ASTROPHYSICAL EVIDENCE ON PHYSICS
BEYOND THE STANDARD MODEL

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ABSTRACT

Astrophysics and cosmology can be used to test the standard model of particle physics under conditions and over distance and time scales not accessible to laboratory experiments. Most of the astrophysical observations are in good agreement with the standard model. In particular, primordial nucleosynthesis, supernova explosions, stellar evolution and cosmic background radiations have been used to derive strong limits on physics beyond the standard model. However, the solution of some important astrophysical and cosmological problems may require new physics beyond the standard model. These include the origin of the initial conditions, large scale structure formation, the baryon asymmetry in the observed Universe, the dark matter problem, the solar neutrino problem and some cosmic ray puzzles. Here I review some important developments relevant to some of these problems, which took place most recently.
Gravitational lensing observations have become a very powerful tool for verifying the existence of dark matter, for mapping its distribution in galactic halos and clusters and for studying its nature. Here we consider two important applications of gravitational lensing in search of new physics.

1. TESTS OF GENERAL RELATIVITY AT LARGE DISTANCES AND DARK MATTER

There are at least two good reasons for testing the validity of Einstein’s General Relativity (EGR) and its weak field limit, Newtonian Gravity (NG), over cosmic distances;

(a) It has not been tested before over such distances - All astronomical tests of EGR and NG, so far, were limited to the solar system (see e.g., Weinberg 1972; Will 1984) and to close binary systems (Damour and Taylor 1991) (PSR 1913+16, 4U1820-30 and PSR 0655+64), i.e., to distance scales less than a few Astronomical Units, whereas EGR and NG have been applied to astronomical systems such as galaxies, clusters of galaxies, superclusters and the whole Universe, which are typically $10^6 - 10^{15}$ times larger.

(b) The dark matter problem - All the dynamical evidence from galaxies, clusters of galaxies, superclusters and large scale structures that they contain vast quantities of non luminous dark matter (for a recent review see e.g., Gould 1995) has been obtained assuming the validity of EGR or Newton’s laws for such systems. As we shall see below there are good reasons to believe that most of this dark matter is non baryonic. However, in spite of extensive laboratory searches no conclusive evidence has been found either for finite neutrino masses (minimal extension of the standard model) or for the existence of other particles beyond the standard model that can form dark matter. This has led some authors to question the validity of EGR and NG over large distances and to suggest (see for instance Sanders 1990 and references therein) that perhaps EGR and NG are only approximate theories of gravity and that a correct theory of gravity will eliminate the dark matter problem. Indeed alternative theories (Mannheim and Kazanas 1989) to General Relativity or modifications of Newton’s laws (e.g., Milgrom and Beckenstein 1984; Sanders 1984) have been proposed in order to explain the observations without invoking dark matter.

Gravitational macro lensing observations can be used to test EGR and NG over cosmological distances (Dar 1992; Dar 1993). EGR predicts that light which passes at an impact parameter $b$ from a spherical symmetric mass distribution is deflected by an angle which, for small angles, is given approximately by

$$\alpha \approx \frac{4GM(b)}{c^2b},$$

where $G$ is Newton’s gravitational constant and $M(b)$ is the mass interior to $b$. The mass $M(r)$ enclosed within a radial distance $r$ from the center is given by Kepler’s third law $M(r) \approx \frac{v_{cir}^2r}{G}$, where $v_{cir}$ is the circular velocity of a mass orbiting at a distance $r$ from the center. Consequently, spiral galaxies, which have flat rotation curves ($v_{cir} \approx \text{const.}$) have $M(r) \propto r$, $\rho(r) \propto 1/r^2$, and $M(b)/b \approx \pi v_{cir}^2/2G$, which give rise to a constant
deflection angle independent of impact parameter,

\[ \alpha = 2\pi \left( \frac{v_{\text{cir}}}{c} \right)^2. \]  

(2)

For large spiral galaxies, \( v_{\text{cir}} \sim 250 \text{ km s}^{-1} \) and \( \alpha \sim 1'' \). In elliptical galaxies, or clusters of galaxies, whose total mass distributions are well described by singular isothermal sphere distributions \( \rho(r) \approx (1/2\pi G)(\sigma_{\|}/c)^2 r^{-2} \), the squared circular velocity is replaced by \( v_{\text{cir}}^2 = 2\sigma_{\|}^2 \), where \( \sigma_{\|} \) is the one-dimensional line-of-sight velocity dispersion in the galaxy or the cluster, respectively. For a typical large elliptical galaxy with \( \sigma_{\|} \sim 200 \text{ km s}^{-1} \) the constant deflection angle is \( \alpha \sim 1.5'' \) while for a rich cluster with \( \sigma_{\|} \sim 1000 \text{ km s}^{-1} \) the constant deflection angle is \( \alpha \sim 30'' \). Hence, the Large optical telescopes, VLA and VLBI radio telescopes have been used to discover and study gravitational lensing of quasars and galaxies by galaxies and clusters of galaxies (see, e.g., Blandford and Narayan 1992).

EGR and Newton’s laws can be tested over galactic and intergalactic distances by comparing the deflection of light which is extracted from these observations and the deflection of light which is predicted from the measured rotation curves or line-of-sight velocity dispersions in these systems. However the deflection of light cannot be measured directly and must be deduced from the multiple image pattern (angular positions and relative magnifications) of the source which is produced by the lens. Generally, this requires a complicated inversion procedure (see e.g. Blandford and Narayan 1992 and references therein) and additional assumptions. However, for testing EGR one can select the gravitational lensing cases where the lens is simple, the pattern-recognition is straightforward and the deflection angle can be read directly from the simple multiple image pattern:

**Einstein Rings, Crosses, and Arcs:** On the rare occasion that a lensing galaxy with a radially symmetric surface density happens to lie on the line-of-sight to a distant quasar it forms in the sky a ring image (Cholson 1924; Einstein 1936) of the quasar around the center of the lensing galaxy, whose angular diameter is

\[ \Delta \theta = 4\theta_r \approx 2 \frac{D_{\text{LS}}}{D_{\text{OS}}} \alpha \approx 4\pi \frac{D_{\text{LS}}}{D_{\text{OS}}} \left( \frac{\sigma_{\|}}{c} \right)^2, \]  

(3)

where \( D_{\text{OL}}, D_{\text{LS}}, \) and \( D_{\text{OS}} \) are the Observer-Lens, Lens-Source and Observer-Source angular diameter distances, respectively. Five Einstein rings, MG1131+0456, 1830-211, MG1634+1346, 0218+357 and MG1549+3047 were discovered thus far by high resolution radio observations (see e.g., Blandford and Narayan 1992 and references therein) but, only for MG1634+1346 are the redshifts of both the lens and the ring image known, allowing a quantitative test of EGR. When the source is slightly off center, the ring breaks into a pair of arcs, as actually observed for the ring image MG1634+1346 of a radio lobe of a distant quasar (Langston et al 1989, 1990).

When the lens has an elliptical surface density and the line of sight to the source passes very near its center, the Einstein ring degrades into an “Einstein Cross”, i.e., four images that are located symmetrically along the two principal axes (and a faint fifth image at the center), with a mean angular separation between opposite images given approximately by Eq.3, as observed in the case of Q2237+0305 (Rix et al 1992 and references therein).
When an extended distant source, such as a galaxy, lies on a cusp caustic behind a giant elliptical lens, such as a rich cluster of galaxies, it appears as an extended luminous arc on the opposite side of the lens (Grossman and Narayan 1988, Blandford et al 1989). The angular distance of the arc from the center of the lens is given approximately by the radius of the Einstein ring. Giant arcs (Soucail et al 1988; Lynds and Petrosian 1989) were discovered, thus far, in the central regions of 13 rich clusters (see e.g., Blandford and Narayan 1992 and references therein) and in six cases, Abell 370, 963 and 2390, Cl0500-24, Cl2244-02 and Cl0024+1654 the redshifts of both the giant arc image and the cluster are known and the velocity dispersion in the cluster has been estimated from the redshifts of the member galaxies or the X ray emission, allowing a quantitative test of EGR.

**Gravitational Time Delay:** In the thin lens approximation the time delay predicted by EGR is a sum of the time delay due to the difference in path length between deflected and undeflected light rays and the time delay due to the different gravitational potential felt by the light rays

\[
\Delta t \approx (1 + z_L) \left[ \frac{D_{OL} D_{OS}}{2c D_{LS}} (\vec{\theta}_I - \vec{\theta}_S)^2 - \frac{\phi(\theta_I)}{c^3} \right],
\]

(4)

where \(\phi(\theta_I)\) is the gravitational potential of the lens at \(\theta_I\). Thus, the time delay between two images A,B, due to a lensing galaxy with nearly spherical isothermal mass distribution that lies near the line-of-sight to the source (even if it is embedded in a large cluster with an approximately constant deflection angle over the whole image), in the thin lens approximation reduces to a simple form,

\[
\Delta t_{A,B} \approx 2\pi (1 + z_L) \left( |\vec{\theta}_A| - |\vec{\theta}_B| \right) \left( \frac{\sigma_\parallel}{c} \right)^2 \frac{D_{OL}}{c},
\]

(5)

which can also be written as

\[
\Delta t_{A,B} \approx (1 + z_L)(|\vec{\theta}_A| - |\vec{\theta}_B|) |\vec{\theta}_A - \vec{\theta}_B| \frac{D_{OS} D_{OL}}{D_{LS} 4c}.
\]

(6)

Note that while the deflection angle is dimensionless, i.e., depends only on dimensionless parameters, the time delay is dimensionfull and depends on the absolute value of the Hubble parameter (through \(D_{OL}\)) and can be used to measure \(H_0\). For the double quasar Q0957+561 Eq. 6 yields \(H_0 \approx (76 \pm 4)/\Delta t(Y) \approx 70 \pm 5 \text{ km s}^{-1} \text{Mpc}^{-1}\), for \(\Delta t \approx 1.1Y\) (Vanderriest et al 1989; Schild 1990; Pelt et al 1994).

Fig. 1 summarizes our comparison between the above EGR predictions and observations on the most simple known cases of gravitational lensing of quasars and galaxies by galaxies or cluster of galaxies. These include the Einstein Ring MG1654+1346, the Einstein Cross Q2237+0305, the giant Einstein Arcs in the clusters A370, Cl2244-02 and Cl0024+1654 and the time delay between the two images of the Quasar Q0957+561. The agreement between the predictions and the observations confirm within errors (the error bars are
statistical only and do not include model uncertainties) the validity of EGR and NG over
distances of 0.1kpc - 0.1 Mpc, i.e., $\sim 10^6 - 10^9$ times larger than the size of the solar
system. Moreover, the gravitational lensing observations confirm that most of the mass
of galaxies, groups and clusters of galaxies consists of dark matter and (following Tyson
et al 1990 and Tyson 1991) have been used extensively to map the distribution of dark
matter in clusters of galaxies.

2. EVIDENCE FOR NON BARYONIC DARK MATTER

The astrophysical evidence for non baryonic dark matter is considered by many to be
the best evidence for physics beyond the standard model. The main evidence for non
baryonic dark matter comes from comparisons between the average densities of bary-
onic and gravitating matter in the Universe (e.g. Kolb and Turner 1991). The average
baryon density is best inferred from Big-Bang Nucleosynthesis, while the average density
of gravitating matter in the Universe is presently best determined from the dynamics of
clusters of galaxies and large scale structures, from X-ray observations of clusters and
from gravitational lensing observations. We shall first review this evidence.

2.1 The Mean Baryon Density From Big-Bang Nucleosynthesis

The predictions of the Standard Big-Bang Nucleosynthesis (SBBN) theory (Peebles 1966;
Wagoner, Fowler and Hoyle 1967; Wagoner 1973; Yang et al 1984) for the primordial
abundances of the light elements (H, D, $^3$He, $^4$He, and $^7$Li) depend on low energy nuclear
cross sections and on three additional parameters, the number of flavours of light neutrinos, $N_{\nu}$, the neutron lifetime, $\tau_n$, and the ratio of baryons to photons in the Universe,
$\eta \equiv n_b/n_\gamma$. The relevant nuclear cross sections are known from laboratory mea-
surements (e.g., Caughlan and Fowler 1988 and references therein). The measurements at
the Large Electron Positron Collider (LEP) at CERN gave $N_{\nu} = 3.04 \pm 0.04$ (e.g., Mana
and Martinez 1993). Measurements of $\tau_n$ in neutron bottles and Penning traps coupled
with previous measurements yielded the weighted average (see Particle Data Group 1994)
$\tau_n = 887 \pm 2.0$ s. Finally, measurements of the cosmic microwave background radiation
by COBE (Mather et al 1994) gave a black body temperature $T = 2.726 \pm 0.017$ K, which
yields $n_\gamma = 20.28 T^3 \approx 411 \pm 8$ cm$^{-3}$. Hence, SBBN theory predicts quite accurately (see
Fig. 1) the primordial abundances of the light elements as function of a single unknown
parameter, $n_b$, the mean baryon number density in the Universe. Thus, the primordial
abundances of the light elements, as inferred from observations, can be used to test SBBN
theory and determine this number. Indeed, it has been claimed repeatedly that the pre-
dictions of SBBN theory agree with observations if $\eta_{10} \equiv \eta \times 10^{10} \approx 4$, which implies
that most of the nucleons in the Universe are dark (e.g., Kolb and Turner 1990; Walker
et al 1991; Smith et al 1993 and references therein). Moreover, based on these analyses,
many limits on physics beyond the standard particle physics model (new interactions;
new weakly interacting particles; additional neutrino flavours; masses, mixings, magnetic
moments, decay modes and lifetimes of neutrinos) were derived by various authors.

However, the claimed concordance between SBBN theory and the observed abundances
of the light elements extrapolated to their primordial values had a rather poor confidence
level, was demonstrated for primordial abundance of $^4$He which deviated significantly
from its best value as inferred from observations and relied heavily on the highly uncertain extrapolated values for the primordial abundances of D+3He. Hence, SBBN could provide neither reliable evidence that most of the baryons in the universe are dark nor reliable limits on physics beyond the standard particle physics model (Dar, Goldberg and Rudzsky 1992). In fact Dar, Goldberg and Rudzsky (1992) argued that the theoretical upper bound on primordial D+3He that was estimated by Walker et al (1991) from a galactic evolution model is highly uncertain and the best values of the primordial abundances of 4He, and 7Li as inferred from observations indicate that η0 ≈ 1.60±0.10. This value yields a mean baryon mass density in the present Universe which is not significantly larger than the total mass density of matter visible in the V, IR, UV, X and Radio bands, provided that the true value of the Hubble constant is close to its value measured recently (Freedman et al 1994) by the repaired Hubble Space Telescope, H0 = 80±17 km s⁻¹ Mpc⁻¹. It predicts, however, a primordial abundance (by numbers) of D, [D]p/[H]p ≈ (2.10 ± 0.20) × 10⁻⁴, which is larger by about an order of magnitude than that observed in the galactic interstellar medium (Linsky 1993).

During the past three years new observations and refined analyses have greatly improved the estimated values of the primordial abundances of the light elements:

**Helium 4:** The most accurate determinations of the primordial abundance of 4He are based on measurements of its recombination radiation in very low metallicity extragalactic HII regions which are the least contaminated by stellar production of 4He. A number of groups have obtained high-quality data for very metal-poor, extragalactic HII regions which they used to extrapolate to zero metallicity yielding a primordial abundance (by mass) of Yp= 0.228 ± 0.005 (Pagel et al 1992), Yp= 0.226 ± 0.005 (Mathews et al 1992), Yp= 0.230±0.005 (Skillman and Kennicutt 1993), Yp= 0.229±0.004 (Izotov et al 1994), where 1σ statistical and systematic errors were added in quadrature. A weighted average yields

\[
Y_p = 0.228 ± 0.005 .
\] (7)

It is not inconceivable that systematic errors (e.g., due to collisional excitation, contribution of neutral Helium, interstellar reddening, UV ionizing radiation, grain depletion, non-homogeneous density and temperature, etc.) are larger; however, there is no empirical evidence for that.

**Deuterium:** Deuterium is easily destroyed already at relatively low temperatures. Consequently, its abundance observed today can only provide a lower limit to the big-bang production. Measurements of its abundance in the local interstellar medium (LISM) made recently by the Hubble Space Telescope (Linsky et al. 1993), gave [D]/[H]= (1.65±0.07) × 10⁻⁵. From the analysis of solar-wind particles captured in foils exposed on the moon and studies of primitive meteorites, Geiss (1993) deduced a pre-solar abundance of [D]/[H]= (2.6 ± 1.0) × 10⁻⁵. These values can be used as lower bounds on primordial Deuterium. High redshift - low metallicity quasar absorption systems offer the possibility of observing its abundance back in the past in very primitive clouds (Webb et al 1991). Recent measurements of the absorption spectrum of the distant quasar Q0014+813 in a low-metallicity high redshift (z= 3.32) hydrogen cloud, by Songaila et al (1994) with the Keck 10m telescope at Mauna Kea, Hawaii, and by Carswell et al (1994) with the
4m telescope at Kit Peak, Arizona showed an absorption line at the expected position of the isotopically shifted Lyman α line of Deuterium. The line shape was best fitted with Deuterium abundance of
\[ [D]/[H] \approx 2.5 \times 10^{-4}. \] (8)

(The probability that the absorption line is due to a second hydrogen cloud with a Lyman α absorption line at the position of the isotopically shifted deuterium line, was estimated as 3% and 15% by Songaila et al (1994) and Carswell et al (1994), respectively.) The above value is an order of magnitude larger than the interstellar value and a factor of three larger than the 95% confidence level upper bound on the primordial abundance of D+\(^3\)He that was inferred by Walker et al (1991). However, Walker et al (1991) used an uncertain galactic chemical evolution model to extrapolate their estimated presolar D+\(^3\)He abundance to zero cosmic age. Moreover, interstellar measurements of D and \(^3\)He abundances show large variations from site to site and the solar system values may not be a typical sample of galactic material 4.5 GY ago.

**Helium 3:** From measurements of \([\text{\(^3\)He}]/[\text{\(^4\)He}]\) in meteorites and the solar wind Geiss (1993) concluded that the presolar abundance of \(^3\)He is \([\text{\(^3\)He}]/[\text{H}]= (1.5 \pm 0.3) \times 10^{-5}\). However, any further extrapolations to zero cosmic age of the \(^3\)He (or the \(^3\)He+D) abundance extracted from solar system or interstellar observations are highly uncertain because \(^3\)He is both produced (via D(p,\(\gamma\))\(^3\)He) and destroyed (via \(^3\)He(\(^3\)He,2p)\(^4\)He and \(^4\)He(\(^3\)He,\(\gamma\))\(^7\)Be) in early generation stars. Hogan (1994) has recently suggested that the envelope material in low mass stars is mixed down to high temperature after they reach the giant branch, so that the \(^3\)He is destroyed before the material is ejected. Indeed from radio observations of highly ionized Galactic HII regions Balser et al (1994) and Wilson and Rood (1994) inferred \([\text{\(^3\)He}]/[\text{H}]\) values that ranged between \((6.8 \pm 1.5) \times 10^{-6}\) for W49 and \((4.22 \pm 0.08) \times 10^{-5}\) for W3. Hyperfine emission in the planetary nebula N3242 indicates (Rood, Bania and Wilson 1992) a large enrichment, \(^3\)He/H\(\approx 10^{-3}\). These spread values show that the presently observed \(^3\)He abundances apparently reflect complicated local chemical evolution and do not allow a reliable determination of the primordial \(^3\)He abundance from presently observed solar or LISM abundances.

**Lithium 7:** The primordial abundance of \(^7\)Li was determined from the most metal poor, Population II halo stars. Such stars, if sufficiently warm (\(T \gtrsim 5500K\)), have apparently not depleted their surface Lithium and are expected to have nearly a constant \(^7\)Li abundance reflecting its abundance at the early evolution of the Galaxy (Spite and Spite 1982a,b). High-precision LiI observations of 90 extremely metal poor halo dwarfs and main sequence turnoff stars have been performed recently by Thorburn (1994). From the surface \(^7\)Li abundances of the hottest metal-deficient stars (\(T \sim 6400K\)) Thorburn estimated
\[ [\text{\(^7\)Li}]/[\text{H}] = (1.7 \pm 0.4) \times 10^{-10}. \] (9)

Thorburn’s data suggest a slight systematic variation of the \(^7\)Li abundance with surface temperature, possibly indicating some depletion from a higher primordial value by processes that transport \(^7\)Li inward to regions where it can be burned. However, the amount
of depletion is constrained by the relatively narrow spread in $^7$Li abundance for a wide range of surface temperatures and metallicities and by the observation of $^6$Li in population II stars by Smith, Lambert, and Nissen (1993) and by Thorburn (1994): Big-bang production of $^6$Li is negligible. It is presumably produced by cosmic-rays. Since $^6$Li is burned much more easily than $^7$Li and yet still observed with an abundance expected for cosmic-ray production, depletion of $^7$Li cannot have been very significant.

In Fig. 2 we compare the predictions of the SBBN theory and the observed abundances of the light elements extrapolated to their primordial values. The confidence level of the agreement between the two using the standard $\chi^2$ test as function of $\eta_{10}$ is also shown in Fig. 2. (Errors were assumed to be statistical in nature. Experimental and theoretical uncertainties were added in quadrature). Fig. 2 shows that the primordial abundances of the light elements as inferred from observations are in very good agreement (confidence level higher than 70%) with those predicted by SBBN theory for $\eta_{10} \approx 1.60\pm0.1$. The corresponding mean cosmic baryon number density is $n_b = \eta n_\gamma = (6.6 \pm 0.5) \times 10^{-8} \text{cm}^{-3}$, which yields a baryon mass density (in critical density units $\rho_c \equiv 3H_0^2/8\pi G$) of

$$\Omega_b \equiv \rho_b/\rho_c = (0.0058 \pm 0.0007)h^{-2} \approx 0.01 \pm 0.004 \ ,$$

where $h = 0.80 \pm 0.17$ is the Hubble constant in units of $100 \text{ km s}^{-1}\text{Mpc}^{-1}$ measured by the repaired Hubble Space Telescope (Freedman et al 1994).

2.2 The Baryonic Mass Fraction in Clusters of Galaxies

Rich clusters of galaxies are the largest objects for which total masses can be estimated directly. In fact, the need for astrophysical dark matter was first identified for such systems by Zwicky in 1933.

The total mass enclosed within a distance $R$ from the centers of clusters of galaxies has been determined by three independent methods:

a) From the virial theorem applied to the radial velocities of cluster members assuming that the velocities are distributed isotropically and that light traces mass.

b) From analyses of the distribution of giant arcs and arclets produced by gravitational lensing of distant galaxies by the gravitating mass in clusters of galaxies.

c) From the X-ray emission of intergalactic hot gas which is trapped in the deep gravitational potential of rich clusters, under the assumption that the gas is relaxed.

All three methods yield similar results. When coupled with photometric measurements of the light emitted by the galaxies in the clusters they yield an average total mass to blue light ratio of $<M/L> = (230 \pm 30)h\text{M}_\odot/\text{L}_\odot$. The density of blue light in the Universe was measured (e.g., Loveday et al 1992) to be $\rho_L = (1.83 \pm 0.35) \times 10^8 h^2 \text{Mpc}^{-3}$. If the mean M/L ratio for clusters represents well the mean M/L ratio in the Universe then the mean cosmic density is

$$\Omega = \frac{\rho_L <M/L>}{\rho_c} \approx 0.15h \approx 0.12 \pm 0.2 \ .$$

This density is larger by more than an order of magnitude than the baryon density inferred from Big-Bang Nucleosynthesis and provides the best evidence for non-baryonic dark
matter. This conclusion is further confirmed by recent observations with the ROSAT X-ray Telescope: The positional sensitive proportional counter (PSPC) on board the ROSAT observatory has been used recently to measure the spectral and spatial distribution of X-ray emission from many rich clusters. These measurements have been used to determine the total gravitating mass, $M_t$, of the clusters and the fraction of that mass which is in the form of X-ray emitting hot gas, $M_{gas}$. Photometric measurements of the light emitted by the galaxies in the clusters have been used to estimate the total stellar mass, $M_\ast$, in the clusters. It was found (e.g., Briel et al 1992, White et al 1993 and references therein) that $M_\ast/M_t \approx 0.01$ and $< M_{gas}/M_t > \approx 0.05h^{-3/2}$, i.e., the known forms of baryonic matter account only for a small fraction of the total mass. In fact, numerical simulations of structure formation indicate that the ratio of baryonic to non baryonic mass is preserved in cluster formation (e.g. White et al 1993). Consequently, the observed baryonic fraction in clusters and Big-Bang nucleosynthesis imply that

$$\Omega \approx \frac{M_t}{M_b} \Omega_b \approx \frac{0.0058h^{-2}}{0.01 + 0.05h^{-3/2}} \approx 0.12 \pm 0.2,$$

in good agreement with the above independent estimate. If the cosmic dark matter consists of massive neutrinos then the neutrino masses satisfy $\Omega h^2 \approx \Sigma m_\nu$, i.e., $\Sigma m_\nu \approx 7 \pm 2 \text{ eV}$. This is also the neutrino mass which generates in a self consistent way (Tremaine and Gunn 1979) the gravitational potentials and the sizes of clusters of galaxies as determined from X-ray measurements and from the dispersion of velocities of the galaxies in the clusters.

### 2.3 Galactic Dark Matter and Gravitational Microlensing

The observed flat rotation curves of spiral galaxies, including our Milky Way (MW), indicate that they have extensive halos of dark matter (see e.g., Gould 1995). Paczyński (1986) has suggested that if the halo dark matter is made of brown dwarfs (low mass stars whose mass is below that required to ignite hydrogen, i.e., less than $0.08M_\odot$ for primordial chemical composition) it can be detected by their gravitational lensing of background stars. For galactic distances the splitting of the source into multiple images is too small (typically micro arcsec) to be resolved, but the lensing causes a typical magnification of the source which is time dependent due to the relative motion of the Earth, lens and source:

$$A(t) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}; \quad u(t) = \left[u_{\text{min}} \left(\frac{2(t - t_{\text{max}})}{t}ight)\right]^{1/2},$$

where $t = 2r_E/v$ is the time for the line of sight to move through two Einstein radii $D_E = 2r_E = 4\sqrt{GM_D D_{LS}/D_{OS}}$ and $u(t)$ is the distance between the lens and the line of sight in units of $r_E$.

Three experiments (MACHO, EROS and OGLE) reported (Alcock et al 1993; Aubourg et al 1993; Udalski et al 1993; Sutherland et al 1995; Moscoso 1995) the detection of more than 50 microlensing events, most of which are in the direction of the galactic
center and only 5 are of stars in the Large Magelanic Cloud (LMC) at a distance of \( D_{OS} \approx 50 \) kpc. The number of events both in the directions of the galactic center and of the LMC is much more than expected from the known population of stars in the MW, but the number of events in the direction of the LMC is much smaller than expected if the MW halo is spherical and consists entirely of MAssive Compact Halo Objects (MACHOs). In particular, the MACHO experiment detected 3 microlensing events in \( \sim 10^7 \) star-year monitoring of LMC stars. They explored a range of different halo profiles (Alcock et al 1995) and found a total mass of MACHOs interior to 50 kpc of \( 8^{+14}_{-6} \times 10^{10} M_\odot \) relatively independent of the assumed model for the MW halo. For a naive spherical halo model it implies that the halo mass fraction in MACHOs is \( f = 0.2^{+0.33}_{-0.14} \) and the most likely MACHO mass is \( M_L = 0.06^{+0.11}_{-0.04} M_\odot \), as demonstrated in Fig. 3.

Recently, Sackett et al 1994 reported the discovery of a faint red halo in the edge-on galaxy NGC5907 with a radial density distribution similar to that observed for dark halos \( (\rho \sim r^{-2}) \) and an inferred M/L ratio of 350-500, similar to that expected for subdwarf stars. This suggested that its dark halo is actually a faint red halo made of subdwarf stars. As NGC5907 is similar to our MW in type and radius it also suggests that subdwarf stars constitute the MW dark halo and give rise to the microlensing events seen by MACHO, EROS and OGLE. However, Bahcall et al 1994, using the wide field camera of the repaired Hubble Space Telescope (HST) have searched for red subdwarfs in our MW galaxy and found very few such stars and that they can contribute no more than 6% to the mass of the MW dark halo and no more than 15% to the mass of the MW disk. Thus, the microlensing and HST observations suggest that most of the MW halo consists of non baryonic dark matter.

3. THE SOLAR NEUTRINO PROBLEM - AN UPDATE

The Sun is a typical main sequence star that is believed to generate its energy by fusion of protons into Helium nuclei through the pp and CNO nuclear reactions chains which also produce neutrinos. These neutrinos have been detected on Earth in four pioneering solar neutrino experiments, thus basically confirming that the sun generates its energy via fusion of hydrogen into helium. However, all four experiments measured solar neutrino fluxes which are significantly smaller than those predicted by the standard solar model (SSM) of, e.g., Bahcall and Pinssenault 1992 (hereafter BP).

The HOMESTAKE Cl experiment reported (Cleveland et al 1995) an average production rate of \( ^{37} \text{Ar} \) of \( 2.55 \pm 0.25 \) SNU \( (1 \text{SNU} = 10^{-36} \text m^{-2} \text s^{-1} \text captures per atom) \) by solar neutrinos above the 0.81 MeV threshold energy during 24 years (1970-1993) of observations which is \( 32 \pm 5\% \) of the \( 8 \pm 3(3\sigma) \) SNU predicted by the SSM of BP.

KAMIOKANDE II and III observed electron recoils, with energies first above 9 MeV and later above 7 MeV, from elastic scattering of solar neutrinos on electrons in water. Their 5.4-year data show a spectrum consistent with \( ^8 \text{B} \) solar neutrino flux of (Kajita 1994) \( (2.7 \pm 0.2 \pm 0.3) \times 10^{6} \text{cm}^{-2}\text{s}^{-1}, \) which is \( 48\% \pm 9\% \) of that predicted by the SSM of BP.

GALLEX, the European Gallium experiment at the Gran Sasso underground laboratory, measured (Anselman et al 1995) a capture rate of solar neutrinos by \( ^{71} \text{Ga} \) of \( 79 \pm 10 \pm 6 \) SNU compared with \( 131.5^{+21}_{-17} \) SNU, predicted by the SSM of BP.
SAGE, the Soviet-American Gallium Experiment in the Baksan underground laboratory reported (Abdurashitov et al 1995) an average capture rate of solar neutrinos by $^{71}Ga$ of $74^{+13+5}_{-12-7}$ SNU during 1990-1993.

The discrepancies between the observations and the SSM predictions have become known as the solar neutrino problem. Table I summarizes these discrepancies for three different SSM calculations (Bahcall and Pinsenault 1992; Turck-Chieze and Lopes 1993; Dar and Shaviv 1994).

| Exp.             | Data       | SSM – BP | SSM – TC | SSM – DS |
|------------------|------------|----------|----------|----------|
| $^{37}$Cl (HOMESTAKE) | $2.55 \pm 0.17 \pm 0.18$ | $8.0 \pm 3.0$ | $6.4 \pm 1.4$ | $4.2 \pm 1.2$ |
| $^{71}$Ga (SAGE)  | $73^{+18+5}_{-16-7}$ | $131.5^{+21}_{-17}$ | $123 \pm 7$ | $113 \pm 7$ |
| $^{71}$Ga (GALLEX) | $79 \pm 10 \pm 6$ | $131.5^{+21}_{-17}$ | $123 \pm 7$ | $113 \pm 7$ |
| H$_2$O (KAM II + III) | $2.7 \pm 0.2 \pm 0.3$ | $5.7 \pm 2.5$ | $4.4 \pm 1.1$ | $2.7 \pm 0.8$ |

The results of Homestake, GALLEX and SAGE are in SNU, while those of Kamiokande are in $10^6 cm^{-2} s^{-1}$. Note that the results of Kamiokande are consistent with the SSM predictions of Dar and Shaviv (1994; 1995), but the results of the Cl and Gallium experiments differ significantly from their SSM predictions.

Bahcall and Bethe (1990, 1993) argued that the solution of the solar neutrino problem requires new physics beyond the Standard Electroweak Model (Glashow 1961; Weinberg 1967; Salam 1968) because the signal in the Cl detector due to the pep, $^7$Be, CNO and $^8$B solar neutrinos, is smaller than that expected from the $^8$B solar neutrinos alone as observed by Kamiokande. But, for a $1.06 \times 10^{-42} cm^2$ capture cross section in $^{37}$Cl of $^8$B neutrinos (Bahcall 1989), the flux observed by Kamiokande implies a minimal capture rate of $2.86 \pm 0.41$ SNU in the Cl experiment. During the same period (1986-1993) Homestake observed (Cleveland et al. 1995) a capture rate of $2.78 \pm 0.35$ SNU ($2.55 \pm 0.25$ SNU is the average over 24 years) which does not provide conclu evidence for new physics beyond the standard particle physics model. However, taken at their face values, the joint results of Kamiokande and of Homestake indicate a strong suppression of the SSM $^7$Be flux (see e.g., Dar 1993, Bahcall 1995), which according to the SSM is expected to contribute $\sim 1$SNU to the capture rate in the Cl experiment.

Additional indication for the suppression of the $^7$Be flux is provided by the Gallium experiments: Since the net reaction in the pp chains and CNO cycle is the conversion of protons into Helium nuclei, conservation of baryon number, charge, lepton flavour and energy requires that

$$4p + 2e^- \rightarrow 4^He + 2\nu_e + Q ,$$

where $Q = 26.73 \text{ MeV}$, i.e., two $\nu_e$’s are produced in the Sun per 26.73 MeV release of nuclear energy. Thus, if the Sun is approximately in a steady state where its nuclear energy
production rate equals its luminosity (less than 1/2% of the solar energy is produced by gravitational contraction) then the $\nu_\odot$ flux at Earth is given by

$$\phi_{\nu_\odot} = \frac{2L_\odot}{Q - 2\bar{E}_\nu} \frac{1}{4\pi D^2},$$

(15)

where $L_\odot$ is the luminosity of the Sun, $D$ is its distance from Earth, and $\bar{E}_\nu$ is the average $\nu_\odot$ energy. The bulk of the solar neutrinos are pp neutrinos. Consequently, $\bar{E}_\nu \approx \bar{E}_\nu(pp) \approx 0.265 \text{ MeV}$, and Eq.1 yields $\phi_{\nu_\odot} = \Sigma_i \phi_{\nu_i} \approx 6.50 \times 10^{10} \text{ cm}^{-2} \text{s}^{-1}$. Such a pp flux produces 76 $SNU$ in Gallium. The tiny flux (relative to the pp flux) of the $^8$B solar neutrinos observed in Kamiokande increases the signal by 7 $SNU$ to 83 $SNU$. Thus, the $79 \pm 10 \pm 6 \text{ SNU}$ measured by GALLEX and the $73^{+18+5}_{-16-7} \text{ SNU}$ measured by SAGE leave little room for the $\sim 30 \text{ SNU}$ contribution of the $^7$Be solar neutrinos predicted by the SSM (in the SSM the flux of $^7$Be neutrinos is $\sim 7\%$ of the flux of pp neutrinos but a $^7$Be neutrinos has a capture cross section in $^{71}\text{Ga}$ which is $\sim 6.2$ times larger than that of a pp neutrino).

Does the Solar Neutrino Problem imply new physics beyond the standard particle physics model?

A recent milestone experiment by GALLEX, namely, the calibration of the GALLEX experiment with an artificial $^{51}\text{Cr}$ source (Anselmann et al 1995a) has eliminated the trivial solution to the Solar Neutrino Problem, namely, that the accuracy of the results of the radiochemical experiments has been largely overestimated (the measured ratio of the production rate of $^{71}\text{Ge}$ by neutrinos from an artificial $^{51}\text{Cr}$ source placed inside the GALLEX detector to the rate expected from the known source activity was $R = 1.04 \pm 0.12$). Standard physics solutions to the solar neutrino problem have now the difficult task of explaining the strong suppression of the $^7$Be solar neutrino flux. Such a suppression is not ruled out by standard physics. For instance, collective plasma effects near the center of the Sun may align the electron and $^7$Be spins and may change the branching ratios of $e^-$ capture by $^7$Be to the ground and excited states of $^7\text{Li}$. If it causes a strong reduction in the flux of 0.862 MeV $^7$Be solar neutrinos with an increase in the flux of 0.384 MeV $^7$Be solar neutrinos it may explain the observations since the 0.384 MeV neutrinos are below the threshold for capture in the Cl detector and have a smaller capture cross section in Gallium.

A more elegant and exciting solution to the Solar neutrino problem is neutrino oscillations and the MSW effect (Mikheyev and Smirnov 1986; Wolfenstein 1978,1979). Fig. 4 shows the regions of mixing parameters $\Delta m^2$ and $\sin^2 \theta$ of $\nu_e$’s which can solve the Solar Neutrino Problem. Only future solar neutrino experiments, such as the SNO heavy water experiment (Ewan et al 1987) which will be able to detect the conversion of solar $\nu_e$’s into $\nu_\mu$’s and/or $\nu_\tau$’s, or Super Kamiokande (Kajita 1994) which will be able to detect deviations from the normal beta decay energy spectrum of $^7$Be neutrinos, will be able to confirm that the solution to the Solar Neutrino Problem requires physics beyond the standard model and that Nature made use of the beautiful MSW effect.
4. COSMIC RAY EVIDENCE FOR NEW PHYSICS?

Cosmic ray observations have often been proposed as evidence for new physics. In most of these cases cosmic ray puzzles turned out to be the results of a combination of poor statistics, improperly understood detection techniques and complicated physics. There are, however, some cosmic ray anomalies which perhaps require new physics. Here I will shortly discuss two of them, the atmospheric neutrino anomaly and the observations of ultrahigh energy cosmic rays above the Greisen-Zatsepin-Kuzmin energy cutoff.

4.1 THE ATMOSPHERIC NEUTRINO ANOMALY

Atmospheric neutrinos arise from the decay of secondaries (π, K and μ) produced in cosmic ray initiated cascades in the atmosphere. Neutrinos with energies below ∼ 1 GeV are mainly produced by \( \pi \to \mu \nu_\mu \) and \( \mu \to e \nu_e \nu_\mu \) decays and one roughly expects \( (\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e) \approx 2 \). Above ∼ 1 GeV some of the muons reach the ground before decay and the \( (\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e) \) ratio increases with increasing \( E_\nu \). Since the probability of muon to decay before reaching the ground depends on zenith-angle the neutrino flavour ratio also depends on zenith-angle. This ratio has been measured in various large underground neutrino detectors, NUSEX (Aglietta et al 1989), FREJUS (Berger et al 1990), SOUDAN-2 (Goodman 1995) IMB-3 (Becker-Szendy et al 1992; 1995) and KAMIOKANDE (Kajita 1994) and was compared with Monte Carlo calculations. Some experiments (SOUDAN-2, IMB-3 and KAMIOKANDE) found significant discrepancies between the observed and calculated ratio. This is summarized in Table II.

| Exp.       | \( \nu_e \) | \( \nu_\mu \) | \( \nu_e (MC) \) | \( \nu_\mu (MC) \) | \( (\nu_e/\nu_\mu)_{DATA}/(\nu_e/\nu_\mu)_{MC} \) |
|------------|-------------|--------------|----------------|-------------------|-------------------------------|
| NUSEX      | 18          | 32           | 20.5           | 36.8              | 0.99±0.35±?                   |
| FREJUS     | 57          | 108          | 70.6           | 125.8             | 1.06±0.19±0.16 ± 0.15         |
| SOUDAN-2   | 35.3        | 33.5         | 28.7           | 42.1              | 0.64 ± 0.17 ± 0.09            |
| IMB-3      | 325         | 182          | 257.3          | 268.0             | 0.54 ± 0.05 ± 0.12            |
| KAM(≤ GeV) | 248         | 234          | 227.6          | 356.8             | 0.60±0.06±0.05 ± 0.05         |
| KAM(≥ GeV) | 98          | 135          | 66.5           | 162.2             | 0.57±0.08±0.07 ± 0.07         |

In estimating the event rate, NUSEX, FREJUS and SOUDAN-2 used the flux calculations of Barr et al 1989 while IBM-3 used that of Lee and Kho 1990 and KAMIOKANDE used that of Honda et al 1990. If the \( \nu_e \) excess and and the \( \nu_\mu \) deficiency are real they may be due \( \nu_e \leftrightarrow \nu_\mu \) oscillations. The region of neutrino oscillation parameters (\( \Delta m^2 \) and \( \sin^2 \theta \)), which can explain the results of Kamiokande, is shown in Fig.3 (borrowed from Kajita 1994). Note that this region for \( \nu_e \leftrightarrow \nu_\mu \) oscillations does not overlap with that inferred from the MSW solution to the Solar Neutrino Problem.

It should be noted that the evidence for the atmospheric neutrino anomaly comes mainly from the light water Cerenkov detectors. Much larger statistics will be provided by Super Kamiokande in a couple of years and the long baseline neutrino oscillation experiments should provide more definite experimental evidence.

4.2 VERY ENERGETIC COSMIC RAYS BEYOND THE GZK CUTOFF
Greisen (1966) and Zatsepin and Kuzmin (1966) have pointed out that if very high energy cosmic rays are produced at cosmological distances, as inferred from their isotropy, their energy spectrum should be cutoff around \( E \sim m_\pi (2m_p + m_\pi)/4E_\gamma \sim 10^{20}eV \), the threshold energy for photoproduction in head-on collisions with photons of the microwave background radiation (MBR) whose average energy is \( \bar{E}_\gamma \approx 2.7kT \approx 6.32 \times 10^{-4}eV \).

For protons above \( 3 \times 10^{20}eV \) the attenuation length is less than 30 Mpc (Stecker 1968; Hill and Schramm 1985; Yoshida and Teshima 1993). Nuclei and gamma rays have even shorter attenuation lengths (Puget et al 1976; Wdowczyk et al 1972).

By combining all the data accumulated for more than 30 years on the the highest energy cosmic rays from the extensive air shower array experiments at Volcano Ranch, Haverah Park, Sydney, Yakutsk, Dugway and Akeno significant evidence for the GZK has been accumulated. That is, only several cosmic rays exceeding \( 10^{20}eV \) have been observed compared with expectation of more than 25 if there is no cutoff and their energy extends beyond \( 10^{20}eV \) with the same power index (Hayashida et al 1994).

Recently, however, the two most energetic cosmic rays have been observed by the Fly’s Eye (\( E = 3.2 \pm 0.9 \times 10^{20}eV \); Bird et al 1994), by the Akeno Giant Air Shower Array (\( E = (1.7 - 2.6) \times 10^{20}eV \); Hayashida et al 1994) from directions in the sky where no nearby cosmic accelerators, such as active galactic nuclei, have been seen (because of their high magnetic rigidity the arrival directions of these cosmic rays should point approximately to their sources). It suggests a diffuse origin of the ultrahigh energy cosmic rays. But, what can be this origin? The lack of known conventional diffuse sources of ultrahigh energy cosmic rays calls for alternative diffuse sources such as cosmic strings or annihilation of magnetice monopoles or of other very massive relic particles from the Big-Bang.

A detailed discussion of the possible nature and origin of the ultrahigh energy cosmic rays has been made by Elbert and Sommers 1994. However, many more cosmic ray events above the GZK cutoff are needed before any definite conclusions regarding their identity and origin can be made.
REFERENCES

Abdurashitov, J.N. et al., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 60
Aglietta, M. et al., 1989, Europhys. Lett. 8, 611
Anselmann, P. et al., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 68
Anselmann, P. et al., 1995a, Phys. Lett. B (in press).
Alcock, C. et al., 1993, Nature, 365, 621
Alcock, C. et al., 1995, Univ. of Washington Preprint, Jan. 1995
Aubourg, E. et al., 1993, Nature, 365, 623
Balser, D.S., Bania, T.M., Brockway, C.J., Rood, R. T. and Wilson, T.L., 1994, ApJ
Bahcall, J.N., 1989, Neutrino Astrophysics (Cambridge Univ. Press, 1989)
Bahcall, J.N. et al., 1994, ApJ. 435, L51
Bahcall, J.N., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 98
Bahcall, J.N. and Bethe, H.A. 1990, Phys. Rev. Lett. 65, 2233
Bahcall, J.N. and Bethe, H.A. 1993, Phys. Rev. D. 47, 1298.
Bahcall, J.N. and Pisonneault, M., 1992, Rev. Mod. Phys. 64, 885.
Barr, G. et al., 1989, Phys. Rev. D 39 3532
Becker-Szendy, R. et al., 1992, Phys. Rev. D 46, 3720
Becker-Szendy, R. et al., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 333
Berger, Ch. et al., 1990, Phys. Lett. 245, 305.
Bethe, H., 1939, Phys. Rev. 55, 103.
Bird, D.J., et al., 1994 ApJ. 424, 491
Blandford, R.D. et al., 1989, Science 245, 824
Blandford, R.D. and Narayan, R., 1992, Ann. Rev. Astron. Astrophys. 30, 311.
Cholson, O., Astron. 1924, Nachr. 221, 329
Carswell, R.F. et al., 1994, MNRAS, in press
Caughlan, G.R. and Fowler, W.A., 1988, Atom. and Nucl. Data Tables, 40, 284
Clayton, D., 1968, Principles of Stellar Evolution & Nucleosynthesis (McGraw-Hill)
Cleveland et al., 1995 Nucl. Phys. B (Proc. Suppl.) 38, 47
Damour, T. and Taylor, J.H., 1991, ApJ. 366, 501
Dar, A., 1992, Nucl. Phys. B (Proc. Suppl.) 28A, 321top
Dar, A., 1993, in Particle Physics and Cosmology (eds. V. Matveev et al.)
Dar, A., 1993a, Proc. 1st Rencontre De Vietnam on Astroparticle Phys. (ed. Tran Thanh Van)
Dar, A., Goldberg, J. and Rudzsky, M. 1992, Technion Preprint PHR- 92-12
Dar, A. and Shaviv, G., 1994, Proc. VI Int. Workshop on Neutrino Telescopes, p. 303
(ed. M. Baldo-Ceolin); Shaviv, G., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 81.
Einstein, A., 1936, Science 84, 506
Ewan, G.T. et al., 1987, Sudbury Neutrino Observatory Proposal SNO-87-12
Elbert, J.W. and Sommers, P., 1994 (to be published)
Freedman, W.L. et al., 1994, Nature, 371, 757
Geiss, J., 1993, in Origin and Evolution of the Elements, eds. N. Prantzos et al. (Cambridge University Press, 1993) p. 89
Glashow, S. 1961, Nucl. Phys. 22, 579
Goodman, M. C., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 337
Gould, A., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 371
Greisen, K., 1966, Phys. Rev. Lett. 16, 748
Grossman, S.A. and Narayan, R., 1988, ApJ. Lett. 324, L37
Hayashida N. et al., 1994, Phys. Rev. Lett. 73, 3491
Hill, C.T. and Schramm, D.N., 1985, Phys. Rev. D 31, 564
Hogan, C., 1994, Astrophys. Bull. Board preprint astro-ph/9407038
Honda, M. et al., 1990, Phys. Lett. B 248, 193
Izotov, Y., Thuan. X.T. and Lipovetsky, V.A., 1994, ApJ. 435, 647
Kajita, T., 1994 ICCR-Report 332-94-27 (December 1994).
Kolb, R. and Turner, M., 1991, The Early Universe (Addison Wesley-1990)
Langston, G.I. et al., 1989, Astr. J. 97, 1283
Langston, G.I. et al., 1990, Nature 344, 43 (1990)
Lee, H. and Koh, Y.S., 1990, Nuov. Cim. 105B, 883.
Linsky, J.L. et al., 1993, ApJ, 402, 694
Loveday, J. et al., 1992, ApJ. 390, 338
Lynds, R. and Petrosian, V., 1989, ApJ. 336, 1
Mana, C. and Martinez, M., 1993, Nucl. Phys. B (Proc. Suppl.) 31, 163
Mannheim, P.D. and Kazanas, D. 1989 Ap. J. 342, 635
Mather, J.C. et al., 1994, ApJ, 420, 439
Mathews, G.J. et al., 1993, ApJ, 403, 65
Mathews, G.J., and Malaney, R.A., 1993, Phys. Rep., 229, 147
Mikheyev, P. and Smirnov, A. Yu. 1986, Nuov. Cim. 9C, 1986
Milgrom, M. and Bekenstein, J., 1984, ApJ. 286, 7
Moscoso, L., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 387
Paczynski, B., 1986, Astrophys. J. 304, 1
Pagel, E.J. et al., 1992, MNRAS, 255, 325
Particle Data Group, 1994, Phys. Rev. D50, 1173
Peebles, P.J.E., 1966, ApJ., 146, 542
Peebles, P.J.E., 1993, Principles of Physical Cosmology, (Princeton Series in Physics)
Pelt, J. et al., 1994, Astron. and Astrophys. 286, 775
Puget, J.L. et al., 1976, ApJ. 205, 638
Rix, H.W., Schneider, D.P. and Bahcall, J.N., 1992, Astron. J.
Rood, R.T., Bania, T.M., and Wilson, T.L. 1992, Nature, 355, 618
Sackett, P. et al., 1994, Nature 370, 441
Salam, A. 1968, in "Elementary Particle Theory", p. 367 (ed. N. Svartholm, Almqvist and Wiksells, Stockholm 1968)

Sanders, R.H., Asstron. Astrophys. 1984, Lett. 136, L21

Sanders, R.H., 1990, Astron. Astrophys. Rev. 2, 1 and references therein.

Schild, R.E., 1990, Astron. J. 100, 1771

Skillman E.D. and Kennicutt, R.C. Jr., 1993, ApJ, 411, 655

Smith, V.V., Lambert, D.L. and Nissen, P.E., 1993, ApJ, 408, 262

Smith, M.S., Kawano, L.H. and Malaney, R.A., 1993, ApJ (Suppl.), 85, 219

Songaila, A. et al., 1994, Nature, 368, 599

Soucail, G. et al., 1988, Astro. Astrophys. Lett. 172, L14

Spite, M. and Spite, F., 1982a, Astron. and Astrophys., 115, 357

Spite, M. and Spite, F., 1982b, Nature, 297, 483

Stecker, F.W., 1968, Phys. Rev. Lett. 21, 1016

Sutherland, W. et al., 1995, Nucl. Phys. B (Proc. Suppl.) 38, 380

Thorburn, J.A., 1994, ApJ, 421, 318

Tremaine, S. and Gunn, J.E. 1979, Phys. Rev. Lett. 42, 407

Turck-Chieze, S. et al. 1988, Ap. J. 335, 415

Turck-Chieze, S. and Lopes, I. 1993, Ap. J. 408, 347

Tyson J. A. et al., 1990, ApJ, 349, L1

Tyson, J.A., 1991, A.I.P. Conf. Proc. 222, 437

Udalski, A., et al., 1993, Acta Astronomica, 43, 289

Vanderriest, C. et al., 1989, Astron. Astrophys. 215, 1

Wagoner, R.V., Fowler, W.A. and Hoyle, F., 1967, ApJ, 148, 3

Wagoner, R.V. 1973, ApJ, 179, 343

Walker, T.P. et al., 1991, ApJ, 376, 51

Webb, J.K., 1991, MNRAS, 250, 657

Weinberg, S. 1967, Phys. Rev. Lett. 19, 1264

Weinberg, S. 1972, Gravitation And Cosmology (John Wiley & Sons 1972).

White, S.D.M. et al., 1993, Nature 366, 429

Will, C.M., 1984, Physics Reports 113, 345 and references therein.

Wilson, T.L. and Rood, R.T., 1994, Ann. Rev. Astron. Astrophys. 32, in press

Wdowczyk, J. et al., 1972, J. Phys. A 5, 409

Wolfenstein, L. 1978, Phys. Rev. D17, 2369

Wolfenstein, L. 1979, Phys. Rev. bf D20, 2634

Yang, J. et al., 1984, ApJ. 281, 493

Yoshida, S. and Teshima, 1993, M., Prog. Theor. Phys. 89, 833

Zatsepin , G.T. and Kuzmin, V.A., 1966, Pis’ma Zh. Eksp. Ther. Fiz. 4, 1966

Zwicky, F., 1933, Helv. Phys. Acta, 6, 110
**FIGURE CAPTIONS**

**Fig. 1:** The ratios between the EGR prediction and the observations of the deflection and time delay of light from distant quasars and galaxies by galaxies or clusters of galaxies, displayed at the impact parameter of the deflected light relative to the center of the lens, for the Einstein Cross Q2237+05, the Einstein Ring MG1654+1346, the double quasar Q0957+561 and the Einstein Arcs in A370, Cl2244-02, and Cl0024+1654. The estimated errors in the ratios include the quoted observational errors and the errors in the theoretical estimates due only to errors in measured parameters and the absence of precise knowledge of $\Omega$ and $h$, but not systematic errors.

**Figure 2.** (a) The primordial mass fraction of $^4$He and the abundances (by numbers) of D, $^3$He and $^7$Li as a function of $\eta_{10}$ as predicted by SBBN theory. Also shown are their observed values extrapolated to zero age, as summarized in section III. The vertical line indicates the value $\eta_{10} = 1.6$. (b) The values of $\chi^2$ (left scale) and the corresponding confidence level (right scale) of the agreement between the predicted abundances and those inferred from observations, as function of $\eta_{10}$. Best agreement is obtained for $\eta_{10} \approx 1.60$ with a confidence level above 70%.

**Figure 3.** Likelihood contours for the MACHO mass derived by the MACHO collaboration from their 3 microlensing events of LMC stars. A spherical MW halo of equal mass Machos was assumed (from Alcock et al 1995).

**Figure 4.** The allowed parameter regions of the MSW solution to the solar neutrino problem adopting the SSM predictions of Bahcall and Pinsonnault and of Turck-Chieze and Lopes (from Kajita 1994).

**Figure 5.** The allowed parameter regions of the neutrino oscillation solutions to the atmospheric neutrino anomaly seen by Kamiokande, IMB-3 and Soudan-2 (from Kajita 1994).