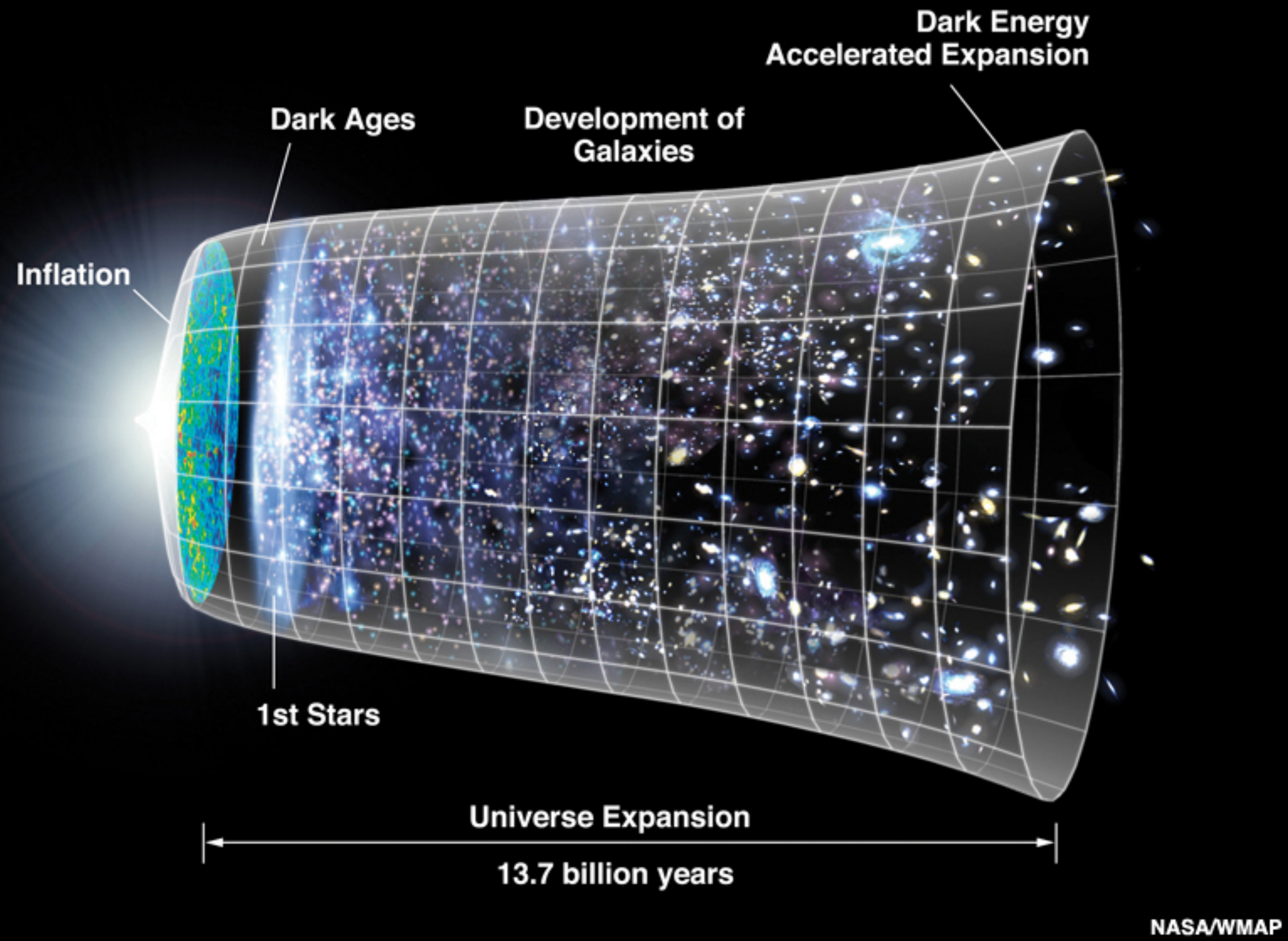
Lecture 26: **Dark Energy** and the Fate of the Universe

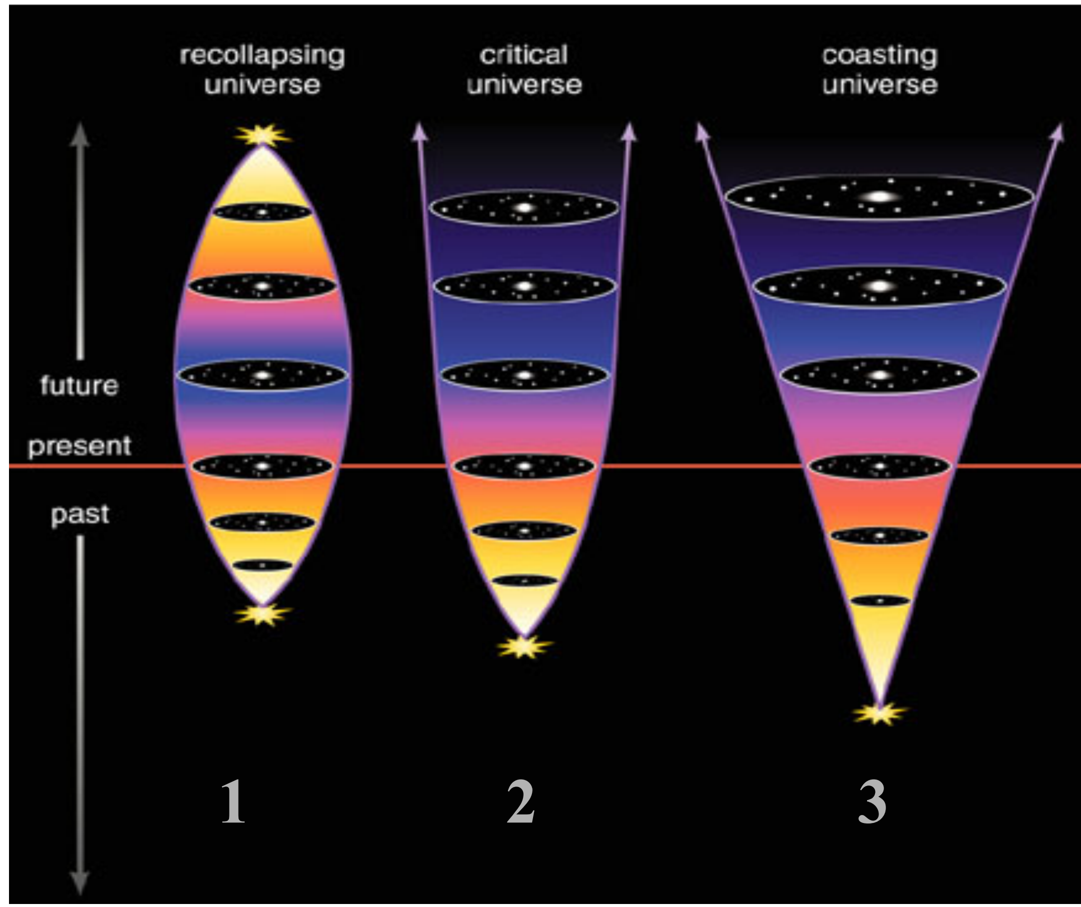


The Fate of the Universe

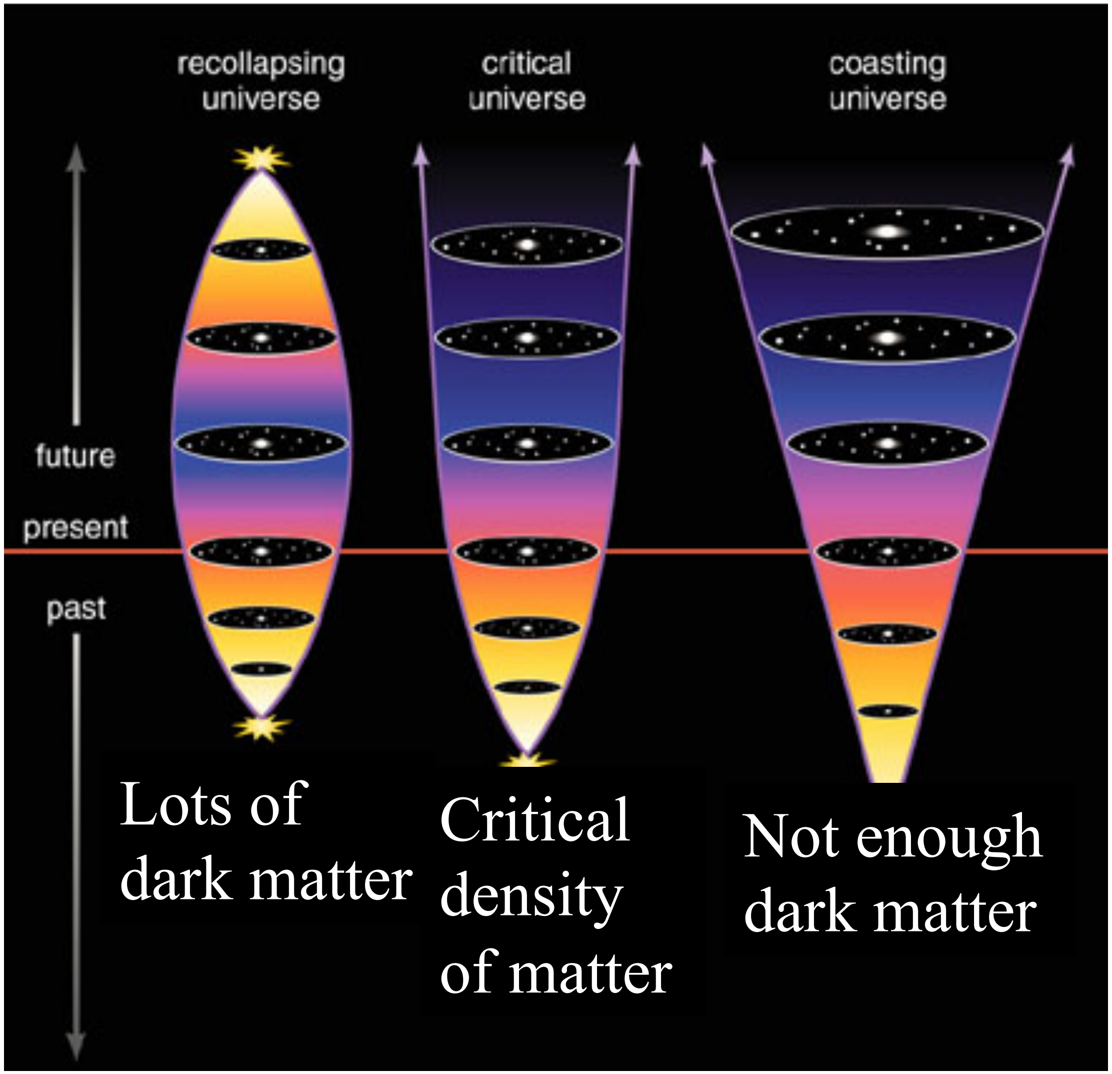
Will the expansion of the universe:

1. Stop & recollapse? (closed universe)
2. Expand more slowly over time? (critical universe)
3. Expand at a constant rate? (coasting/open universe)

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



Expansion of universe



It depends on the total gravity!

- Visible matter <1% needed to halt expansion
- *Fate of universe depends on the amount of dark matter*

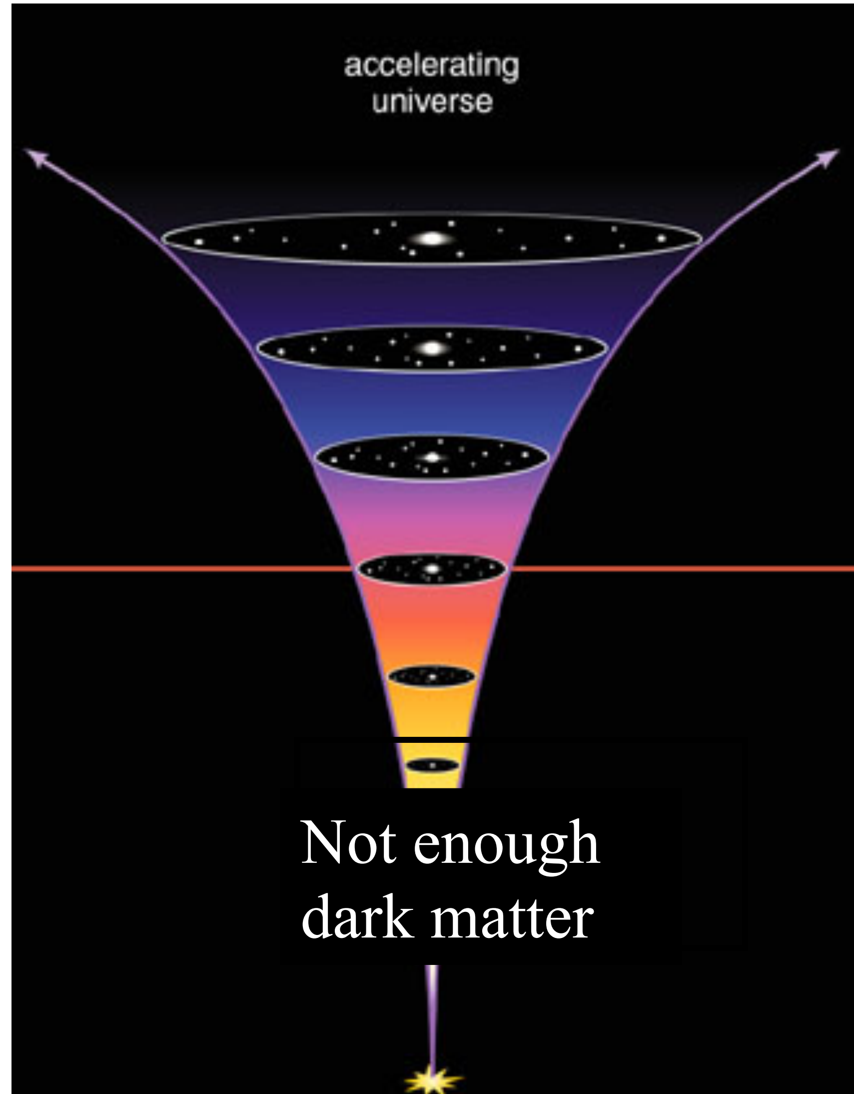
Amount of *total* matter is ~25% of the **critical density**, suggesting fate is eternal expansion

Dark Energy

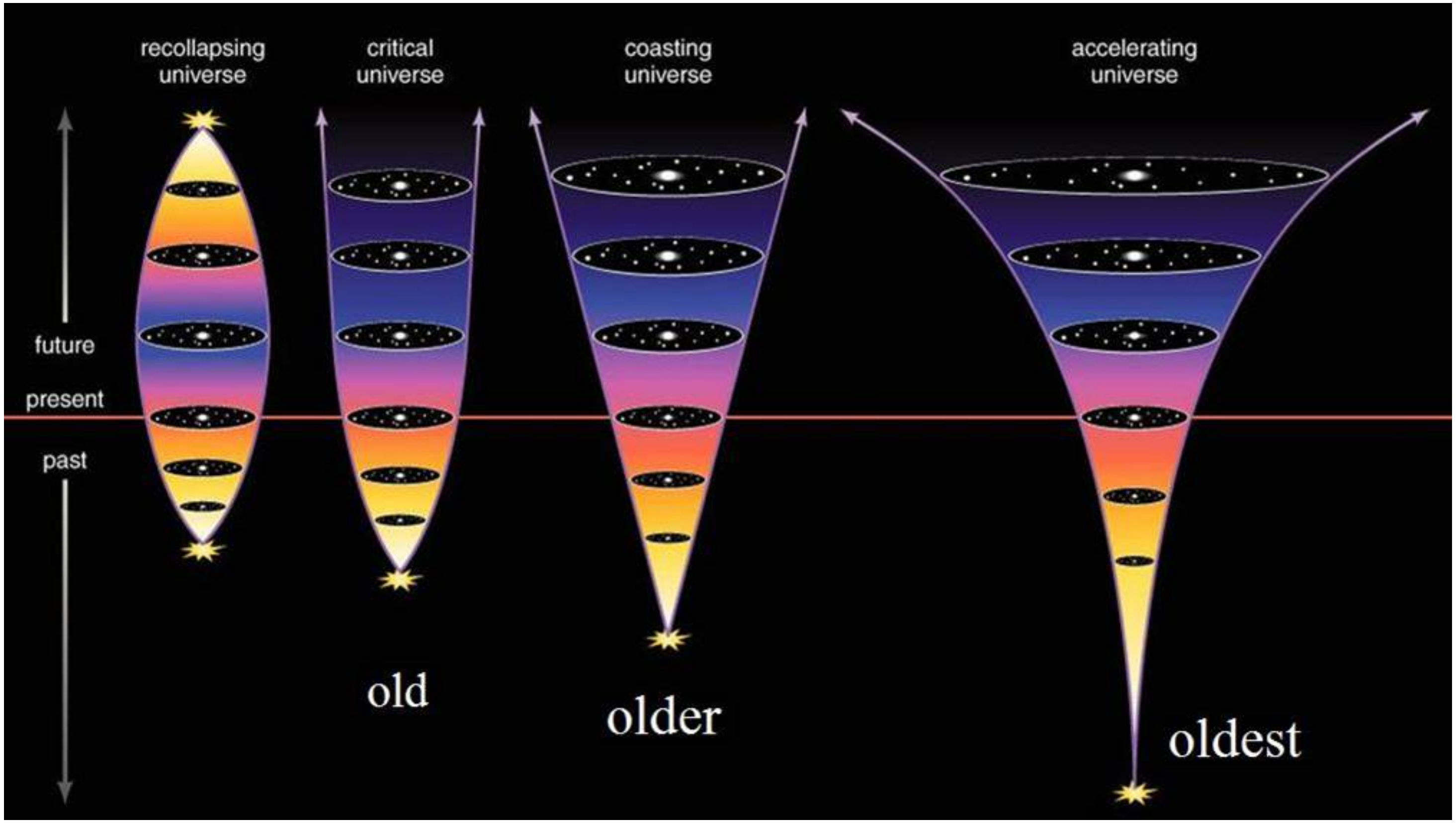
But expansion appears to be *speeding up!*

What could be causing it?

Dark ***energy***



Dark Energy



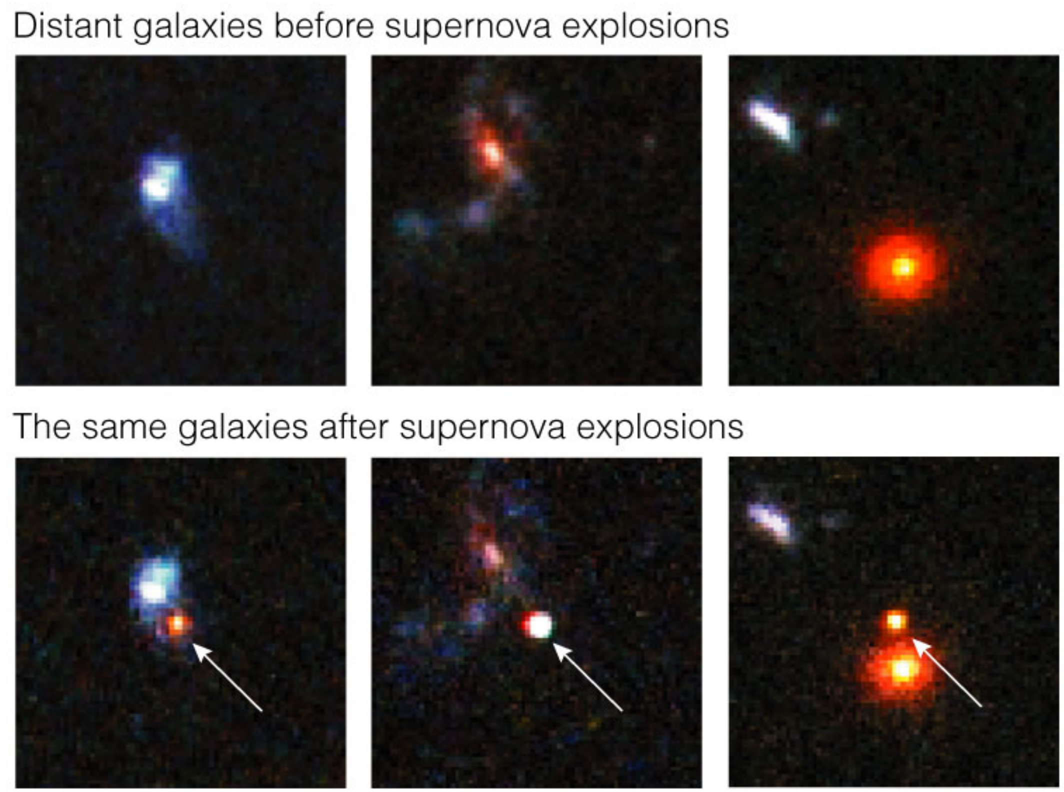
Therefore, the fate of the universe depends on the amount of *both* dark matter and dark energy.

Expansion Rate

How can we measure if the expansion rate has changed?

First, we can measure how far away distant galaxies are.

- The **brightness** of Type I SN tells us their **distance** and how much the universe has expanded since they exploded.
- Supernovae appear *dimmer* than expected. Therefore, they are *farther away.*
- *Greater distance in same time implies faster velocity* ***today.***



Expansion Rate

How can we measure if the expansion rate has changed?

Next, we measure the velocity at various distances.

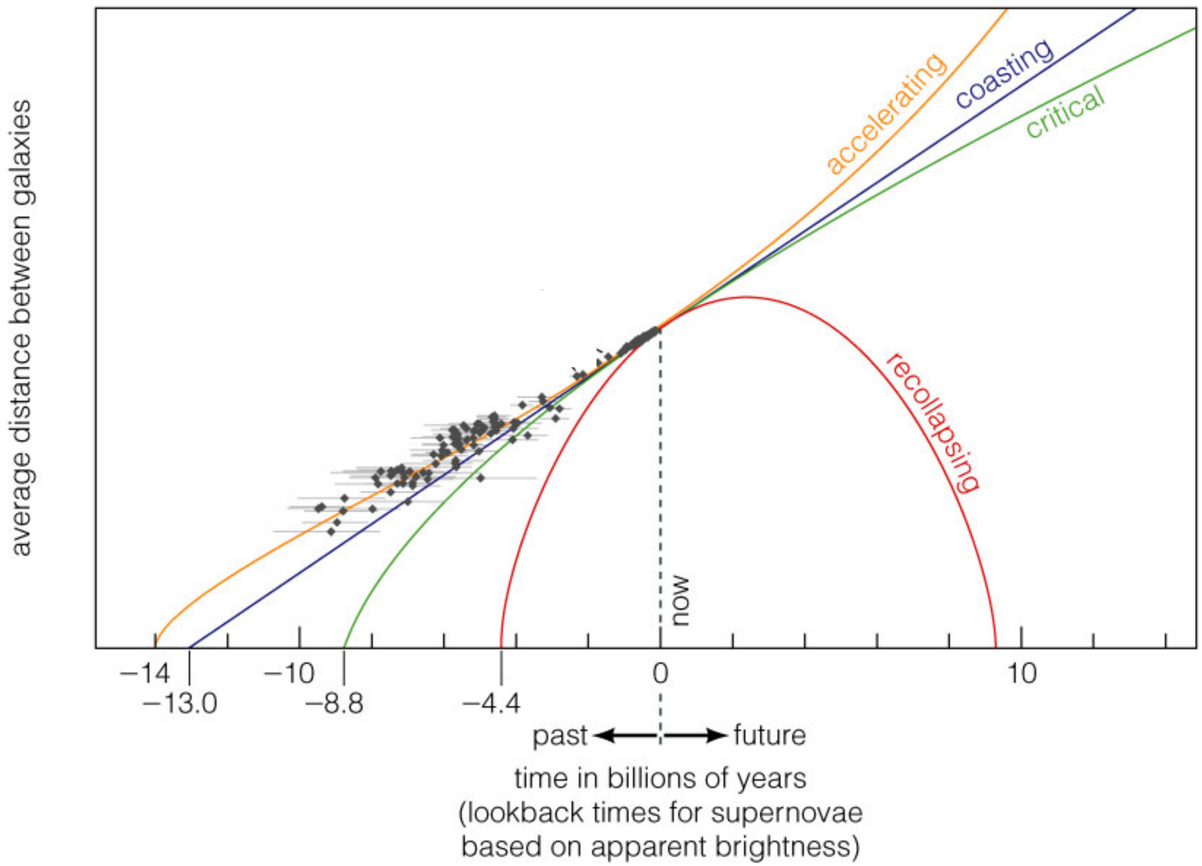
- The **brightness** of white-dwarf SN tells us their *distance.*
- The **redshift** of these SN tell us their *velocity.*

Example: If the radial velocity at 1 billion light-years = 1000 km/sec, what is radial velocity at 5 billion LY?

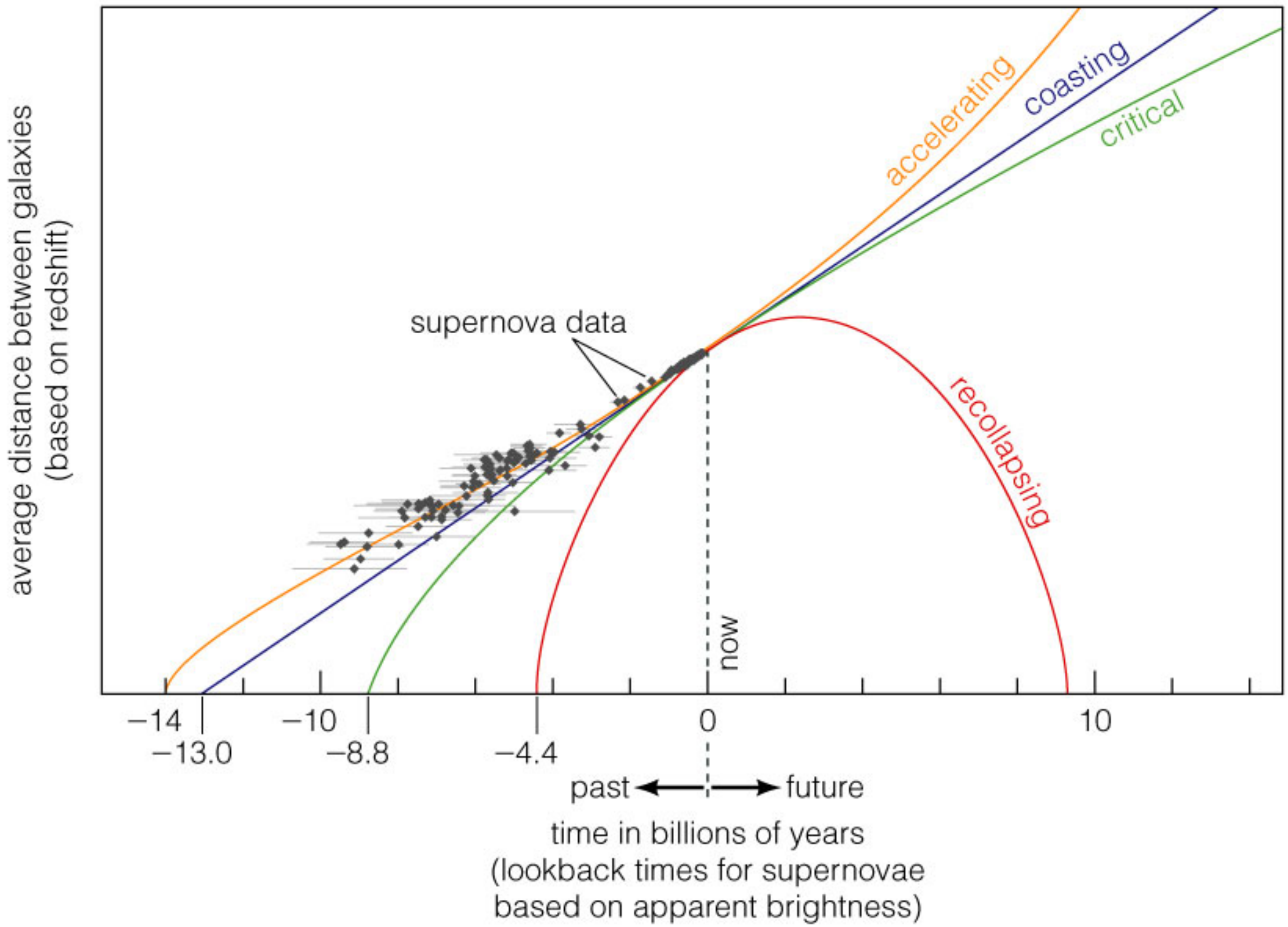
Distance	Velocity	Expansion	Universe
5 billion ly	500 km/sec	Speeding up	Accelerating
5 billion ly	1000 km/sec	Steady	Coasting
5 billion ly	1500 km/sec	Slowing down	Critical/closed

Note: A greater velocity at greater distance means ***we*** are moving away from the distant galaxy more quickly – expansion rate is *increasing*.

How do we know the expansion of the universe is accelerating?



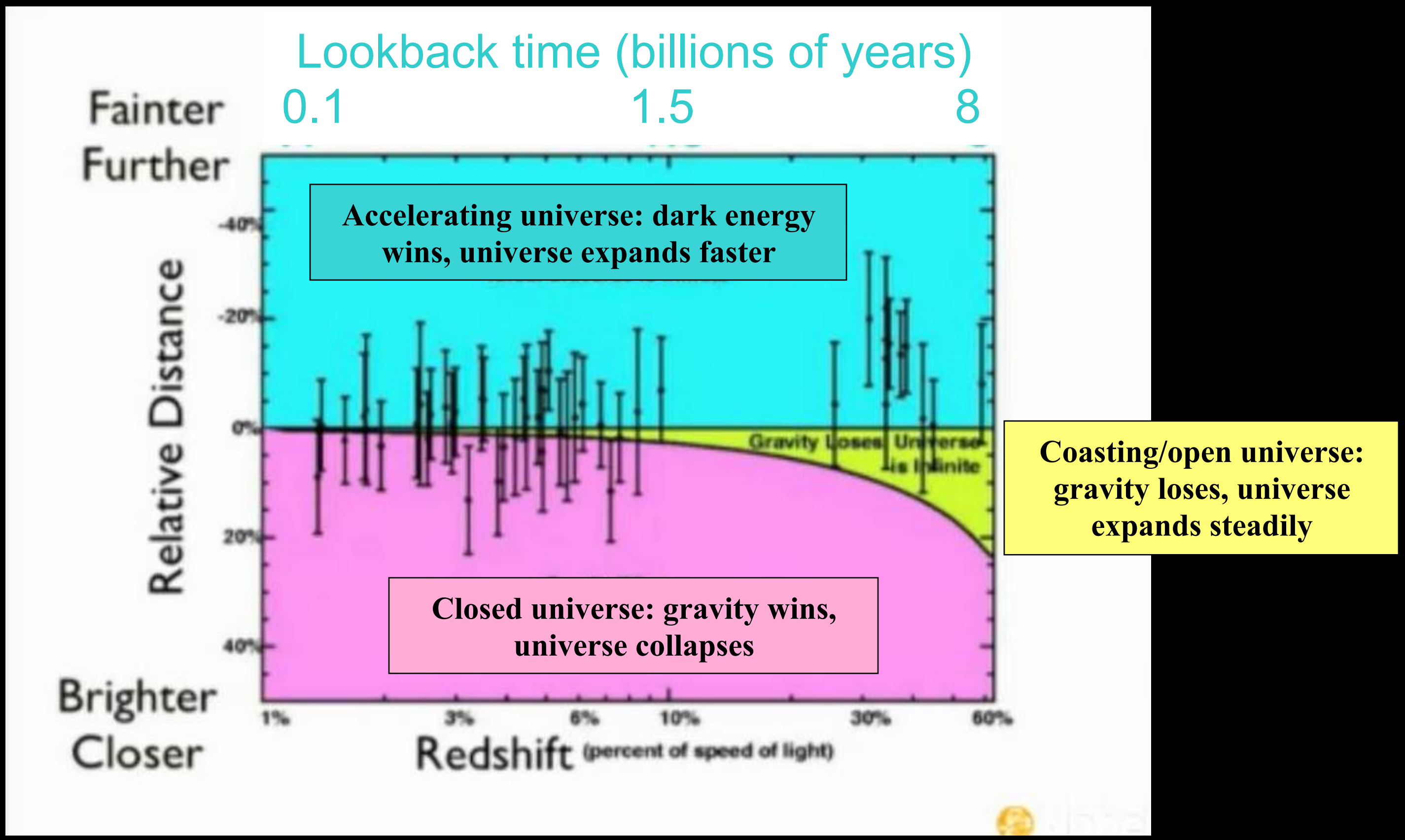
Greater distance in same time implies faster velocity ***today.***



*An **accelerating** universe is the best fit to supernova data.*

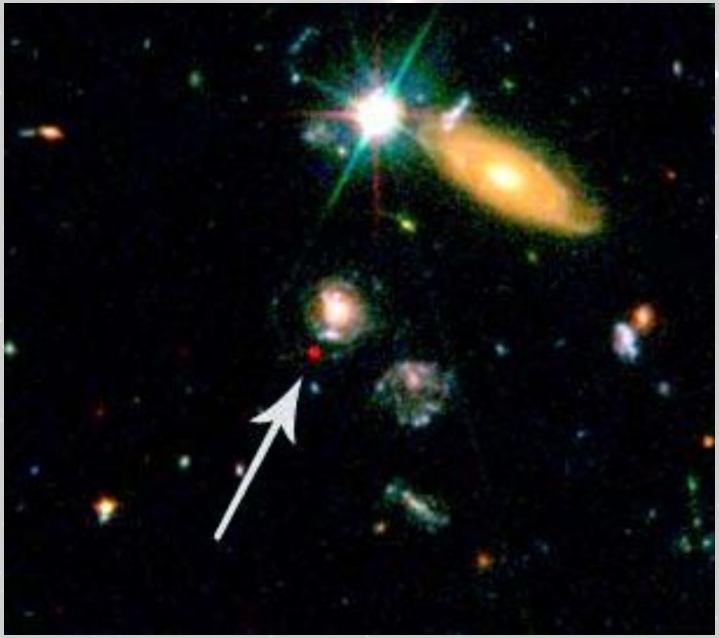
Dark energy: An unknown form of energy exerts a repulsive force causing the expansion of the universe to accelerate.

Results



- Redshift = velocity
- *Expansion rate is not constant at varying distances*
- *Greater distance at same velocity = faster expansion*
- ***Greater velocity at same distance = faster expansion***

Dark Energy



The red spot is the glow of a supernova exploding at a distance of about 8 billion light-years.

- **Observation**: Distant supernovae fainter than expected, are more distant than in a steadily expanding universe. *The expansion of the universe has accelerated over time and is faster today.*
- **Hypothesis**: The space between galaxies is filled with "**dark energy**", which exerts a negative pressure resulting in a "repulsive" gravitational force on all matter.
- **Conclusion:** *Dark energy causes the expansion of the universe to accelerate*, rather than slow down as in a steadily expanding universe.

Dark Energy

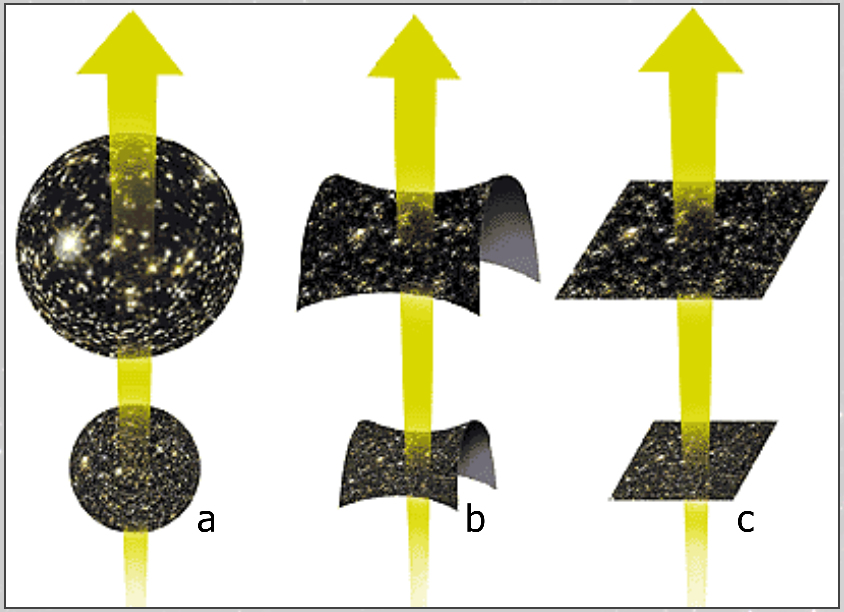
The gravity of the matter in the universe opposes the expansion of the universe.

The geometry of the universe could be:
1.“Closed“ - eventually stops expanding and re-collapses because of gravity
2.“Flat“ - expansion would slow but never quite stop
3.“Open," - gravity is insufficient to keep it from expanding steadily forever

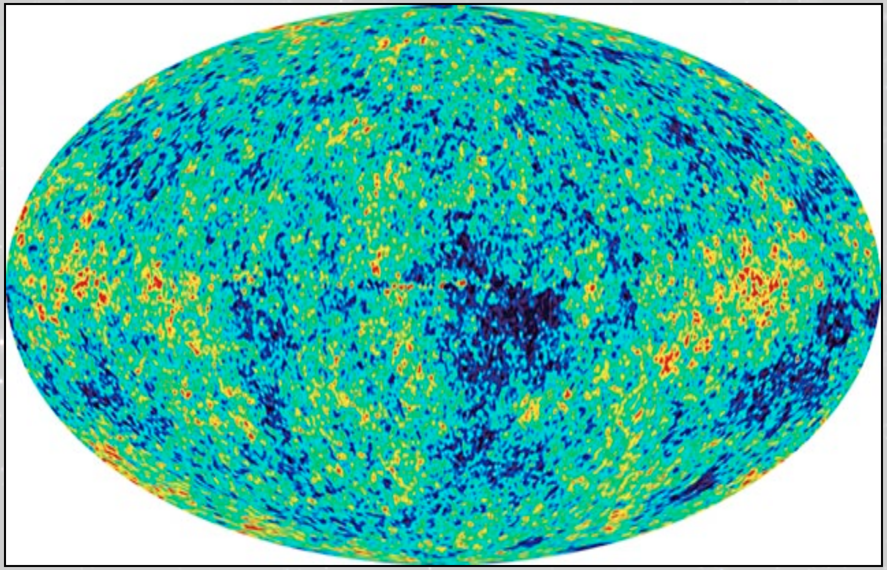
The density is too small to stop the expansion and close the universe; an open universe.
But observations show that the universe is actually flat! How can this be?

The overall shape of space-time can be:

a) **Positive curvature:** like the surface of a sphere. A **closed universe** would eventually collapse.
b) **Negative curvature:** like the surface of a saddle An **open universe** would expand forever.
c) **Flat space:** like a sheet of paper. A **flat universe** expands more and more slowly but never quite stops.



More Evidence for Dark Energy

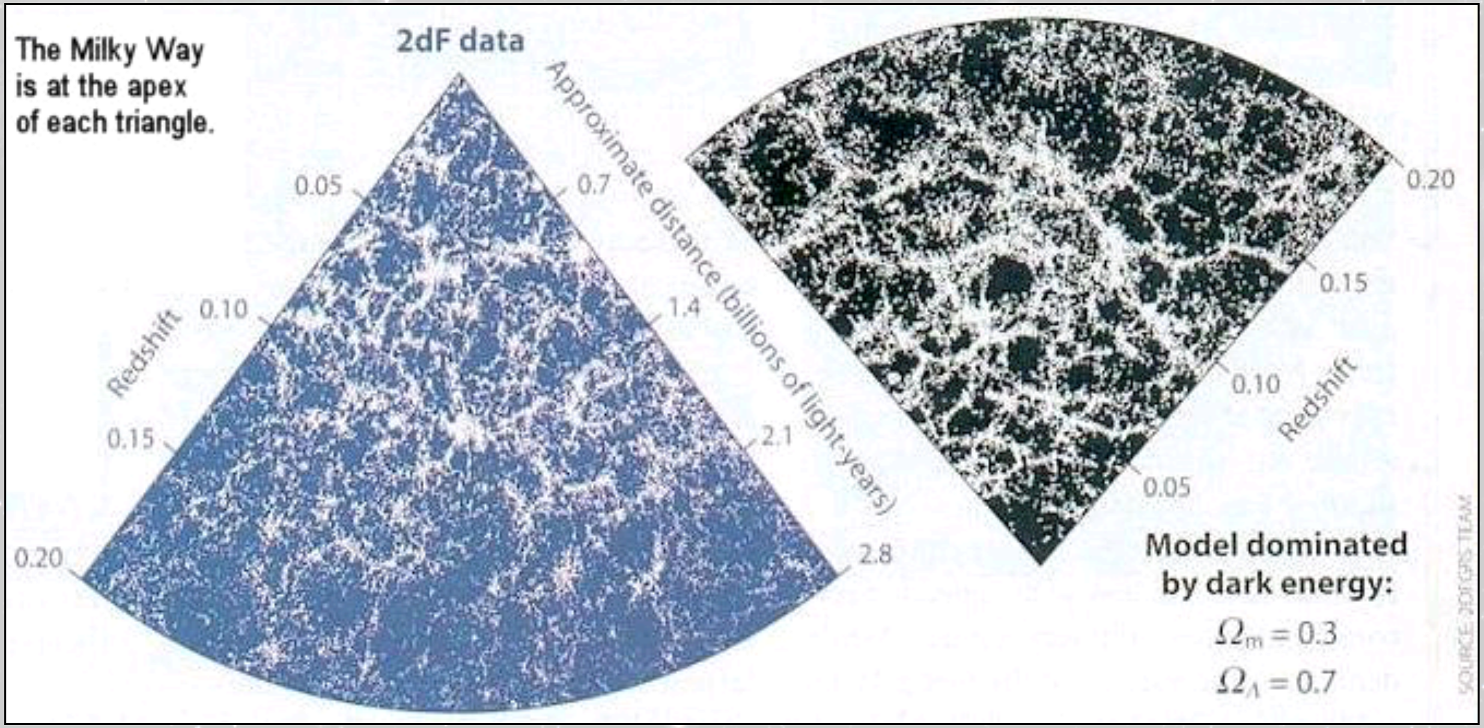


- The **Cosmic Microwave Background** (CMB) is leftover radiation from the Big Bang and shows small fluctuations about 1 degree across.

- *This size of fluctuations matches predictions for* ***a "flat" universe***. But <u>visible and dark matter are insufficient to make it flat; therefore *something must provide the missing "**mass** or **energy**" to make the universe flat*.</u> That something is dark energy.

- The total mass of the universe is far less than the amount needed to make the universe "flat", yet it is. Remarkably, *when dark energy is added to the mass-energy of visible and dark matter, the total can make the universe flat*.

More evidence for Dark Energy



A third line of evidence for dark energy comes from how galaxies are arranged in large-scale structures. *The effect of dark energy balances the effect of dark matter*.

While dark matter increases the size and density of “clumps”, dark energy would have an opposite effect on galaxy clusters (sheets, walls, and voids). Maps of the universe’s structure closely matches a universe with dark energy.

Still more evidence for Dark Energy

- **Galaxy clusters change over time.** Here purple emission is very hot gas detected in X-rays; the optical image shows galaxies.

- The gravity of a cluster's mass fights against increasing expansion caused by dark energy.

- Observations show **early galaxy clusters are more massive than recent ones**. Their growth has slowed over time due to **dark energy resisting gravity and spreading them apart.**

Think/Pair/Share

How does dark energy explain the “shape” of the universe?

A. Dark energy explains the clumping of matter into huge superclusters and immense voids.
B. It counteracts dark matter’ s gravity, slowing the expansion of the universe.
C. Dark energy explains Hubble’ s Law of universal expansion.
D. The total mass/energy of the universe is less than critical amount needed to make the universe "flat”, yet it is flat.

Think/Pair/Share

How does dark energy explain the “shape” of the universe?

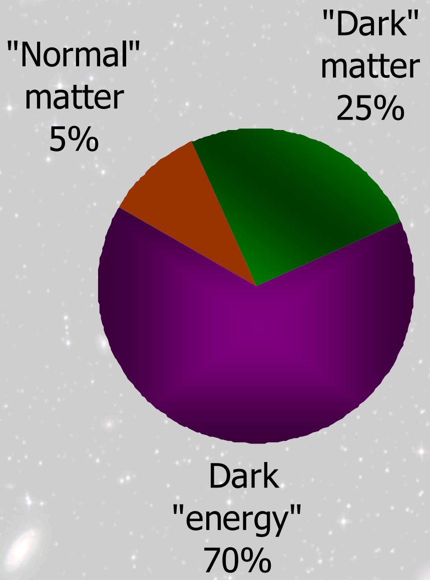
A. Dark energy explains the clumping of matter into huge superclusters and immense voids.
B. It counteracts dark matter’s gravity, slowing the expansion of the universe.
C. Dark energy explains Hubble’s Law of universal expansion.
D. The total mass/energy of the universe is less than critical amount needed to make the universe "flat”, yet it is flat.

A census of the universe

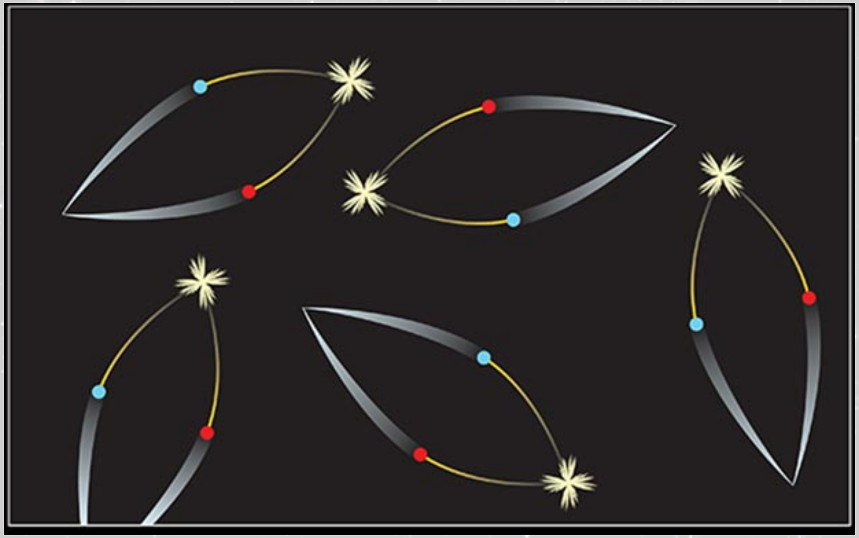
- In the early, smaller universe, gravity dominated over this energy and maintained a constant expansion of universe.
- But as universe expanded and matter separated, dark energy began to dominate over gravity, accelerating the expansion.

This chart illustrates the overall composition of the universe.

"Normal" visible matter:	~ 5%
Normal matter inside stars:	~ 1%
Normal matter outside stars:	~ 4%
Dark matter:	~ 25%
Dark energy:	~ 70%



Virtual particles



So *what is dark energy? What could cause a universal repulsive force?*

Quantum physics allows **“virtual particles” to pop into and out of existence** (as long as they do so very quickly and annihilate each other). **These could impart energy to and stretch spacetime**.

- (Virtual particles are real and have observable effects - the Casimir effect, where forces between metal plates are affected by virtual particles).

As this process occurs throughout the universe, the amount of dark energy density appears to remain the same no matter how much space expands!

Summary

- Since energy and mass are equivalent ($e = mc^2$), *dark energy has a gravitational effect.* **Vacuum energy** is the energy density of empty spacetime.
- The density of dark energy ($\sim 7 \times 10^{-30}$ g/cm^3) is very low, much less than ordinary or dark matter. However, it dominates the universe as it is consistent across ALL of space.
- One example of vacuum energy are **virtual particle pairs** that pop into existence but annihilate too quickly to observe (Heisenberg's **uncertainty principle)**. These may stretch spacetime during their brief existence.
- Two other possible forms for dark energy:
  – the **cosmological constant**, a constant *energy density filling space homogeneously*
  – **Quintessence**, a dynamic quantity whose *energy density varies in time and space.*

What have we learned?

Begin 3 minute review

What have we learned?

What is dark energy?

Current measurements indicate there is not enough dark matter to prevent the universe from expanding forever.

"**Dark energy**" is energy causing the expansion of the universe to accelerate.

How do we know the expansion of the universe is accelerating?

An accelerating universe is the best explanation for the expansion rate measured using white-dwarf supernovae.

CMB indicates a flat universe but matter is insufficient to cause this.

Clumping of galaxy clusters is balanced by dark energy's repulsive effect.

Galaxy clusters are less massive than in early universe.