Dark Matter in the Universe:

MACHOS, WIMPS and Little White Dwarfs

Evalyn Gates
Adler Planetarium
University of Chicago
COSMOLOGY

"If it's not dark, it doesn't MATTER"

science on the smallest
and largest scales

subatomic particles → nucleons → atoms → molecules → ... → galaxies → clusters → super clusters
What does our Universe look like?
What is it made of?
How old is it?
How will it end?
Where do we fit into this picture?
An ancient and still current question:

What is the Universe made of?
Expansion of the Universe

Run the movie backwards

BIG BANG
Large Scale Structure Formation

t → 0
15 billion years ago

? historic event

Hot Big Bang
- smooth, isotropic

galaxies
clusters
superclusters

today
Where is the matter?

- Most of the matter in the Universe is unseen (dark matter).
- Most of this dark matter is in the form of exotic new particles.
- But we haven’t found most of the ordinary matter either -- where is it?
Astronomers tell us that they can't find 90 per cent of the matter in the Universe. Just where is it?


Most astronomers can't find their car keys or their wallets, much less most of the missing matter in the universe. They spend most of their time searching for lost pens or pieces of chalk, so they can scribble indecipherable equations on the blackboard. Obviously they can't be expected to take care of mundane practical matters like storing the very stuff of creation. Besides, they assure us that it's cold, dark matter, so it's not likely to spoil, wherever it is. If I were you, I'd find another profession to pick on. How about plumbers?
Basically, we detect dark matter via its gravitational effects on something else.

1st evidence for dark matter: Zwicky (1930s)  
Coma Cluster of galaxies

Now have evidence on many scales, from the rotation curves of over 1000 spiral galaxies to gravitational lensing of clusters of galaxies
Dynamical Evidence for Dark Matter

Kepler's 3rd law $\rightarrow$ Newtonian gravity

\[ GM = \nu^2 r \]

works very well for our solar system:

Rotation Curve:

orbital velocity

distance
Newtonian prediction for solar mass = $2 \times 10^{30}$ kg
Galaxy NGC 4603
PRC99-19 • STScI OPO
J. Newman (University of California, Berkeley) and NASA
However, when we look at spiral galaxies (like our own) and measure the rotation curve out past where most of the luminous matter is found (via rare stars or gas clouds) we find flat rotation curves (velocity is constant)! 

[Diagram: Graph with axes labeled 'velocity' and 'distance from center', showing a flat line past a certain point, with a dashed line indicating what was expected.]
Weighing the Universe:

\[ \rho = \text{mass-energy density of Universe} \]

\[ \rho_c = \text{critical density} \]

\[ \Omega = \frac{\rho}{\rho_c} \]

\[ \Omega < 1 \quad \text{OPEN} \]

\[ \Omega = 1 \quad \text{FLAT} \]

\[ \Omega > 1 \quad \text{CLOSED} \]
News Headlines in 2000:
The Universe is **FLAT**!

Density of matter/energy in Universe is equal to the critical density
I. Luminous Matter:

Less than 1% of Universe is in visible matter!

Today (z=0)
\[ \Omega_{\text{baryons}} = 0.034 \]
- \( \Omega_{\text{stars}} = 0.0035 \)
- \( \Omega_{\text{gas/galaxies}} = 0.0006 \)
- \( \Omega_{\text{gas/clusters}} = 0.0025 \)

\[ \frac{\Omega}{3} \]

\[ \Omega \]

\[ z=2-4 \quad \Omega_{\text{baryons}} = \]

\[ z\sim1100 \quad \Omega_{\text{baryons}} = 0.04 \]
II. Ordinary (baryonic) Matter:

Big Bang Nucleosynthesis
Theory of the formation of the light elements (Deuterium, Helium, Lithium) in the early Universe (about 1 minute after the Big Bang) predicts the observed abundances of these elements if

~5% of the Universe is in ordinary matter
Big Bang Nucleosynthesis (BBN)

\[
\begin{align*}
  {^2}_1H & \leftrightarrow {^2}_0He + e^- + \gamma \\
  {^3}_1H & \leftrightarrow {^2}_0He + e^- + \gamma \\
  n & \leftrightarrow p + e \\
  n & \leftrightarrow p + e \\
  n & \leftrightarrow p + e \\
  p & \leftrightarrow n + e + \gamma
\end{align*}
\]

These reaction rates are all sensitive to the ratio of protons + neutrons (baryons) to the photons in the universe.

\* \( t \approx 0.01 - 100 \) sec
Inventory of the Universe

- Matter in stars & gas (galaxies) < 1%
- Ordinary (baryonic) matter 5%

→ most of the ordinary matter is “dark”
III. Total Matter:

Observations of Clusters of Galaxies indicate

~ 35% of Universe in Matter
Weighing a Cluster of Galaxies:

Galaxy Cluster Abell 2218
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08
Found: Most of Missing Matter
Lost Around Edges of Universe

By JOHN NOBLE WILFORD

SAN ANTONIO, Jan. 16 — Scientists think they have identified what may account for at least half of the missing mass of the universe, the mysterious and invisible matter that shapes galaxies and keeps them from flying apart.

A substantial amount of the so-called dark matter, thought to constitute as much as 90 percent of the universe, is nothing exotic or hypothetical, as some theorists have proposed, but is very likely a multitude of unseen burned-out stars known as white dwarfs, scientists reported here today at a meeting of the American Astronomical Society.

The announcement came one day after astronomers here reported that new observations had raised the estimated number of detectable galaxies from 10 to 50 billion. That discovery had great implications for the formation of galaxies but hardly affected estimates of the universe's mass. All the stars, gases and galaxies astronomers have observed through their telescopes probably add up to little more than one percent of the universe's total mass required by most theories. Even if there are 50 billion galaxies they and other inferred matter could hardly account for more than 10 percent of the cosmic mass.

For astronomers, not being able to find most of the universe has been puzzling and frustrating. The international team of scientists that offered the new explanation today said it had detected the gravitational signatures of objects in the halo surrounding the Milky Way. They ranged in size from one-tenth the mass of the Sun to the mass of the Sun. Objects in that mass range that are undetectable by light telescopes, radio telescopes and other means, and can be identified only by their gravitational force are most likely to be white dwarfs, remnants of stars that long ago exhausted their nuclear fuel. The Sun's own destiny, in about 5 billion years, is to die and

Continued on Page A12, Column 1
Searching for Dark Matter in our Galaxy:

Gravitational Microlensing
Milky Way Galaxy

Typical Spiral Galaxy with a disk, central bulge, and large dark halo

Total Mass = 2 trillion times the mass of the Sun

Most (> 90%) of this mass is in the Dark Halo of the Galaxy, which extends out over 500,000 light-years from the center of the Galaxy -- much further than the visible disk
Some (all?) of the dark matter in the galactic halo could be in the form of MACHO\textbf{Os}

\textbf{MAssive Compact Halo Objects}

- Jupiter-sized planets
- brown dwarf stars
- faint low-mass stars
- black holes
- white dwarf stars
Gravitational Lensing

Einstein’s Theory of Relativity => light bends around massive objects (spacetime is curved).

A massive object located between Earth and a distant light source can act as a gravitational lens.
FIGURE 4.7
Double image of a quasar, as might be seen by an observer, due to gravitational lensing.
Paczynski suggested in 1986 that gravitational microlensing could be used to detect MACHOs in the halo of our Galaxy.

As a MACHO passes near the line-of-sight to a star in the Large Magellanic Cloud, the star will appear to brighten and then return to normal (twinkle!)

How much the star brightens depends on how close the MACHO comes to the line-of-sight.

How long it appears to be brighter depends on how fast the MACHO is moving and how massive it is.
The LMC is 50 kpc (169,000 light-years) away from Earth.

The rate of lensing events for stars in the LMC (if the halo of our Galaxy is made up entirely of MACHOs) is

0.000001 events/star/year

==> one in a million!
Microlensing Experiments

Bulge

50 kpc

(b, l) = (-32.8, 281)

LMC
Several experiments have now detected MACHOs!

The MACHO experiment has reported 13-17 events lasting an average of about 90 days.
So what are the MACHOs?

The only hint we have from the microlensing events comes from the event duration.

The MACHO mass implied by the observed events is about 1/2 the mass of the Sun.

- Very faint, low-mass hydrogen-burning stars
- White dwarfs: burnt out cores of stars like the Sun
White Dwarf Stars in M4

PRC95-32 · ST ScI OPO · August 28, 1995 · H. Bond (ST ScI), NASA
Is the Halo of the Galaxy filled with White Dwarfs?

**NO!**

White dwarfs are remnants of stars like the Sun

~3/4 of the mass of original star is gently blown off as metal-enriched gas and dust when the star runs out of fuel

~1/4 becomes white dwarf
If even 20% of the Galactic Halo is in the form of White Dwarfs:

• Too many metals produced
• Too much light produced by original stars
• Almost all the baryons in the Universe were processed through the first generation of stars in the Universe
In any case, we now know that MACHOs make up at most a small fraction of the dark matter in the galaxy...

Need to look at more exotic dark matter candidates
Standard Model
of
Particle Physics

Quarks
{ u, c, t, d, s, b }

Leptons
{ e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau }

Gauge Bosons
{ \gamma, W, Z, \text{gluons} }

Electromagnetic
Weak nuclear
Strong nuclear
Sudbury Neutrino Observatory

1000 ton heavy water detector
SuperKamiokande

50 kton water detector
Threshold ~ 5 MeV
The Sun in Neutrinos  (SuperKamiokande Collaboration)

http://superk.physics.sunysb.edu/superk/physics/solar-neutrino
Neutrino Oscillations

- require \( m_\nu \neq 0 \)
- weak eigenstate \( \neq \) mass eigenstate

\[
\nu_e = \cos \Theta |\nu_1\rangle + \sin \Theta |\nu_2\rangle
\]

\[
P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\Theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
\]

Vacuum Oscillations

\( \Theta \): vacuum mixing angle
\( \Delta m^2 \equiv |m_1^2 - m_2^2| \)
Neutrino Oscillations

- electron neutrino's ($\nu_e$) produced in the sun
- on their way through the sun or to the earth "oscillate" into another type of neutrino (which cannot be detected by the experiment)

- for this to occur $\Rightarrow$ neutrinos must have mass!
Matter enhanced Oscillations

→ MSW

\[ \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \]

\[ H = \begin{bmatrix} a_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{2E_v} \cos 2\theta + a_\mu \end{bmatrix} \]

\[ a_e = G_F \frac{2N_e - N_n}{\sqrt{2}} \quad \text{and} \quad a_\mu = G_F \frac{-N_n}{\sqrt{2}} \]

\[ N_e = e^- \text{ number density} \]

\[ G_F = \text{Fermi constant} = 1.4 \times 10^{-49} \text{ erg cm}^2 \]
→ Wolfenstein term: additional potential for $\nu_e$ in matter due to charged current interactions

resonance condition

$$\left. \sqrt{2} G_F N_e \right|_{\text{res}} = \frac{\Delta m^2}{2E} \cos 2\theta$$

Parke's formula

$$PC(\nu_e \rightarrow \nu_x) = \frac{1}{2} + \left( \frac{1}{2} - P_{\text{jump}} \right) \cos 2\theta_m \cos 2\theta$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left[ \sin^2 2\theta + \left( \frac{a_{12} G_F N_e}{4m^2} - \cos 2\theta \right)^2 \right]}$$

$$P_{\text{jump}} = \exp \left[ -\frac{\pi^2 \Delta R}{2L_m\text{res}} \right]$$

$\Delta R = \text{width of res.}$

$L_m\text{res} = \text{matter osc. length at res.}$
HOT DARK MATTER (light neutrinos)

Neutrinos decouple from matter at about the time of nucleosynthesis. At this time they are still moving at almost the speed of light (relativistic).

Neutrinos are essentially collisionless after decoupling, and they can smooth out density perturbations on scales of the horizon size as long as they remain relativistic.

Thus, neutrinos cannot form structures on scales smaller than the free-streaming scale, which is the size of the horizon at the time when they become non-relativistic.

For a 30 eV neutrino, this corresponds to about 40 Mpc.

See, e.g.,

http://cfa-www.harvard.edu/~mushite/modelcmp.html
Summary

- Evidence for neutrino mass
  - solar $\nu$'s
  - atmospheric $\nu$'s
    - LSND

- Neutrino Dark Matter
  - at most 15% of matter
    - but $\Omega_\nu \approx \Omega_\ast$!

- Many new (nu) experiments:
  - short & long baseline osc. exp
  - solar exp.
  - $\nu$ telescopes
Inventory of the Universe

- Luminous Matter in stars & gas (galaxies) < 1% (detected)
- Ordinary (baryonic) matter ~ 5% (from formation of light nuclei in early Universe)
- Matter in neutrinos ~ 0.4% (detected)
- Total matter ~ 35% (observations)
- Where (what) is the missing matter???
Most of the Matter in the Galaxy and the Universe is likely to be in the form of Cold Dark Matter, such as

**WIMPS**

**Weakly Interacting Massive Particles**
Cold Dark Matter

Axions

The axion arises in one very elegant solution to a problem (the strong-CP problem) in the theory of quarks and their interactions (quantum chromodynamics or QCD).

It has a very small mass

\[ m_a \approx 10^{-5} \text{eV} \sim 10^{-10} \text{me} \]

WIMPs

Supersymmetry (SUSY) theories postulate "supersymmetric partners" for the particles we know. The lightest of these partners, the neutralino, may be stable with a mass

\[ m_{\text{LSP}} \sim 20 \text{ GeV - few hundred GeV} \]
Physics beyond the Standard Model of particle physics

Supersymmetric theories contain extra particles

LSP = lightest SUSY particle, with a mass in the range of 20 GeV - TeV may be stable and would be a good CDM candidate
\( \text{LSP} \rightarrow \text{susy dark matter} \)

Physics beyond the Standard Model

Stable particle \( \chi \) with mass \( m_\chi \)

for \( T \gg m_\chi \rightarrow n_\chi \propto T^3 \)

but as Universe cools and

\( T \ll m_\chi \rightarrow n_\chi \propto \frac{1}{T}\)

include expansion of Univ. \rightarrow shortly after

\( T \lesssim m_\chi \rightarrow \) annihilation rate \( \lesssim \) expansion rate

\( \Rightarrow \) relic abundance of \( \chi \) particles

\[ \Omega_\chi h^2 = \frac{m_\chi n_\chi}{\sqrt{c}} \geq \left( \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

\[ \langle \sigma v \rangle \gg 10^{-2} (100 \text{ GeV})^{-2} \sim 10^{-25} \text{cm}^3 \text{s}^{-1} \quad (a \sim 10^{-7}) \]

\( \Rightarrow \text{WIMP}! \)
MSSM:

Standard Model particles
+

squarks

electrons

neutrinos

gluinos

chargedinos

neutralinos

$\tilde{g}, \tilde{H}, \tilde{\chi}$

$\rightarrow$ large model parameter space
Axions

Non-thermal relic

\[ L_{\text{QCD}} = L_{\text{pert}} + \theta \frac{g^2}{32\pi^2} G \tilde{G} \]

violates CP

\[ \Rightarrow \theta \lesssim 10^{-10} \]

"strong-CP problem"

Peccei-Quinn Soln:
introduce global \( U(1)_{PQ} \) symm.
broken at \( f_{PQ} \)

\[ \Rightarrow \theta \text{ dynamical field (Nambu-Goldstone mode)} \]

pseudo-Goldstone boson \( \rightarrow \text{axion} \)

produced w/zero momentum
WIMP Searches

• Accelerators
• Direct Detection
  Cryogenic detectors which measure the energy deposited when WIMP collides with nucleus
• Indirect Detection
  Look for annihilation products (cosmic gamma rays or high energy neutrinos)

Axions: Tunable microwave cavity immersed strong mag. field
Ordinary matter = 5%

- luminous < 1%
- neutrinos < 1%
- gas ~ 3%
- MACHOs ~ 0.5%

==============
total 5%

WIMPS = 30%

Where is the other 65%???
Inventory of the Universe

- Luminous matter in stars & gas (galaxies) <1%
- Ordinary (baryonic) matter 5%
- Total matter 35%
- →Cold Dark Matter ~30%
- “Dark Energy” ~65%
Still Many Questions:

What is the Dark Matter?

What is the Dark Energy?
"I'll be working on the largest and smallest objects in the universe—superclusters and neutrinos. I'd like you to handle everything in between."