# Lecture 37: Dark Matter & Dark Energy
## Readings: Sections 26-8 and 28-7

## Key Ideas
Dark Matter
- Matter we cannot see directly with light
- Most of the matter in the Universe?
- Detected only by its gravity
  - Rotation Curves of Spirals
  - Velocity "Dispersion" in Ellipticals
  - Velocity Dispersion in Clusters of Galaxies
  - Gravitational Lensing by Clusters of Galaxies
- Possible Dark Matter Candidates
  - Baryonic (detected with microlensing)
  - Non-baryonic (has to be some!)

Dark Energy
- Vacuum energy of the Universe
- Responsible for acceleration of the Universe's expansion
- Detected in Hubble diagram of distant Type Ia Supernovae

Dark Matter/Energy or New Form of Gravity
- Solar System Examples

## Galaxy Rotation Curves Revisited
Spiral Galaxies rotate such that:
- Speed rises from the center to the inner disk
- Speed becomes constant (flat) in the outer disk
- Requires Dark Matter to explain such high speeds so far away from most of the visible matter in the galaxy.

## Mass Distribution in Galaxies
Most of the stars are in the inner 10 kpc

If stars provided all of its mass we expect
- Rotation speed should rise to a *maximum* in the inner parts
- Then *fall steadily* with radius outside of R~10 kpc

But the rotation curve stays flat!
- Outer parts are rotating *faster* than expected

Need <u>more mass at large radii</u> than is observed in the stars and gas alone.

## Dark Matter in Elliptical Galaxies

*Velocity dispersion*=spread in speeds of stars. Greater if there is more matter. Way to detect matter that is "dark" in elliptical galaxies (or clusters of galaxies) that don't have systematic rotation.

## Dark Matter in Galaxy Clusters

1933: Fritz Zwicky measured the motions of galaxies in the Coma cluster
    Found velocities of +/- 1000 km/sec relative to the cluster center
    This is greater than the escape velocity computed by adding up the light of the cluster!
Zwicky suggested that "dark matter" adds extra gravity to hold the cluster together.

*Subsequent observations show that galaxy clusters are 90-99% dark matter.*

## Coma Cluster

X-ray gas in cluster is extremely hot=particles moving very fast
Need lots of matter to keep X-ray gas in clusters from escaping.

## Gravitational Lensing in a Rich Cluster

Einstein's theory predicts that light will be bent by matter.
Again, lots of matter (more than seen in visible light) is needed to explain the amount of bending we observed.

## Dark Matter

Called "Dark Matter" because it cannot be detected directly using light.
It is only detected by its *Gravitational Effects"*
    Outer parts of galaxies *rotate faster than expected* from the starlight
    Galaxies in clusters *orbit faster than expected* from the starlight
    Hot X-ray gas that would otherwise evaporate from a galaxy cluster stays confined.
*What is Dark Matter made of?*

## Baryonic Dark Matter

Ordinary matter ("baryons") made of protons & neutrons

Candidates

- Brown Dwarfs & Jupiter-sized planets
- Cold stellar remnants (black holes, neutron stars & white dwarfs)
- Primordial black holes (Big Bang leftovers)
- Frozen hydrogen snowballs

Collectively called

- Massive Compact Halo Objects (MACHOs)

## Gravitational Microlensing

If a MACHO passes between Earth & a more distant background star

- GR predicts that the MACHO's mass bends the starlight of the more distant star.
- Get a "Gravitational Microlens" that briefly magnifies the background star.

Chance alignments are very rare

- Most should last only for a few weeks
- Must monitor millions of stars for many years

Handy animation of microlensing model at
www.jpl.nasa.gov/releases/2004/103.cfm

Handy animation of an actual microlensing event at
bulge.princeton.edu/~ogle/ogle3/big235-53.html

## Microlensing Searches

Multi-year monitoring of LMC & SMC to search for microlensing from MACHOs

- Watched ~12 Million stars for 6 years
- Found only 13-17 halo microlensing events
- Most likely mass range ~0.15-0.9$M_{Sun}$ making them Jupiters up to white dwarfs

*MACHOs can make up only 20% of the halo of the Milky Way. So they are not the whole answer to the dark matter puzzle.*

## Not all Dark Matter is Baryonic

Big Bang nucleosynthesis sets a firm bound on the amount of baryonic matter in the Universe.

$\Omega_b$~0.04

If there was more "normal matter", then the $^2H$ would all fuse with other p, n, $^2H$, etc. and there would be no deuterium left in the Universe.

Therefore $\Omega_{nb}$ ~0.26

## Nucleosynthesis Depends on the Density of Baryons

Deuterium is very sensitive to the density of baryons in the first three minutes.

Higher Density=More Encounters

## Non-Baryonic Dark Matter

Fundamental particles that only interact via gravitation and the weak force

<u>Massive neutrinos</u>

Produced in large numbers in the Big Bang??

<u>Exotic new particles</u>

Predicted by some particle theories

Possible candidates makes dark matter a more attractive theory

Weakly Interacting Massive Particles: WIMPs

## Example of New Physics

Supersymmetry

For every standard particle, there is a corresponding supersymmetric particle

Electron—Selectron

Quark –Squark

Photon—Photino

Some of these particles are predicted to have masses, but to be weakly interacting.

Exactly what we want!

## Conservation Laws

Basic Idea:
  Before=After
Energy conservation
  Energy before=Energy after
Other quantities conserved
  Lepton number
  Nucleon number
  Momentum
Led to the discovery of the neutrino

## Axions

A type of particle proposed to conserve CP-symmetry
Frank Wilczek proposed to name the new particle after a brand of detergent, because it “cleaned up” this problem with QCD theory.
Properties of axions
  Low-mass (but not zero!)
  Very low probability of interaction
Just what we want!

## Dark Matter Annihilation

Depending on the kind of particle it is, the dark matter may be its own anti-particle.

Particle-particle annihilation changes mass into energy.

Detect this radiation as gamma-rays

Searches currently underway but
  Lots of sources of gamma-rays other than dark matter

How often dark matter annihilates is unknown

## Particle Dark Matter Searches

Attempts to directly dark matter

Estimate of the masses of neutrinos (must be very tiny)

Particle accelerator experiments searching for new massive particles in collisions

Searches for "cold dark matter" particles hitting the Earth from space and for gamma-rays from annihilation

*So far, no convincing detections have been reported, but the searches go on…*

## Dark Matter Summary

~90% of the matter in the Universe is unknown at the present

Active searches underway for the dark matter particles, both for DM-related reasons and to test new theories of physics.

It is possible that the dark matter could be not even weakly interacting with ordinary matter, but non-interacting. Detecting it in that case would be really tough!

## Dark Energy

Type Ia Supernova distances to galaxies have suggested that our Universe is:

Infinite

Spatially Flat ($\Omega_0$=1)

Accelerating ($\Omega_\Lambda$>$\Omega_m$)

The extra expansion is due to ***Dark Energy***

Extra energy filling the Universe

Acts to inflate the Universe against gravity

## What is Dark Energy?

We know even less about Dark Energy than we do about Dark Matter.

Cosmological Constant ($\Lambda$)

Vacuum energy component whose density is constant over cosmic history.

Generic Dark Energy

Could vary in density over cosmic time

Candidates include scalar fields, quintessense….

Very Low Density ($10^{-29}$gm/cm$^3$) but exists everywhere

## Matter & Energy Content of the Universe

$\Omega_m$ divided into

$\Omega_b$=0.04

stars=0.004

gas=0.036

$\Omega_{dm}$=0.26 (mostly non-baryonic)

$\Omega_\Lambda$=0.70

## A Radical Suggestion

Maybe Dark Matter & Dark Energy don't exist at all!

Is our theory of gravity wrong on large scales?

<u>Problems:</u>

None of the alternative theories of gravity have survived key tests of detailed predictions

Some alternatives aren't very testable!

Hard to reconcile these theories with observed gravitational lensing

## Examples from the Solar System

Motion of Mercury did not agree with Newtonian mechanics

Answer: *General Relativity*

Motions of Uranus did not agree with Newtonian mechanics

Answer: *New matter (aka Neptune)*

## The Precessing Orbit of Mercury

## New Theory of Gravity for the Solar System

Nineteenth century explanation

Small planet in the inner solar system affecting the orbit of Mercury

Planet called Vulcan, but never detected

Einstein’s explanation

Newton’s Law of Gravity gives incorrect answers in strong gravitational fields

General Relativity explains the orbit

## Discovery of Extra Matter in the Solar System

Uranus was discovered by Herschel in 1781.
Its motions deviated slightly from the predictions of Newton’s Laws.

In 1845, Urbain Leverrier & John Couch Adams independently argued that a new planet’s gravity could explain Uranus’ motion.

In 1846, Neptune was discovered by astronomers at the Berlin Observatory.

## Studying Dark Matter & Energy

An extremely active area of research

- Experimental
- Observational
- Theoretical

We’d really like to know what makes up the Universe!