Ordinary Matter vs Dark Matter

- Matter occupies 30% and dark energy occupies 70% of the energy of the universe at present.
- What do we mean by "matter"?
 - Ordinary matter: atoms
 - Atoms exist in the form of gas (most), plasma, dust, rocks, liquid
 - Extra-ordinary matter: dark matter
 - Dark matter (is believe to) exist in the form of freelymoving particles
- How much does the ordinary matter exist? What about dark matter? How can we tell?

Weighing Atoms

- Where are atoms?
 - Hot gas in clusters of galaxies
 - Warm gas in the intergalactic medium
 - Cold gas in hydrogen clouds

All Gas







• "Cold" (T<0.1 million K) hydrogen clouds absorb background light.

- They appear as "dark clouds"
- They are also called the "Lyman-alpha clouds"

Cold Clouds



Lyman-alpha Forest



• Quasars are so bright that they can be used as a "lighthouse" which sheds light on Lyman-alpha clouds.



Hot Gas in Clusters

- Hot gas in clusters of galaxies emits Xray via "*bremsstrahlung*" (stopping radiation)
 - The X-ray luminosity is determined by the amount of gas.
 - Dark matter emits nothing.
- X-ray luminosity \rightarrow Gas mass
- Gravitational lensing \rightarrow Total mass
- Clusters represent the cosmic mean $-f = (Gas mass)/(Total mass) = \Omega_{atoms} / \Omega_{m}$
- Observations suggest $f \sim 0.16$ - $\Omega_{atoms} = f \Omega_m \sim 0.05$







• Comparing the measured abundance with theory, $\Omega_{atoms} = 0.05$ has been obtained.

Implications

- The presence of dark matter was first suggested by the rotation curve of galaxies.
- Cosmological measurements weighing atoms suggest that we have too few atoms $(\Omega_{atoms} = 0.05)$ to explain $\Omega_{m} = 0.3$.
 - Therefore, dark matter is not made of atoms.
- 70%: Dark energy
- 25%: Dark matter
- 5%: Atoms (visible)
- 95% of the energy of the universe is dark.

Warm Gas in the IGM

- Warm gas is difficult to see.
 - It is too warm to absorb light via hydrogen lines.
 - It is too cold to emit X-rays.
- It can emit or absorb light via Oxygen lines
 - Oxygen lines have higher energy than hydrogen lines, but not quite as high as X-rays.
- There is little doubt that such gas exists, but no one has been able to map this gas yet (this is a tough measurement)
 - Hopefully in near future it will be measured definitively...





