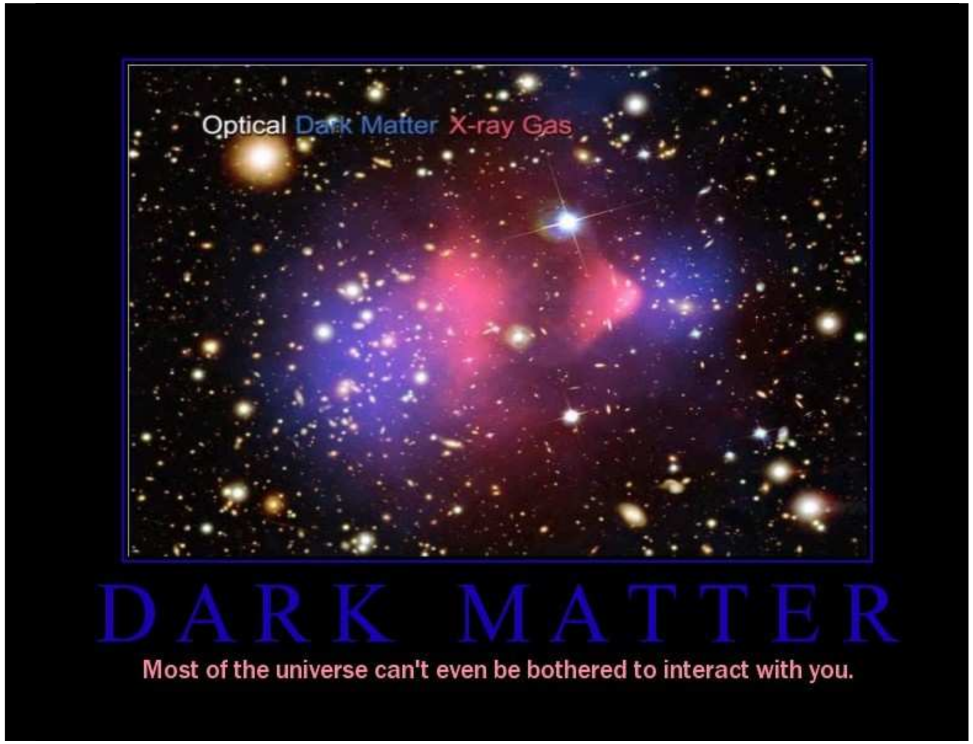



What would the rotation curve (i.e. plot of orbital speed versus distance from center) of the galaxy look like if the mass of the black hole at the center were much greater than the mass of everything else in the galaxy?

- A ...the speed of the objects in orbit would increase.
- B ...the rotation curve of the galaxy would decrease more rapidly than the observed rotation curve but not as rapidly as the predicted curve from the distribution of luminous matter....
- C The curve would fall off even slower then the expected or observed, because there would be more gravity.
- D the curve would be more concave because the high force of the gravity from the black hole. the black holes gravity is so great that no light escapes the pull of its gravity
- E We would observe a Keplerian rotation curve (like the one we observe in the solar system).

What fraction of the mass in the Solar System is composed of Dark Matter? (Choose the closest.)

- A 0%
- B 10%
- C 50%
- D 90%
- E 100%

**Dark Matter** : smoothly distributed.

**Solar System** : Keplerian rotation curve

...thus ≈all Solar System mass is at the center (Sun)

*No significant smoothly distributed contribution*

Our general region of the Galaxy

Dark Matter : $\approx 10^{-23}$ g/cm$^3$ $\approx$ 0.15 $M_\odot$/pc$^3$

Normal Matter : $\approx 10^{-23}$ g/cm$^3$ $\approx$ 0.15 $M_\odot$/pc$^3$
(stars & gas)

Dark Energy : $6.7\times10^{-30}$ g/cm$^3$ = $10^{-7}$ $M_\odot$/pc$^3$

Inside the orbit of Pluto:

$$\text{Volume} = \frac{4}{3}\pi(40\ \text{AU})^3 = \frac{4}{3}\pi(1.9\times10^{-4}\ \text{pc})^3$$

$$\text{Volume} = 2.9\times10^{-11}\,\text{pc}^3$$

$$\text{Density} = \frac{1\ M_\odot}{2.9\times10^{-11}\,\text{pc}^3}$$

$$\text{Density} = 3.5\times10^{10}\,M_\odot/\text{pc}^3 = 2\times10^{-12}\ \text{g/cm}^3$$

## Our general region of the Galaxy

Dark Matter : $\approx 10^{-23}$ g/cm$^3$ $\approx$ 0.15 $M_\odot$/pc$^3$

Normal Matter : $\approx 10^{-23}$ g/cm$^3$ $\approx$ 0.15 $M_\odot$/pc$^3$
(stars & gas)

Dark Energy : $6.7\times10^{-30}$ g/cm$^3$ = $10^{-7}$ $M_\odot$/pc$^3$

## The Universe as a whole

Dark Matter : 2.4x$10^{-30}$ g/cm$^3$ = $3.5\times10^{-8}$ $M_\odot$/pc$^3$

Normal Matter : 0.5x$10^{-30}$ g/cm$^3$ = $0.7\times10^{-8}$ $M_\odot$/pc$^3$
(stars & gas)

Dark Energy : $6.7\times10^{-30}$ g/cm$^3$ = $10.\times10^{-8}$ $M_\odot$/pc$^3$

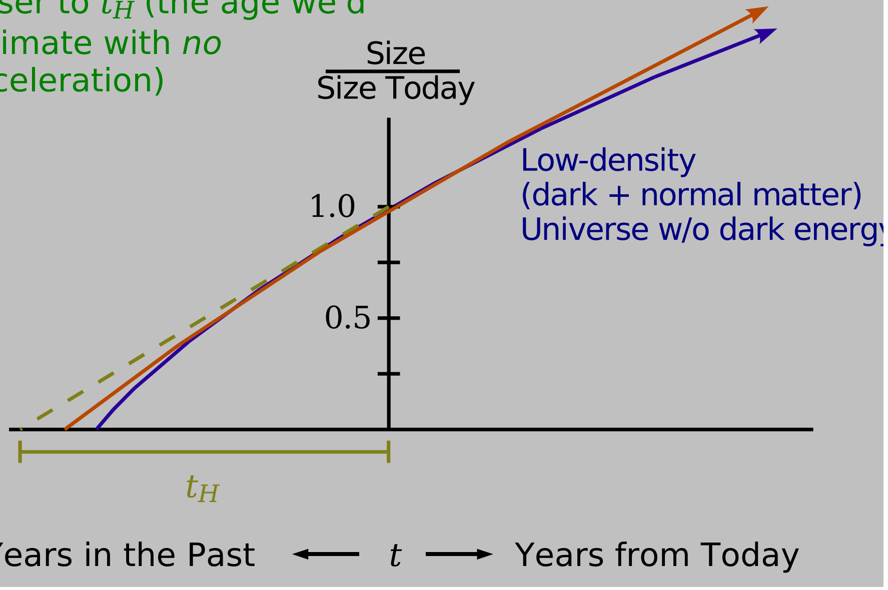
*The Galaxy is a region of enhanced matter density; the Solar System is a region of very enhanced normal matter density!*

*Cup your hands...*

...you are holding:

- $\approx 10^{-21}$ g of dark matter
- $\approx 7\times10^{-28}$ g (equivalent) of dark energy
- $\approx$0.1 g of air (normal matter)

Without Dark Energy:
Less mass = less deceleration = curent age closer to $t_H$ (the age we'd estimate with *no* deceleration)




**Important Note about Dark Matter!!!**

Dark Matter *does not* block light. Light can be blocked by dust or other obscuring material. Dark Matter doesn't interact with light; it neither emits nor absorbs light.

(It's gravity can bend the path of light, just like the gravity of everything else.)

*So what is this freaky Dark Energy thing anyway?!?*

"The thing that is making the Universe's expansion accelerate."

Dark Energy is *not* Dark Matter – they're very different.

Newton's Gravity (the old, outmoded, very useful theory):

Source of gravity is $M$ (an object's mass)

Einstein's General Relativity (the way cool current theory)

Source of gravity is $\rho+3p$

$\rho$ – Energy density (Greek letter rho)
$p$ – Pressure

For normal matter :

$\rho$ comes almost entirely from mass ($E=mc^2$)
$p$ is insignificant unless particle speeds are near $c$

Vacuum Energy : leading candidate for Dark Energy
Vacuum Energy : $p = -\rho$

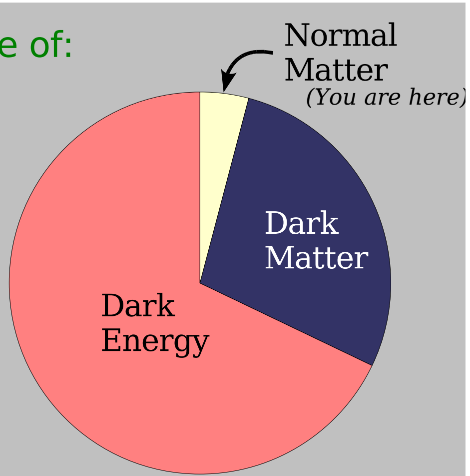
Vacuum Energy has *negative* gravity ⇒ acceleration

What the Universe is made of:

$\Omega_M$ Fraction of the Universe that is matter (normal + dark matter)

$\Omega_\Lambda$ Fraction of the Universe that is dark energy

$\Omega_b$ Fraction of the Universe that is "baryonic" (i.e. normal matter)




**From observations of galaxies and clusters, we need $\Omega_M \approx 0.3$.**