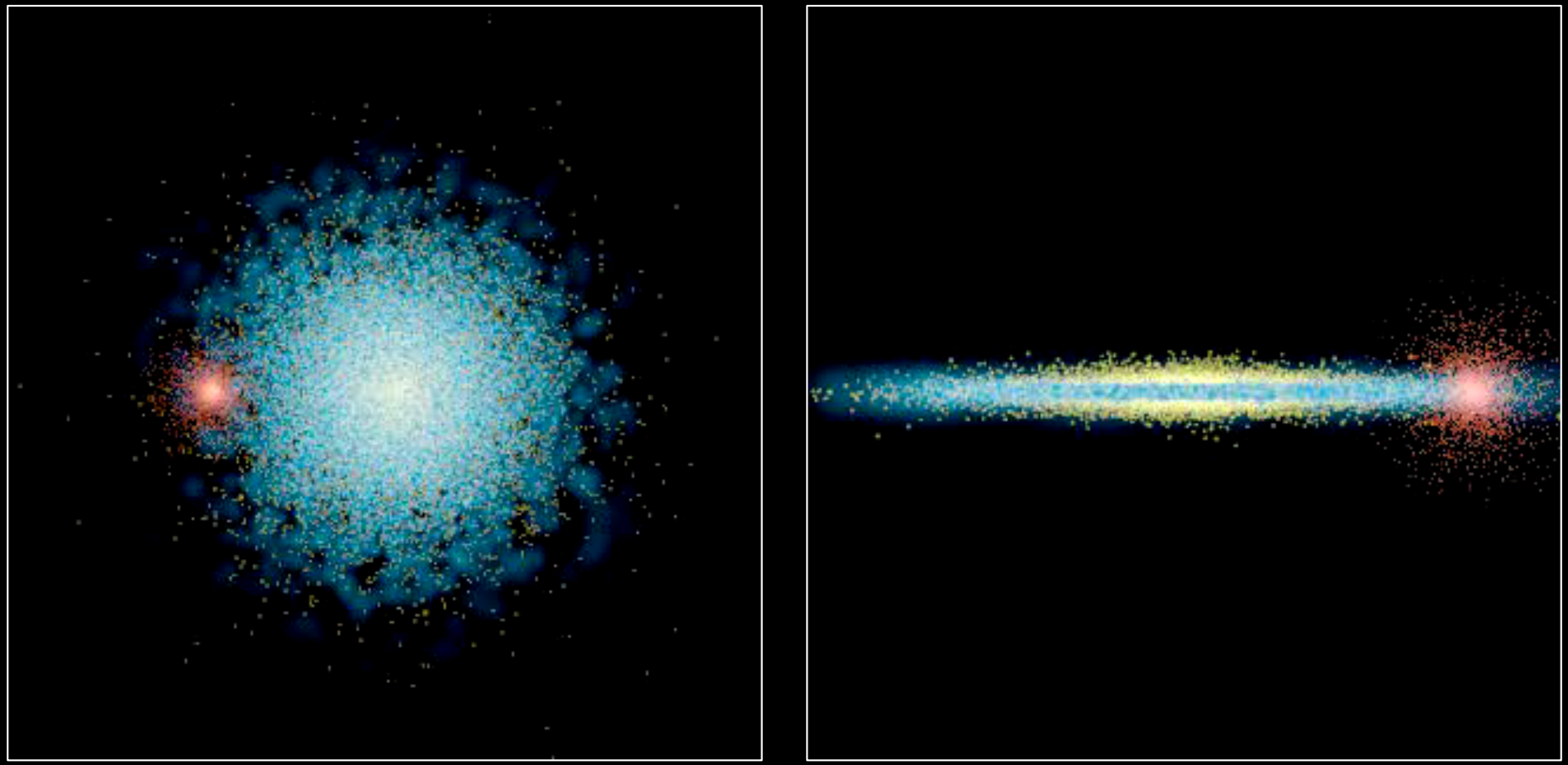
GalCrash

Minor Mergers: Making bigger spiral galaxies

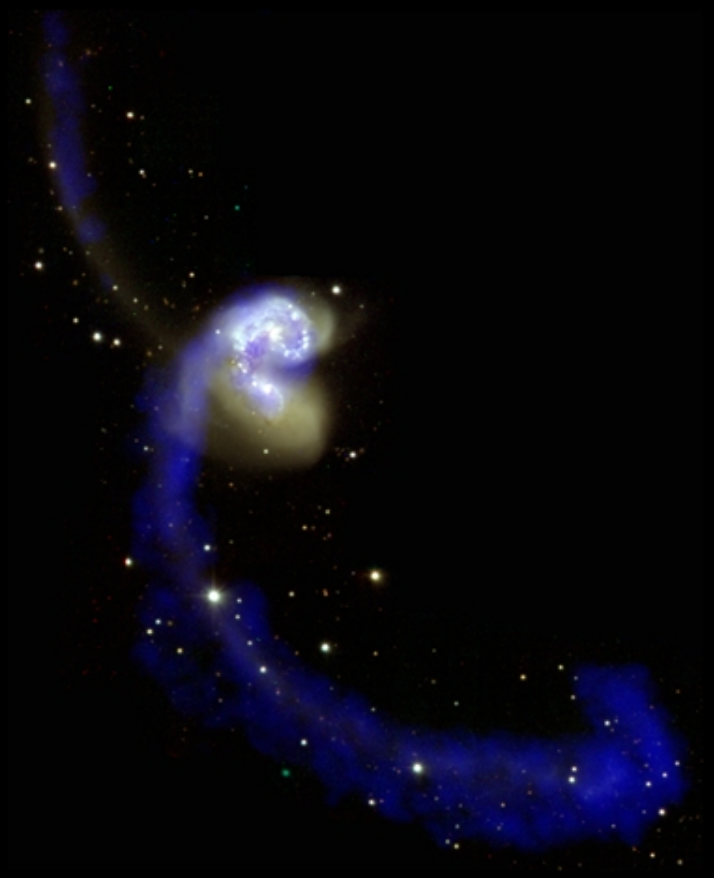


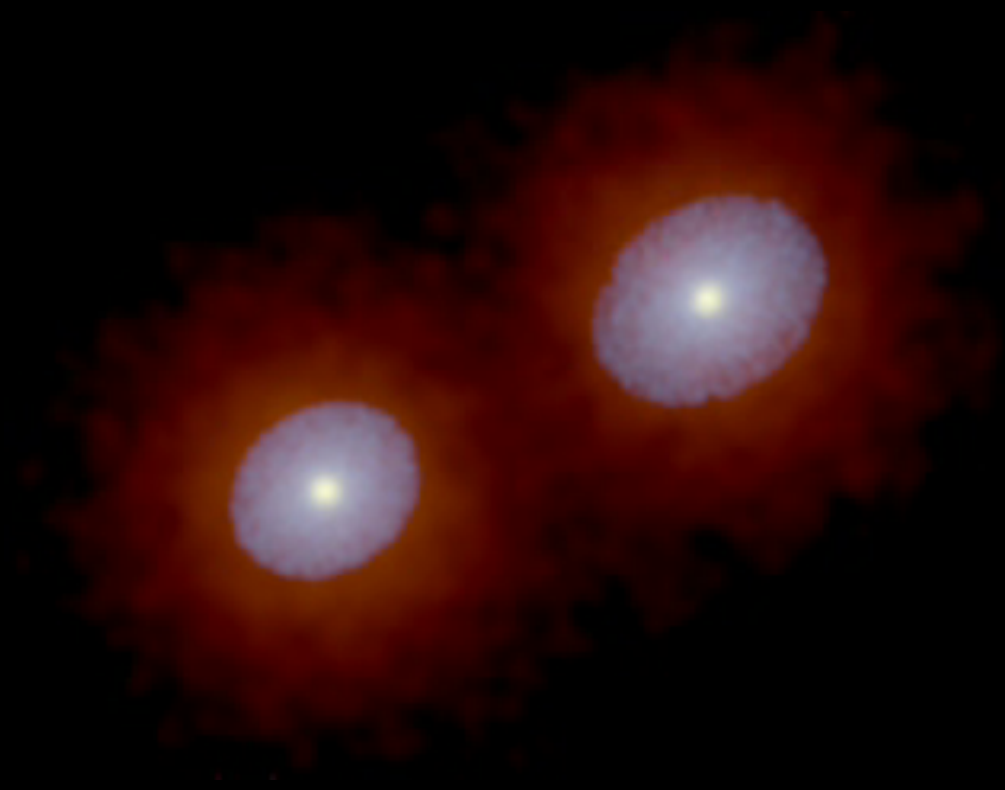


Another simulation of a minor merger:



Major Mergers:
Forming Elliptical Galaxies

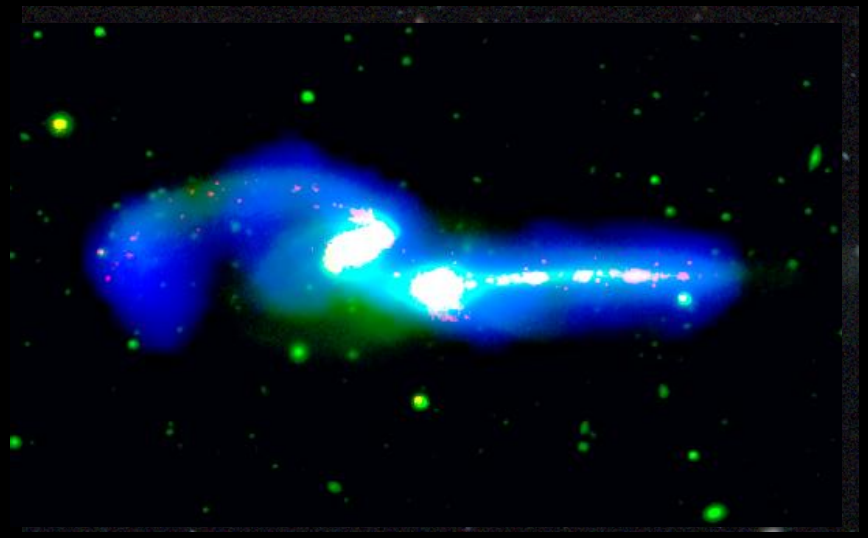


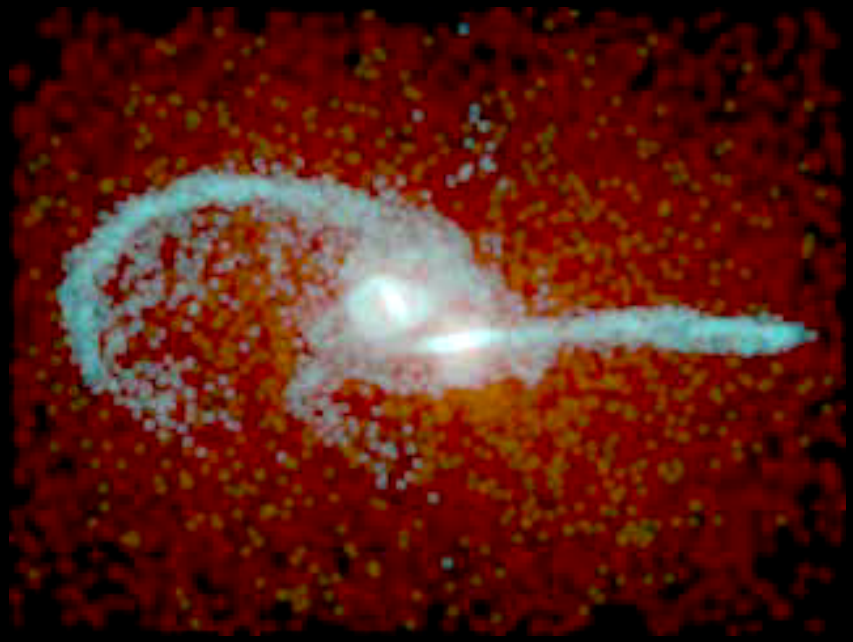


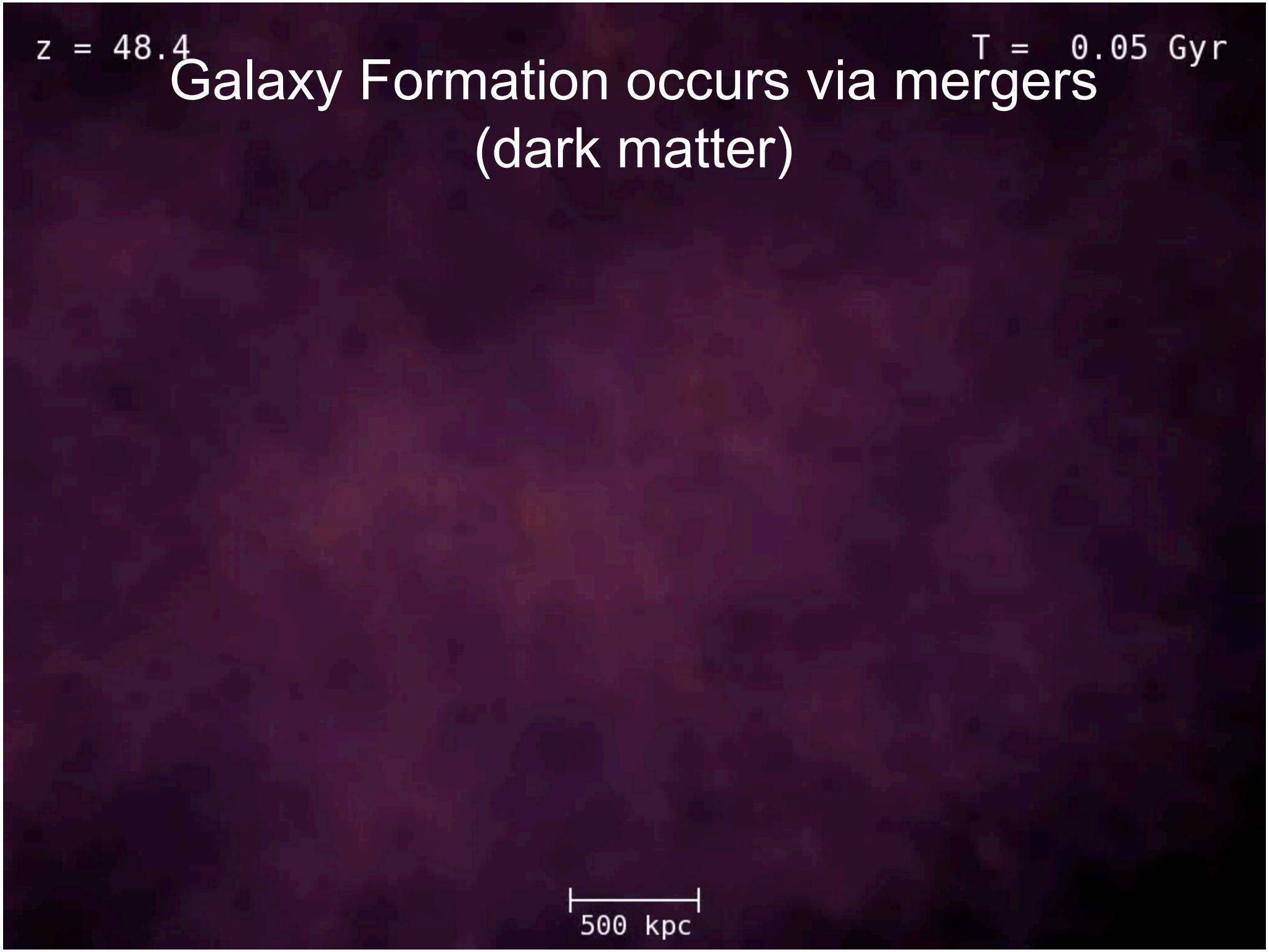
N-body simulation of NGC 4676 “The Mice”

Hibbard & Barnes, in preparation

N-body simulations provide past/future evolution and 3-D geometry

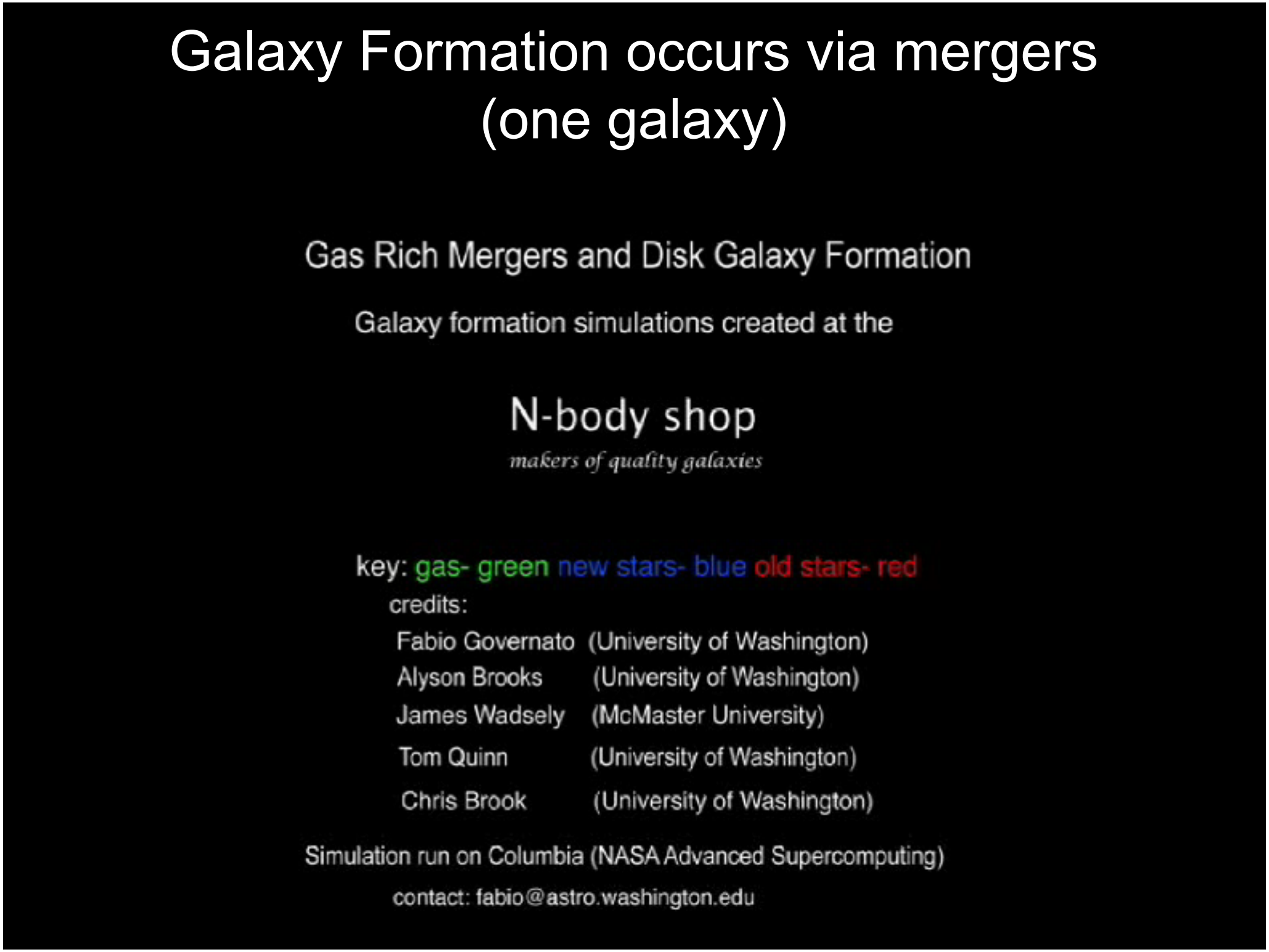




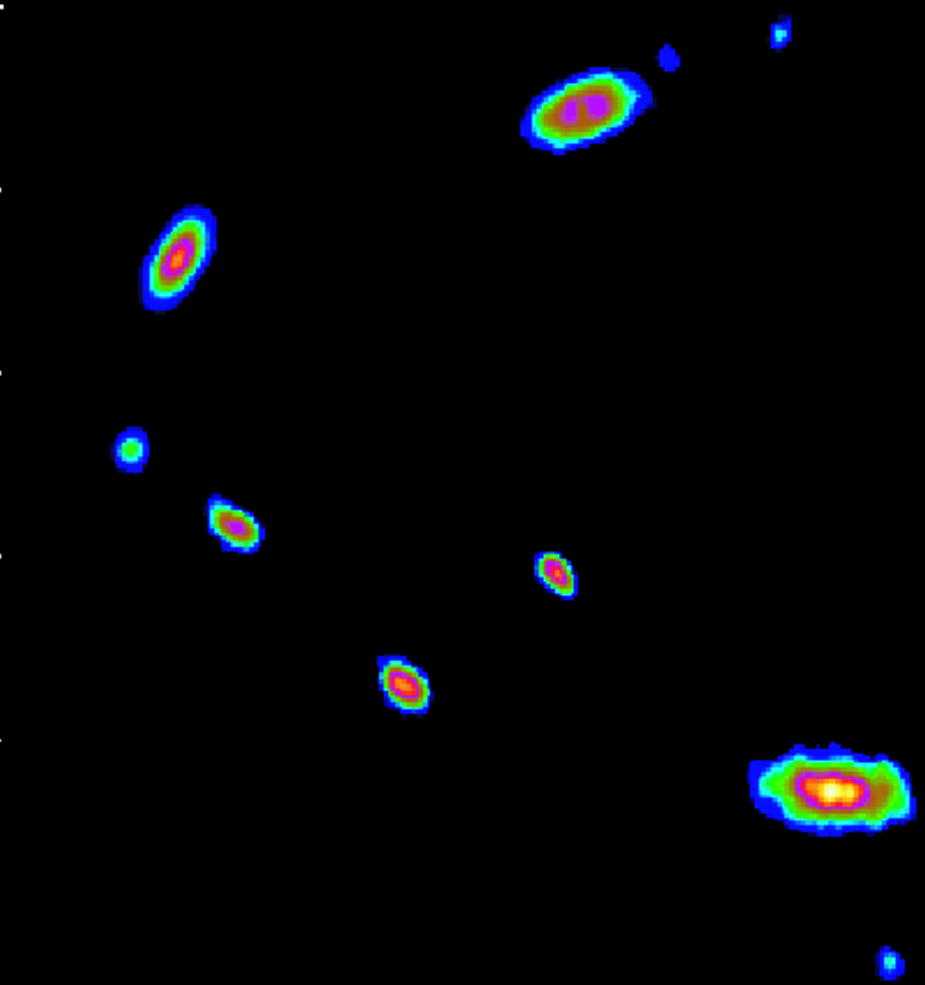

z = 48.4
T = 0.05 Gyr
Galaxy Formation occurs via mergers
(dark matter)
500 kpc

Galaxy Formation occurs via mergers (dark matter and gas)

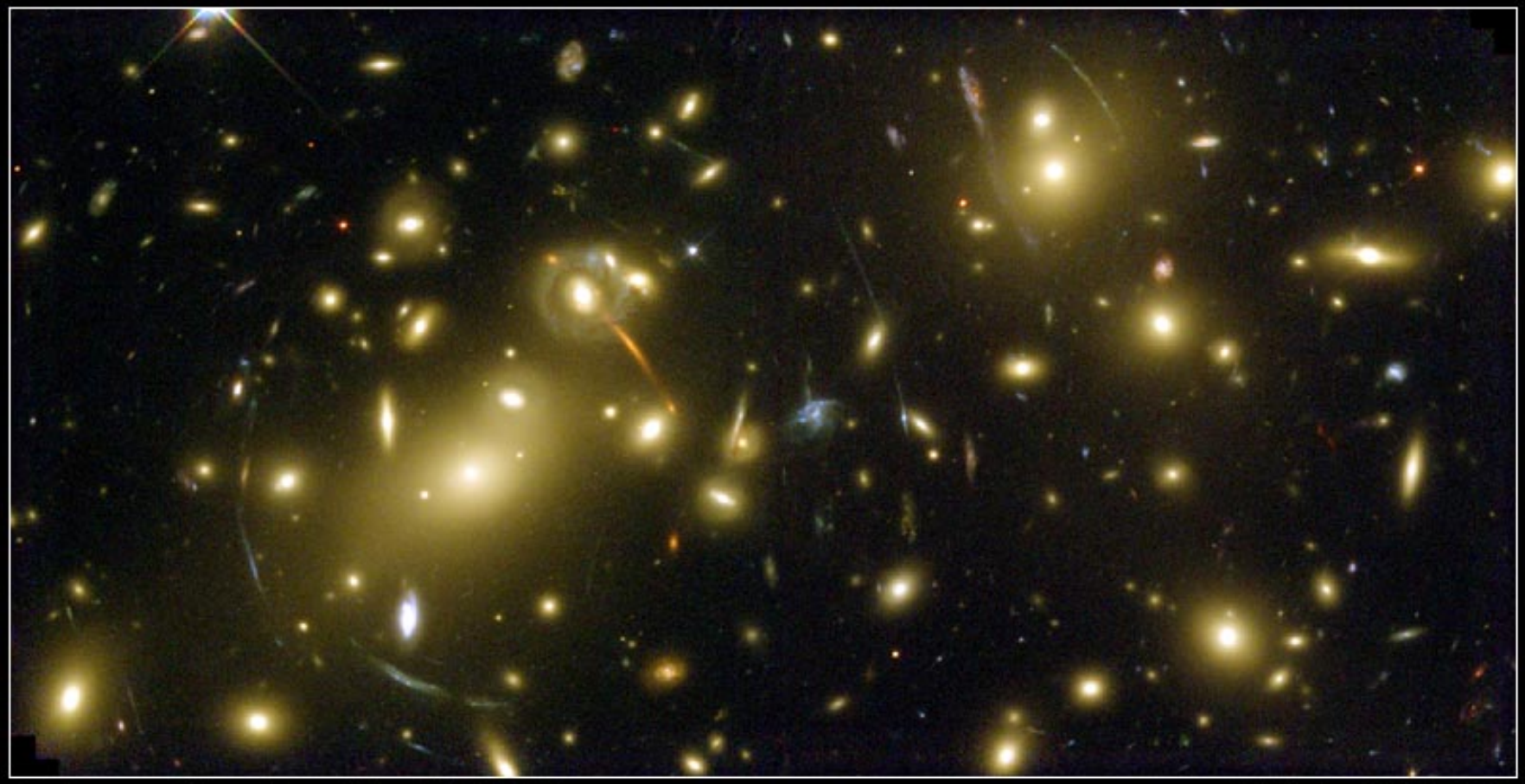
Galaxy Formation occurs via mergers (one galaxy)



Where do interactions occur?
Groups of Galaxies



Clusters of Galaxies



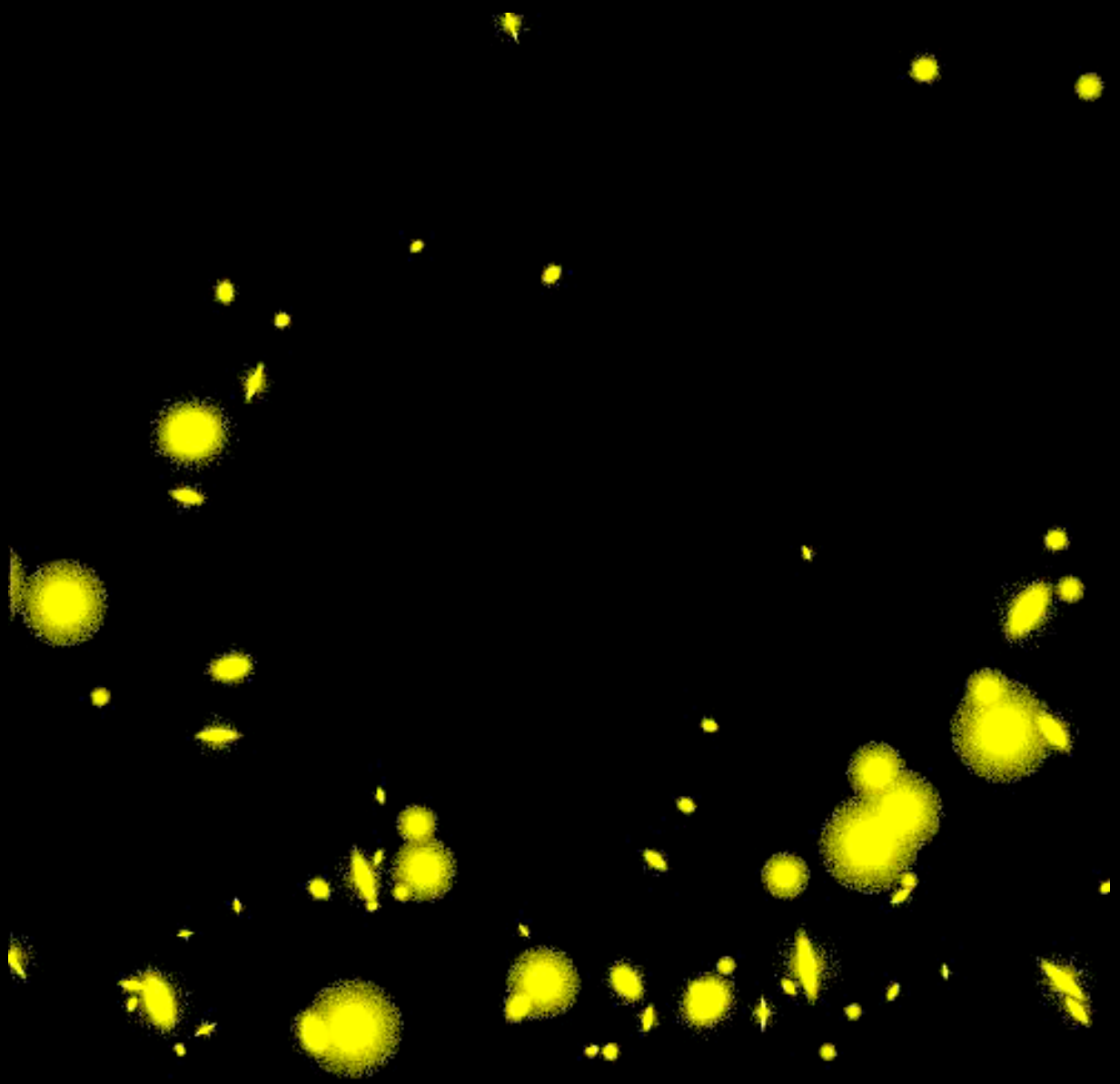
Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

See the arcs of light?
Those are gravitational lensed images of background galaxies
Their shape is due to the dark matter in the cluster.

Galaxy Interactions in Clusters

The Future:
Forming Even Larger Galaxies?



Starburst Galaxies

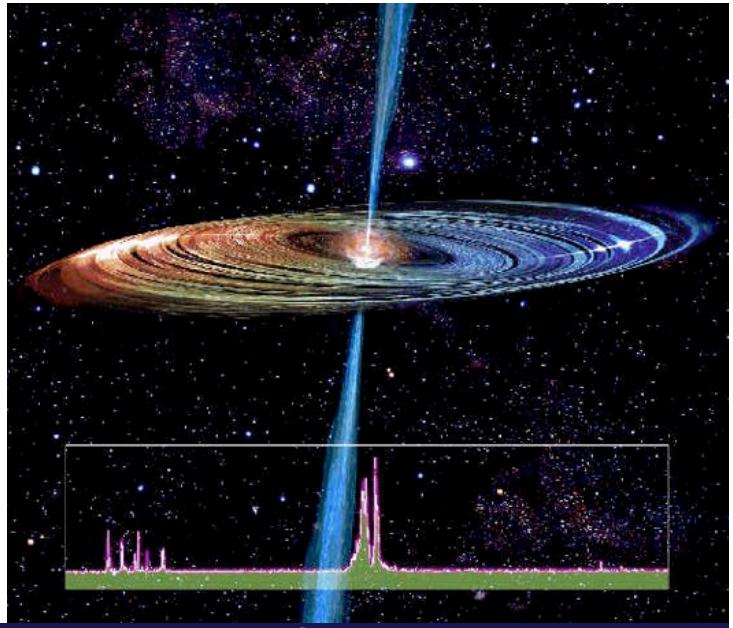
- Galaxy interactions can compress gas clouds in a galaxy triggering star formation (particularly in the center of a galaxy).
- It can also fuel a black hole in the center of a galaxy.
- Major mergers may also form elliptical galaxies.

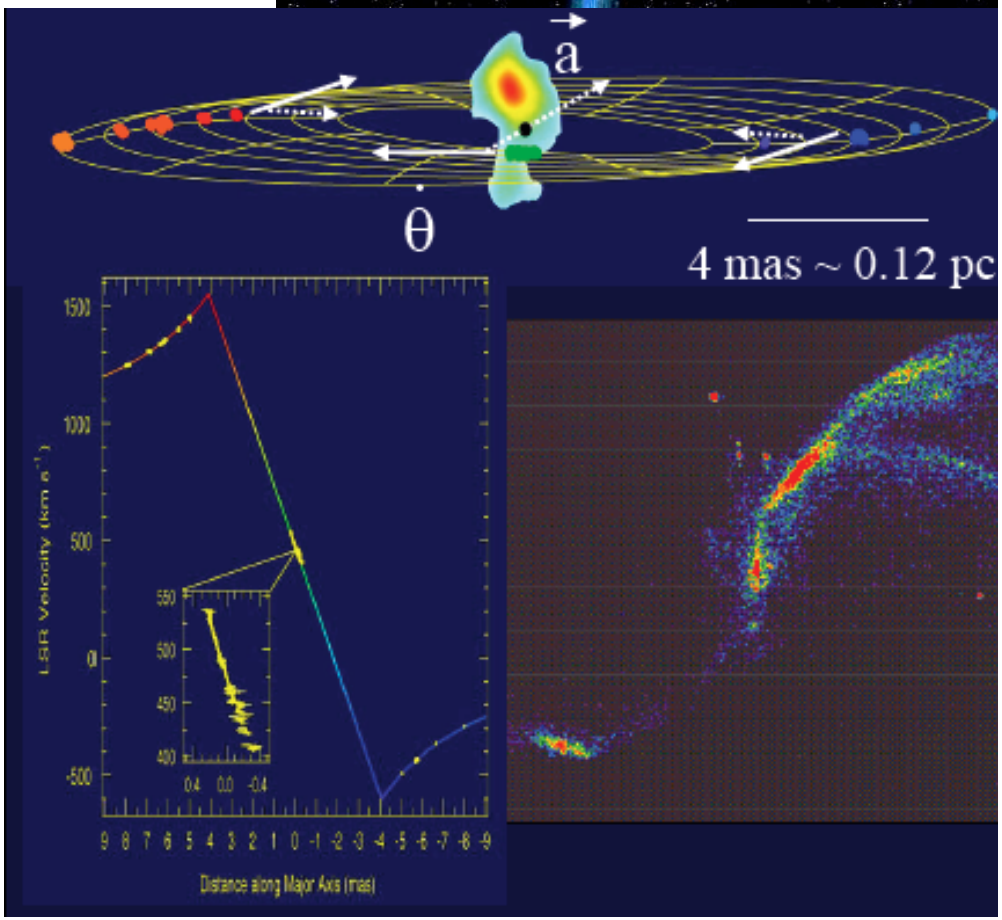
Active Galaxies

- Often referred to as Active Galactic Nuclei (AGN)
- Otherwise normal galaxies with an active black hole in their center that is producing jets (often seen in radio light).
- May be triggered by interactions
- Jets can affect the surrounding galaxies.

Supermassive Black Holes

- Astronomers use widely separated radio telescopes to trace the motion of objects in the center of other galaxies.
- We can measure both the apparent motion of these objects and their velocities.
- Combined, these data allow us to measure the mass of the black hole
- We also see radio jet coming from near the black hole.
- **Supermassive Black holes are found in all galaxies with spheroids (ellipticals and early-type spirals)**





Which type of galaxy is **most** likely to contain a supermassive black hole?

A. Dwarf irregular
B. Elliptical
C. Irregular
D. A spiral galaxy with a small bulge.

How do we measure the mass of a galaxy?

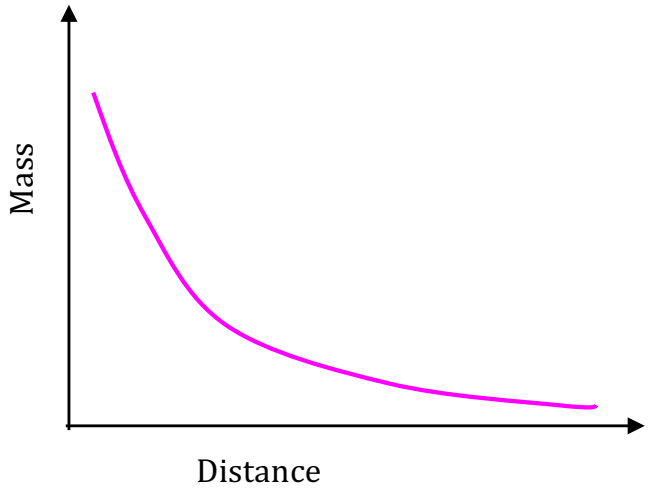
- We need to know the mass of a galaxy in order to determine its nature and how it formed.
- Different physics are involved in forming a single star as opposed to a cluster of stars and in contrast to an entire galaxy.
- There are a couple methods.

How do we measure the mass of a galaxy?

Method 1: Count all the stars and gas in a galaxy and add up all their masses.

Pros: It is a relatively straight-forward measurement. Getting the total gas mass is fairly easy and robust.

Cons: It is pretty hard to actually count all the individual stars in a galaxy so you have to assume you know what types of stars are in the galaxy.



How do we measure the mass of a galaxy?

Method 2: Use the motions of objects in the galaxy to determine the mass.

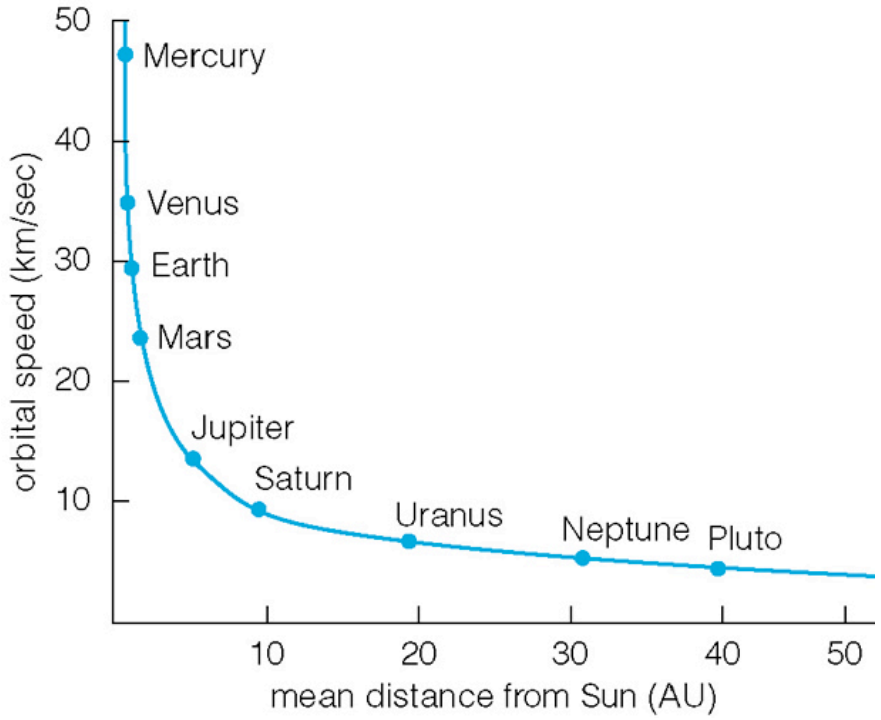
Pros: Simple measurement that gives you *all* the mass of a galaxy.

Cons: Need to have an object emitting light in order to measure mass at that position.

Mass of the Solar System

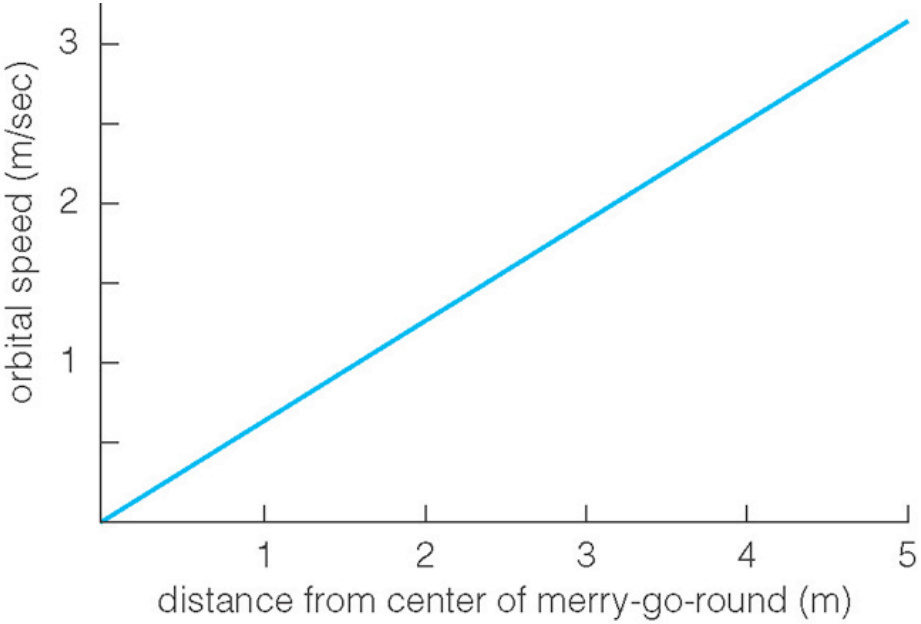
- What is the mass of the solar system?
  - about 1 solar mass
- Where is most of the mass in the solar system?
  - in the center
- We can use the velocity of the planets versus their position to measure the mass of the solar system.

Mass of the Solar System



- This is what the *rotation curve* of the Solar System looks like.
- As the semi-major axis of a planet is increased, its velocity decreases.
- This curve is called a *Keplerian rotation curve.*
- **It implies that all the mass is in the center of the system.**
- This is the same rotation curve as is seen for objects around black holes.

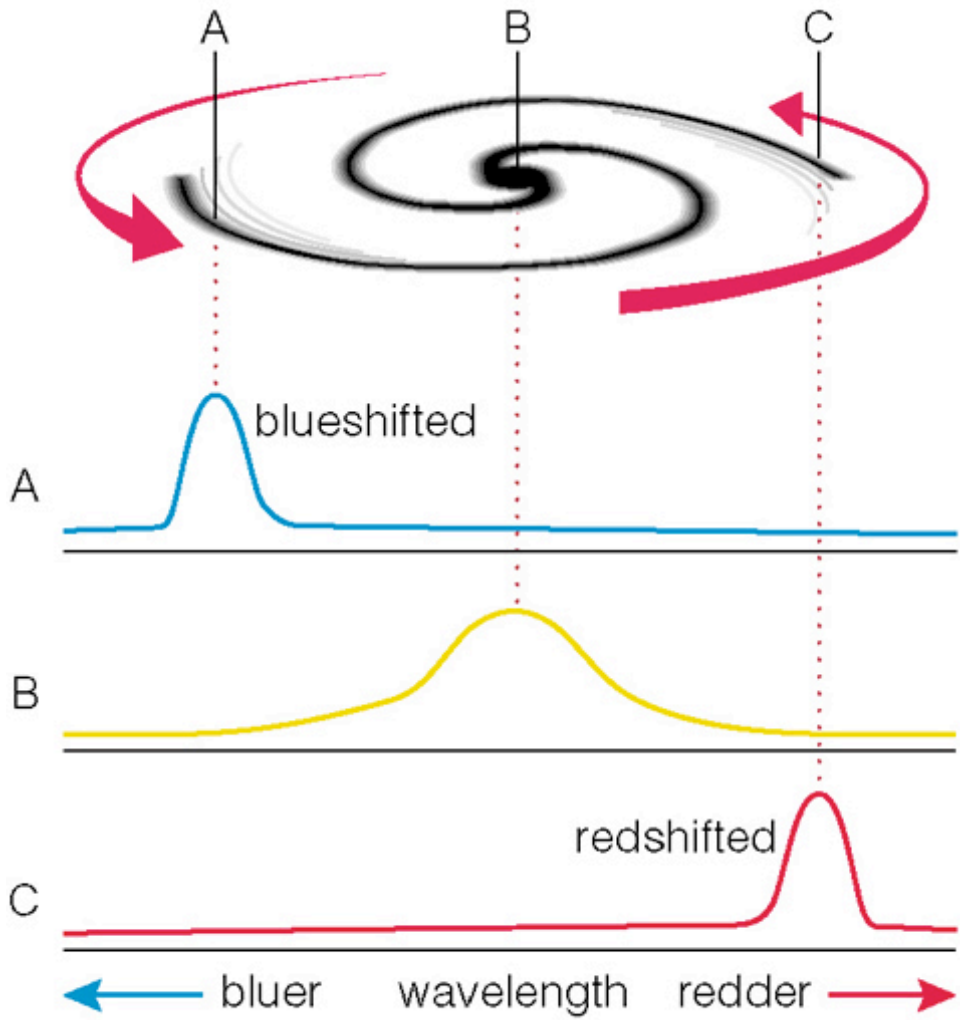
Mass of a merry-go-round



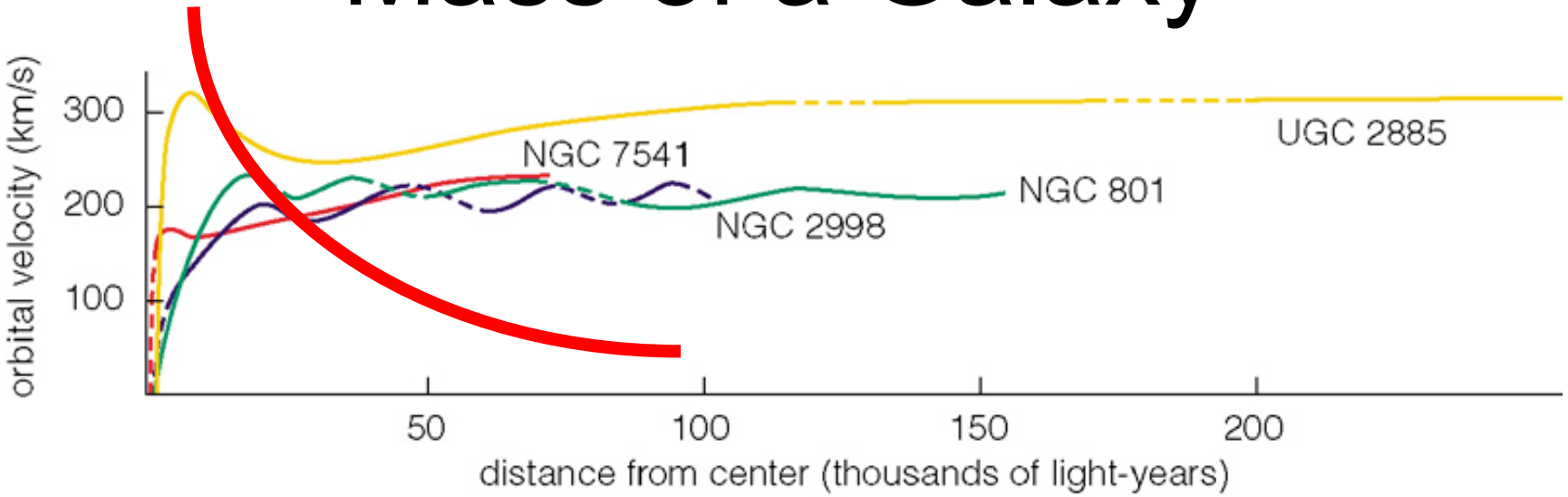
- As you move from the center to the edge, you go faster and faster since each part of the merry-go-round needs to complete a circle in the same amount of time.
- As you move to the edge, more of the mass of the merry-go-round is between you and the center.
- This curve implies that mass is ***increasing*** with radius.

Mass of a Galaxy

- Using the Doppler effect we can measure the rotation of a spiral galaxy.
- One side is blue-shifted, one side is red-shifted with respect to the center.
- The total shift corresponds to the rotation velocity of the galaxy



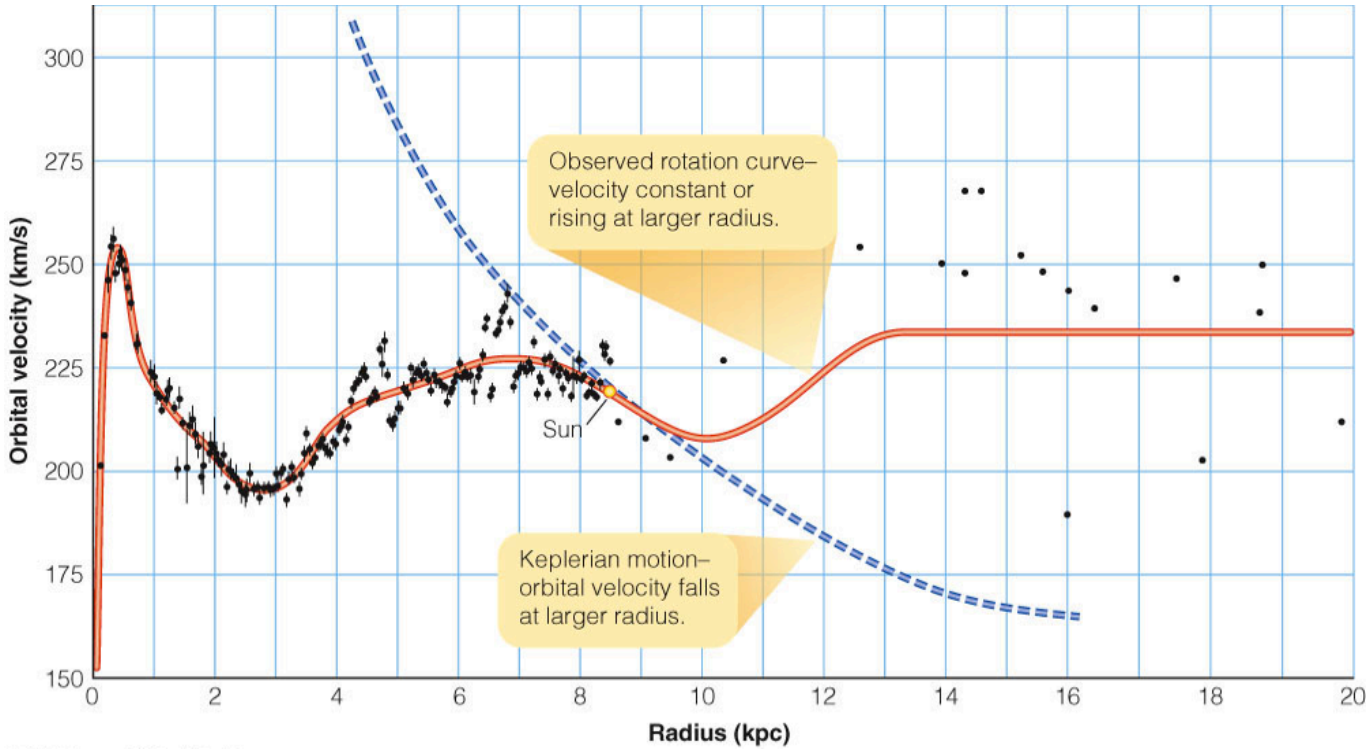
Mass of a Galaxy



- For **all** spiral galaxies, we see a rotation curve like those above.
- The center parts look like a merry-go-round (solid body)
- The outer parts are flat.
- The height and extent of the curve give you the total mass.
  - **higher and longer curves = larger total mass**
- **No** galaxy has a *declining, Keplerian* rotation curve.
- **This implies that the mass of a galaxy continues to increase with radius.**

Mass of the Milky Way

- Same rotation curve seen for the Milky Way.
- The mass continue to increase beyond the edge of the disk of stars and gas out to the very edge of the halo.
- **What is this missing mass???**

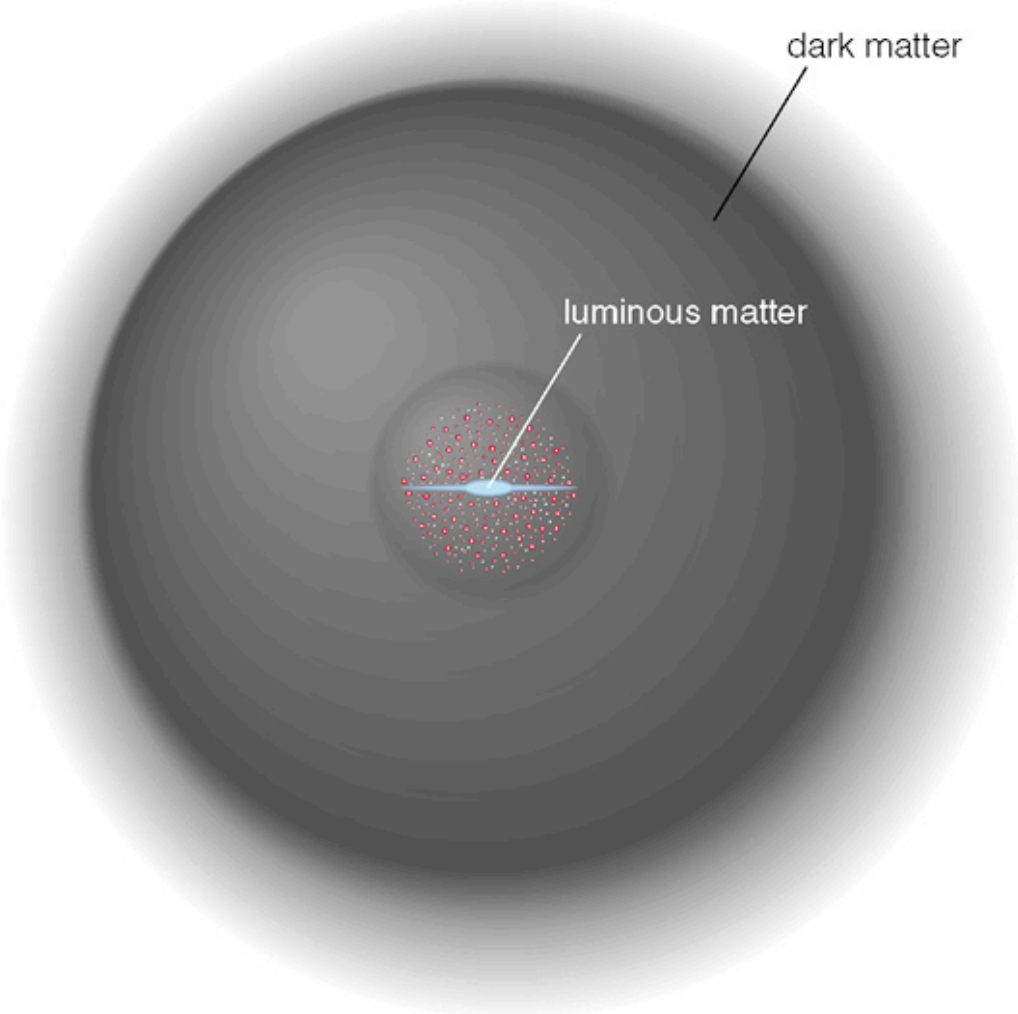


Masses of other galaxies

- While not all galaxies rotate, the motions of their stars and gas **all** indicate some missing mass.
- The motions of galaxies in pairs, in groups, and in clusters also provide evidence for missing mass.
- As does gravitational lensing by clusters.

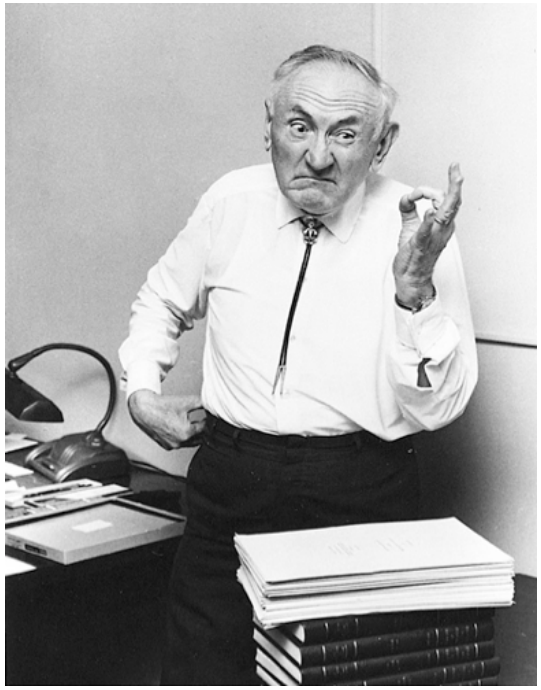
Mass in stars versus Total Mass

- Most of the missing mass is in the outskirts of galaxies.
- Can only account for about 10% of the total mass of galaxies in stars and gas.



Dark Matter

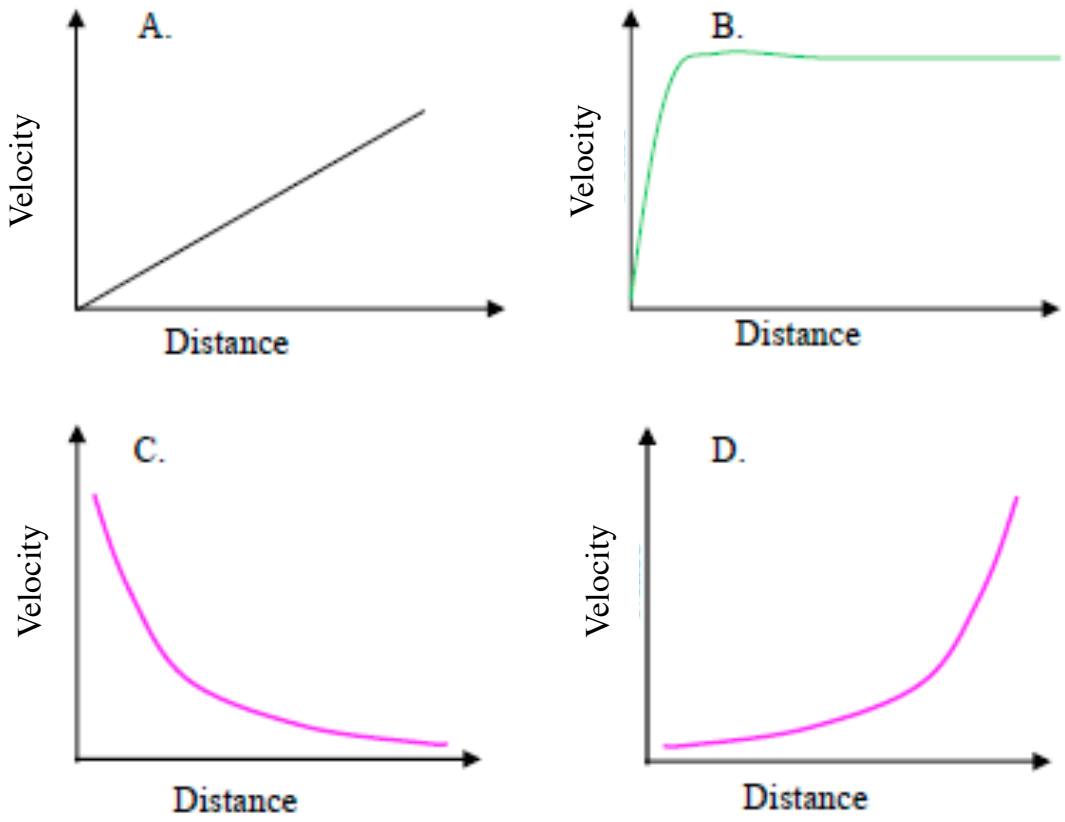
- This missing mass is called *dark matter*. It is matter that does not emit light, or at least can't be seen.
- **You are a form of dark matter.**
- It is **not** the same as a dark nebula or black holes.
- First suggested to exist by Fritz Zwicky in the 1930s!
- Observational evidence first provided in the 1970s by Vera Rubin.
- We still don't know what it is only that it is seen almost everywhere.



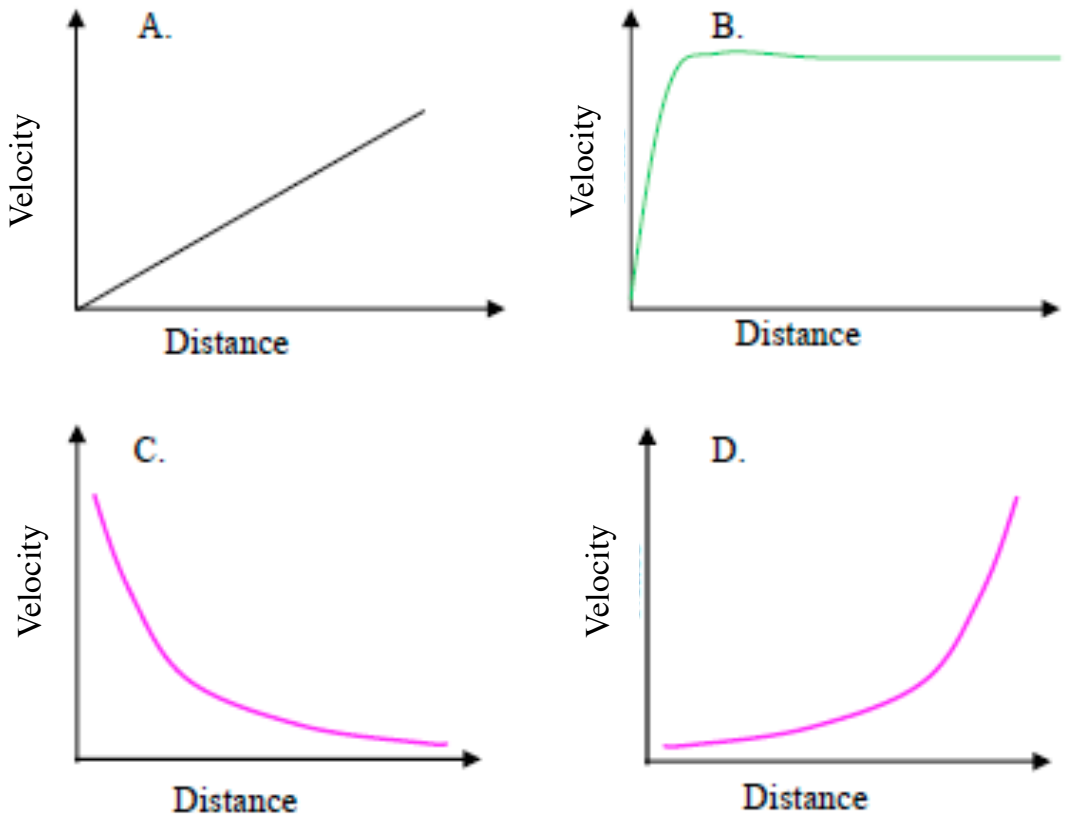
Which of the following does not provide evidence for the existence of dark matter?

A. Rotation Curves of galaxies
B. The orbits of the planets
C. Gravitational lenses
D. Motions of galaxies in groups
E. They all provide evidence

Which of the following could be a rotation curve for the solar system?



Which of the following could be a rotation curve for stars around a supermassive black hole?



Which of the following rotation curves would be for a galaxy?