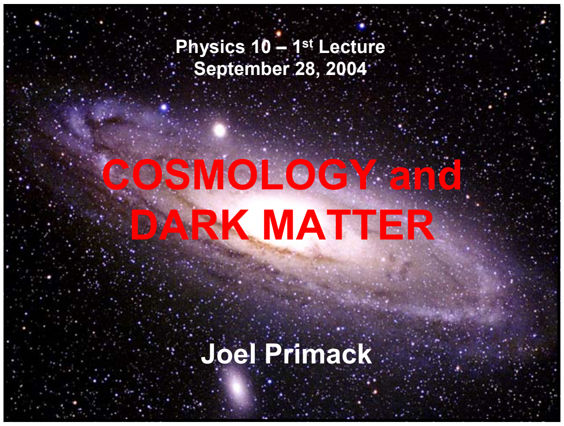
Physics 10 – 1st Lecture
September 28, 2004

COSMOLOGY and DARK MATTER

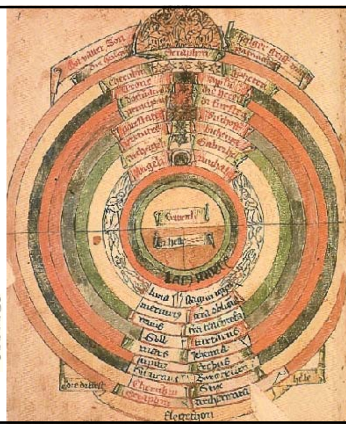
Joel Primack



Introduction

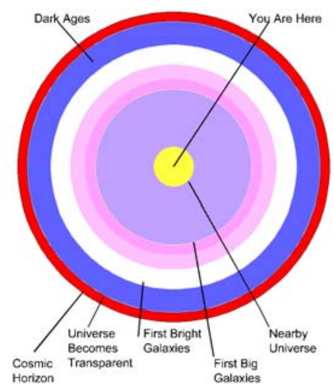
Modern cosmology–the study of the universe as a whole–is undergoing a scientific revolution. New ground- and space-based telescopes can now observe every bright galaxy in the universe, and see back in time to the cosmic dark ages before galaxies formed. We can read the history of the early universe in the ripples of heat radiation still arriving from the Big Bang. We now know that everything that we can see makes up only about half a percent of what is there, and that most of the universe is made of invisible stuff called “dark matter‘” and “dark energy.” The Cold Dark Matter theory based on this appears to be able to account for all the main features of the observable universe, including the details of the heat radiation and the large scale distribution of galaxies, although there are possible problems understanding some aspects of the structure of galaxies. Modern cosmology is developing humanity's first story of the origin and nature of the universe that might actually be true.

Medieval Universe

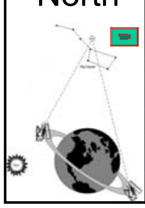


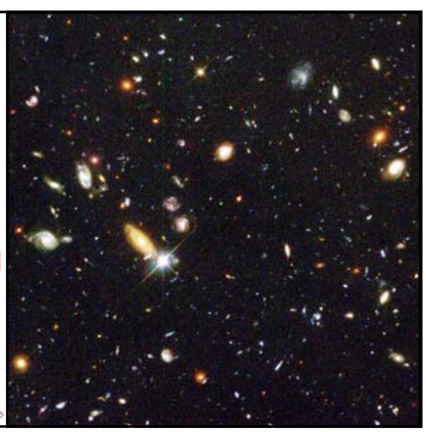
The geocentric pre-Copernican Universe in Christian Europe. At center, Earth is divided into Heaven (tan) and Hell (brown). The elements water (green), air (blue) and fire (red) surround the Earth. Moving outward, concentrically, are the spheres containing the seven planets, the Moon and the Sun, as well as the "Twelve Orders of the Blessed Spirits," the Cherubim and the Seraphim. German manuscript, c. 1450.

At the Center of Cosmic Spheres of Time

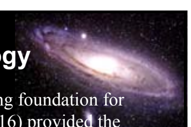


The Hubble Deep Field North





Modern Cosmology

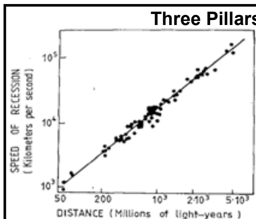


A series of major discoveries has laid a lasting foundation for cosmology. Einstein’s general relativity (1916) provided the conceptual foundation for the modern picture. Then Hubble discovered that “spiral nebulae” are large galaxies like our own Milky Way (1922), and that distant galaxies are receding from the Milky Way with a speed proportional to their distance (1929), which means that we live in an expanding universe. The discovery of the cosmic background radiation (1965) showed that the universe began in a very dense, hot, and homogeneous state: the Big Bang. This was confirmed by the discovery that the cosmic background radiation has exactly the same spectrum as heat radiation (1989), and the measured abundances of the light elements agree with the predictions of Big Bang theory if the abundance of ordinary matter is about 5% of critical density.

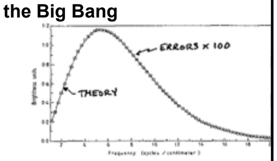
Successful Predictions of the Big Bang

First Prediction	First Confirmation
Expansion of the Universe Friedmann 1922, Lemaitre 1927 based on Einstein 1916	Hubble 1929
Cosmic Background Radiation	
Existence of CBR Gamow, Alpher, Hermann 1948	Penzias & Wilson 1965
CBR Thermal Spectrum Peebles 1966	COBE 1989
CBR Fluctuation Amplitude Cold Dark Matter theory 1984	COBE 1992
CBR Acoustic Peak	BOOMERANG 2000 MAXIMA 2000
Light Element Abundances Peebles 1966, Wagoner 1967	D/H Tytler et al.1997

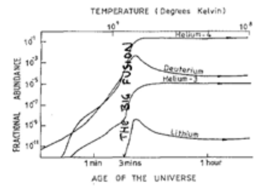
Three Pillars of the Big Bang



A modern illustration of Hubble's Law, displaying the increase of recession speed of galaxies growing in direct proportion to their distance.



The variation of the intensity of the microwave background radiation with its frequency, as observed by the COBE satellite from above the Earth's atmosphere. The observations (boxes) display a perfect fit with the (solid) curve expected from pure heat radiation with a temperature of 2.73°K.



The detailed production of the lightest elements out of protons and neutrons during the first three minutes of the universe's history. The nuclear reactions occur rapidly when the temperature falls below a billion degrees Kelvin. Subsequently, the reactions are shut down, because of the rapidly falling temperature and density of matter in the expanding universe.

FROM John D. Barrow, The Origin of the Universe (Basic Books, 1994)

The Age of the Universe

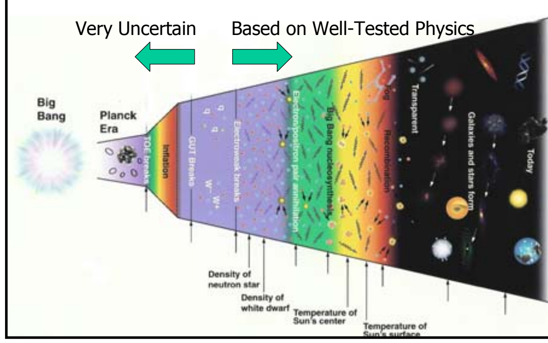
In the mid-1990s there was a crisis in cosmology, because the age of the old Globular Cluster stars in the Milky Way, then estimated to be 16□3 Gyr, was higher than the expansion age of the universe, which for a critical density ($\square_m$ = 1) universe is 9□2 Gyr (with the Hubble parameter h=0.72□0.07). But when the data from the Hipparcos astrometric satellite became available in 1997, it showed that the distance to the Globular Clusters had been underestimated, which implied that their ages are 12□3 Gyr.

Several lines of evidence now show that the universe does not have $\square_m$ = 1 but rather $\square_{tot}$ = $\square_m$ + $\square_\square$ = 1.0 with $\square_m$□ 0.3, which gives an expansion age of about 14 Gyr. (High-redshift supernova data alone give an expansion age of 14.2□1.7 Gyr. The latest cosmic background data give an expansion age of 13.7□0.2 Gyr assuming $\square_{tot}$ = 1.)

Moreover, a new type of age measurement based on radioactive decay of Thorium-232 (half-life 14.1 Gyr) measured in a number of stars gives a completely independent age of 14□3 Gyr. A similar measurement, based on the first detection in a star of Uranium-238 (half-life 4.47 Gyr), gives 12.5□3 Gyr.

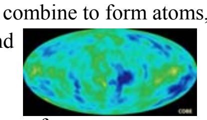
All the recent measurements of the age of the universe are thus in excellent agreement. It is reassuring that three completely different clocks – stellar evolution, expansion of the universe, and radioactive decay – agree so well.

Brief History of the Universe



Brief History of the Universe

- Symmetry breaking: more matter than antimatter
- All antimatter annihilates with almost all the matter
- Big Bang Nucleosynthesis: making light nuclei
- Electrons and light nuclei combine to form atoms, and the cosmic background radiation fills the newly transparent universe

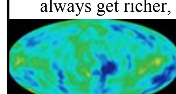


- Galaxies and larger structures form
- Carbon, oxygen, iron, ... are made in stars
- Earth-like planets form around 2nd generation stars
- Life somehow starts and evolves on earth

GRAVITY – The Ultimate Capitalist Principle

The Rich Get Richer and the Poor Get Poorer

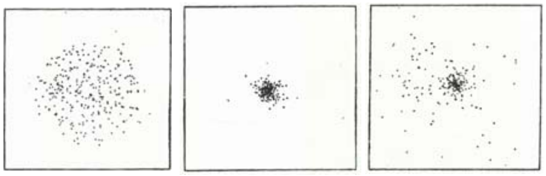
Astronomers say that a region of the universe with more matter is "richer." Gravity magnifies differences—if one region is slightly denser than average, it will expand slightly more slowly and grow relatively denser than its surroundings, while regions with less than average density will become increasingly less dense. The rich always get richer, and the poor poorer.



Temperature map at 380,000 years after the Big Bang. Blue (cooler) regions are slightly denser. *From NASA's **COBE** satellite, 1992.*

The early universe expands ***almost*** perfectly uniformly. But there are small differences in density from place to place (about 30 parts per million). Because of gravity, denser regions expand more slowly, less dense regions more rapidly. Thus gravity amplifies the contrast between them, until…

Structure Formation by Gravitational Collapse



When any region becomes about twice as dense as typical regions its size, it reaches a maximum radius, ***stops expanding***, and starts falling together. The forces between the subregions generate velocities which ***prevent*** the material from ***all falling toward the center***. Through ***Violent Relaxation*** the dark matter quickly reaches a ***stable configuration*** that's about half the maximum radius but denser in the center.

Gravity is inexorable. But in galaxies, and also in planetary systems, it is opposed by motion – circular motion for planets and galactic disks, and random motion for elliptical galaxies and for the dark matter that holds galaxies together. The balance between gravity and motion creates the long-term stability that is essential for the evolution of stars, planets, life, and … us!

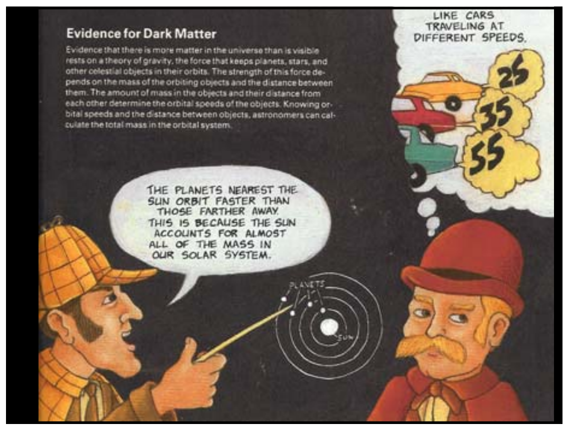
Why Are There Galaxies?

If matter after the Big Bang were distributed absolutely evenly, gravity would have done nothing but slow down the overall expansion. Consequently, in order to make galaxies, gravity must have had some differences in density to work with from the beginning. In 1992 COBE discovered tiny fluctuations in the temperature of the cosmic background radiation in different directions of just the magnitude predicted by the Cold Dark Matter theory eight years earlier.

Illustration for Joel Primack's 1990 *World Book Science Year* article on

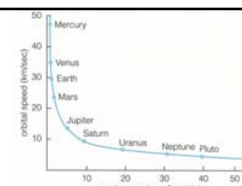
DARK MATTER

Sherlock Holmes: "When you have eliminated the impossible, whatever remains, however improbable, must be the truth…"
– *The Sign of the Four,* Arthur Conan Doyle



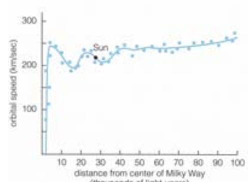
Rotation Curves

Solar System



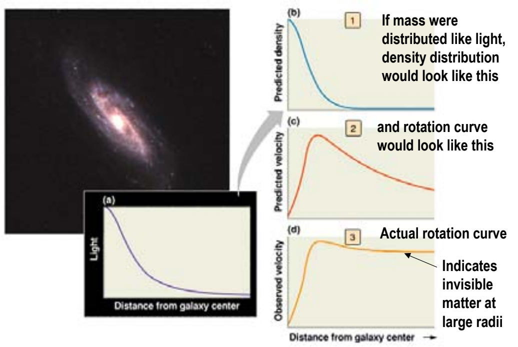
The rotation curve for the planets in our solar system.

Milky Way



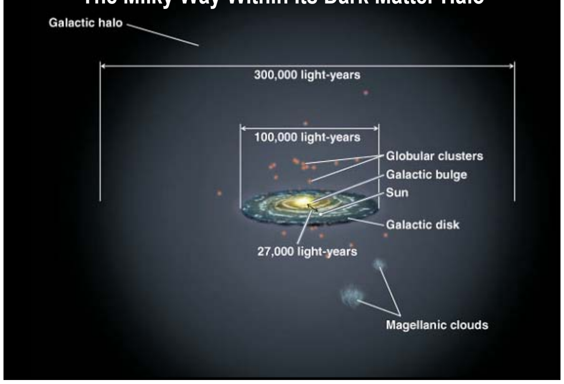
The rotation curve for the Milky Way Galaxy.

Galaxies are held together by dark matter

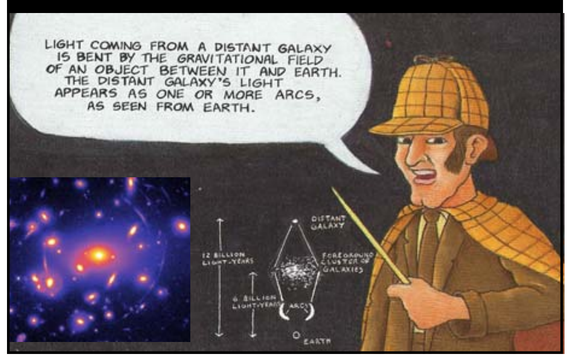


Most of the Mass is in the Dark Matter Halo

The Milky Way Within Its Dark Matter Halo



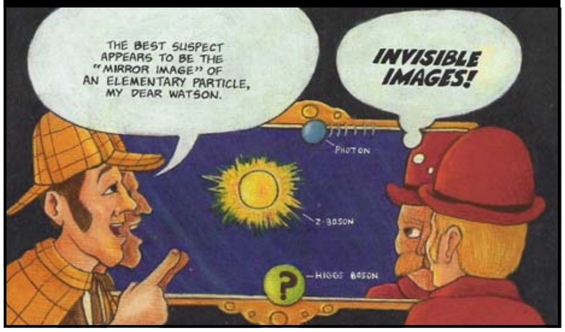
Gravitational Lensing Confirms that Most of the Mass in Galaxy Clusters is Dark Matter



Jupiter-sized objects are not good dark matter suspects

Black Holes are not good suspects either

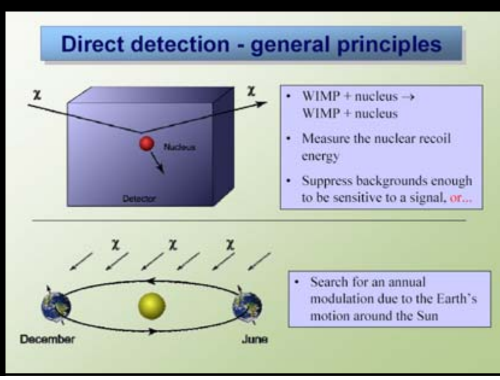
Photon, Z, and Higgs Supersymmetric Partners (*Photino, Zino, Higgsino*) are Prime Suspects



Supersymmetry is the basis of most attempts, such as superstring theory, to go beyond the current "Standard Model" of particle physics. Heinz Pagels and Joel Primack pointed out in a 1982 paper that the lightest supersymmetric partner particle is a good candidate for the dark matter particles – weakly interacting massive particles (**WIMP**s).

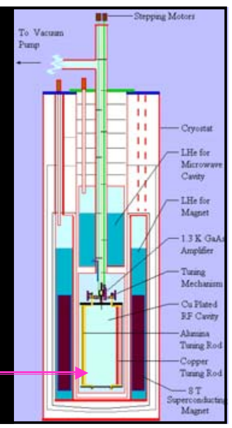
Michael Dine and others pointed out that the **axion**, a particle needed to save the strong interactions from violating CP symmetry, could also be the dark matter particle. Searches for both are underway.

Experiments are Underway for Detection of WIMPs



and also AXIONs

The diagram at right shows the layout of the axion search experiment now underway at the Lawrence Livermore National Laboratory. Axions would be detected as extra photons in the Microwave Cavity.



Supersymmetric WIMPs

When the British physicist Paul Dirac first combined Special Relativity with quantum mechanics, he found that this predicted that for every ordinary particle like the electron, there must be another particle with the opposite electric charge – the anti-electron (positron). Similarly, corresponding to the proton there must be an anti-proton. Supersymmetry appears to be required to combine General Relativity (our modern theory of space, time, and gravity) with the other forces of nature (the electromagnetic, weak, and strong interactions). The consequence is another doubling of the number of particles, since supersymmetry predicts that for every particle that we now know, including the antiparticles, there must be another, thus far undiscovered particle with the same electric charge but with *spin* differing by half a unit.

Spin	Matter (fermions)	Forces (bosons)
2		graviton
1		photon, $W^{\pm}, Z^0$ gluons
1/2	quarks u,d,... leptons $e, \nu_e, \ldots$	
0		Higgs bosons axion

Supersymmetric WIMPs

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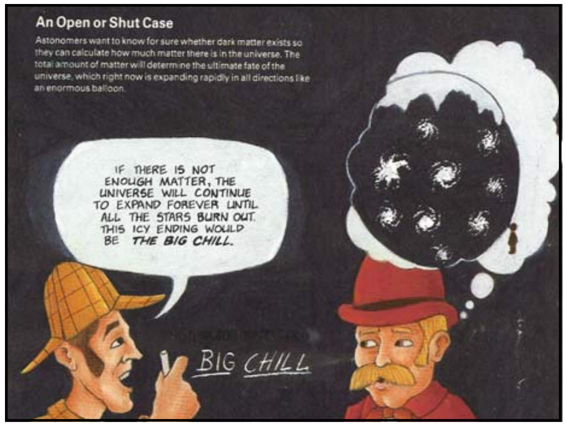
after doubling

Spin	Matter (fermions)	Forces (bosons)	Hypothetical Superpartners	Spin
2		graviton	gravitino	3/2
1		photon, $W^{\pm}, Z^0$ gluons	photino, winos, zino, gluinos	1/2
1/2	quarks u,d,... leptons $e, \nu_e, \ldots$		squarks $\tilde{u}, \tilde{d}, \ldots$ sleptons $\tilde{e}, \tilde{\nu}_e, \ldots$	0
0		Higgs bosons axion	Higgsinos axinos	1/2

Note: Supersymmetric cold dark matter candidate particles are underlined.

Supersymmetric WIMPs, continued

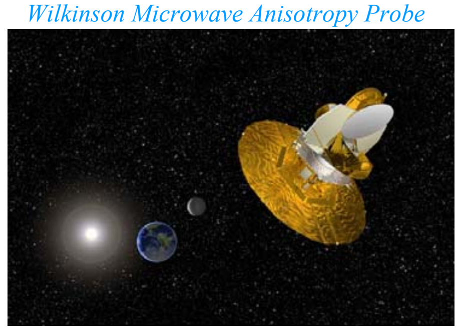
Spin is a fundamental property of elementary particles. Matter particles like electrons and quarks (protons and neutrons are each made up of three quarks) have spin ½, while force particles like photons, W,Z, and gluons have spin 1. The supersymmetric partners of electrons and quarks are called selectrons and squarks, and they have spin 0. The supersymmetric partners of the force particles are called the photino, Winos, Zino, and gluinos, and they have spin ½, so they might be matter particles. The lightest of these particles might be the photino. Whichever is lightest should be stable, so it is a natural candidate to be the dark matter WIMP. Supersymmetry does not predict its mass, but it must be more than 50 times as massive as the proton since it has not yet been produced at accelerators. But it will be soon, if it exists!



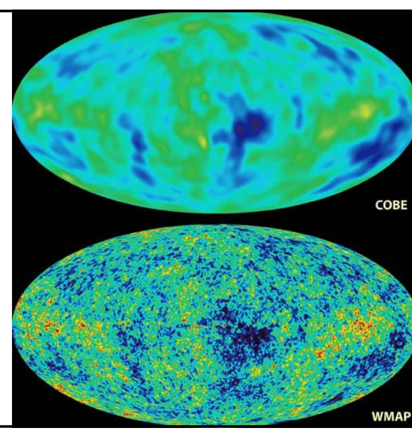
We now know that there is not nearly enough matter for a big crunch.

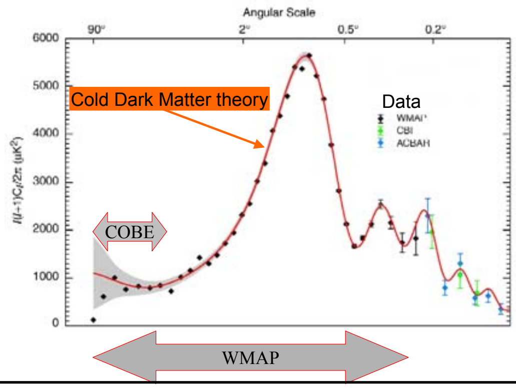
NASA's WMAP satellite

Wilkinson Microwave Anisotropy Probe



results reported: March 2003





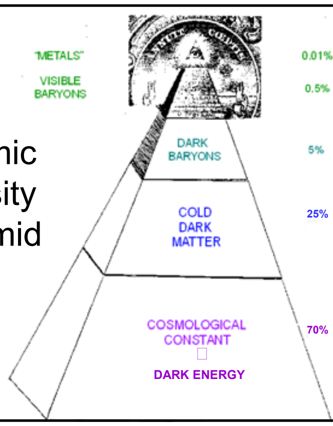
Cosmic Density Pyramid: Visible Matter

"METALS" = CHEMICAL ELEMENTS HEAVIER THAN HYDROGEN & HELIUM

"BARYONS" = ATOMS (ORDINARY MATTER)

"VISIBLE BARYONS" = HYDROGEN & HELIUM MOSTLY IN STARS

Cosmic Density Pyramid



The Big Questions of Modern Cosmology

What happened before the Big Bang to make the early universe so uniform, but with tiny ripples in density? **Cosmic Inflation**?

What is the **dark matter** that enabled the tiny ripples in density to grow into galaxies, clusters, and voids? Cold Dark Matter **WIMPs**? **Axions**?

What is the **dark energy** that is making the expansion of the universe accelerate?

How did **galaxies form and evolve?**

A new scientific cosmology is emerging today.

The ratio of **Theory**/**Data** has recently flipped from almost □ to almost **0**!

Today the data is flowing in so fast from new telescopes and other new scientific instruments that the question is whether a single one of the current theories can survive. If it does, it will be revolutionary.

The advent of a new cosmology can radically change the culture of its time. The scientific revolution of the l6th-l7th centuries helped end the Middle Ages and bring about the European Enlightenment. But it also split scientific knowledge from human meaning.

How will a new picture of the universe at the turn of the 21st century affect global culture?