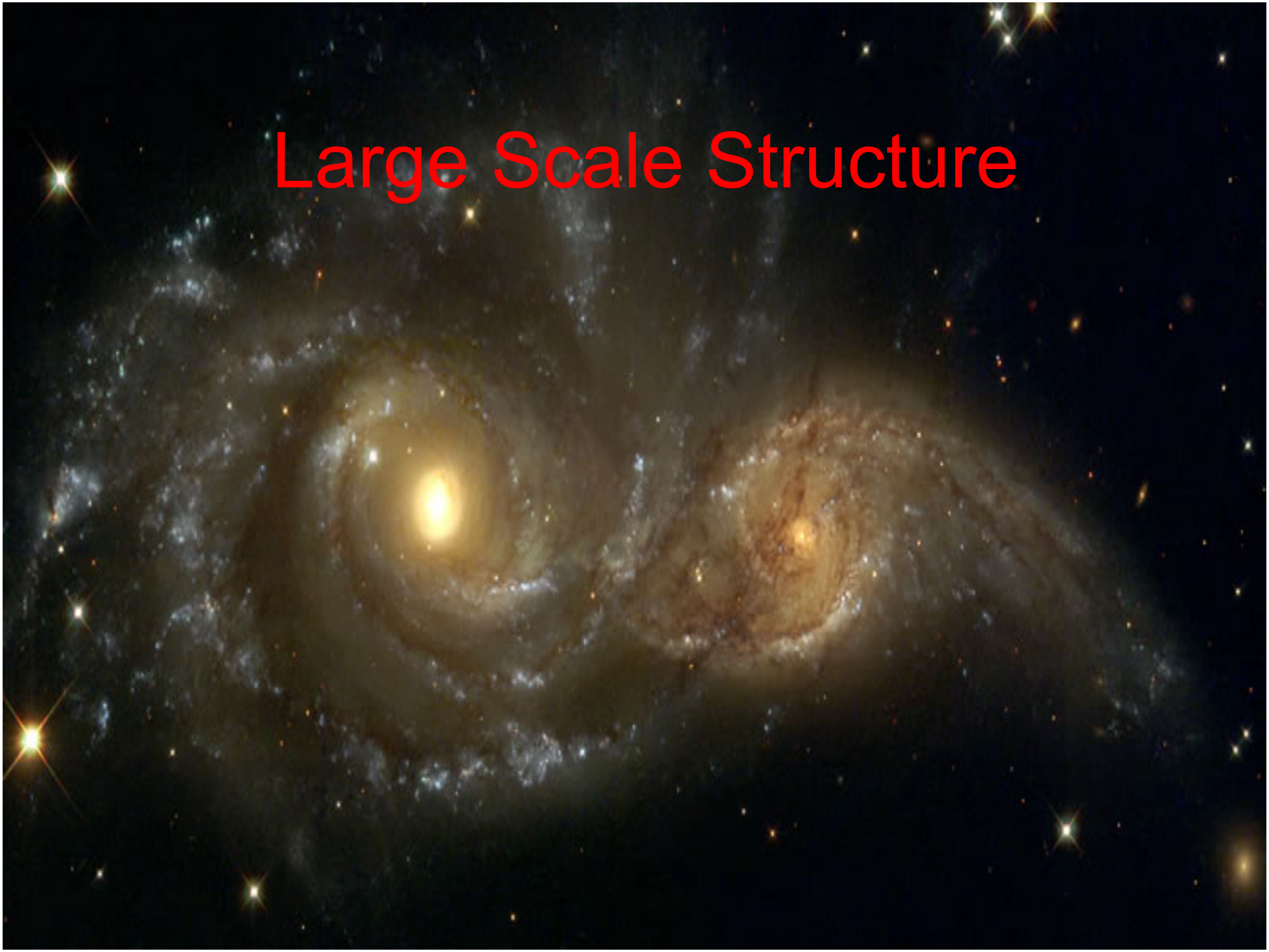
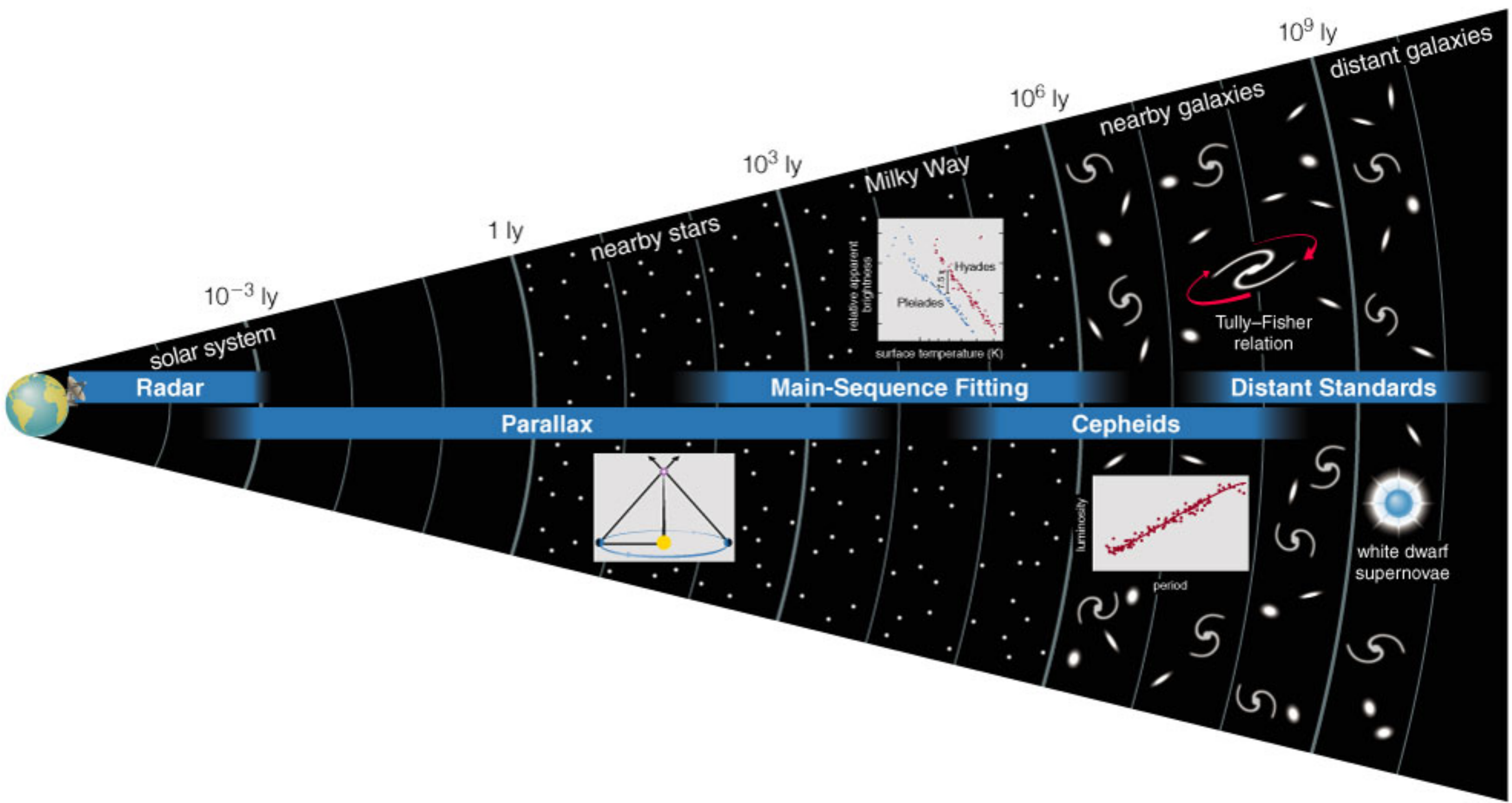
Large Scale Structure



Measuring Distance in Universe--

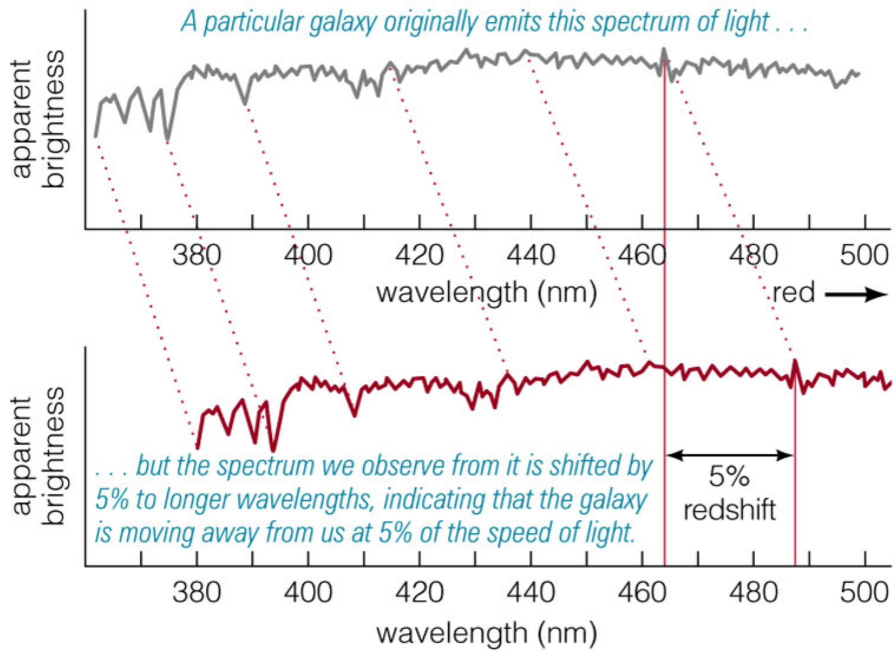
a ladder of steps, building from nearby



Redshift distance

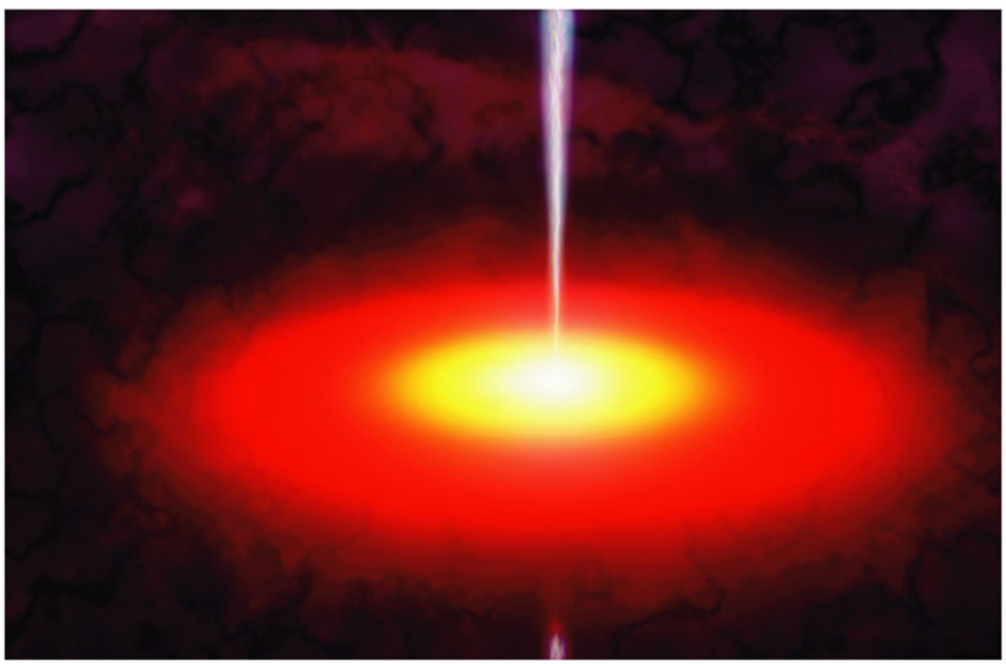
- Redshift = z = $(\lambda_{observed} - \lambda_{rest}) / \lambda_{rest}$
- Every part of a distant spectrum has same redshift.
- For low speeds velocity given by: $v = c\,z$

(In other words, 10% redshift is v= .1 c = 3×10^4 km/sec)



Active Galactic Nuclei

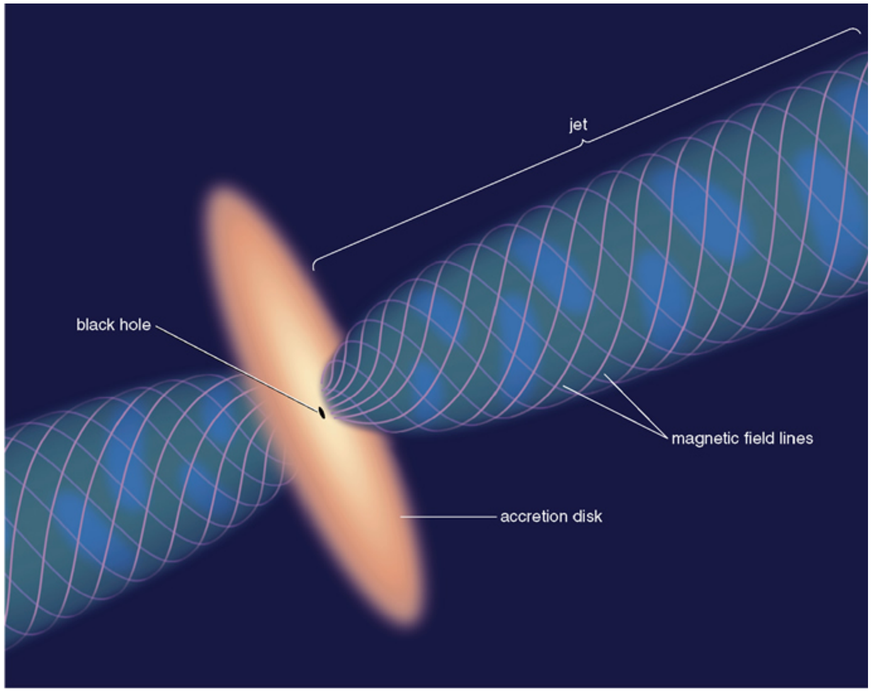
- The energy is generated from matter falling onto a **supermassive black hole**…
  - 1.2 x 10^9 M_{sun} for NGC 4261
  - 3 x 10^9 M_{sun} for M87
- …which is at the center (nucleus) of the galaxy.

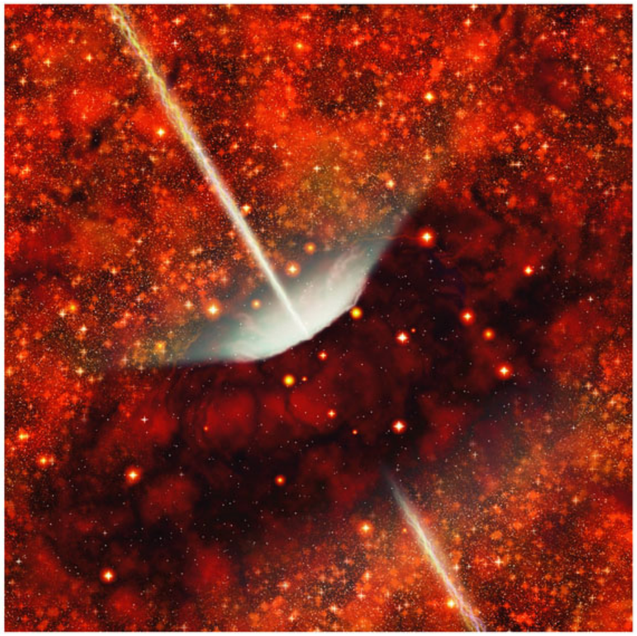


- Matter swirls through an accretion disk before crossing over the event horizon.
- Gravitational pot. energy lost
  - = mc^2 the mass energy
  - 10 – 40% of this is radiated away
- Process is very efficient for generating energy.

Active Galactic Nuclei

- Formation of the Jets
  - magnetic fields in accretion disks are twisted
  - they pull charged particles out of the disk and accelerate them like a slingshot
  - particles bound to magnetic field; focused in a beam





- Orientation of beam determines what we see:
  - if beams points at us, we see a quasar
  - if not, the molecular clouds/dust of the galaxy block our view of the nucleus
  - so we see a radio galaxy
  - lobes are where jets impact intergalactic medium

Mergers of Galaxies

•How did galaxies form?

•Were galaxies born at their present size, or were they smaller in the past? How do galaxies grow?

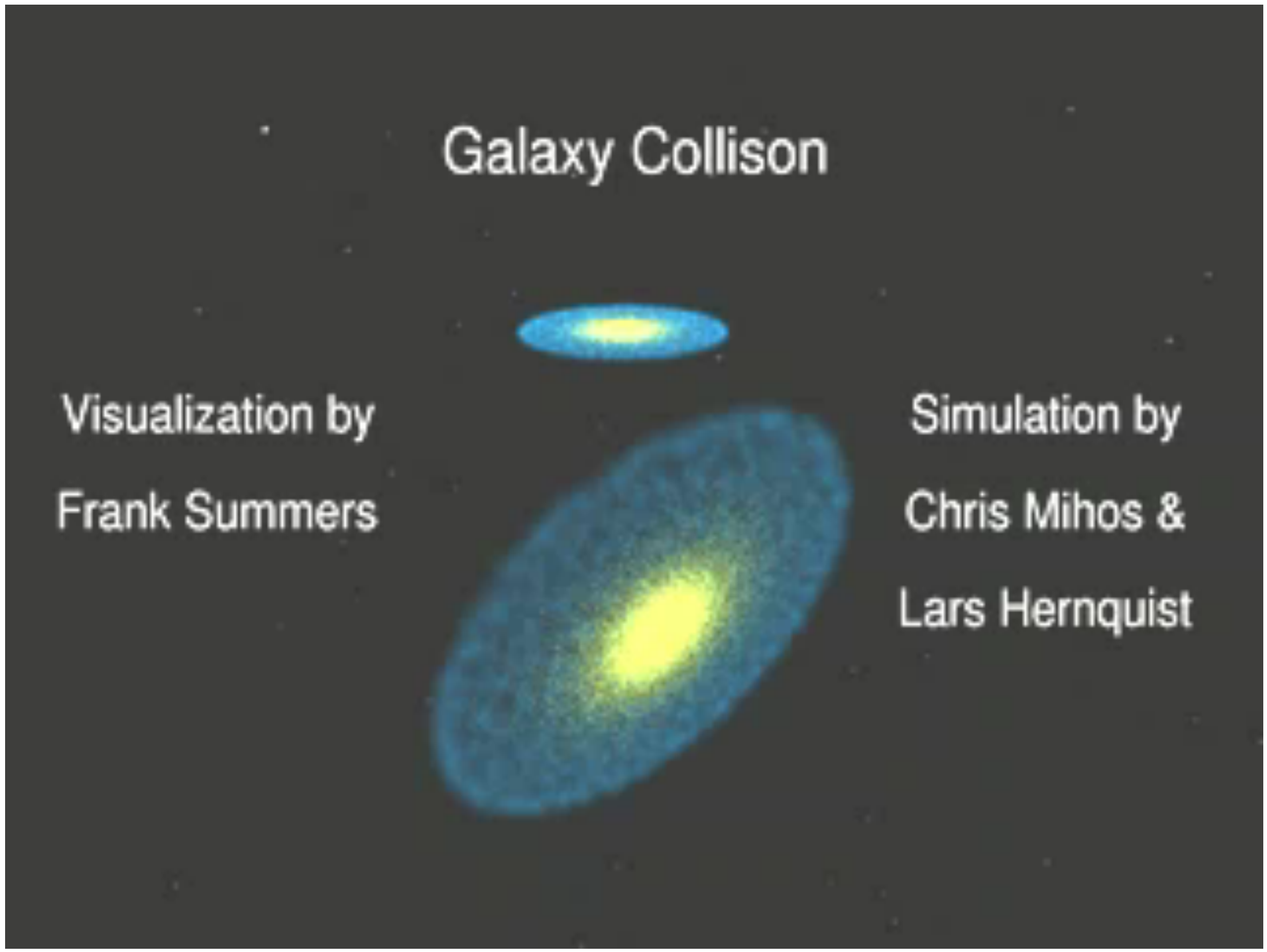
•What happens when two galaxies collide?

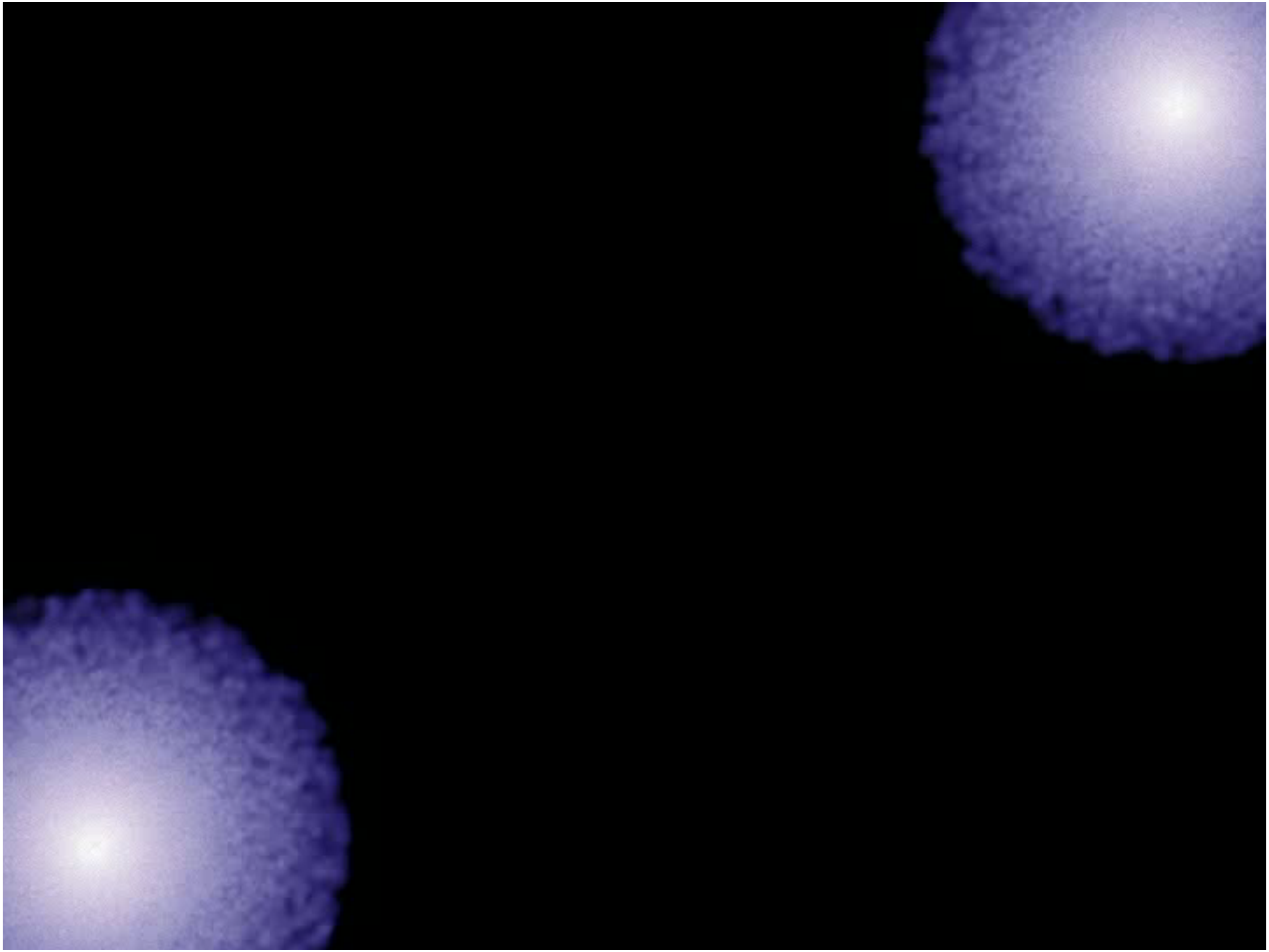
• Why were Quasars more abundant in the past than at present?

•What has happened to the giant black holes in Quasars?

Merging of Galaxies

•Galaxies are mass fluctuations. The fluctuations attract each other and merge into a bigger galaxy

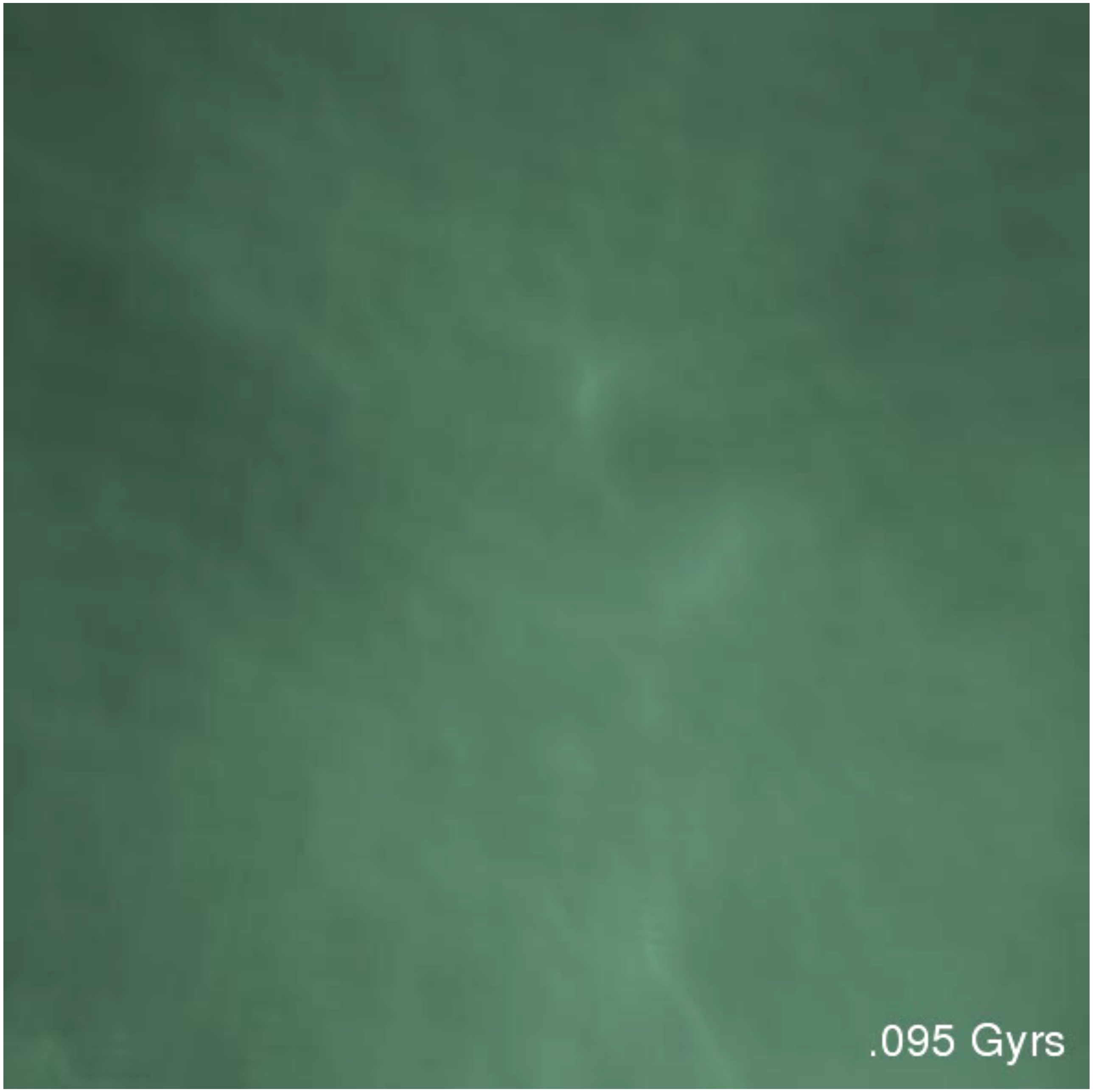




Hierarchical formation of a galaxy

Only baryonic component is shown– the DM controls the gravity.

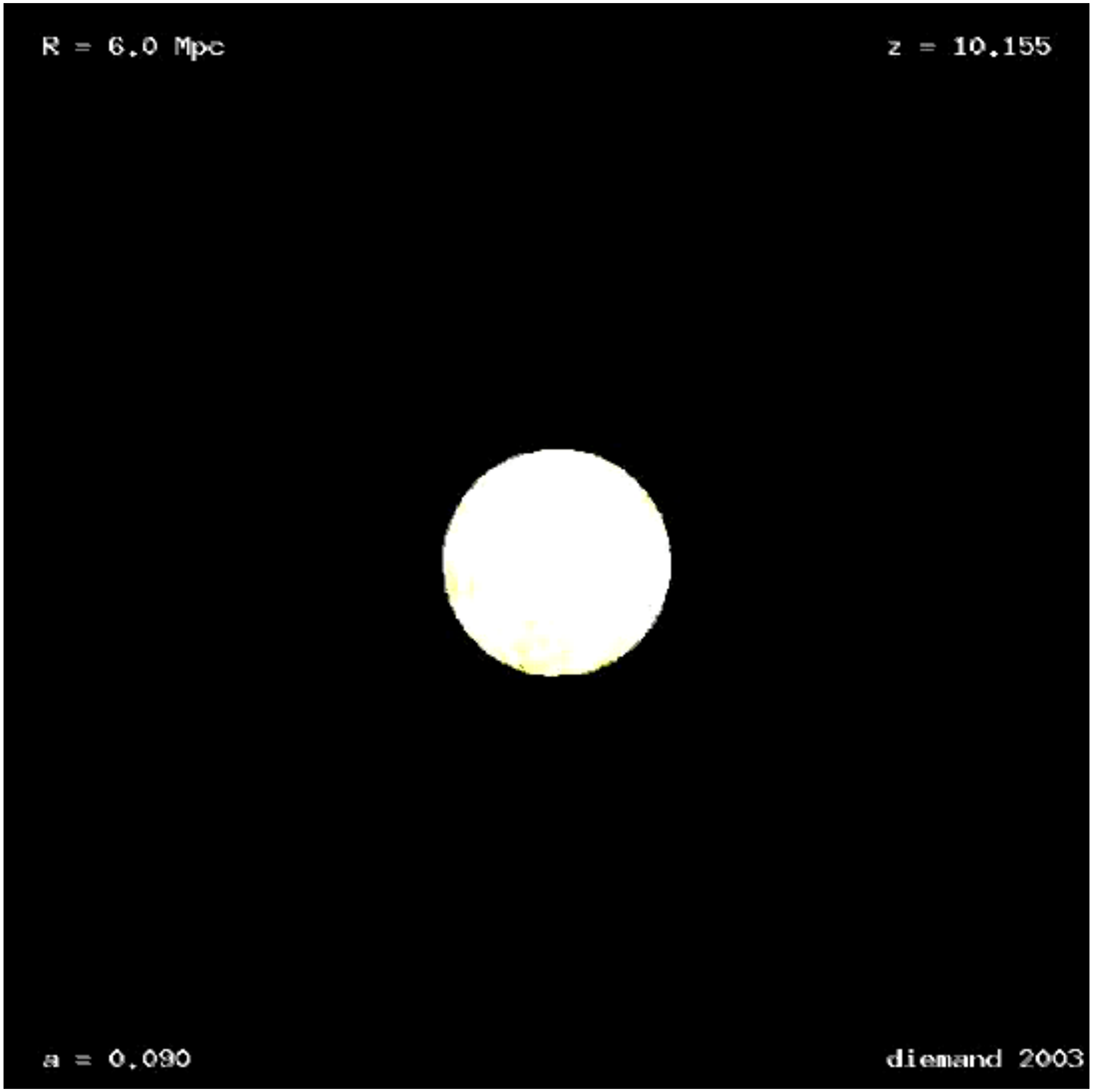
Note the small galaxies merge to form a larger galaxy

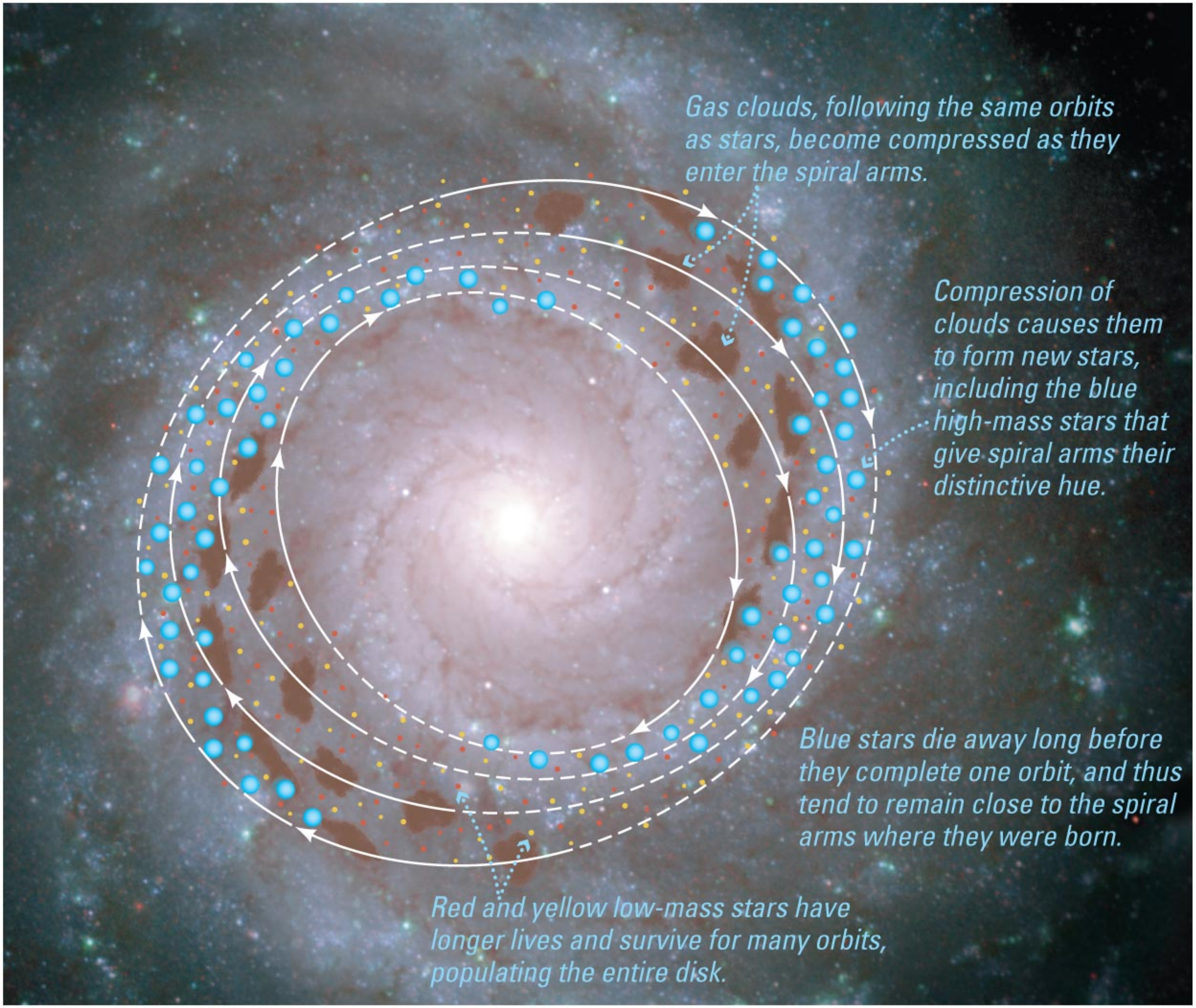



0 Gyrs

The Formation of Structure in the Universe

Simulation by Ben Moore





Gas clouds, following the same orbits as stars, become compressed as they enter the spiral arms.
Compression of clouds causes them to form new stars, including the blue high-mass stars that give spiral arms their distinctive hue.
Blue stars die away long before they complete one orbit, and thus tend to remain close to the spiral arms where they were born.
Red and yellow low-mass stars have longer lives and survive for many orbits, populating the entire disk.

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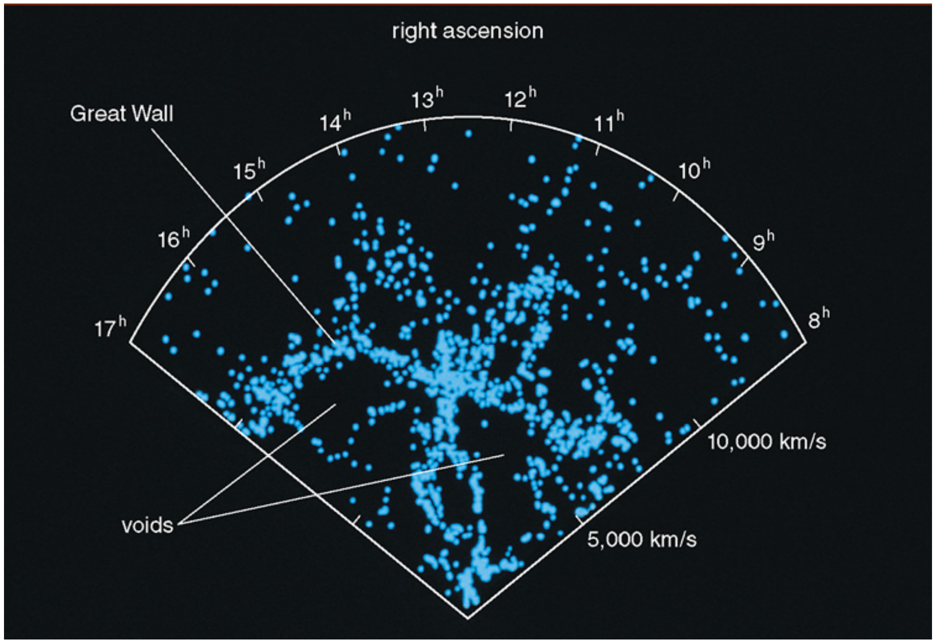
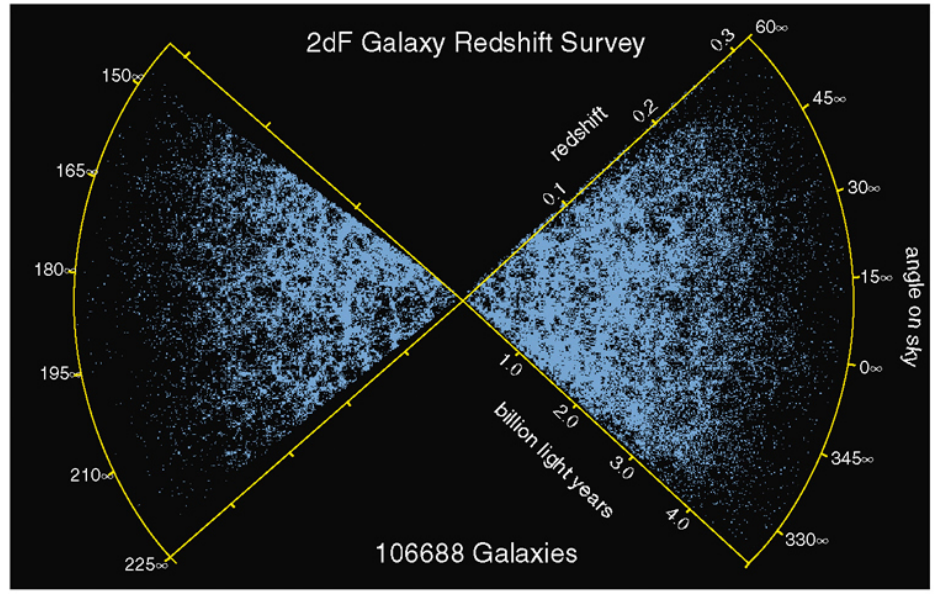
Large Scale Structure of the Universe

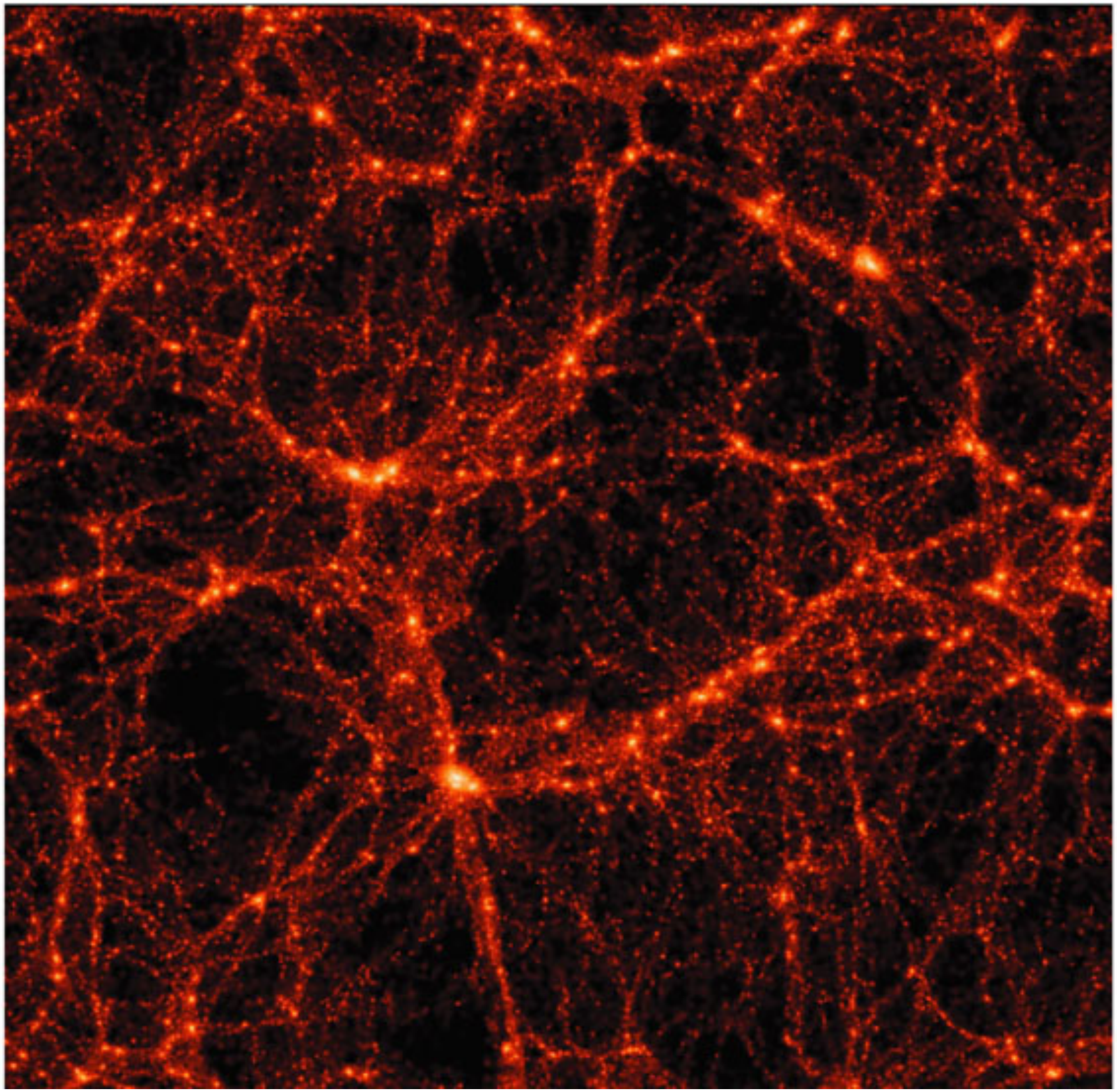


slice of the Universe out to 7 x 10^8 ly



slice of the Universe out to 4 x 10^9 ly

- On scales of 10^8 ly, galaxies are distributed in gigantic chains and sheets surrounding great voids.
  - Galaxies are usually clustered together into "groups", "clusters", "superclusters". Large filamentary shapes, very non-random distribution.
  - A hierarchy of structure. Why does it exist, what does it tell us?
- On scales of several x 10^9 ly, galaxies appear evenly distributed.



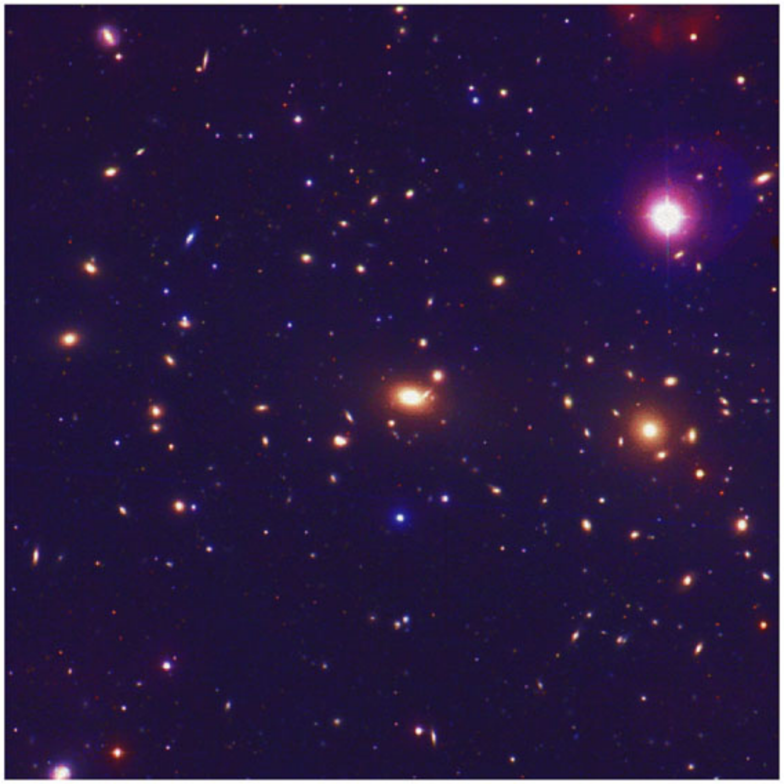
The Masses of Galaxy Clusters

- In clusters of galaxies, the timescale for an orbit is very long. Galaxies may be orbiting each other, or buzzing about like bees in a swarm, but on a human timescale nothing appears to move.

- In spite of this, it is possible to estimate the mass of a cluster of galaxies, using the same trusty equation for circular orbits:

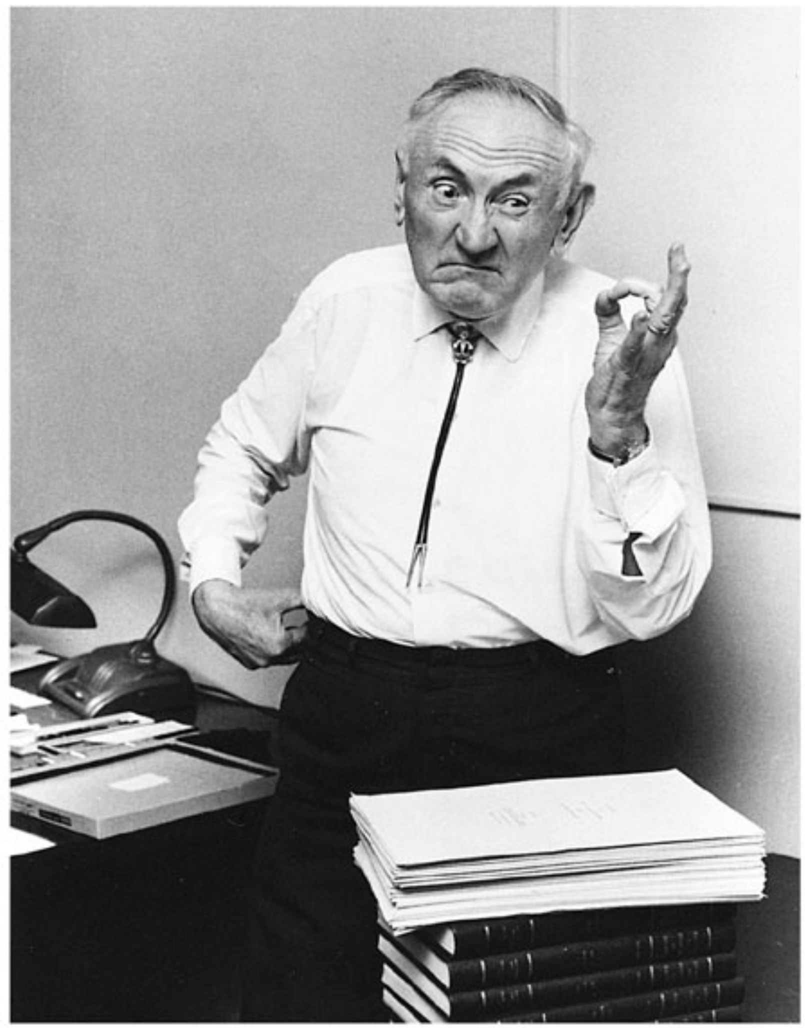
$$\mathbf{v^2 = GM/r}$$

- *Example: The Coma cluster of galaxies, first discussed by F. Zwicky, 50 years ago.*
- The cluster has a measured size on the sky of θ = 1. degree, and has a recession velocity of 6900 km/s.
- Using Hubble's law, $v=H_0 d$, we find, for H_0 = 70 km/s/Mpc,
- d= 100 Mpc.
- By small angle approximation, $r = (\theta/57.3)d \sim 2$ Mpc



Fritz Zwicky

- A different sort of astronomer.
    - First to show ‘missing mass’ in Coma cluster



Measuring mass of cluster

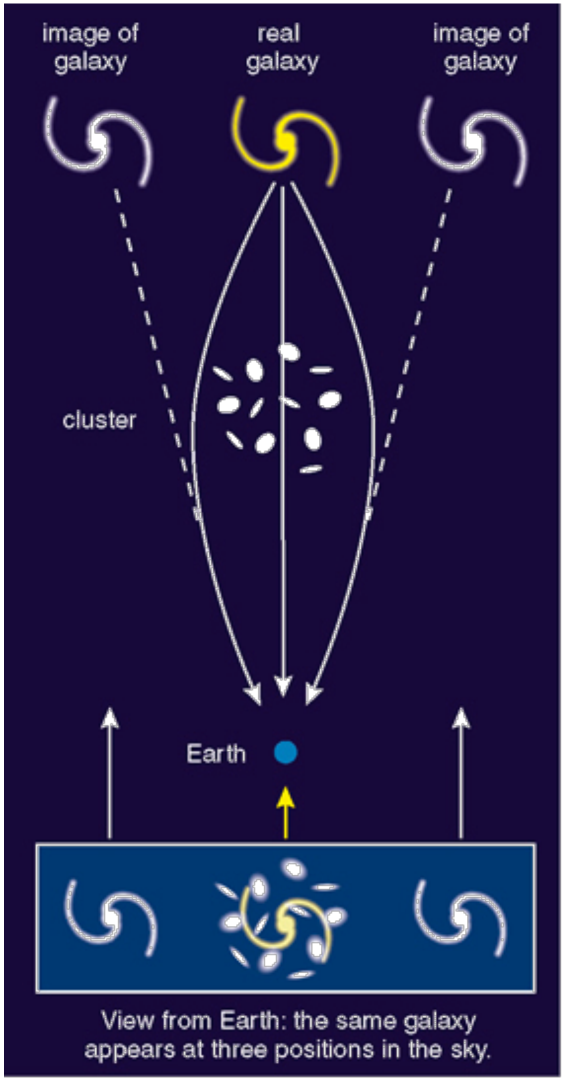
- Characteristic random velocity within coma cluster:
  v = 1000 km/s
- (this is *not* a typo!!)

$$M = v^2 r / G = 4 \times 10^{14} M_{sun}$$

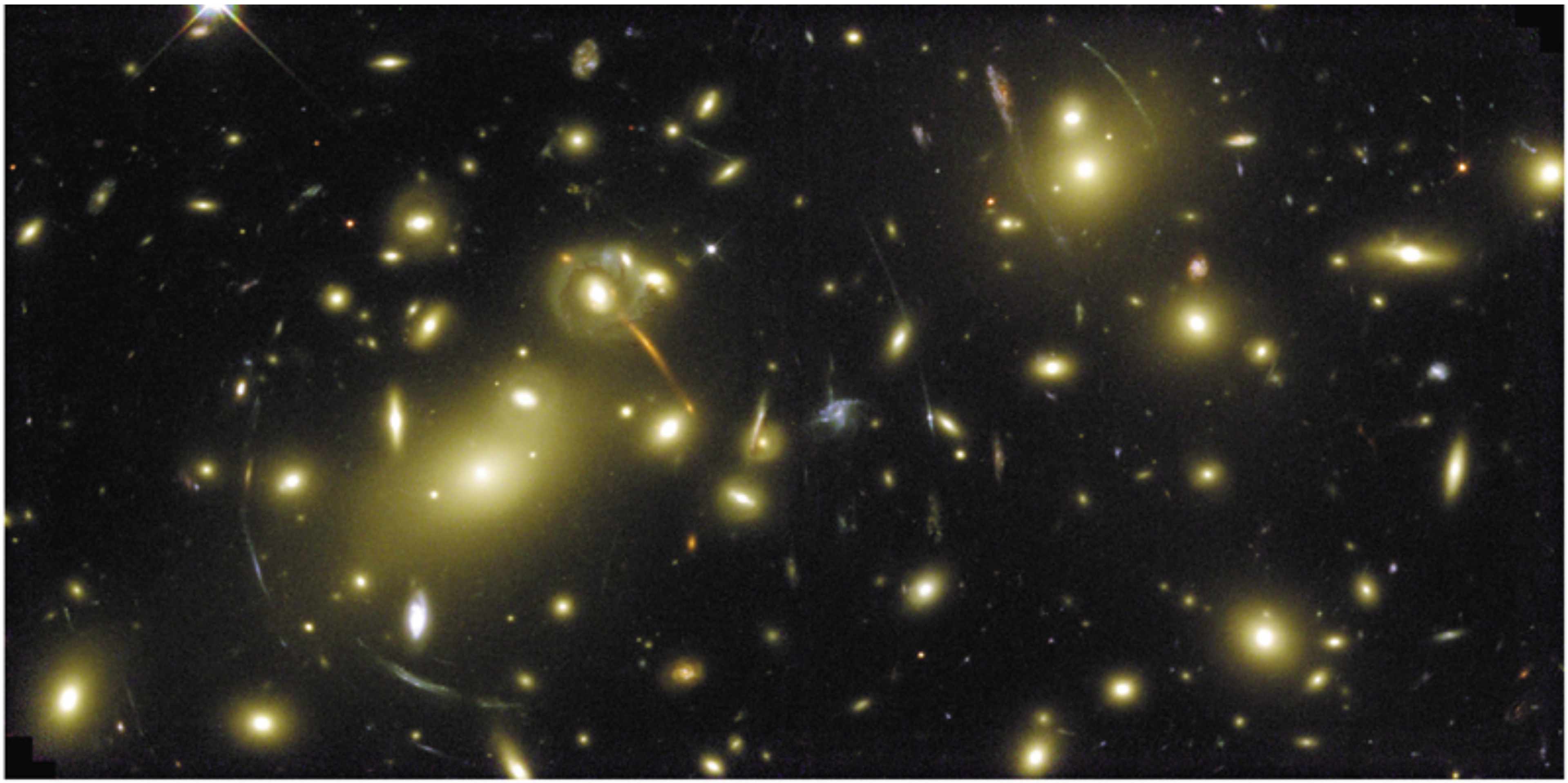
- *This is more than **50 times** the mass one would estimate by simply adding all the starlight from the cluster and multiplying by the mass per star.*
- *The Coma cluster, like all other clusters of galaxies, is **dominated** by **dark matter.***
- What is the mysterious dark matter?

Lensing by cluster

Indicative of Dark Matter

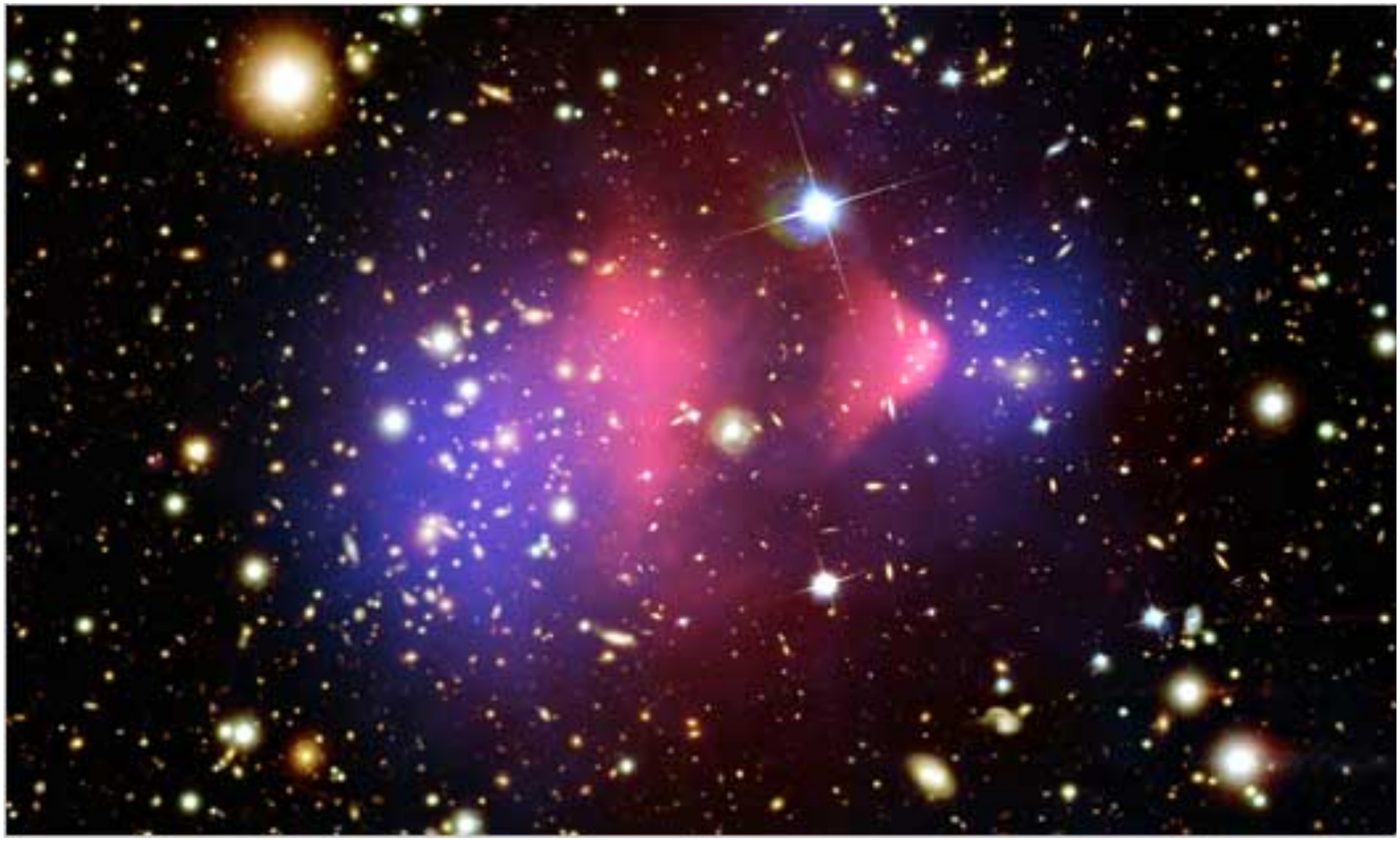


Strong Lensing by Foreground Galaxy Cluster



Bullet Cluster

red image: Baryonic matter seen in X-rays
blue image: dark matter seen by lensing of background galaxies



Gravitational Lensing

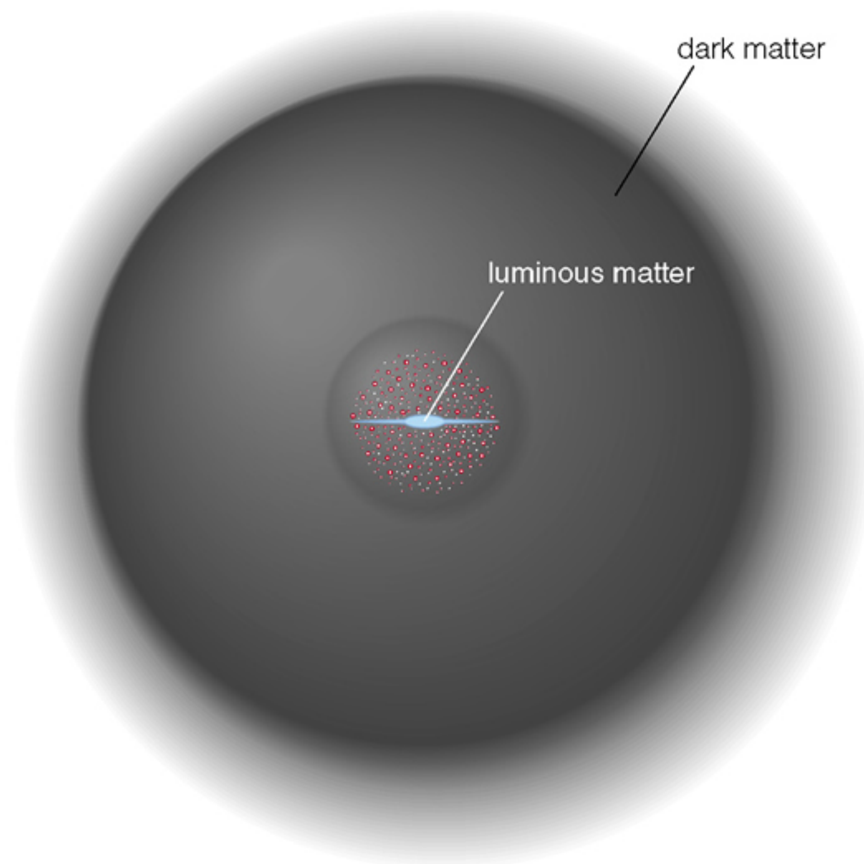
How does it work?

What is Dark Matter?

- Recall the rotation curve of the Milky Way Galaxy.
  - atomic H clouds beyond our Sun orbit faster than predicted by Kepler's Law
  - most of the Galaxy's light comes from stars closer to the center than the Sun

- There are only two possible explanations for this:
  - we do not understand gravity on galaxy-size scales
  - the H gas velocities are caused by the gravitational attraction of unseen matter…called **dark matter**

- If we trust our theory of gravity...
  - there may be 10 times more dark than luminous matter in our Galaxy
  - luminous matter is confined to the disk
  - dark matter is found in the halo and far beyond the luminous disk

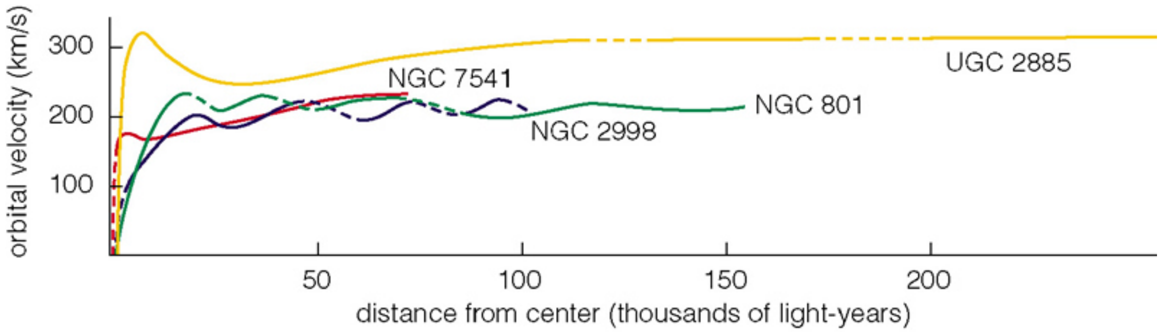


Determining Mass Distribution

- In Spiral Galaxies
  - measure the Doppler shift of the 21-cm radio line at various radial distance
  - construct a rotation curve of the atomic Hydrogen gas (beyond visible disk)
  - calculate the enclosed mass using Kepler's Law

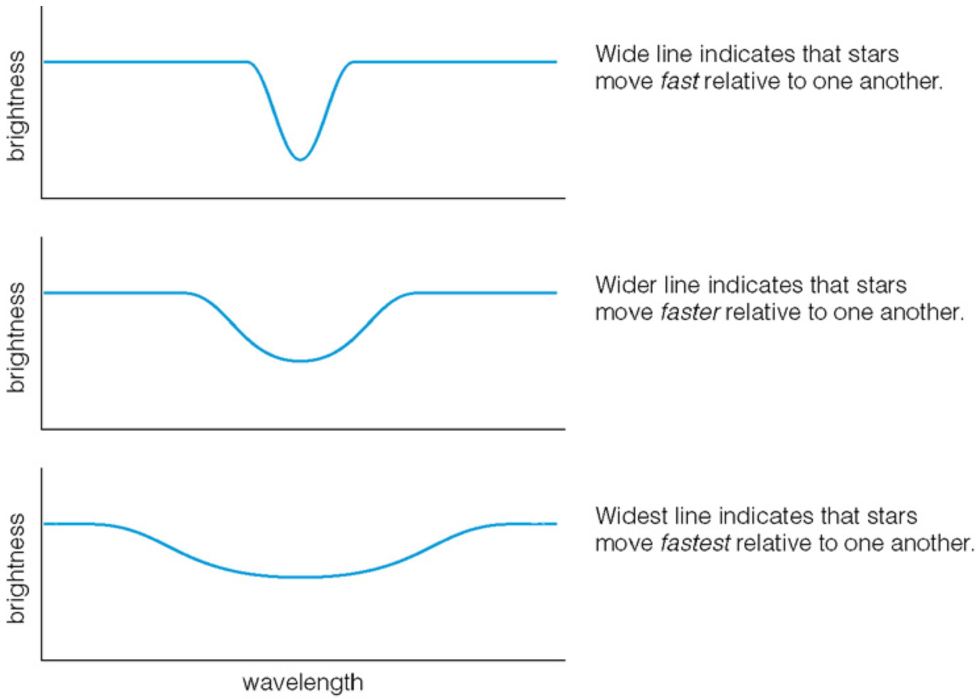
meas_doppler_shifts_for_gal.swf

Determining Mass Distribution



- Rotation curves of spirals…
  - are flat at large distances from their centers
  - indicates that (dark) matter is distributed far beyond disk

- In Elliptical Galaxies
  - there is no gas
  - measure the average orbital speeds of stars at various distances
  - use broadened absorption lines
- Results indicate that dark matter lies beyond the visible galaxy.
  - we can not measure the total amount of dark matter, since we can see only the motions of stars



Mass-to-Light Ratio…

- …is the mass of a galaxy divided by its luminosity.
    - we measure both mass [M_{sun}] and luminosity [L_{sun}] in Solar units
- Within the orbit of the Sun, M/L = 6 M_{sun}/L_{sun} for the Milky Way
    - this is typical for the inner regions of most spiral galaxies
    - for inner regions of elliptical galaxies, M/L = 10 M_{sun}/L_{sun}
        - not surprising since ellipticals contain dimmer stars
- However, when we include the outer regions of galaxies…
    - M/L increases dramatically
    - for entire spirals, M/L can be as high as 50 M_{sun}/L_{sun}
    - dwarf galaxies can have even higher M/L
- Thus we conclude that most matter in galaxies are not stars.
    - the amount of M/L over 6 M_{sun}/L_{sun} is the amount of dark matter

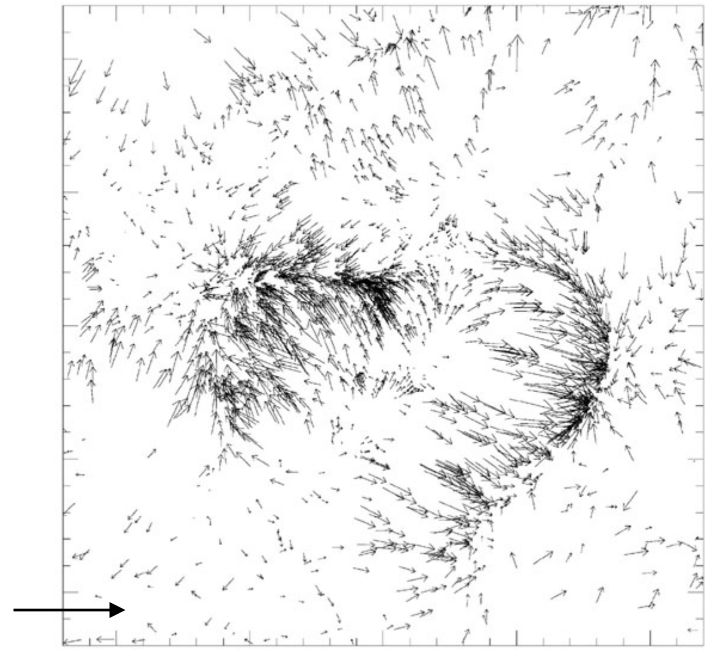
What is Dark Matter Made Of?

- Dark matter could be made out of protons, neutrons, & electrons.
  - so-called “ordinary” matter, the same matter we are made up of
  - if this is so, then the only thing unusual about dark matter is that it is dim
- However, some or all of dark matter could be made of particles which we have yet to discover.
  - this would find this to be “extraordinary” matter
- Physicists like to call ordinary matter **baryonic matter**.
  - protons & neutrons are called baryons
- They call extraordinary matter **nonbaryonic matter**.

An Extraordinary Matter Candidate

- We have already studied a nonbaryonic form of matter:
  - the **neutrino**…detected coming from the Sun
  - neutrinos interact with other particles through only two of the natural forces:
    - gravity
    - weak force (hence we say they are "weakly interacting")
  - their masses are so low & speeds so high, they will escape the gravitational pull of a galaxy…they can **not** account for the dark matter observed
- But what if there existed a *massive* weakly interacting particle?
  - physicists call them "Weakly Interacting Massive Particles" or **WIMPs**
  - these particles are theoretical; they have not yet been discovered
  - they would be massive enough to exert gravitational influence
  - they would emit no electromagnetic radiation (light) or be bound to any charged matter which could emit light
  - as weakly interacting particles, they would not collapse with a galaxy's disk
  - yet they would remain gravitationally bound in the galaxy's halo

The Growth of Structure

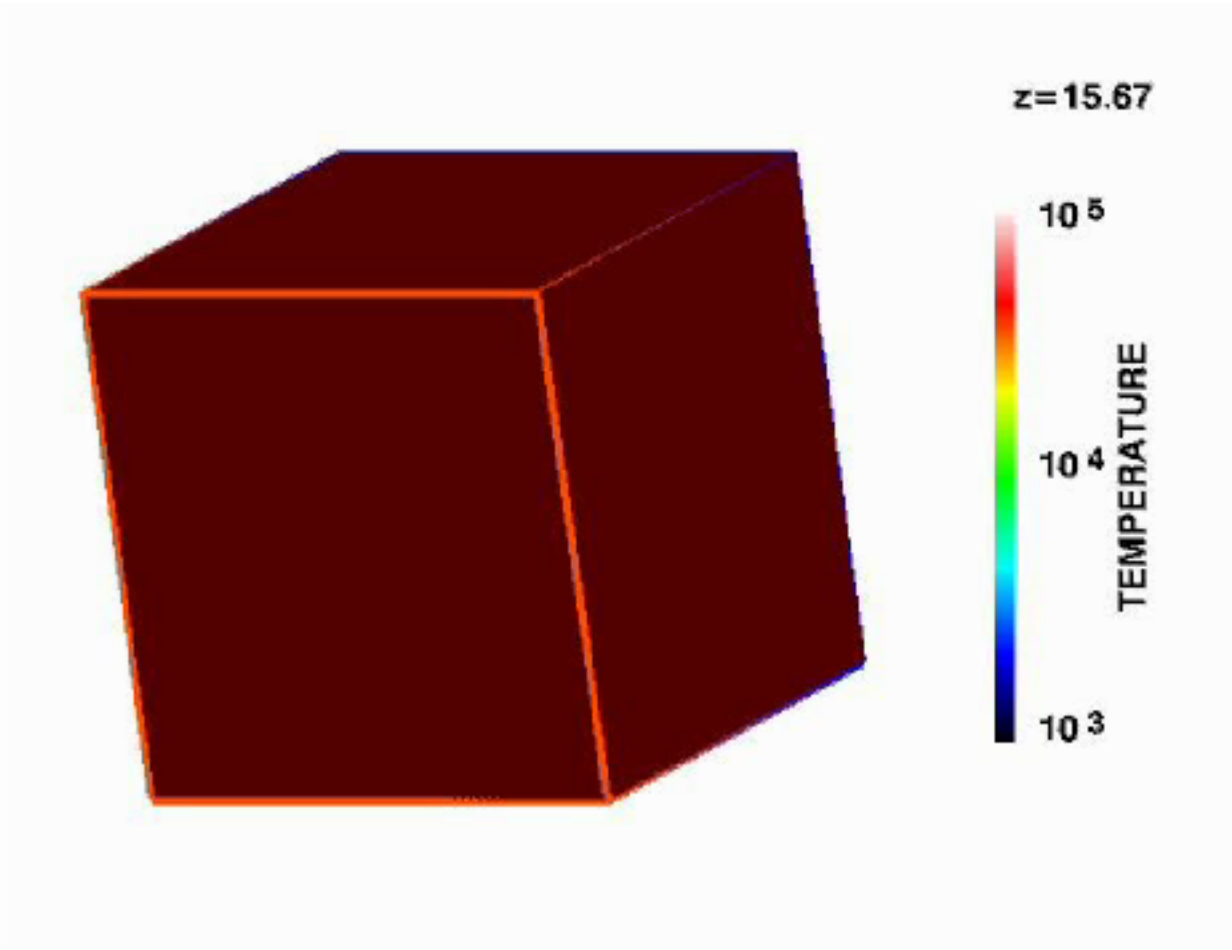


- At close range, gravitational attraction overcomes the Hubble expansion.
  - we see this in a galaxy's **peculiar velocity**
  - although the Universe as a whole expands, individual galaxies attract one another
  - peculiar velocity is a galaxy's deviation from the Hubble Law
  - can measure it for galaxies out to 3×10^8 ly
- We project that Universal structure began with slight enhancements in the density of matter in the early Universe.
  - these regions collapsed into protogalactic clouds to form *galaxies*
  - individual *galaxies* fell in towards one another to form *clusters*
  - individual *clusters* are now congregating to form *superclusters*
- These "collapses" against Universal expansion are facilitated by dark matter.

Computer Simulation of Structure Formation

--How did Universe become so ionized by z=6?

brown color represents neutral Hydrogen



$$z = \frac{\Delta\lambda}{\lambda} = redshift$$

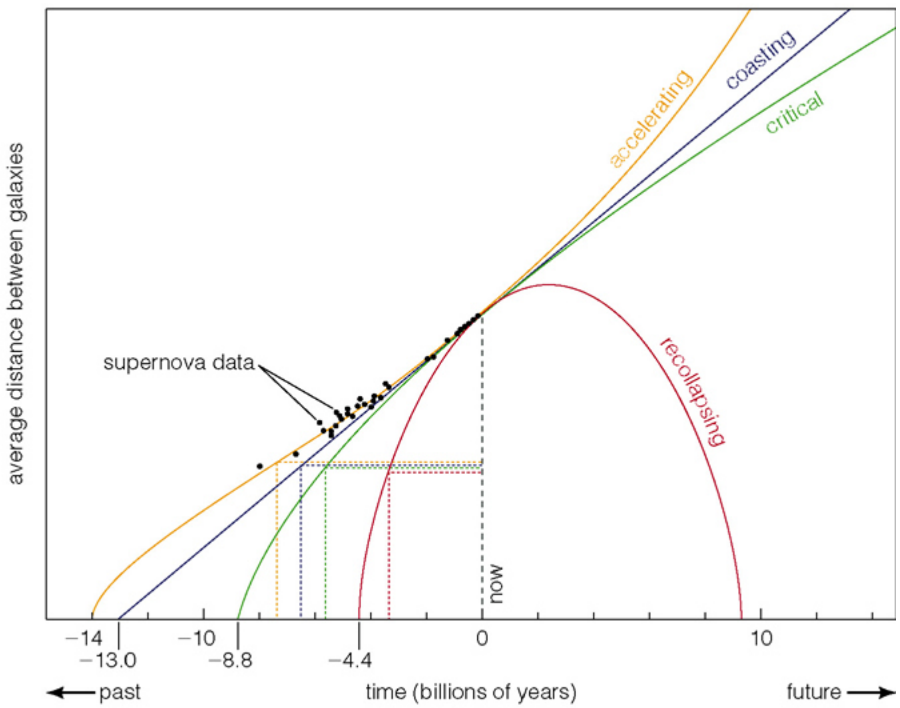
simulation courtesy of
Prof. Nickolay Gnedin,
University of Colorado

The Critical Density

- We have seen that gravitational attraction between galaxies can overcome the expansion of the Universe in localized regions.
  - how strong must gravity be to stop the entire Universe from expanding?
  - it depends on the total mass density of the Universe
- We refer to the mass density required for this gravitational pull to equal the kinetic energy of the Universe as the **critical density**.
  - if mass < critical density, the Universe will expand forever
  - if mass > critical density, the Universe will stop expanding and then contract
- The value of H_o tells us the current kinetic energy of the Universe.
  - this being known, the critical density is 10^{-29} g / cm^3
  - all the luminous matter that we observe accounts for < 1% of critical density
  - for dark matter to stop Universal expansion, the average M/L of the Universe would have to be 1,000 M_{sun}/ L_{sun} … a few times greater than clusters
- This line of research suggests the Universe will expand forever!

Does Gravity alone Influence the Expansion?

- Recent observations of white dwarf supernovae in very distant galaxies have yielded unexpected results.
  - remember, white dwarf supernovae make very good standard candles. The supernovae are apparently fainter than predicted for their redshifts



- At a given cosmological redshift
  - galaxies should be closer to us…

    i.e. shorter lookback time

    …for greater Universal mass densities
  - these supernova are farther back in time than even the models for an ever-expanding (coasting) Universe predict
- This implies that the Universal expansion is *accelerating*!
  - there must be an as yet unknown force which repels the galaxies
  - a **dark energy**

How Mass Density affects the Expansion of the Universe

universe_and_mass_density.swf

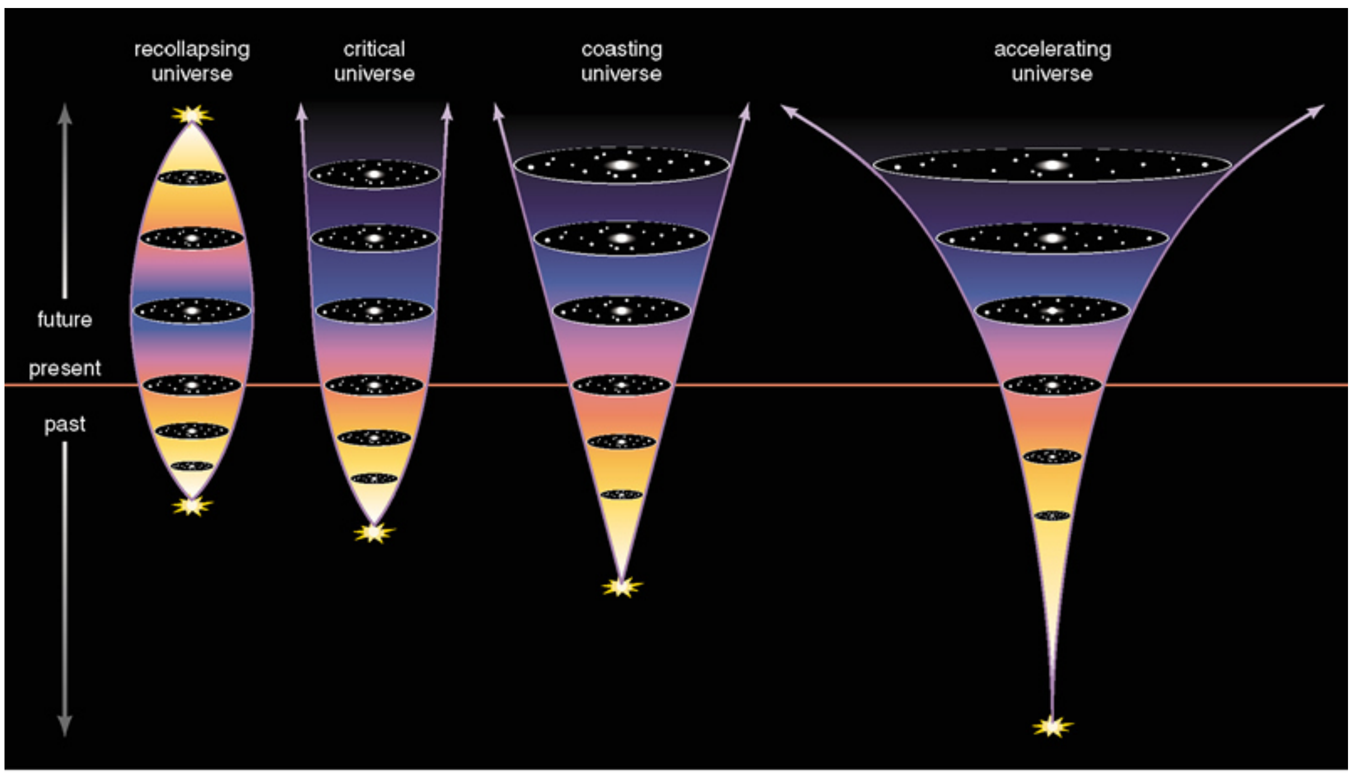
How Mass Density *and* Dark Energy affect the Expansion of the Universe

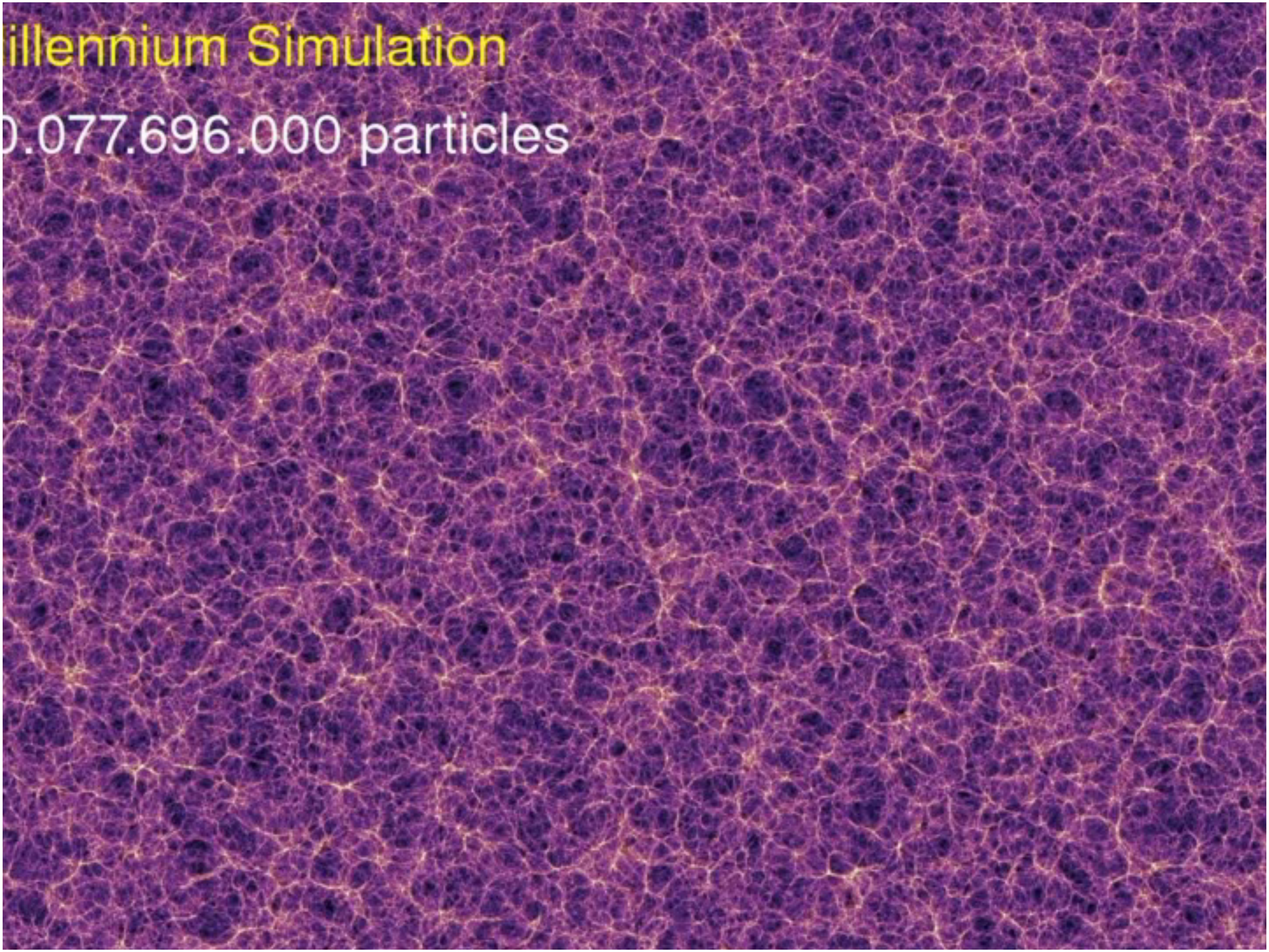
universe_history_and_fate.swf

Four Models for the Future of the Universe

1. Recollapsing Universe: the expansion will someday halt and reverse
2. Critical Universe: will not collapse, but will expand more slowly with time
3. Coasting Universe: will expand forever with little slowdown
4. Accelerating Universe*: the expansion will accelerate with time

   *currently favored

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