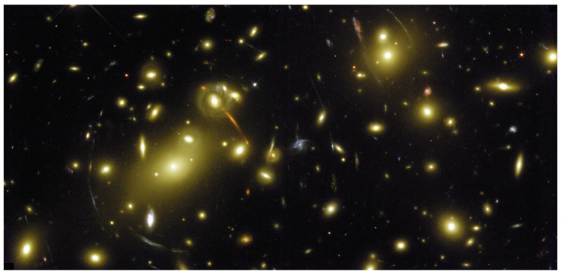
Chapter 22
Dark Matter, Dark Energy, and the Fate of the Universe



Agenda

- Hand Back tests
- Ch. 22
- ?

22.1 Unseen Influences in the Cosmos

- Our goals for learning
- What do we mean by dark matter and dark energy?

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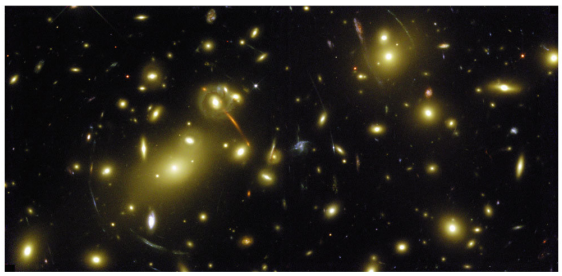


Unseen Influences

Dark Matter: An undetected form of mass that emits little or no 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: ~ 4.4%
  - Normal Matter inside stars: ~ 0.6%
  - Normal Matter outside stars: ~ 3.8%
- Dark Matter: ~ 25%
- Dark Energy ~ 71%

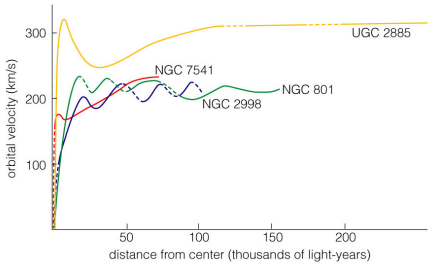
What have we learned?

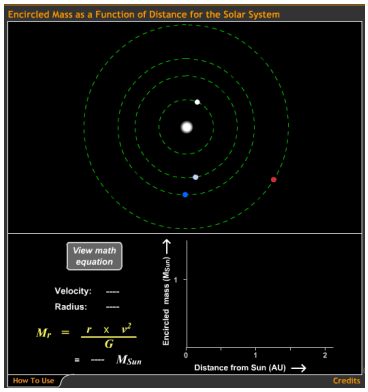
- What do we mean by dark matter and dark energy?
  - "Dark matter" is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds
  - "Dark energy" is the name given to whatever might be causing the expansion of the universe to accelerate

22.2 Evidence for Dark Matter

- Our goals for learning
- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?

What is the evidence for dark matter in galaxies?



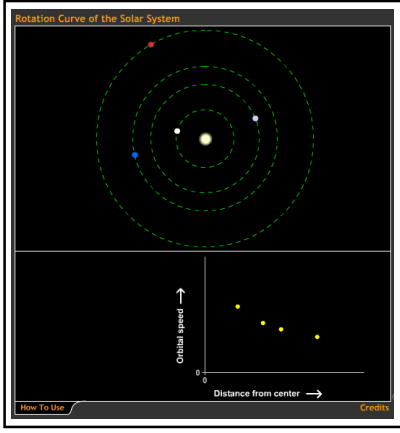


We measure the mass of the solar system using the orbits of planets

- Orb. Period
- Avg. Distance

Or for circles:

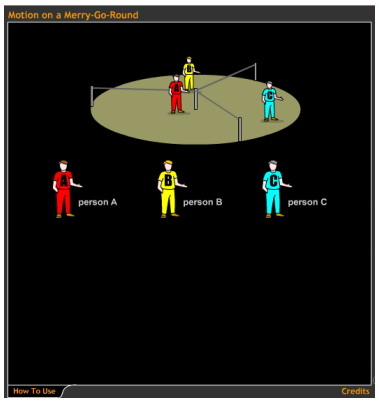
- Orb. Velocity
- Orbital Radius



Rotation curve

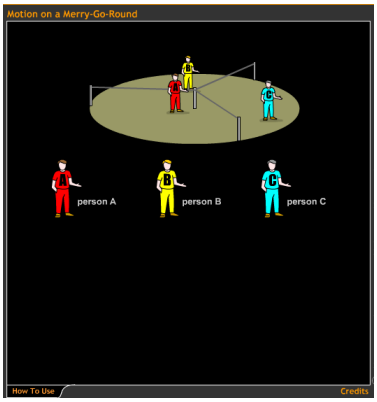
A plot of orbital velocity versus orbital radius

Solar system's rotation curve declines because Sun has almost all the mass



Who has the largest orbital velocity?

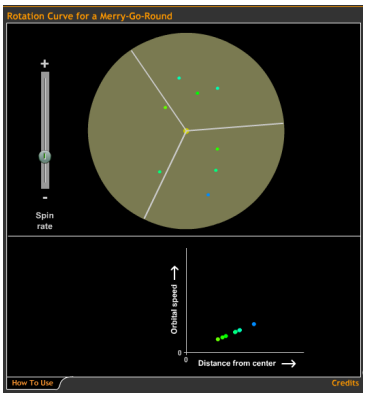
A, B, or C?



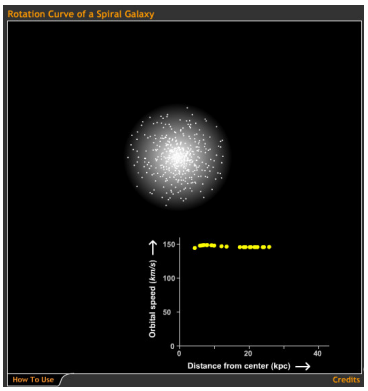
Who has the largest orbital velocity?

A, B, or C?

Answer: C

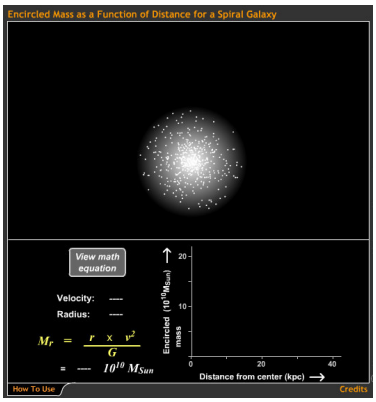


Rotation curve of merry-go-round rises with radius



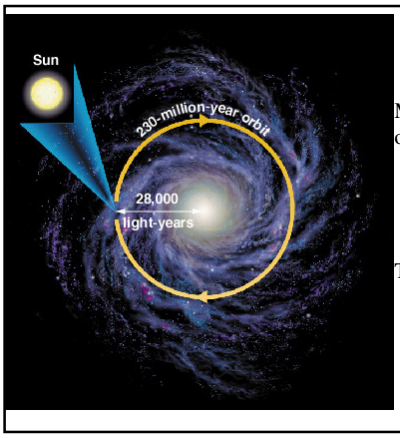
Rotation curve of Milky Way stays flat with distance

Mass must be more spread out than in solar system



Mass in Milky Way is spread out over a larger region than the stars

Most of the Milky Way's mass seems to be ***dark matter!***

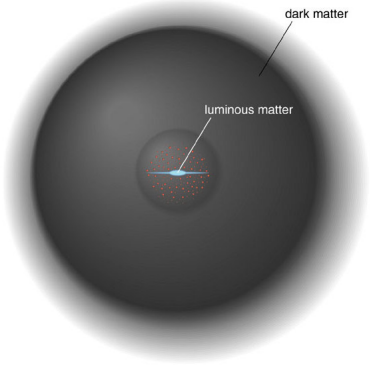


Mass within Sun's orbit:

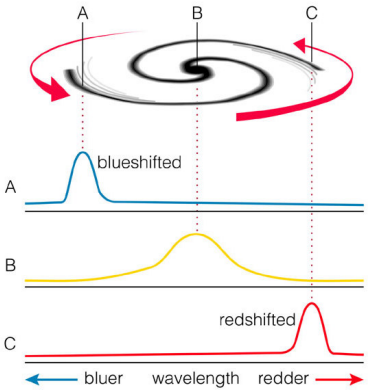
$1.0 \times 10^{11}\ M_{Sun}$

Total mass:

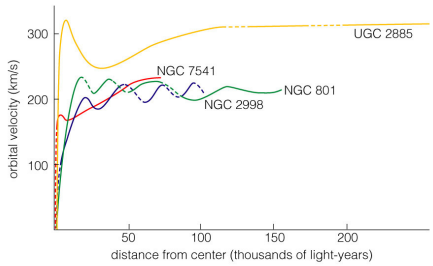
$\sim 10^{12}\ M_{Sun}$



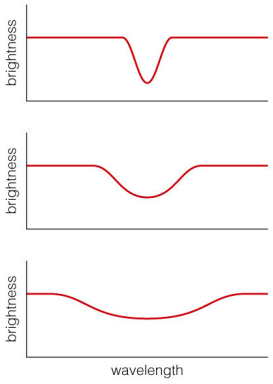
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter



We can measure rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic H



Spiral galaxies all tend to have flat rotation curves indicating large amounts of dark matter



Broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting

These galaxies also have dark matter

Thought Question

What would you conclude about a galaxy whose rotational velocity rises steadily with distance beyond the visible part of its disk?

A. Its mass is concentrated at the center
B. It rotates like the solar system
C. It's especially rich in dark matter
D. It's just like the Milky Way

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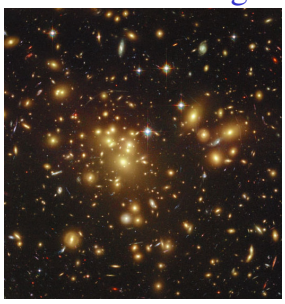
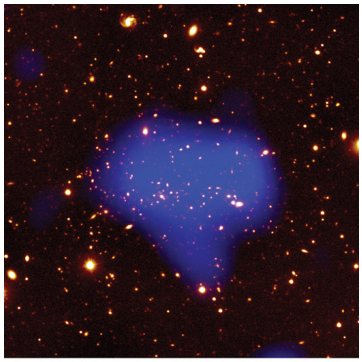
What is the evidence for dark matter in clusters of galaxies?



We can measure the velocities of galaxies in a cluster from their Doppler shifts

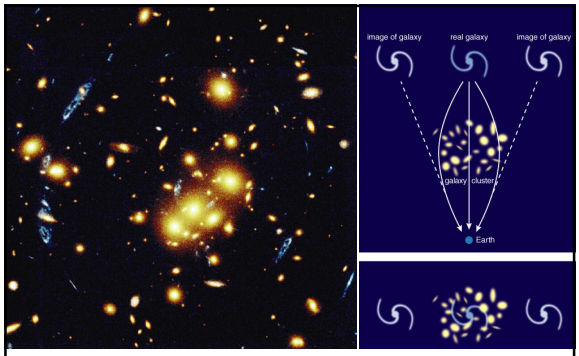
The mass we find from galaxy motions in a cluster is about ***50 times*** larger than the mass in stars!



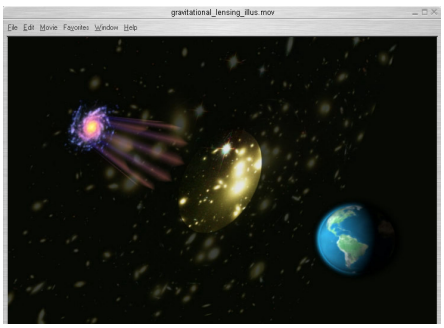
Clusters contain large amounts of X-ray emitting hot gas

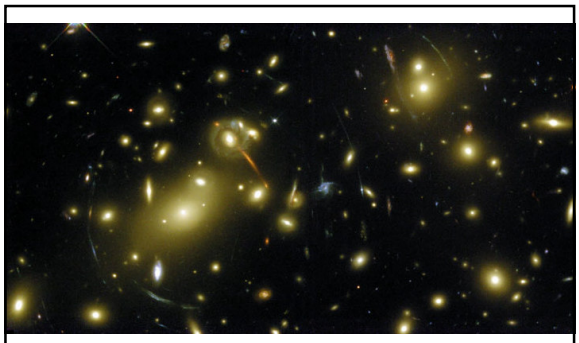
Temperature of hot gas (particle motions) tells us cluster mass:

85% dark matter
13% hot gas
2% stars



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





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

Thought Question

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

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

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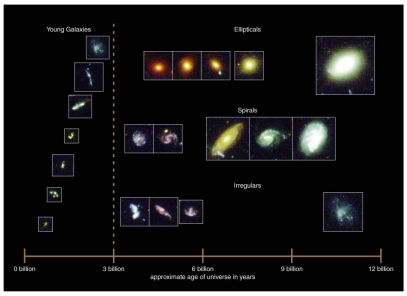
Does dark matter really exist?



Our Options

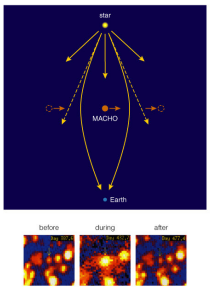
1. Dark matter really exists, and we are observing the effects of its gravitational attraction
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

Our Options

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 astronomers prefer option #1

What might dark matter be made of?



How dark is it?

How dark is it?

… 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
- Extraordinary Dark Matter (WIMPS)
  - Weakly Interacting Massive Particles: mysterious neutrino-like particles

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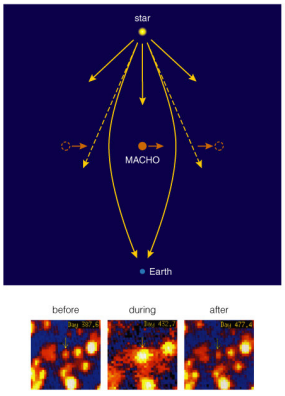
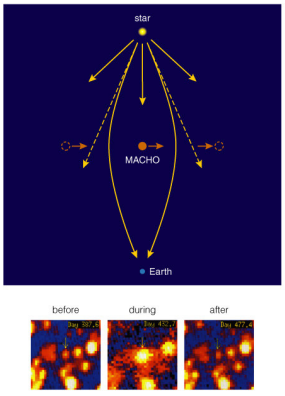
The Best Bet



MACHOs occasionally make other stars appear brighter through lensing



MACHOs occasionally make other stars appear brighter through lensing

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

Why Believe in WIMPs?

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

What have we learned?

- 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 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

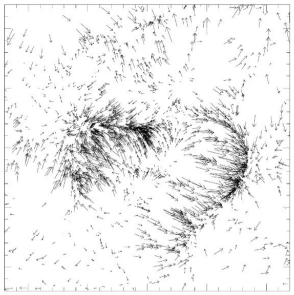
What have we learned?

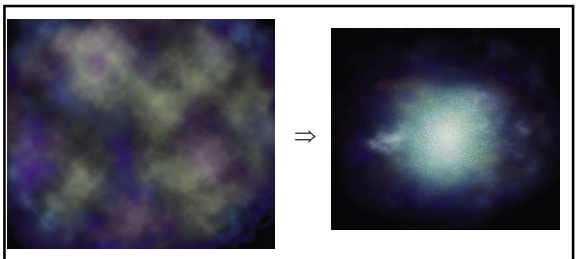
- Does dark matter really exist?
  - Either dark matter exists or our understanding of our gravity must be revised
- What might dark matter be made of?
  - There does not seem to be enough normal (baryonic) matter to account for all the dark matter, so most astronomers suspect that dark matter is made of (non-baryonic) particles that have not yet been discovered

22.3 Structure Formation

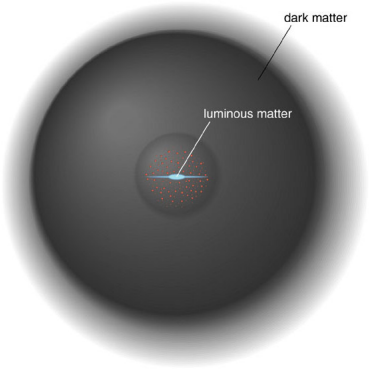
- Our goals for learning
- What is the role of dark matter in galaxy formation?
- What are the largest structures in the universe?

What is the role of dark matter in galaxy formation?

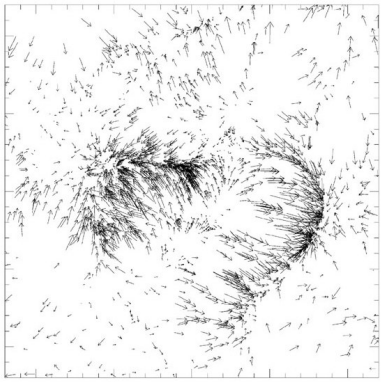




Gravity of dark matter is what caused protogalactic clouds to contract early in time



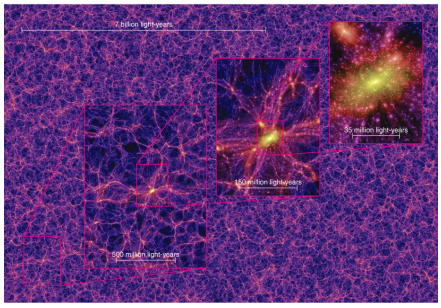
WIMPs can't contract to center because they don't radiate away their orbital energy

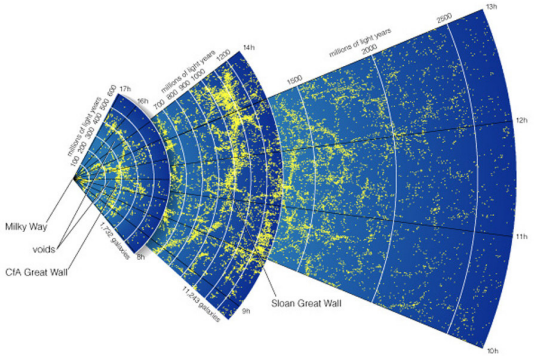


Dark matter is still pulling things together

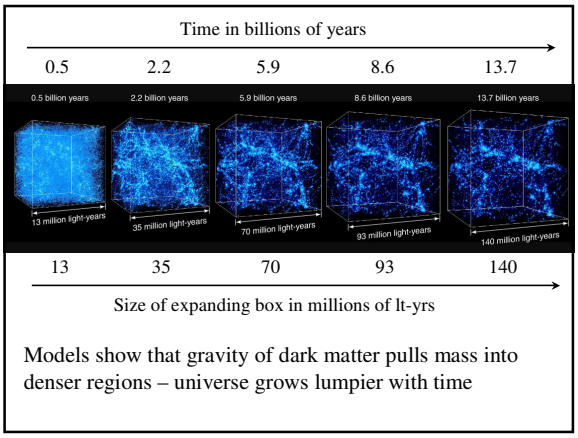
After correcting for Hubble's Law, we can see that galaxies are flowing toward the densest regions of space

What are the largest structures in the universe?

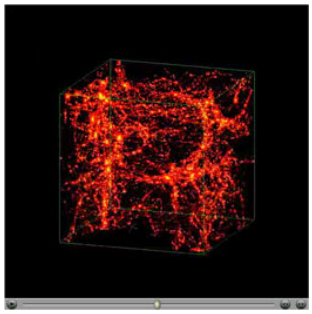




Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***



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



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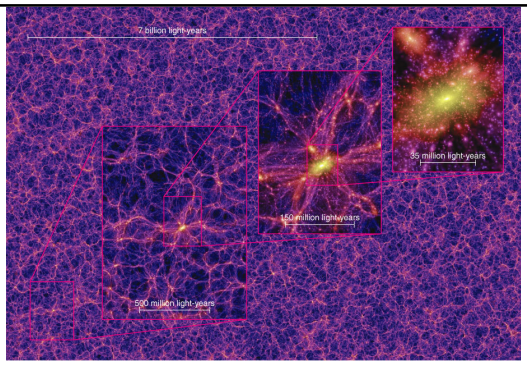


Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs

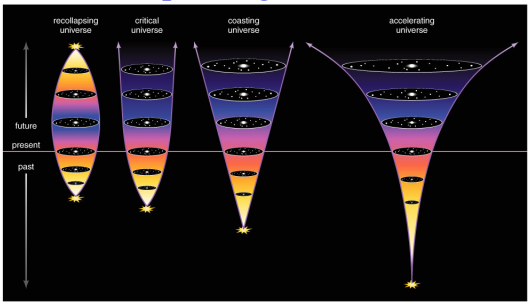
What have we learned?

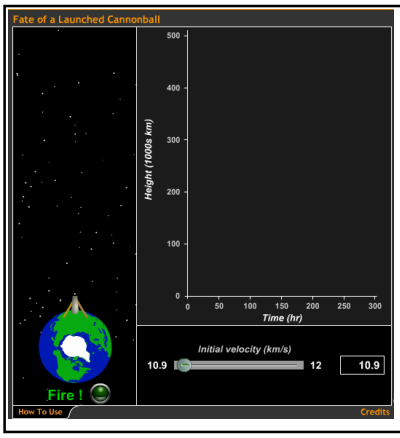
- What is the role of dark matter in galaxy formation?
  - The gravity of dark matter seems to be what drew gas together into protogalactic clouds, initiating the process of galaxy formation
- What are the largest structures in the universe?
  - Galaxies appear to be distributed in gigantic chains and sheets that surround great voids

22.4 The Fate of the Universe

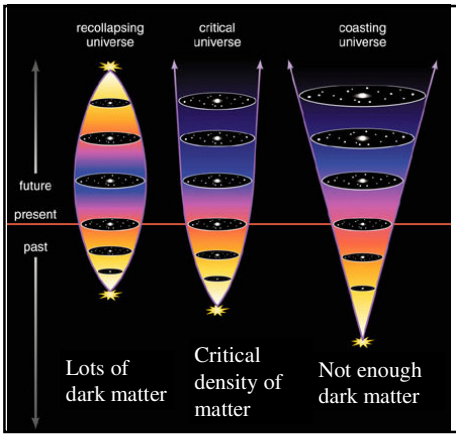
- Our goals for learning
- Will the universe continue expanding forever?
- Is the expansion of the universe accelerating?

Will the universe continue expanding forever?



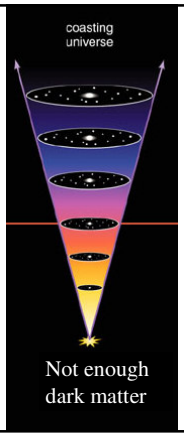


Does the universe have enough kinetic energy to escape its own gravitational pull?



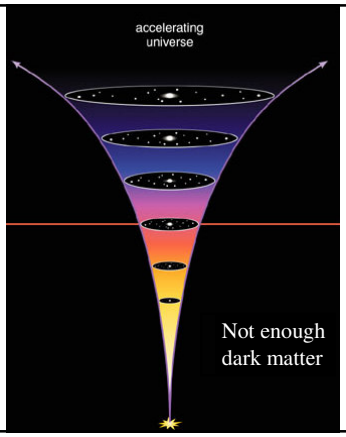
Fate of universe depends on the amount of dark matter

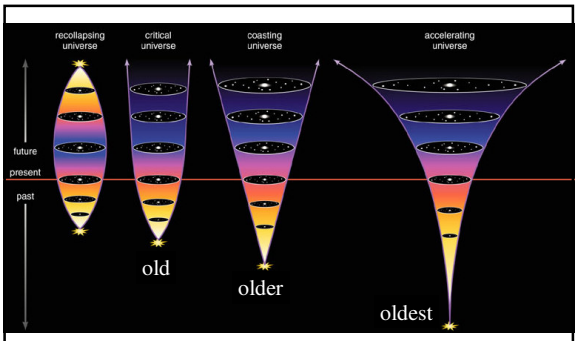
Amount of dark matter is ~25% of the critical density suggesting fate is eternal expansion



But expansion appears to be speeding up!

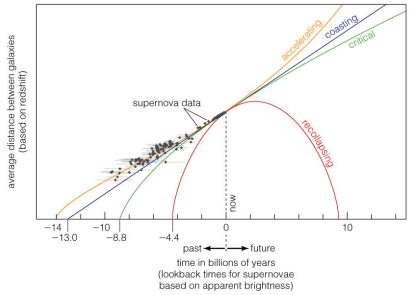
Dark Energy?





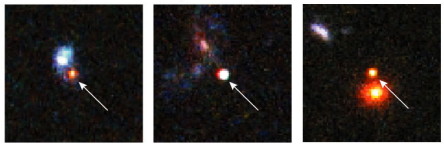
Estimated age depends on both dark matter and dark energy

Is the expansion of the universe accelerating?

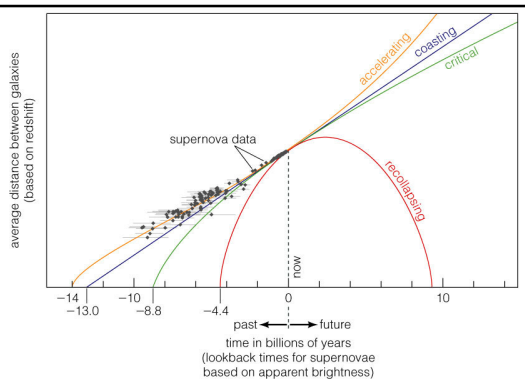


Distant galaxies before supernova explosions

The same galaxies after supernova explosions



Brightness of distant white-dwarf supernovae tells us how much universe has expanded since they exploded



Accelerating universe is best fit to supernova data

What have we learned?

- Will the universe continue expanding forever?
  - Current measurements indicate that there is not enough dark matter to prevent the universe from expanding forever
- Is the expansion of the universe accelerating?
  - An accelerating universe is the best explanation for the distances we measure when using white dwarf supernovae as standard candles