Title
THE DIALOGUE BETWEEN PARTICLE PHYSICS AND COSMOLOGY

Author
Sadoulet, B.

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B. Sadoulet

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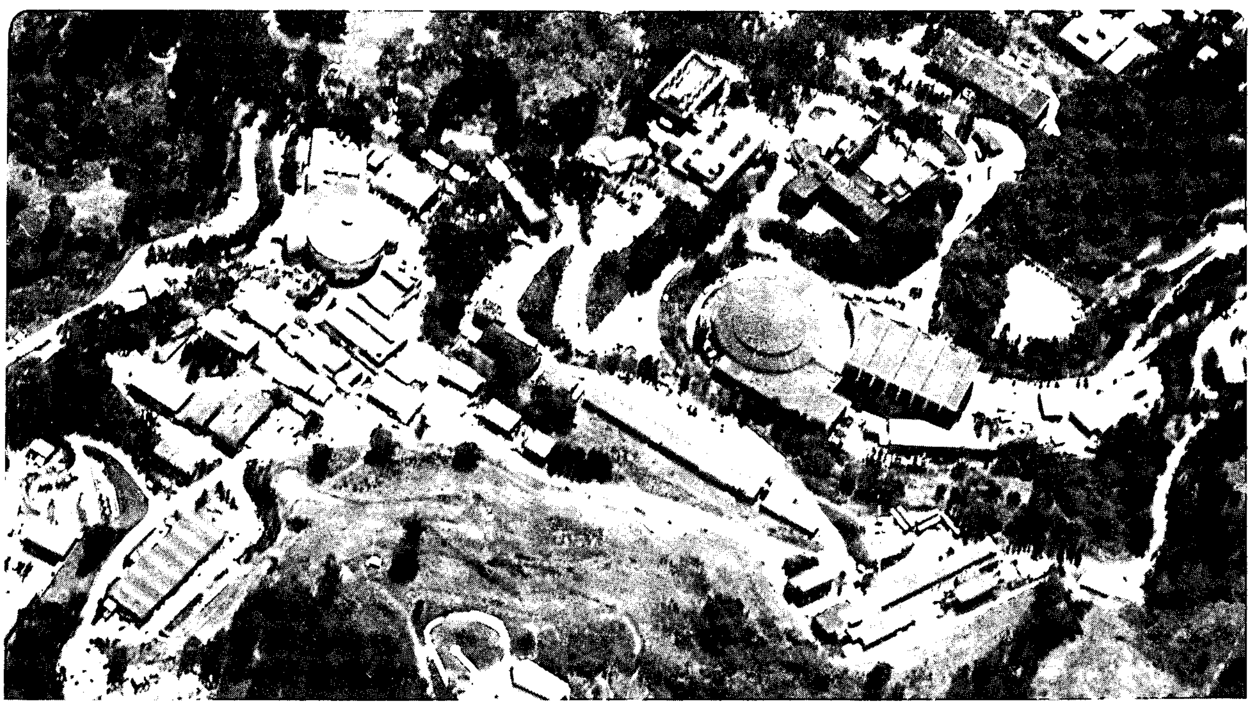

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The Dialogue Between Particle Physics and Cosmology

Bernard Sadoulet
Department of Physics
and Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

1-Introduction

In the last decade, a very close relationship has developed between particle physics and cosmology. The purpose of these lectures is to introduce particle physicists to the many scientific connections between the two fields. Before entering into the discussion of specific topics, I will first show that particle physics and cosmology are completely interdependent.

1.1 Cosmology Needs Particle Physics

Many central problems of cosmology may have their solution in particle physics. Let me take two central examples:

•*Why is the universe made of matter and not of a mixture of matter and antimatter?*

From the absence of antinuclei in cosmic rays and the absence of strong extragalactic γ radiation, we can infer [Steigman, 1976] that there is no antimatter until at least the Virgo supercluster, which is at 20 megaparsecs (One parsec, abbreviated as 1 pc, is 3.26 light years or 3.09 10^{16} m). This may look surprising if there has been a Big Bang, since the laws of nature are symmetric between particles and antiparticles to a high degree of accuracy. We would have naively expected that the initial energy condenses into an equal amount of quarks and antiquarks. A potential solution may be given by particle physics. A prototype of these baryogenesis models [Ellis et al., 1979] attributes the excess of quarks to a slight CP asymmetry in the decay of a particle X in the early universe.

•*What is the nature of the Dark Matter?*

As we will see, more than 90% of the mass in the universe does not radiate any electromagnetic waves and may be of a different nature than the ordinary baryonic matter. An explanation of this fundamental scientific puzzle, may be again provided by particle physics. Many models, such as supersymmetry, quite naturally expect that an additional component of non-baryonic particles will remain from the early universe and may be responsible for the dark matter.

There are also more technical problems, which particle physics may solve:

•*Value of basic cosmological parameters*.

It is difficult to understand why the average density of the universe is so close to the critical density. Unless the universe actually does have the critical density, it is expected to diverge very rapidly from it . The extreme isotropy of the 2.7 K microwave background is another mystery, since a naive extrapolation backward indicates that points of the sky more than a few degrees apart, should have never been in causal contact and therefore cannot have the same temperature. These puzzling results may be explained by particle physics. It makes it quite natural for a phase transition to occur in the early universe at the time of a spontaneous symmetry breaking. With the proper characteristics, such a phase transition would lead to an inflationary episode where the size of the universe increases very rapidly. This rapid increase may bring the density back to a value extremely close to the critical density and sufficiently separate events which were in causal contact, so that they later appear out of causal contact. Such phase transitions are expected in many particle physics models.

•*Origin of the large scale structure of the universe.*

In order to understand the origin of the large scale structure of the universe, galaxies, clusters and superclusters of galaxies, the cosmologist relies more and more on particle physics. The formation of galaxies is usually attributed to a gravitational collapse of density fluctuations. But what is the origin of these fluctuations? One proposal is that they are due to quantum fluctuations at the time of inflation. In these kinds of models, as we will see, it is necessary to add another component such as topological singularities (cosmic strings) or dark matter, which may be some exotic particles. A different class of models attributes the collapse to an overdensity triggered by explosions. There again, particle physics is called upon to provide powerful enough phenomena such as the radiation from superconducting strings. Even if some of these proposals seem quite arbitrary, it is fascinating to think that structure at the quantum scale may be responsible for the large scale structure, and thus, as in Blaise Pascal's intuition, the infinitely small is connected to the infinitely large.

1.2 Particle Physics Needs Cosmology

The goal of particle physics is to understand the fundamental forces of nature. In particular, the unification of forces is a central question. Unfortunately, the unification scale appears to be very high and out of reach of man-made accelerators. Figure 1.1 shows the coupling constants behavior with energy, which indicates an unification scale above 10^{15} GeV [Ellis, 1983]. If new families of particles exist, the unification scale will be pushed even higher. The absence of proton decay at the 10^{31} year level also indicates a very high value.

How then can we get experimental information on the physics at the unification scale? Two approaches may be attempted. We can look at subtle consequences at low energy of the physics at very high energy. Searches for proton decays and the

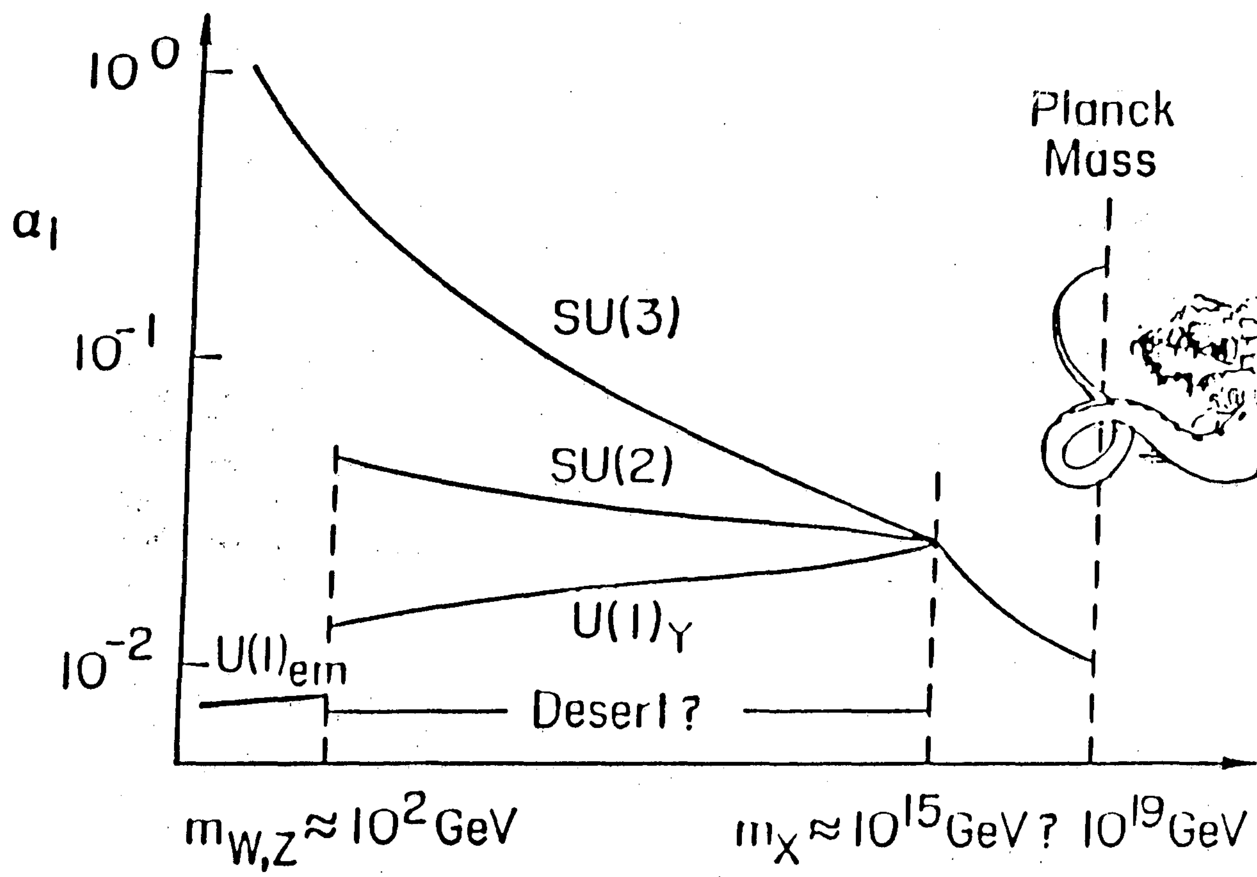


Figure 1.1: Sketch of the unification of SU(3), SU(2) and U(1) gauge couplings [Ellis, 1983]

measurement of neutrino masses are typical of this route. We can also study a system which has gone through the unification scale, namely the early universe. If the Big Bang picture is correct, the universe went through a period of high temperature and may carry the imprints of physics at ultra high energy.

1.2.1 Hints from the early universe.

The status of the universe today give hints and provide important constraints on theoretical models. Typically, an otherwise attractive theoretical model will have to be rejected because it leads to conflicts with basic cosmological parameters or to unacceptable distortions of the standard cosmological scenario. Let us give a few examples:

• *Spectrum of particles*

The spectrum of particles has to be compatible with both the density and the composition of the present universe. For instance, the first type of constraint limits the masses of Dirac neutrinos. Masses between approximately 30 eV/c^2 and 2 GeV/c^2 would overclose the universe [Lee and Weinberg,1977]. The primordial abundance of helium requires the number of particle species relativistic at the time of nucleosynthesis to be smaller than approximately 13 [Yang et al., 1984]. This constrains the number of particles with mass smaller than 1MeV. In particular, the number of neutrino families has to be smaller than five.

• *New objects*

Objects which are still unknown may have been created when the temperature in the early universe was higher than the energy available at our accelerators and may have survived. For instance, very massive particles may be present around us, such as: monopoles and dark matter particles. Topological singularities, such as cosmic strings generated at time of phase transitions, may have observable consequences, creating linear discontinuities of temperature in the 2.7 K background or a linear pattern of gravitational lensing.

• *Parameters in models*

Cosmology also fixes important parameters in particle physics models. For instance, baryogenesis models trying to explain the absence of antimatter around us have to reproduce the ratio of the number of protons to the number of photons which is necessary for the standard primordial nucleosynthesis to work. SU(5) was unable to do so and could have been rejected on that ground only, even if protons had happened to decay at the required rates. More complex models can usually be adjusted to meet this demand.

Even though the concept of inflation is very attractive and successful, no model without adjustable parameters has been able to reproduce the required amount of inflation and the amplitude of density fluctuations necessary for galaxy formation. Here again, cosmological constraints help to fix the shape of the potential.

In summary, cosmology more and more constrains model building and begins to play the role that the measurement of the g-2 of the muon had played a few years ago!

1.2.2 The Cosmos as a particle physics laboratory.

Coming back now to the first approach of trying to see at low energies the consequences of the physics at very high energy, we find that the effects may be so small that only the cosmos can provide the masses, densities, and scales necessary to see them. Obvious examples are the neutrino oscillations in vacuum, which may require the distance between the sun and the earth to be observable, or the neutrino oscillations in matter which may demand masses as large as that of the sun to have measurable effects.

Gravity is observed mainly in the astronomical realm, and only in that environment can we expect to observe gravitational waves and black holes. Note that in the spirit of the unification of forces, (quantum) gravity will eventually have to come back into the bosom of particle physics.

Finally, very high density states are available only in the cosmos, for instance in the form of neutron stars. The study of these compacts objects may provide important results about the hadronic matter equation of state or about the powerful acceleration mechanisms which may be at work around them.These points will not be discussed further in these notes.

1.3 Conclusion

There are therefore very intimate connections between cosmology and particle physics that have long been recognized by theorists, and an abundant literature exists on the subject. It is, however, difficult at times to gauge the model independence of some arguments and to judge what is founded only on the current orthodoxy or the standard wisdom; moreover, strong statements may be made based on marginal experimental results.

But why,as an experimentalist, am I interested? I can outline three elements:

• *The questions are fascinating!*

Some of the questions that we ask in cosmology are very fundamental. For instance, why are we living in a universe of matter? Note that this is absolutely essential to our own existence, since an universe symmetric in matter and antimatter will be presumably radiation dominated, with no possibility of life unless somehow matter and antimatter got segregated. The nature of dark matter which may represent more than 90% of the universe around us, is another fascinating question.

In spite of their fundamental nature, these kinds of questions are much less abstract that those tackled in "pure" particle physics and are much easier to share with the public at large, who has always been attracted by astronomy and our origin!

This field is also pluridisciplinary and involves many aspects of physics, which makes it very interesting.

• *Experimental cosmology is a "virgin territory".*

Experimental cosmology is a new field which has developed on the margin of extragalactic astronomy and radioastronomy and is still widely open. There is a crying need for more data, and only a relatively small number of experimental teams work on this extremely difficult subject. My belief is that particle physicists can have an impact, for instance, by exporting technologies. To take a personal example, our group is trying to adapt the drift chamber technology, which was so successful at accelerators, to hard X ray and gamma ray astronomy [Sadoulet et al, 1987 and 1988]. I am also convinced that the style of particle physics experimentalists, accustomed to combine a high sophistication of detectors and analysis methods and a scale large enough for the problem to solve, will make a difference.

• *Small experiments are still possible.*

Being a new field, cosmology may not require as large experiments as high energy particle physics to answer fundamental questions. I view it personally as a potential solution to the sociological problems of large collaborations that worry many of us! Let me note, however, that this is by no means automatic. The time scale of any NASA satellite program is probably longer than any large accelerator experiments, and the size of the team and the management requirements much larger.

I have tried to design this course to share with the reader my enthusiasm for cosmology. Skipping over much of the theory, I will attempt to evaluate the experimental results and outline the many points of contact with particle physics.

2. The Expanding Universe

Our first task is to characterize the expanding universe. Here we summarize the classical results. The interested reader may, for instance, read Chapters 14 and 15 of Weinberg [1972].

2.1 The history of the universe as we understand it.

2.1.1 The basic cosmological parameters and their evolution.

If the universe is homogeneous and isotropic on a large enough scale, as it appears to be, it can be characterized simply by a **scale parameter** a(t) (often also written as R(t)). The real coordinate x of a galaxy at rest with respect to the expansion is given at time t by

$$x=a(t)\ r$$

where r is the **fixed comoving coordinate**.The rate of expansion is given by the Hubble "constant"

$$H=\frac{1}{a}\frac{\partial a}{\partial t}.$$

Experimentally, we find that the universe is expanding and light from distant galaxies is redshifted. If we define the red shift as

$$z=\frac{\Delta\lambda}{\lambda}$$

it can be shown to be given, for an object at rest with respect to the Hubble flow, by the ratio of the scale parameter now ($t=t_0$) to the value at the time of emission ($t=t_1$)

$$1+z=\frac{a(t_0)}{a(t_1)}.$$

At very large scale, our universe can be considered as a spatially homogeneous and isotropic space and its metric is the Robertson-Walker metric:

$$ds^2 = dt^2-a^2(t)\ \left\{\frac{dr^2}{1-kr^2} + r^2\, d\theta^2 + r^2 \sin^2\theta\, d\varphi^2\right\}$$

where k is a constant which can be set to 0 or ±1 by proper choice of the units, and is related to the **space curvature**.

The theory of general relativity then allows us to relate the Hubble constant to the average density ρ of the universe by the so called Friedman equation

$$H^2=\frac{8\pi G}{3}\rho - \frac{k}{a^2}+\frac{\Lambda}{3}.$$

This equation which can also be derived (except for the cosmological constant Λ) in Newtonian mechanics, expresses the balance of the kinetic energy given by H^2 and the potential energy (proportional to ρ). The constant k arises then as an integration constant.

Let us discuss first the case where Λ is zero. It is obvious that if k=0 the density is

$$\rho_c = \frac{3H^2}{8\pi G}$$

the so called critical density. Since ρ_c is positive, the expansion rate cannot go through zero and the universe is always expanding. If we define

$$\Omega = \frac{\rho}{\rho_c}$$

in this case $\Omega=1$, and the universe is spatially flat (but curved in space time.

On the other hand if $k>0$, that is, if $\Omega>1$, the expansion rate can go through zero and the universe will recollapse. This corresponds to a closed universe, which is spatially isometric to a 3-sphere.

If $k<0$ which corresponds to $\Omega<1$, the universe is open and will expand forever. Figure 2.1 displays the evolution of a(t) for the three cases.

The additional term Λ is called the cosmological constant. It arises naturally in many particle physics models (but with rather large values) and can be interpreted as the energy density of vacuum (but with negative pressure if $\Lambda>0$).

The Friedman equation has to be complemented by two equations expressing the relation between the pressure and the density (equation of state) and the conservation of energy. Let us examine the evolution of the basic parameters for the case of zero cosmological constant.

In the present **matter-dominated** universe, the pressure is neglible ($p=0$). The conservation of energy states then that

$$\frac{d}{dt}[\rho a^3(t)] = 0.$$

The Friedman equation can then be solved.For instance in the absence of a cosmological constant, and if $k=0$

$$a(t) \propto t^{2/3} \quad .$$

In any case there is an initial singularity. The Friedman equation shows that **the universe cannot be static** and there has been a Big Bang. The age T of the universe is of the order of

$$T \approx \frac{1}{H} \text{ (e.g. } T = \frac{2}{3H} \text{ for } \Lambda=0 \text{ and } k=0).$$

Note that Ω **is usually not a constant**: It can be shown easily that

$$(1-\Omega^{-1}) = (1-\Omega_0^{-1})/(1+z)$$

where Ω_0 is the value of Ω today and that if Ω is different from 1, it will diverge very rapidly from 1. This is the origin of the puzzle we alluded to in the introduction. Why is Ω_0 so close to 1?

During the matter-dominated epoch, the background photon (and neutrino) energies and temperatures evolve as $1/a(t)$ and their energy densities as $a(t)^{-4}$.Therefore at sufficiently early times, the energy density of the universe becomes **radiation dominated.** For a relativistic fluid

$$p = \frac{\rho}{3}$$

and the combination of the Friedman equation and the conservation of energy gives

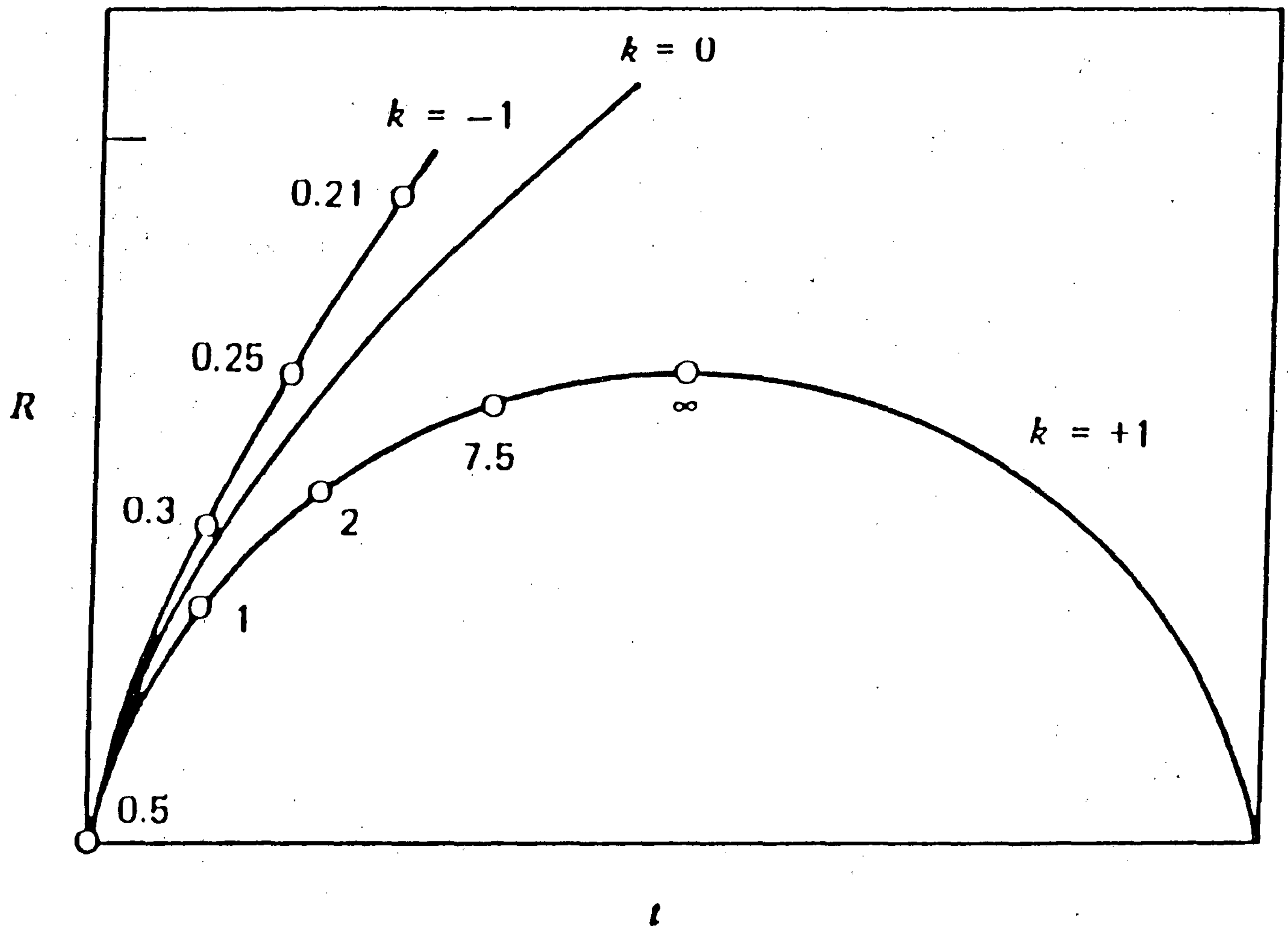


Figure 2.1: Evolution of the scale parameter for various values of k [Weinberg 1972]

$$\rho \approx a(t)^{-4}$$
$$a(t) \approx (NDF)^{1/4}\, t^{1/2}$$
where NDF is the effective number of degrees of freedom, i.e. the sum of the number of boson states and of 7/8 of the number of fermion states.

Note that the spatial curvature term is negligible at that time and that the results above are independent of k. The important point of the equation above is that the evolution speed depends on the number of degrees of freedom. The larger it is, the faster a(t) grows. We will see in Section 3.2, that this is the basis for the constraints on the number of neutrino species provided by primordial nucleosynthesis.

Because of finite time since the Big Bang, there is a maximum radius from which radiation can be seen at a given time and position. This is called the (event) **horizon**. The concept is not intuitive in the (hyper) plane of time versus real spatial coordinates (Fig 2.2a), because light rays on the light "cone" seem to converge to the initial singularity. It is better to consider the plane of time versus comoving spatial coordinates (Fig 2.2b) in which it is obvious that the light cone span a finite extent at time zero. Note that the exact extent of the horizon is a function of the evolution of a(t) and therefore of the equation of state.
Two events cannot be **causally connected** if their past light cones do not intersect (Fig 2.2b). It is in this context that the extreme uniformity of temperature of 2.7 K microwave background is puzzling. If we naively extrapolate backwards, even allowing for an increase of the number of degrees of freedom at earlier times, we discover that two points separated by a few degrees on the sky should have never been in causal contact, and therefore could not possibly have the same temperature. The equation has to be modified to give an exponential increase in a(t) at early times, in order to have their light cones intersect (Fig 2.2c). This is exactly what inflation does!

2.1.2 Implications of Particle Physics

In order to compute the evolution of the cosmological parameters, particle physics is essential because it provides the equation of state at early times.

The interaction rates as a function of energy allow us to decide which particle species are in **thermodynamical equilibrium**. In that case, particle physics provides the number of degrees of freedom. Table 2.1a gives this number as a function of energy for the standard model.

The same interaction rates allow us to compute what happens at the time of the decoupling of a particle species. This is an important argument due to Chiu and Zeldovich, and which has been worked out in detail by Lee and Weinberg [1977]. Let us consider, for example, the equilibrium at high temperature of an hypothetical massive particle δ with the rest of quarks and leptons,

$$\delta\bar{\delta} \leftrightarrow q\bar{q}, l\,\bar{l}$$

As the temperature goes down, the equilibrium is displaced to the right and the δ's drop out of equilibrium. We should not forget, however, that we are in an expanding

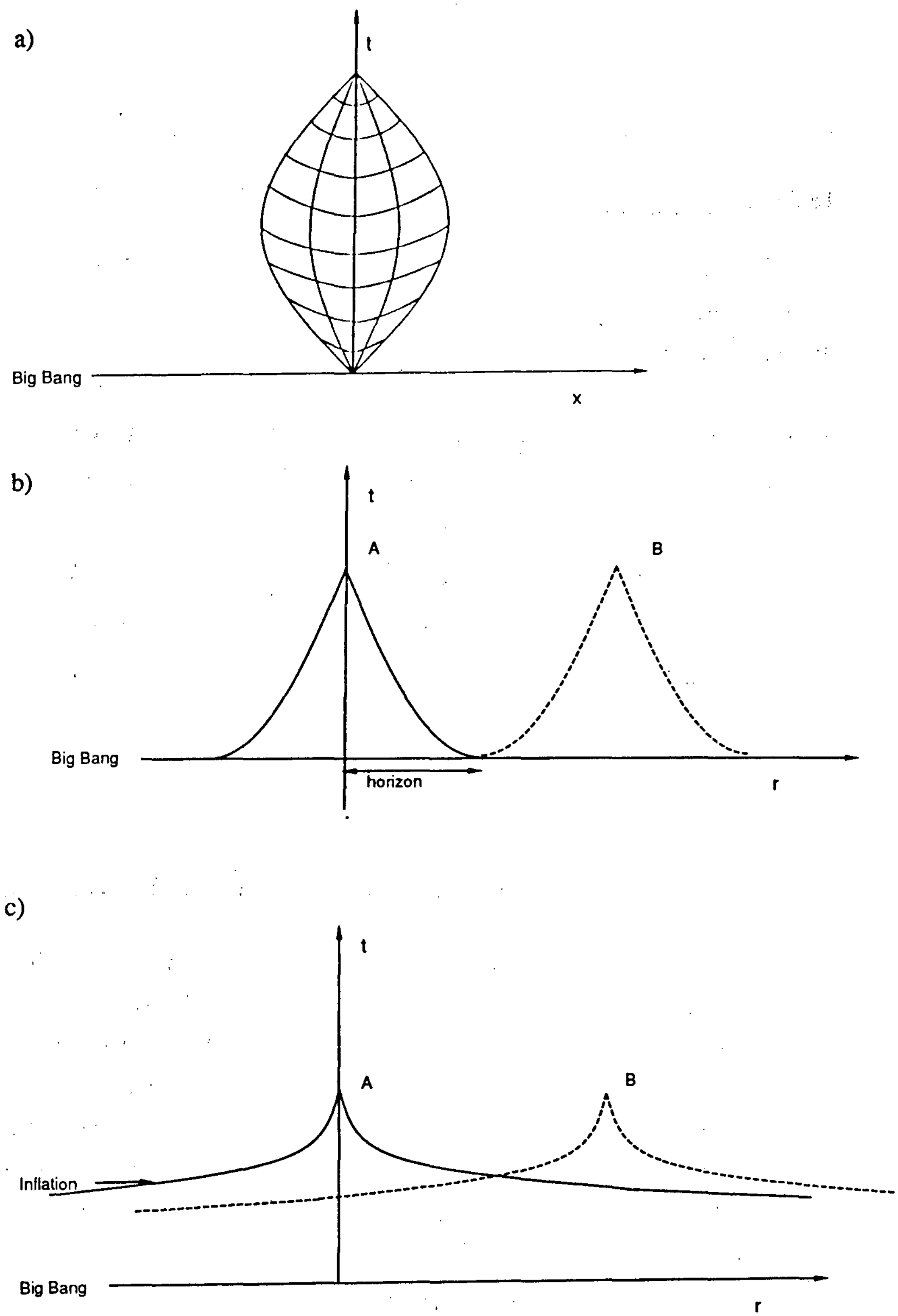


Figure 2.2
a) The light "cone" in real spatial coordinates
b) The light "cone" and the horizon in comoving coordinates

$$r = \frac{x}{a(t)}$$

Events A and B are (barely) causally unconnected
c) The light "cone" and the horizon in comoving coordinates in the case of an inflationary episode - Events A and B are now causally connected

a)

Temperature	New Particles	4N(T)
$T < m_e$	γ's + υ's	29
$m_e < T < m_\mu$	$e^\pm$	43
$m_\mu < T < m_\pi$	$\mu^\pm$	57
$m_\pi < T < T_c$*	π's	69
$Tc < T < m_{strange}$	no π's + u, $\bar{u}$, $\bar{d}$, d + gluons	205
$m_s < T < m_{charm}$	$s\,\bar{s}$	247
$m_c < T < m_\tau$	$c\,\bar{c}$	289
$m_\tau < T < m_{bottom}$	$\tau^\pm$	303
$m_b < T < m_{top}$	$b\,\bar{b}$	345
$m_t < T < m_W$	$t\,\bar{t}$	387

b)

Temperature	Time	Event
10^{19}GeV	10^{-43} s	Planck era (unified?)
10^{15} GeV		Inflation?
10^{12} GeV		Baryogenesis?
300 MeV	10^{-12} s	Quark-Hadron transition
1 MeV		Neutrino freeze-out
200 keV		e+ e- annihilation reheating
100 keV	1-200 s	Nucleosynthesis
.3 eV	10^6 years	Recombination
	10^9 years	Galaxy formation

Table 2.1
a) Effective numbers of degrees of freedom as a function of temperature
b) The important events in the evolution of the universe

universe and that the reaction rate has to be compared to the expansion rate. If the annihilation rate of the δ's is much faster than the expansion rate, they will all disappear, releasing in the universe their mass energy and therefore leading to a reheating. This occurs, for instance, for e^+ and e^- which annihilate completely into photons (except for the small excess of e^- due to baryogenesis). On the other hand, if the annihilation rate is much slower than the expansion rate, the δ particles will be diluted away before having a chance to annihilate and they will stay around, constituting the dark matter, for instance. Variants of this **freeze-out** mechanism play an important role in cosmology (see [Barrow, 1983]), for instance at the time where neutrinos and neutrons drop out of equilibrium around 1 MeV(see Section 3.2).

Another important consequence of physics at high temperature on the evolution of the universe is the possibility of phase transitions. Spontaneous symmetry breaking leads to a first order phase transition, where an important amount of entropy can be released in the universe. This can lead to an **inflationary episode**, where a(t) expands exponentially . If this inflation is large enough, space can be flattened leading to an Ω arbitrary close to 1, explaining why the present density can be still close to the critical density. Moreover, as we have seen, the horizon problem of the 2.7 K cosmic microwave background can be solved. This attractive idea has been originally proposed by Guth [Guth, 1981] and the interested reader is referred to Turner [Turner, 1985]. A lively version of the concept (chaotic inflation) is presented by Linde [Linde, 1987].

Armed with these tools and given a specific particle physics model, it is possible to infer the past evolution of the universe. Table 2.1.b gives the picture obtained in the standard model.

We have added two important events that are not strictly dependent on high energy particle physics. When the temperature drops down to 3000 K, e^- and p recombine into hydrogen, and suddenly the universe becomes transparent to photons. This is the epoch of last scattering of the radiation field that is now the 2.7 K cosmic microwave background. When the universe is 10^9 years old, density fluctuations presumably dating from inflation have been amplified enough by gravitation instability, to lead to the formation of galaxies. Figure 2.3 (after Wilkinson [Wilkinson, 1986]) gives a cartoon of this relatively recent epoch of the universe.

2.2 The present value of the cosmological parameters.

We now turn our attention to the experimental measurement of the cosmological parameters: the expansion rate (the Hubble constant), the average density (Ω), and the age of the universe. The combination of these three quantities will allow us to give an estimate of the cosmological constant.

2.2.1 The Hubble constant

In order to measure the Hubble constant H, it is sufficient to measure at the same time the distance d of objects and their redshift z. To first order,

$$d \approx \frac{cz}{H}$$

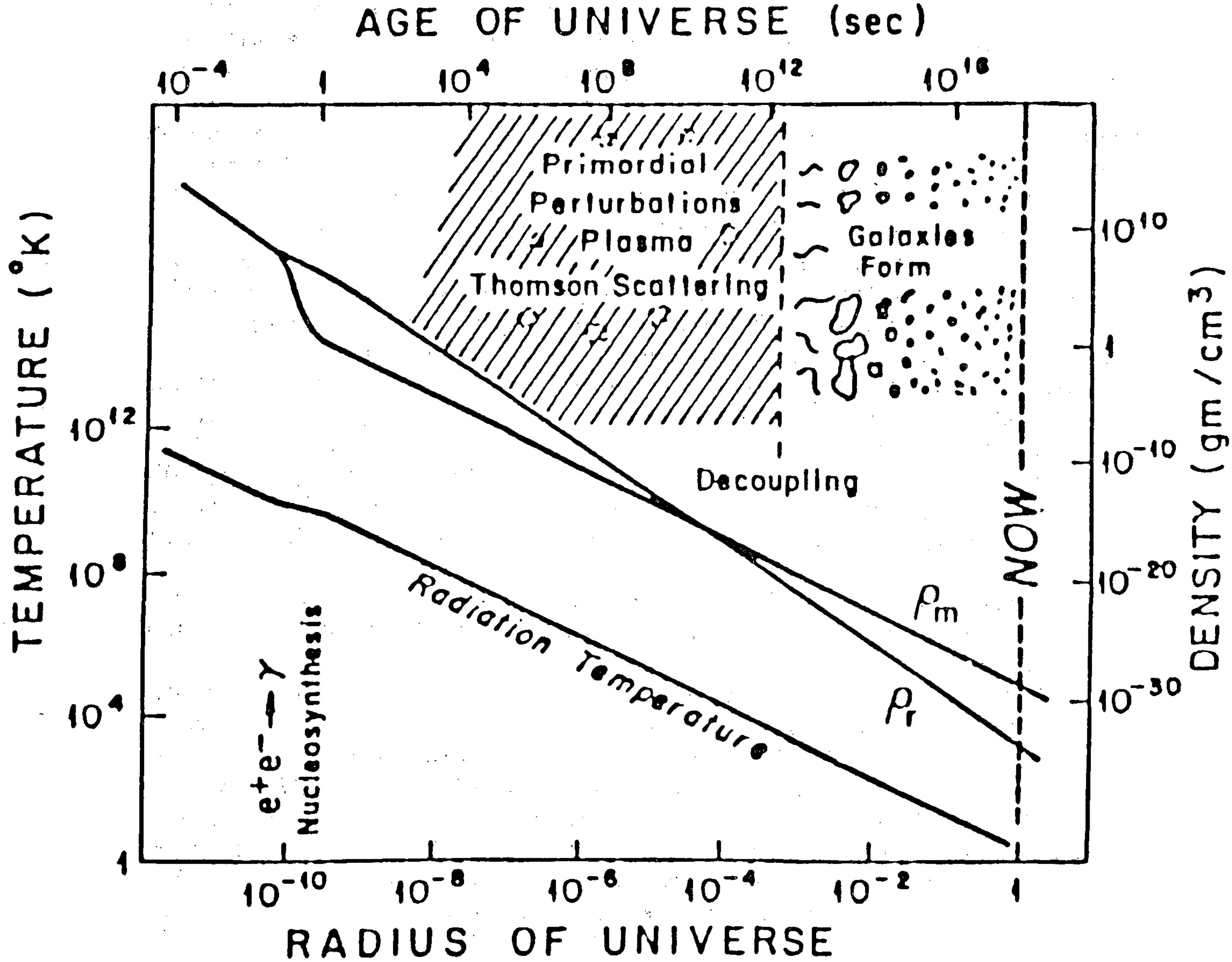


Figure 2.3:
The recent evolution of the universe.
ρ_m is the matter energy density. ρ_r is the radiation energy density.
from [Wilkinson, 1986]

•The observational problem

This is not very simple, however, as it is first difficult to have accurate distance indicators. The basic idea is to use a "standard candle", that is, an object for which the absolute luminosity is well known. However for a specific object, the luminosity depends on more parameters than is usually measured. The physics determining the luminosity may not be very well known, and for distant objects there may be evolution effects; young stars or galaxies may not have the same characteristics as the present ones.

There is also a serious dynamical range problem. It is necessary to go very far so there is no distortion from in-fall motions, which may still be sizeable for distances of 50 Mpc. It would therefore be preferable to work with distances of 100 Mpc or more, that is 10^8 times larger than the distance of the close stars that we can measure by parallax. This represent a factor 10^{16} in luminosity! In order to deal with the problem, one sets up a "ladder" of distance indicators (see Fig 2.4 from [Rowan-Robinson, 1985]), each of which allows one to go a little further and is cross-calibrated with the previous one in the region of overlap. Unfortunately, there is usually very little overlap, decreasing the accuracy of the cross calibration so that the cumulative errors build up rapidly. Astronomers attempt to bypass the cosmological distance ladder with specific objects (e.g. supernova) and to apply as many cross checks as possible, but the systematic errors are still quite large.

To make things worse, there is a strong polarisation of the field. Two groups have been arguing for years, with de Vaucouleurs (e.g. [1981]) claiming consistently values around 100km/s/Mpc while Sandage and Tamman (e.g. [1984]) have been advocating a value of 50km/s/Mpc for 20 years. New groups (e.g. Aaronson et al [1986a and 1986b]) are trying to introduce new methods which could discriminate between the two values (and usually get intermediate estimates).

•The distance ladder

It is not too difficult to understand the basic methods. The first step of the ladder is the determination to the distance of the Hyades (Fig 2.5). This is an open cluster of stars which appears to have a common movement with respect to the solar system. They are sufficiently close (about 40 pc) for their angular velocity on the sky to be measurable; the convergence point of their apparent movements gives the direction of motion; Doppler measurement gives their radial velocity. The combination of these three pieces of information gives their absolute distance.

It is presently not possible to use this type of geometrical method for more distant clusters. However there are a sufficient number of stars in the cluster for the calibration of the temperature-luminosity relationship of usual stars. Most of the life of a star is spent in burning hydrogen, and it stays on the "main sequence" in the luminosity versus temperature plot, the so called Hertzsprung-Russel diagram (Fig 2.6). By comparing the main sequence of more distant clusters with that observed for the Hyades, it is possible to get in turn their distances.

With more clusters of known distance, it is now possible to get enough statistics on pulsating stars (e.g.Cepheids, Fig 2.7), to calibrate their luminosity versus period relationship. This allows us to get to distances of 5 Mpc. At that point, however, stars do not appear luminous enough to be useful anymore, and it is necessary to abandon the relatively well known realm of the physics of stars to attempt to use the physics of galaxies.

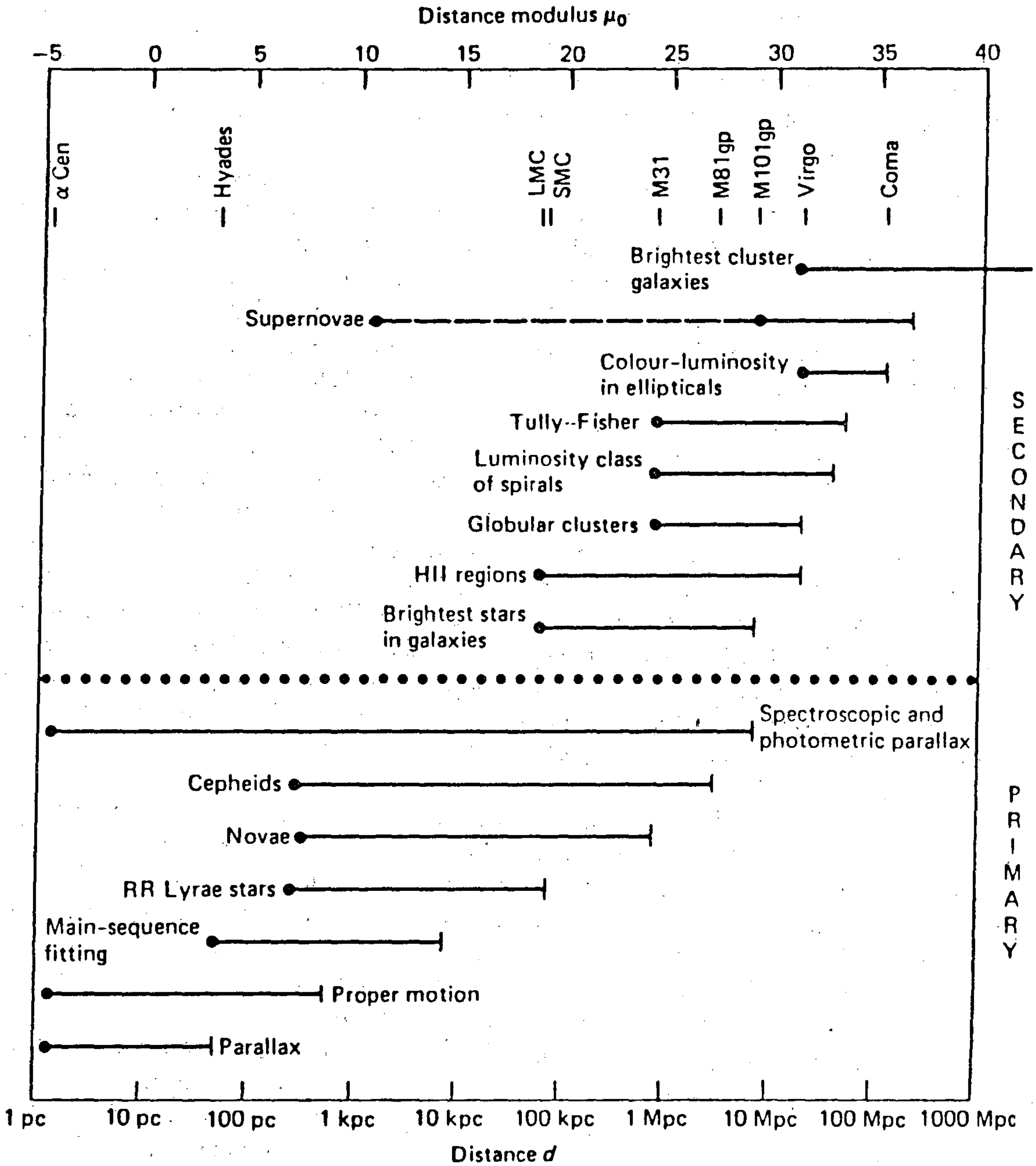


Figure 2.4: The cosmological distance ladder, showing the range of distances over which different distance indicators have been applied. [Rowan-Robinson, 1985]

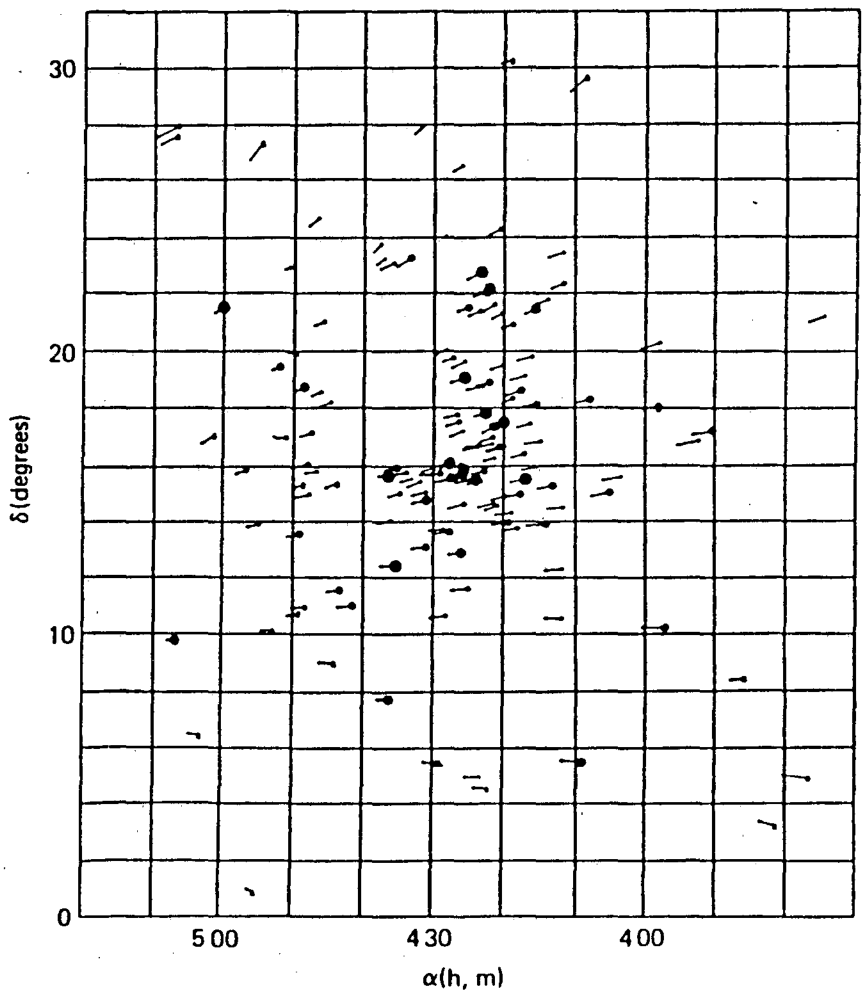


Figure 2.5:
The proper motion of the stars in the Hyades Cluster. δ – declination, α – right ascension. The size of the dots is a measure of the brightness of the stars. The lines denote the direction and magnitude of the proper motions of the stars, which converge to a point off to the left of the figure.
[Heck, 1978]

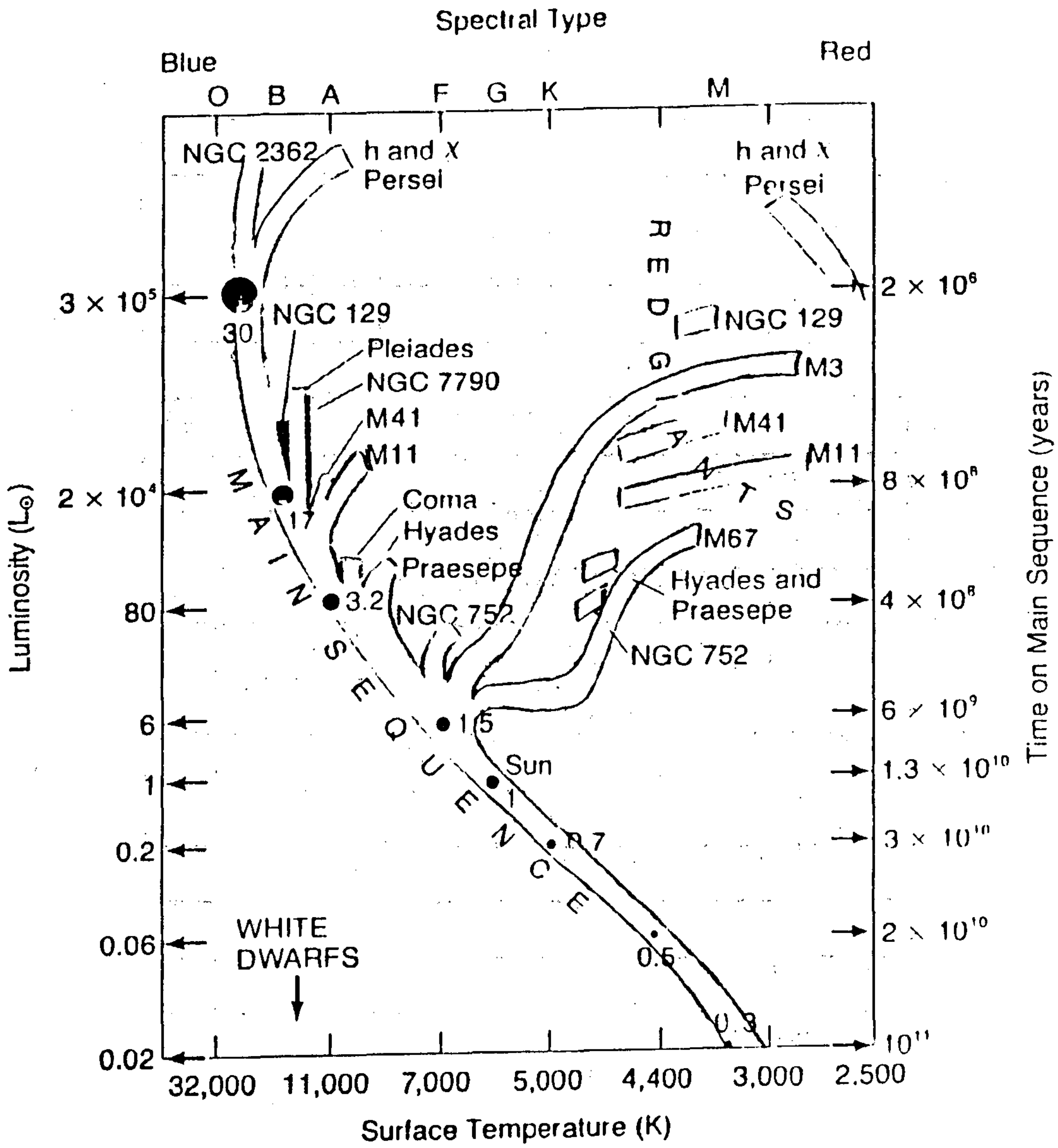


Figure 2.6:
The Hertzsprung-Russell diagram (Adapted from [Silk 1980])

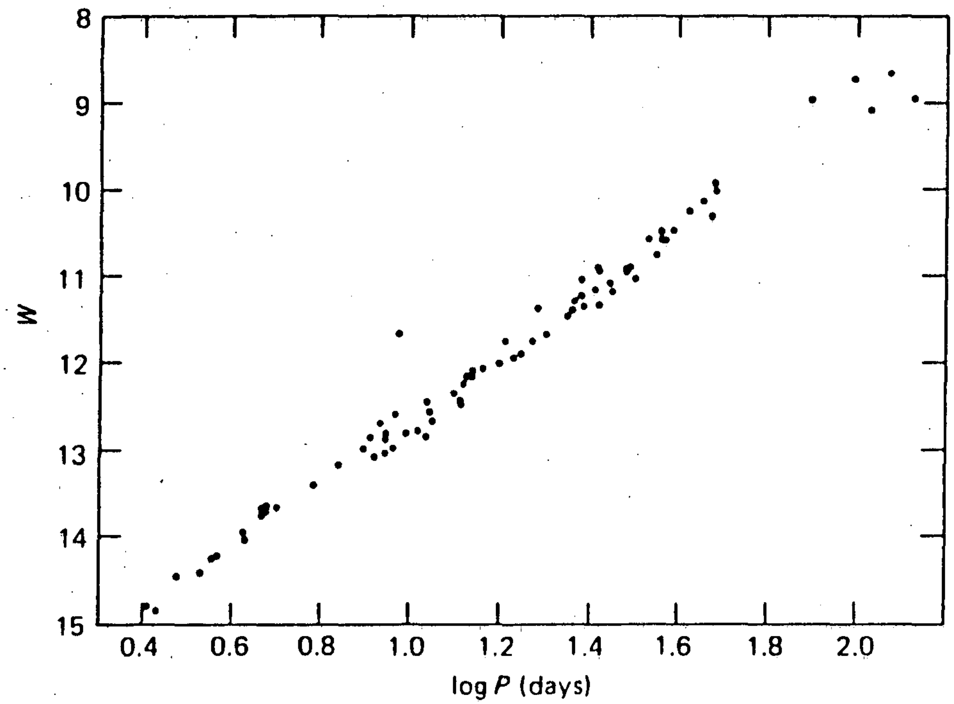


Figure 2.7:
The Period-Luminosity relationship for Cepheids. A plot of W = V - 2.70(B - V) against log P for Cepheids in the Large Magellanic Cloud [Martin et. al., 1979]

For spiral galaxies, which can be cross-calibrated with Cepheids, there are both theoretical and empirical reasons to believe that their absolute luminosity L is related to their angular velocity Δv by the Tully-Fisher relationship (Fig 2.8)

$$L \approx (\Delta v)^4$$

where Δv is obtained from the width of the H_I (21cm) line. The apparent luminosity is measured at 1.6μ in order to decrease the obscuration from the dust always present in spiral galaxies. This method is very encouraging ([Aaronson and Mould [1986b]). However for the time being, there are not enough calibrators, and it does not go far enough, and it is necessary to correct for in-fall motions, which introduces uncertainties.

For elliptical galaxies, which are more luminous and may therefore allow to go at higher distances, a similar relationship exists, the so called Faber-Jackson relationship [Faber-Jackson, 1976]. Recently "the Seven Samurais" [Dressler et al., 1987b] gave an improved version which seem to indicate large scale movements. However this relationship is not yet calibrated against spiral galaxies of known distances and this method has not lead to a Hubble constant determination yet.

These methods, which rely on the **physics** of objects, are gradually displacing statistical indicators, for instance, the first rank (i.e. brightest) red star in a galaxy, the first rank galaxy in a cluster etc..., which were used to go far enough. These statistical methods, based on purely empirical relationships may be quite dangerous since they may be subject to strong evolution effects and to environment dependence. Sandage and Tamman have also emphasized that these indicators may be particularly affected by the Malmquist effect . The Monte Carlo shown in Figure 2.9 illustrates this bias. Because of the geometric effect, the number of galaxies increases with the square of the distance (Fig 2.9.a). However, studies are usually limited to a given apparent luminosity, which cuts out an increasing portion of the scatterplot. As shown in Fig. 2.9b, the indicator seems better than it really is and the remaining objects have a higher luminosity which leads to an overestimate of the Hubble constant H.

•*Conclusion*

From the current determinations, H appears to be between 50km/s/Mpc and 100km/s/Mpc. It is clear that the errors are larger that those quoted by the various groups and are at least 25% r.m.s [Huchra, 1987] (Table 2.2).

In the near future, the direction of progress seems to lie in a better understanding of the physics of galaxies, which will lead to a better calibration and an improvement of the Tully-Fisher relation, and the modified Faber-Jackson relationship✎ Space astronomy will also improve the determination of the first steps of the ladder. The satellite Hipparcus will measure parallaxes to 80 pc and will allow us to check the distance of the Hyades. The Hubble Space Telescope (to be launched in 1988?) will extend parallax measurement up to 300pc, and more importantly may be able to spot Cepheids in the Virgo cluster [Aaronson and Mould 1986b], giving a much wider sample for calibration of galaxy distance measurement. The current efforts to implement optical interferometry (e.g. by C.H. Townes [1986]) will also help.

2.2.2 The average density and the spatial curvature of the universe.

Three types of methods have been used for the measurement of the average density of the universe. It is possible to use virial methods to weigh galaxies. The

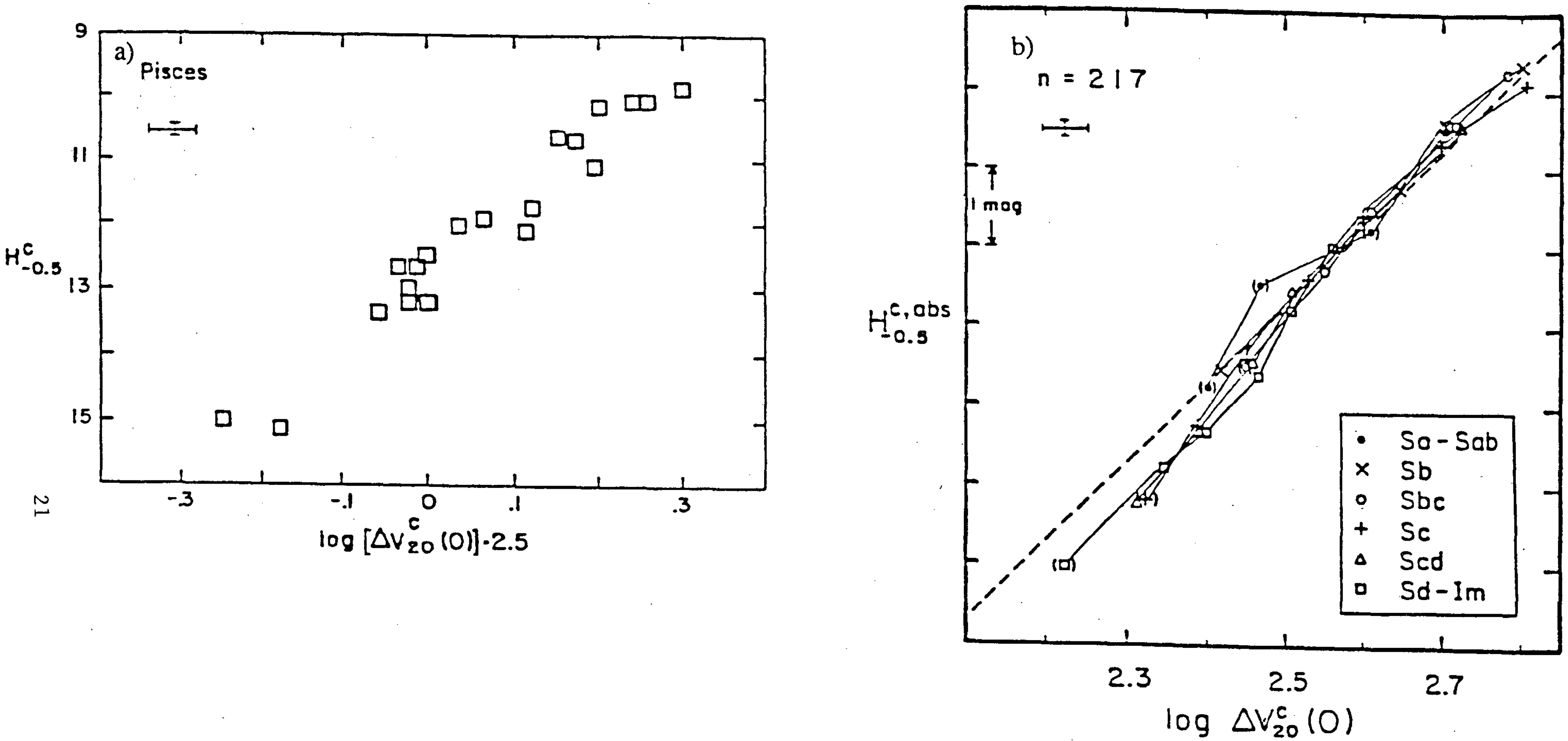


Figure 2.8:
The (infrared) Tully - Fisher Relationship
a) The IR/H relation for galaxies in the Pisces cluster (mean $V_0 \sim 5300$ km s^{-1})
b) Collection of objects in the Local Supercluster binned by morphological type. No evidence of segregation by morphology is visible in this sample. [Aaronson and Mould, 1986]

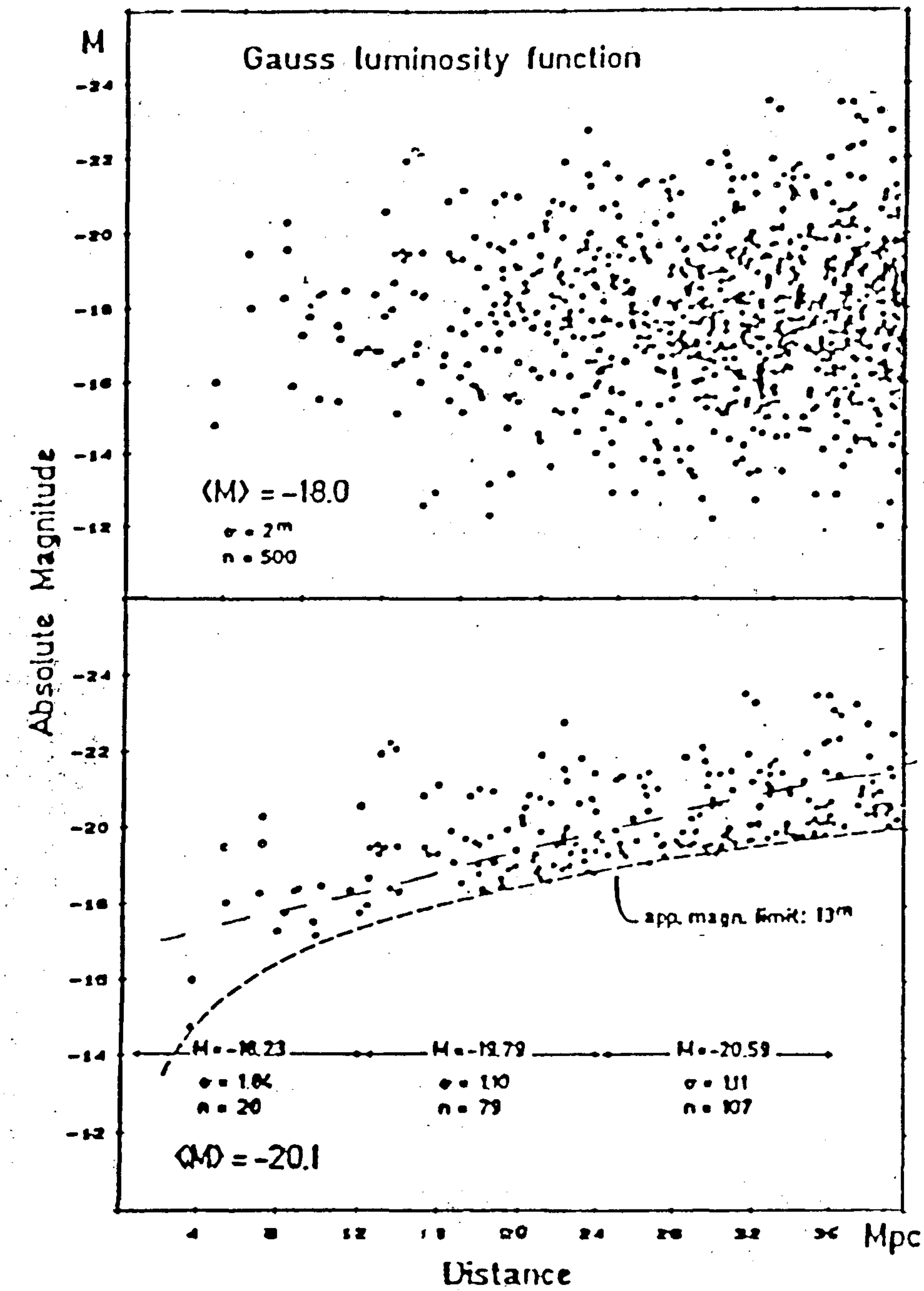


Figure 2.9:
The Malmquist bias. Upper panel: Monte Carlo distribution in distance and absolute magnitude of an arbitrary sample of 500 galaxies within 38 Mpc. Lower panel: The same sample cut by an apparent-magnitude limit of m=13. Note here the increase of the galaxian luminosities with increasing distance and the small effective (observable) scatter σ_m within individual distance intervals. [Tamman, 1987]

RMS ERROR BUDGETS IN ZERO POINTS

TECHNIQUE OR ITEM		FRACTIONAL ERROR
Hyades Modulus		0.05
Extinction in our Galaxy		0.05
Cepheid P-L,P-L-C		0.12[a]
Globular Clusters		dead ?
HII Regions		dead!
Brightest Stars –	Red	0.15[a]
	Blue	0.20[a]
Type I SN		0.16
IR-Tully Fisher		~ 0.15
Virgo Distance (error due to)		
Velocity uncertainty		0.07
Virgo Flow V		0.07
Coma Distance (" ")		
Large Scale Flows		0.1 (!)

Table 2.2
The cumulative errors in the Hubble constant determinations. [Huchra, 1987]

deviations from the Hubble flow depend dynamically on the underlying background density. Finally, one may attempt to measure the curvature of the universe directly.

• *Virial methods.*

The virial theorem states that for a stationary system bound by gravity, the ensemble average of the velocity squared at distance r from the center-of-mass is related to the mass M included in this radius by

$$\langle v^2 \rangle \approx k\, G \,\langle M/r \rangle .$$

This basically is an expression of the equilibrium between the centrifugal force and the centripetal force,

$$v^2/r = GM/r^2 .$$

The constant of proportionality k depends on the geometry of the system and is 1 only for spherically symmetric objects.

This theorem makes it possible to weigh galaxies. Since what it most readily measured in astronomy is the amount of light per unit volume, it is customary to estimate the mass-to-light ratio M/L for the various types of galaxies usually measured in solar units. Since experimentally M/L does not vary rapidly with the size of galaxies of a given type, it is a convenient method to correct for the size of galaxies.

For instance, for spiral galaxies, it is possible to measure the velocity of clouds of atomic [Bosma 1981] or ionized [Rubin et al., 1980] hydrogen orbiting around them by the doppler shift. If we plot the velocity in the plane of the galaxy as a function of the radius (Fig. 2.10), we observe the striking fact that the velocity curves stay flat even outside the luminous disk (which is limited to less than 10 kpc for most galaxies). There is therefore a dark halo which extends much further and

$$\frac{M}{L} \geq 30h \frac{M}{L}\ (\text{sun})$$

where h is the Hubble constant in units of 100 km/s/Mpc. One problem is that it is difficult to know where to stop, and M/L as large as 50 to 80 can be observed in some galaxies where some far orbitting objects can be detected. We do not know whether the halo is truncated abruptly or extend forever with a density

$$\rho \approx \frac{1}{r^2} .$$

Combining these numbers with the known averaged luminosity of spiral per unit volume, we get (e.g.[Primack 1984])

$$\frac{M}{L}\ (\text{spirals}) = 1500\ \Omega h \frac{M}{L}\ (\text{sun})$$

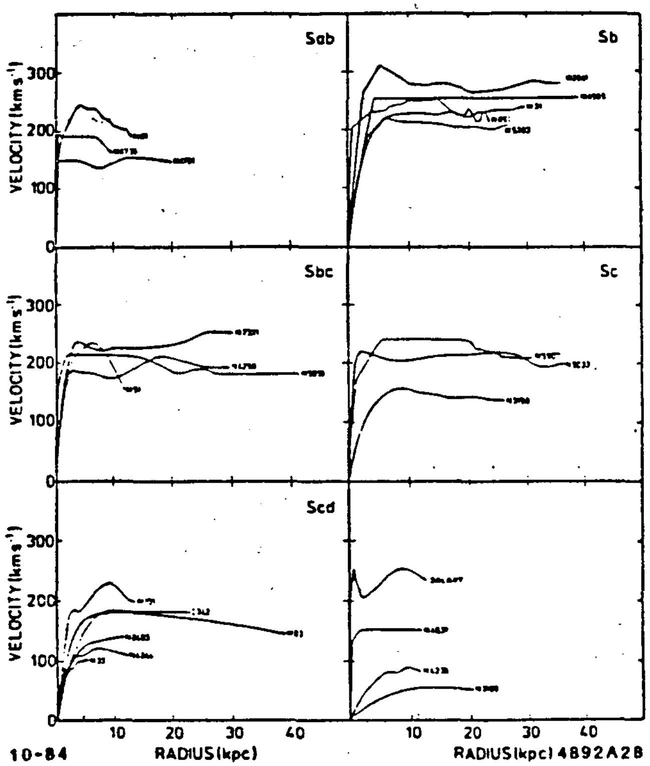
or

$$\Omega\ (\text{spirals}) \geq 0.02.$$

Here $\Omega \equiv \rho/\rho_c$ is the cosmological density in units of critical density $\rho_c \equiv 3H_0^2/8\pi G$ (= $1.9 \times 10^{-29} h^2$ g cm^{-3} = 11 h^2 keV cm^{-3} = 2.8×10^{11} h^2 M Mpc^{-3}), distances are measured in units of parsecs (1 pc = 3.09×10^{18} cm = 3.26 light years), and as we have seen in the previous section, h ≈ 0.5 - 1 is the Hubble parameter H in units of 100 km s^{-1}/Mpc.

Similar numbers are reached for elliptical galaxies when the star dispersion velocity is related to the gravitational potential:

a)



b)

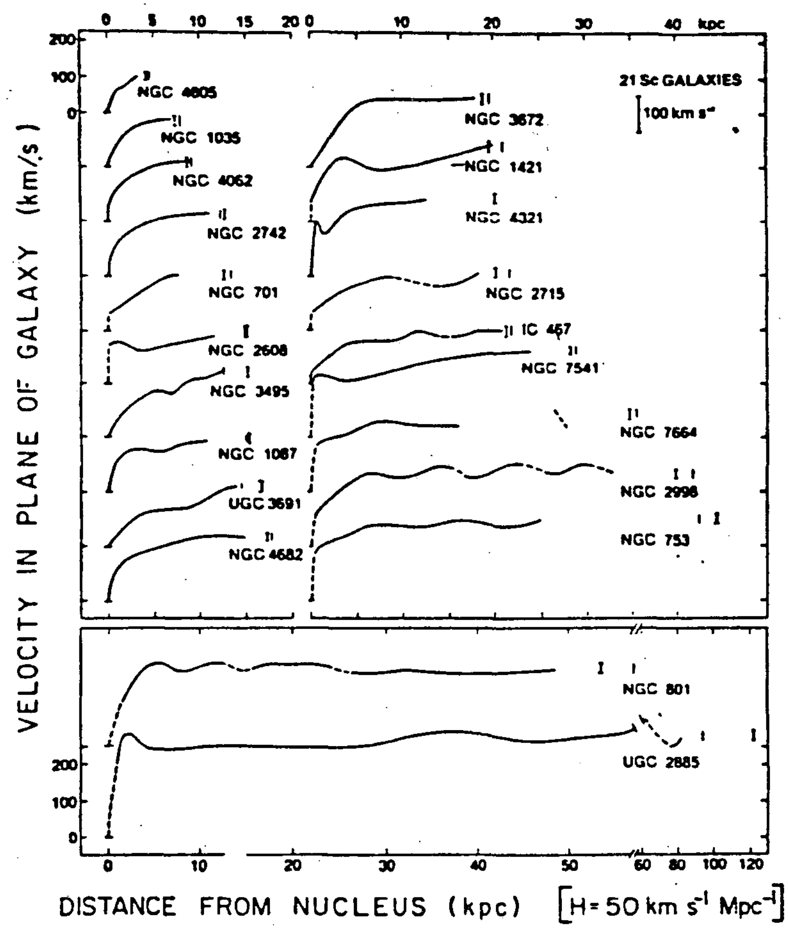


Figure 2.10:
The velocity in the plane of the galaxy plotted as a function of the distance to the galactic center.
a) 21 cm line [Bosma, 1981]
b) H_{II} regions [Rubin, et. al.]

$$\frac{M}{L}\text{ (elliptical)} \approx 50\text{-}80\ h \frac{M}{L}\text{ (sun)}$$

and the conclusion on Ω is not changed

$$\Omega \text{ (galaxies)} \geq 0.02$$

at least twenty times more that the visible part of the galaxies.

The same method can be applied to clusters of galaxies now using the dispersion velocities of the galaxies. The problem is again that there are not sharp boundaries, but typically

$$\Omega \text{ (clusters)} \approx 0.2.$$

All these applications of the virial theorem suffer from the basic problem that they fundamentally measure inhomogeneities of the mass distribution and that they are insensitive to a uniform density.

• *Deviation from the Hubble flow.*

The deviations from the Hubble flow are in principle sensitive to the underlying density. They rely on the fact that the peculiar velocity observed today should be equal to the acceleration due to density fluctuations multiplied by the time of growth of these fluctuations. This time is the Hubble time 1/H modified by a function f of Ω.

More precisely, in the linear theory (e.g.[Peebles 1980])

$$\vec{v} = \frac{1}{H} f(\Omega,H)\ \vec{\nabla} \int \frac{\delta(x')}{|x-x'|} d^3x'$$

where $\delta = \Delta\rho/\rho$ is the density contrast. In practice, it is supposed that galaxies trace mass and that δ can then be obtained as the galaxy density contrast. The above expression is then evaluated for our local group of galaxies and compared to our velocity with respect to the cosmic microwave background. This leads to a determination. Explaining in that way our infall to the Virgo cluster, we obtain $\Omega \approx 0.2$ [Davis and Peebles 1983].

As we will see (Section 3.3), the assumption that galaxies trace mass can be criticized, and may lead to an **underestimate** of the value of Ω. Moreover, practical problems such as the insufficient sampling at large distances (usually corrected by the assumption that the mass distribution is uniform after some distance), or the bias due to obscuration close to the galactic plane lead to significant biases. The latest attempts to minimize these problems using the IRAS catalog [Strauss and Davis, 1987], lead to estimates in the range 0.2-1.

•*Geometry.*

A potentially much better way to measure Ω is to measure directly the curvature of space. However, in order to obtain significant deviation from the Euclidean geometry, it is necessary to go to at least 1000 Mpc.

A first method has been tried for some time by Sandage (see [Sandage and Tamman, 1984]). The basic idea is to detect a curvature in the (luminosity) distance versus red shift. However, as Sandage has himself shown, with present distance indicators (e.g., the apparent luminosity of the brightest galaxies in a cluster) the method is too susceptible to evolution correction and the only limit is that

$$\Omega \leq 2.$$

More recently, Loh and Spillar [1986] have studied the densities of galaxies as a function of red shift. The basic idea is that for sufficiently small red shift ($z << 4$) so that the galaxies are already formed, their number should trace the volume. Fig. 2.11 shows their results from which they deduce

$$\Omega = 1.2 \pm 0.3.$$

Although these observations suggest that $\Omega \geq 0.3$, they need to be confirmed. Table 2.3 summarizes these results.

	Scale (h^{-1}Mpc)	Ω
Visible parts of galaxies	≈0.01	0.002
Halos of galaxies	≈0.1	0.02-0.2
Clusters	≈1.	≈0.2
Virgo infall	≈10	≈0.2
Large scale infall	≈30	0.2-1
Geometry	3000	0.3-2

Table 2.3
Cosmological Density Estimates

2.2.3 The age of the universe.

The age of the universe can be determined in two different ways.

•*Radioactive dating*

By looking at the relative abundances of radioactive decay products in meteorites, it is possible to precisely date the solar system. The solar system appears to be 4.5 10^9 years old and this is an absolute lower limit to the age of the Universe!

Using more theoretical input on the ratios of various isotopes when they are formed in supernovae (r process), it is possible to deduce a lower limit to the age of the universe from the present ratio of $^{235}U/^{238}$-U, for instance. In that way we obtain

$$T \leq 11\ 10^9 \text{ years.}$$

•*Star evolution*

An independent method relies entirely on the theory of star evolution. From the position of the stars of a globular cluster in the temperature - luminosity plot (Hertsprung- Russell diagram), it is possible to compute the age of the globular cluster. The estimated age increases as expected when the metallicity decreases pointing to a halo collapse 17±2 10^9 years ago [Iben and Renzini 1984]. There is a general consensus of values of this magnitude and it seems extremely difficult to obtain values below 15 10^9 years with the current understanding of star evolution.

2.2.4 Conclusion - Value of the cosmological constant.

By comparing the values of the Hubble constant H, Ω and the age T of the universe, it is possible to obtain the cosmological constant Λ. Figure 2.12 summarizes the relationships. They are easy to obtain from the Friedman equation. The important point to notice is that for zero cosmological constant

$$HT \leq 1.$$

But H = 1.02 10^{10} h year^{-1} where again h is the Hubble constant in units of 100 km/s/Mps. If we accept the age given by globular clusters of 16 10^9 years, it is

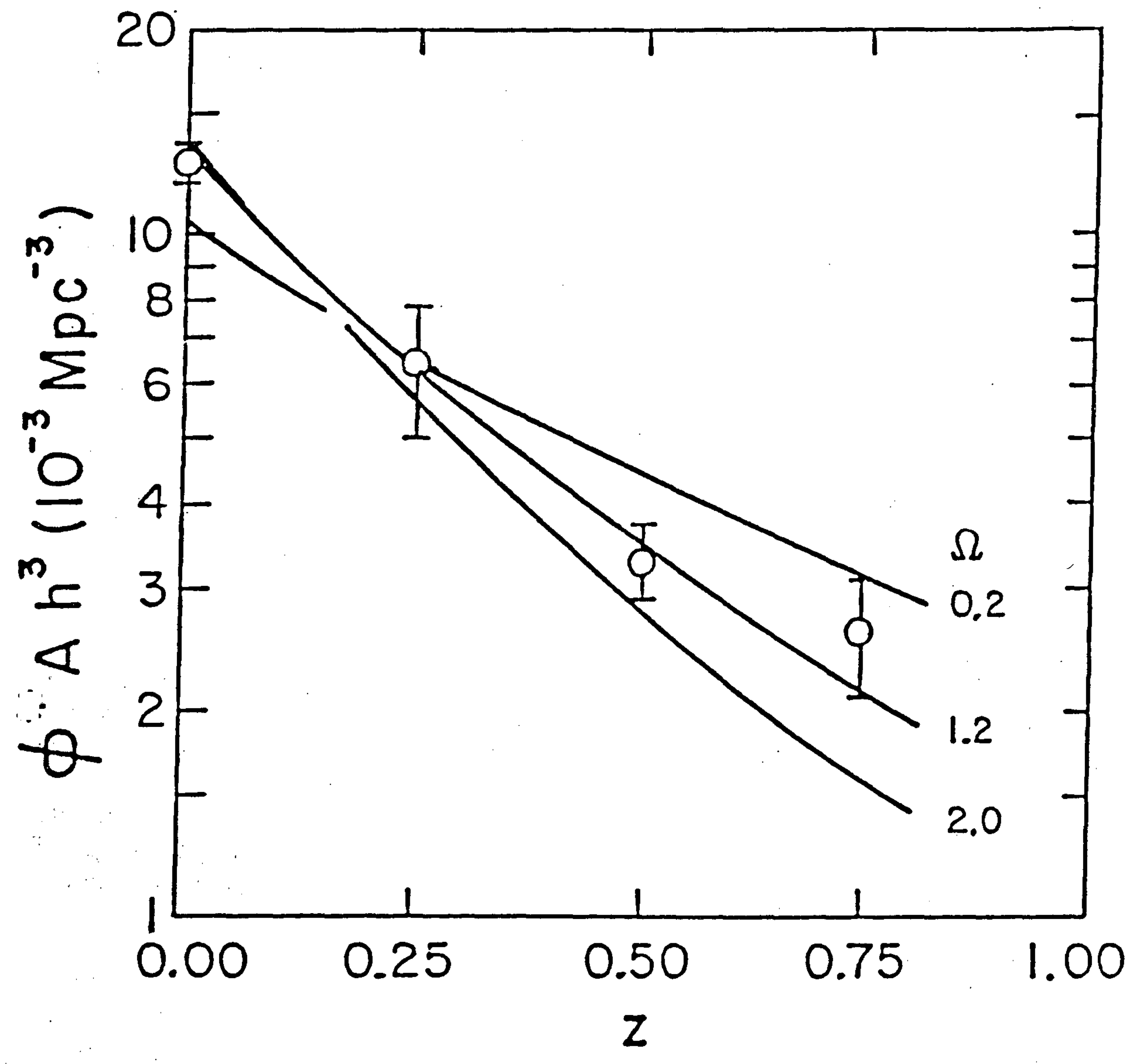


Figure 2.11: Number density of galaxies vs. z [Loh and Spillar, 1986]

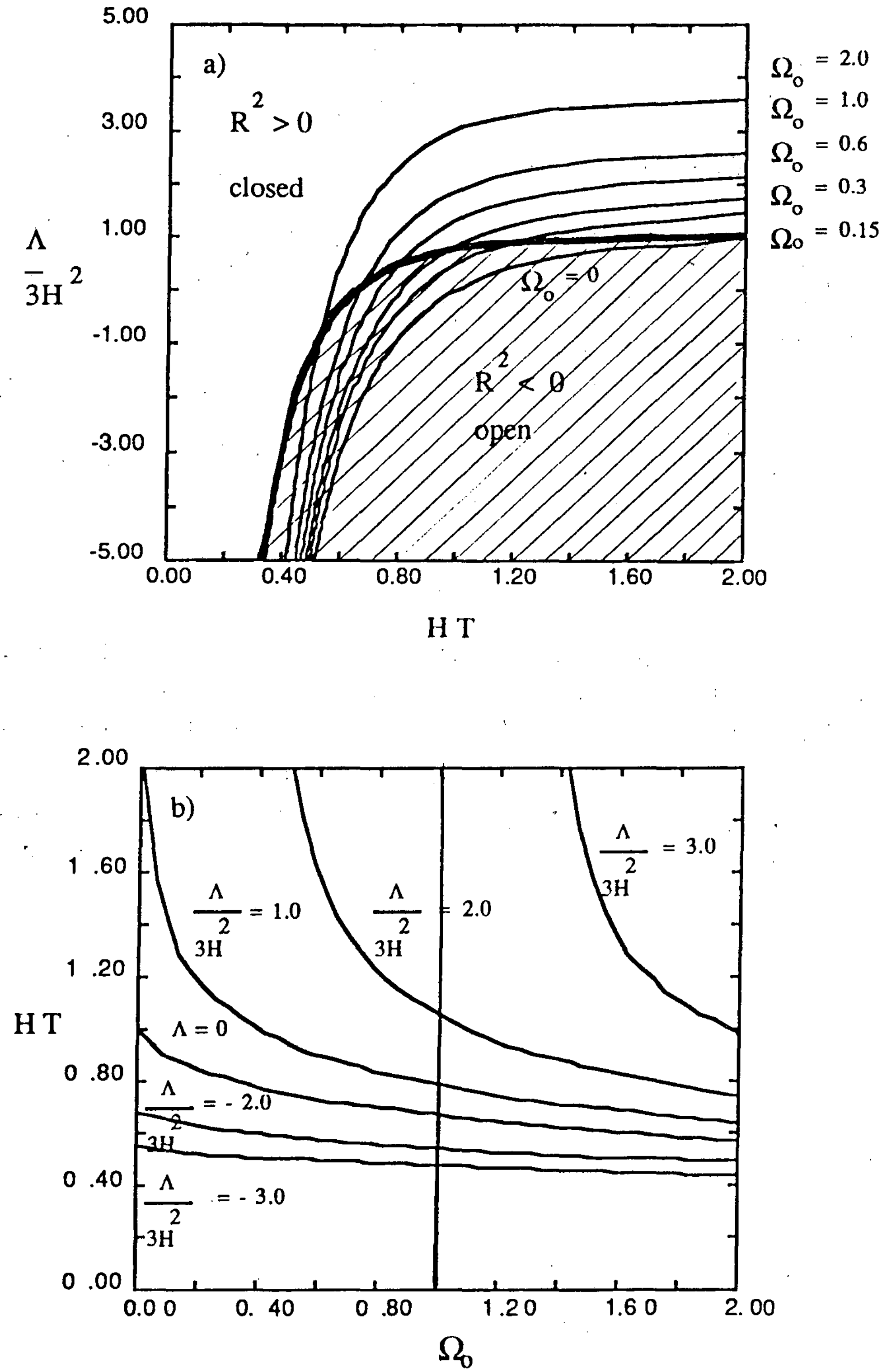


Figure 2.12:

a) plot of $\frac{\Lambda}{3H^2}$ vs. HT for various values of Ω_0

b) plot of HT vs. Ω_0 for various values of $\frac{\Lambda}{3H^2}$

impossible to reconcile $\Omega = 1$, $\Lambda = 0$ and a Hubble constant of 100 km/s/Mpc as advocated by de Vancouleurs.

More generally, Table 2.4 give the possible values.

Ω	$\frac{H}{\text{km/s Mpc}}$	$\frac{\Lambda}{3H^2}$	Proponents
1	40	0	Cosmologists
0.2	50	0	Sandage and Tamman [1984]
1	100	2.3	de Vancouleurs [1981]
0.2	100	1.3	de Vancouleurs [1981]

Table 2.4
Values of H and Λ

Note that an H value of 40 km/s/Mpc would not be in contradiction with the determination of Sandage and Tamman (Tamman private communication).

Without entering into the controversy of the Hubble constant, it is clear, however, that in any case $\frac{\Lambda}{3 H^2}$ is small. This is difficult to understand in the particle physics models where the cosmological constant arises from the energy of the vacuum. Many authors prefer to postulate an unknown mechanism (related to inflation?) which constrains Λ to be zero.

3-Relics from the Early Universe

After the analysis of the universe as we see it today and of the measurement of the basic cosmological parameters, we now turn to the discussion of what could be learned about the early universe from various relics: the different types of radiation (photons, neutrinos, monopoles, gravitational wave background, etc.), the chemical composition of the present universe, and the large scale structure of galaxies.

3.1 Radiation from the Early Universe.

3.1.1 The electromagnetic radiation.

Photons are the most obvious probes of the events in the early universe, provided the intervening medium is transparent. The computation of the red shift of the last scattering as a function of the wavelength shown in Fig. 3.1 [Smoot, 1988] demonstrates that two windows are opened onto the early universe, the far infrared region and the hard X-ray and γ-ray region. Figure 3.2 [Turner 1983] shows the observed diffuse radiation as a function of the photon wavelength. Extragalactic radiation is indeed detected in the two windows between 20 cm and 0.5 mm and from 1 keV to 100 Gev. We examine these two regions in turn.

3.1.1.1 The 2.7K microwave background.

The first region, limited at the bottom by synchrotron radiation and above by dust emission in our galaxy, happens to house the black body radiation which is expected from the early universe. Above a temperature of 3000^o (0.3 eV), the universe is too hot for atomic hydrogen to exist and it was opaque to photons. As the temperature drops below this limit (around 10^6 years after the Big Bang), the tail of the Maxwell distribution above the hydrogen ionization energy becomes negligible, protons and electrons recombine and the universe suddenly becomes transparent to the electromagnetic radiation. The electromagnetic radiation is red shifted by a factor 1000 and appears today as a microwave background. This radiation, discovered in 1964 by Penzias and Wilson, is the best proof of the Big Bang.

In the last twenty years, an intense experimental effort has attempted to establish the spectrum and angular distribution of this cosmic microwave background.

a) The microwave background spectrum.

Theoretically, one expects a black body spectrum (cf. [Weinberg 1972], Sections 15.4-15.5) unless there has been a release of energy just before recombination which did not have the time to thermalize. Of course if the universe has been reionized since then (e.g., in a bright era due to the rapid explosion of very massive stars), we also expect deviations due to scattering of the original photons on the plasma electrons (comptonisation). This will be the case as well if an additional component was produced relatively recently by another phenomenon (such as dust emission). Thus a measurement of the spectrum is important, both to establish the black body character and the present temperature of the radiation field, and to learn about energy release mechanisms around or after recombination.

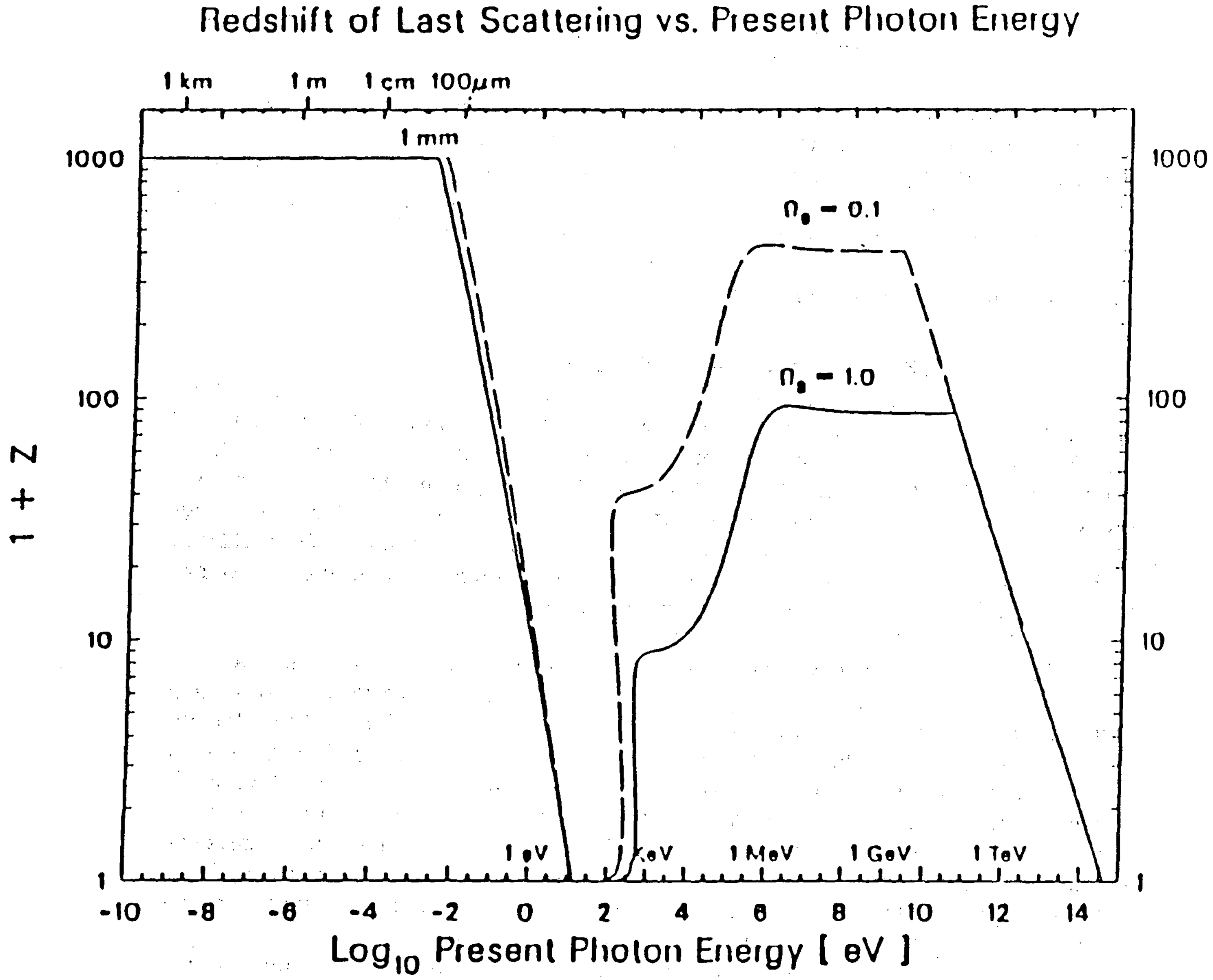


Figure 3.1: Redshift of the last scattering as a function of wavelength [Smoot, 1988]

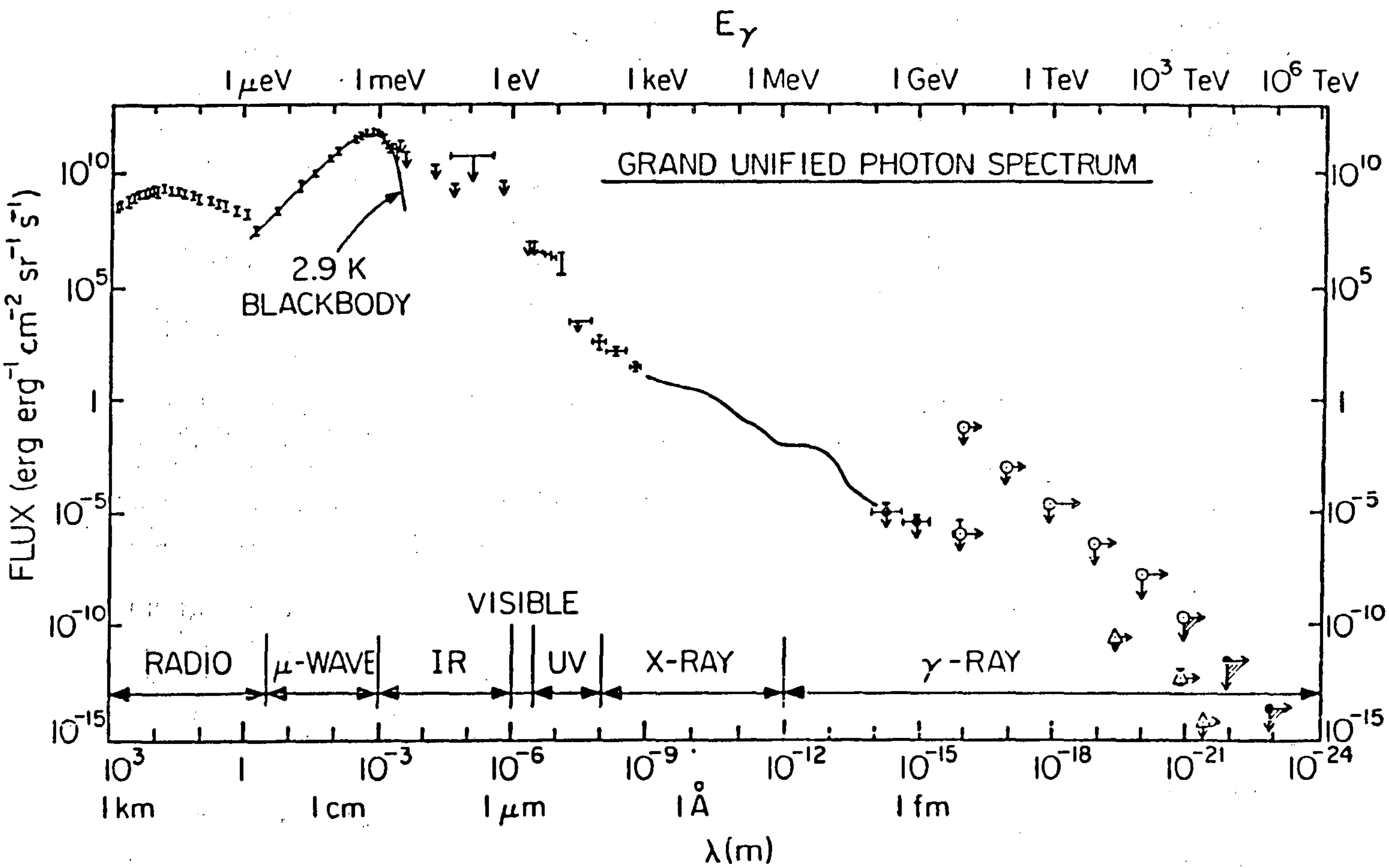


Figure 3.2: The observed diffuse radiation as a function of the photon wavelength [Turner, 1983]

Experimentally, the spectrum is measured by a series of reasonably narrow band absolute radiometers. The receiver is either a conventional RF amplifier (for $\lambda >$ 2 mm) or a bolometer (at lower wavelength), alternating ("chopping") between the sky and a calibrated black body source of temperature around 3 K, in order to measure the absolute flux. Figure 3.3 shows, as an example, the apparatus of Peterson et al [1986]. These experiments are quite difficult because of contributions from the atmosphere, from the galaxy, from the earth and from the warm sections of the antenna which are at temperatures much greater than 3 K. Figure 3.4 gives an estimation of the brightness of the diffuse components [Lange et al., 1988]. At larger wavelength, it is possible to do the measurement from the ground (at the top of a high mountain) [e.g., Smoot et al., 1985]. Millimetric wavelengths, where the turnover point is located, requires working aboard a balloon [e.g., Peterson et al., 1985]. Smaller wavelengths can only be explored with rockets [e.g., Matsumoto et al., 1987] or satellites [Mather,1987]. Note that the flux at a specific wavelength can be estimated through the exitation of interstellar molecules (CN, see [Meyer and Jura, 1984]).

Up until last year, all the measurements were consistent with a temperature of 2.74 ± 0.026 K [Wilkinson, 1986]. The experiment of Woody and Richards [Woody and Richards, 1981] had shown that the spectrum was indeed turning over as expected from a black body spectrum, but the slight excess indicated by their result has not been confirmed by a new experiment by the same group [Peterson et al., 1985].

However, a new rocket experiment by the Nagoya-Berkeley group [Matsumoto et al., 1988] shook-up this consistent picture [Fig. 3.5a,b]. A definite excess representing 20% of the energy stored in the background radiation is observed below a wavelength of a millimeter. Of the various possible explanations, the emission by dust at a red shift of $z \approx 10$ best fit the data. However, this scenario is at variance with the present view of galaxy formation which is believed to be at $z \approx 4$.

COBE, the Cosmic Background Explorer statellite [Mather, 1987] which is supposed to be launched in the coming year (1989), will easily check this result. However, because of the NASA rules, its instruments were finalized along time ago. More up-to-date detectors flown on rockets or smaller lead time (Japanese or Russian) satellites may therefore have an impact. Ground measurements at long wavelength will also be improved.

In spite of the experimental uncertainties, these measurements have interesting implications, for particle physics, in particular, in that they allow us to place limits on the decay of particles in the early universe. Figure 3.6(a) and (b) gives two examples of limits which can be put on the lifetime and masses of unstable neutrinos.

b) Isotropy of the 2.7 K microwave background.

It is possible to measure the spatial isotropy of the microwave background with similar detectors. Chopping is done between various portions of the sky, attempting to keep the various backgrounds as constant as possible. The r.m.s. variation of the effective temperature is thus measured. For small scale fluctuations, it is necessary to use large ground based radio telescopes [Uson and Wilkinson, 1984, 1985], or even interferometers [Partridge and Knoke, 1986] .

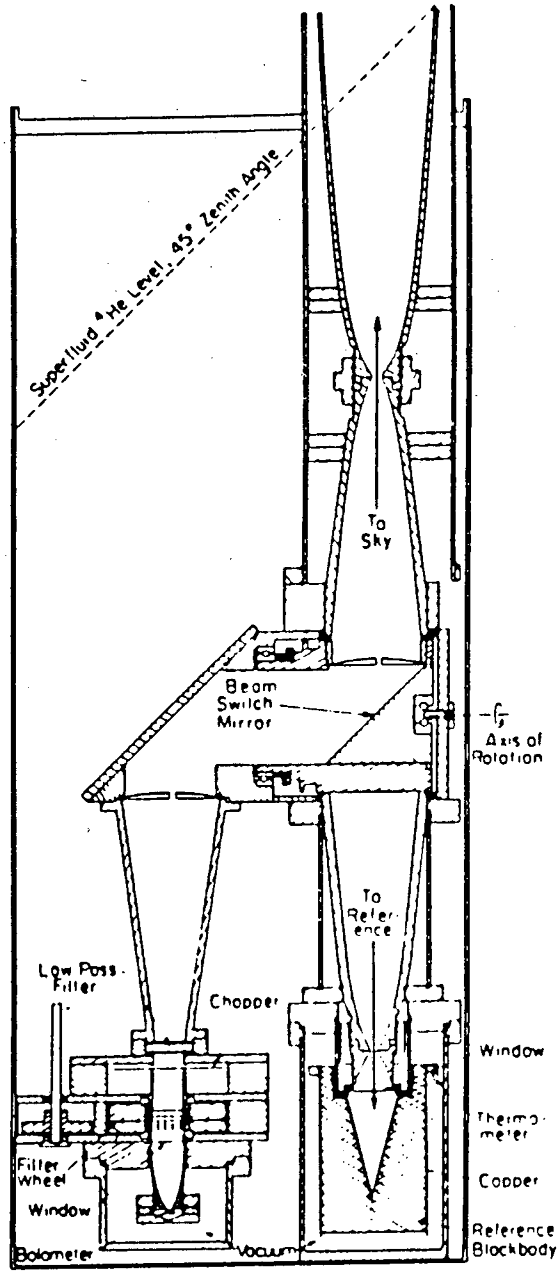


Figure 3.3: Apparatus used for the experiment of Peterson et.al. 1986

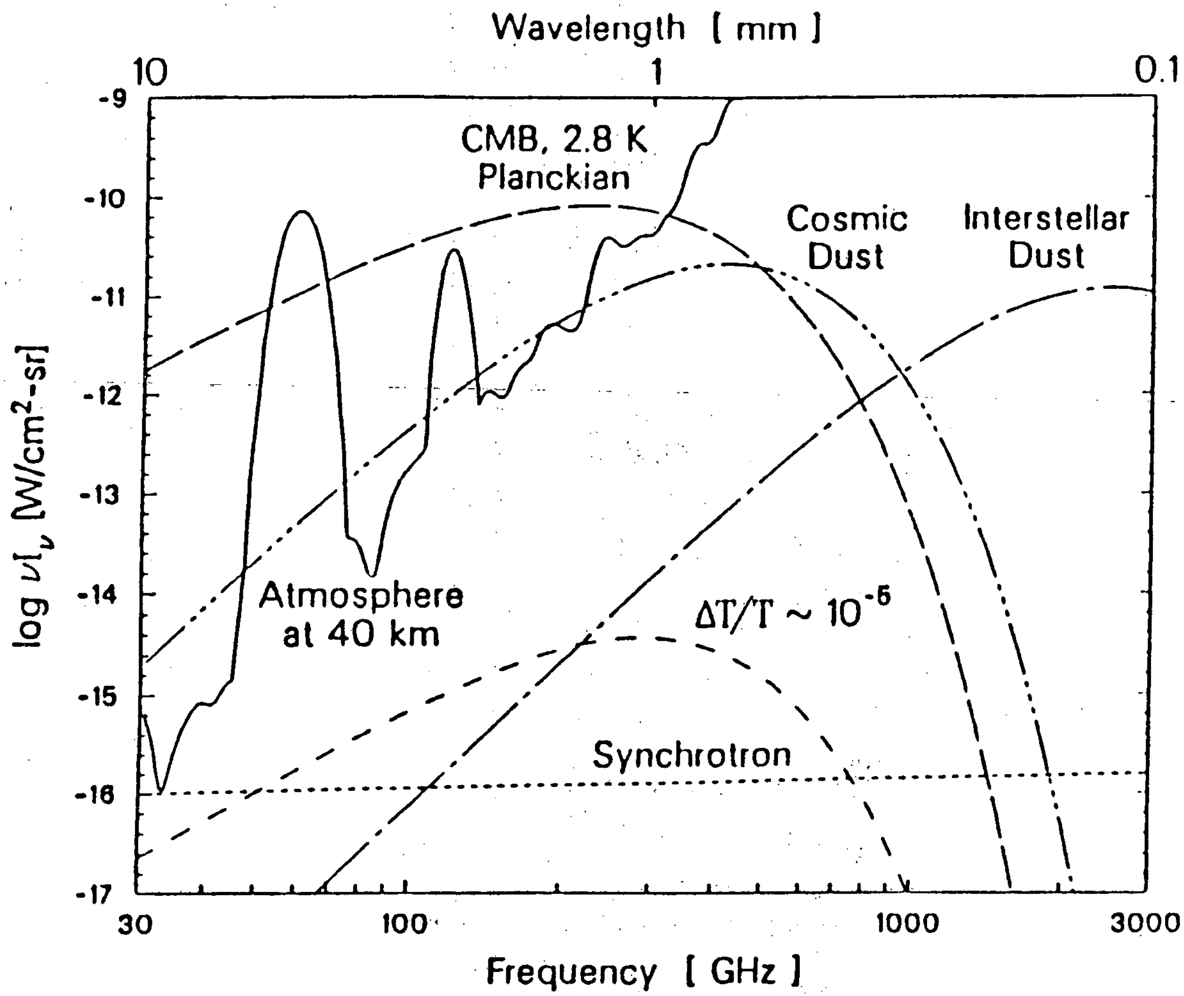


Figure 3.4: An estimation of the brightness of the diffuse components in the wave length range of 10mm to 0.1mm (from [Lange et al. 1988]):

(1) the cosmic microwave background, modeled as a Planck spectrum with temperature 2.8K;

(2) a sub-millimiter due to emission from cosmic dust at high red shift, fit to the result of Matsumoto et. al. [1988];

(3) galactic synchrotron and interstellar dust emission typical of high galactic latitudes;

(4) the atmospheric brightness seen by an instrument with 15% spectral bandwidth at an altitude of 40km;

(5) a temperature anisotropy in the cosmic microwave background with $\Delta T/T=10^{-5}$.

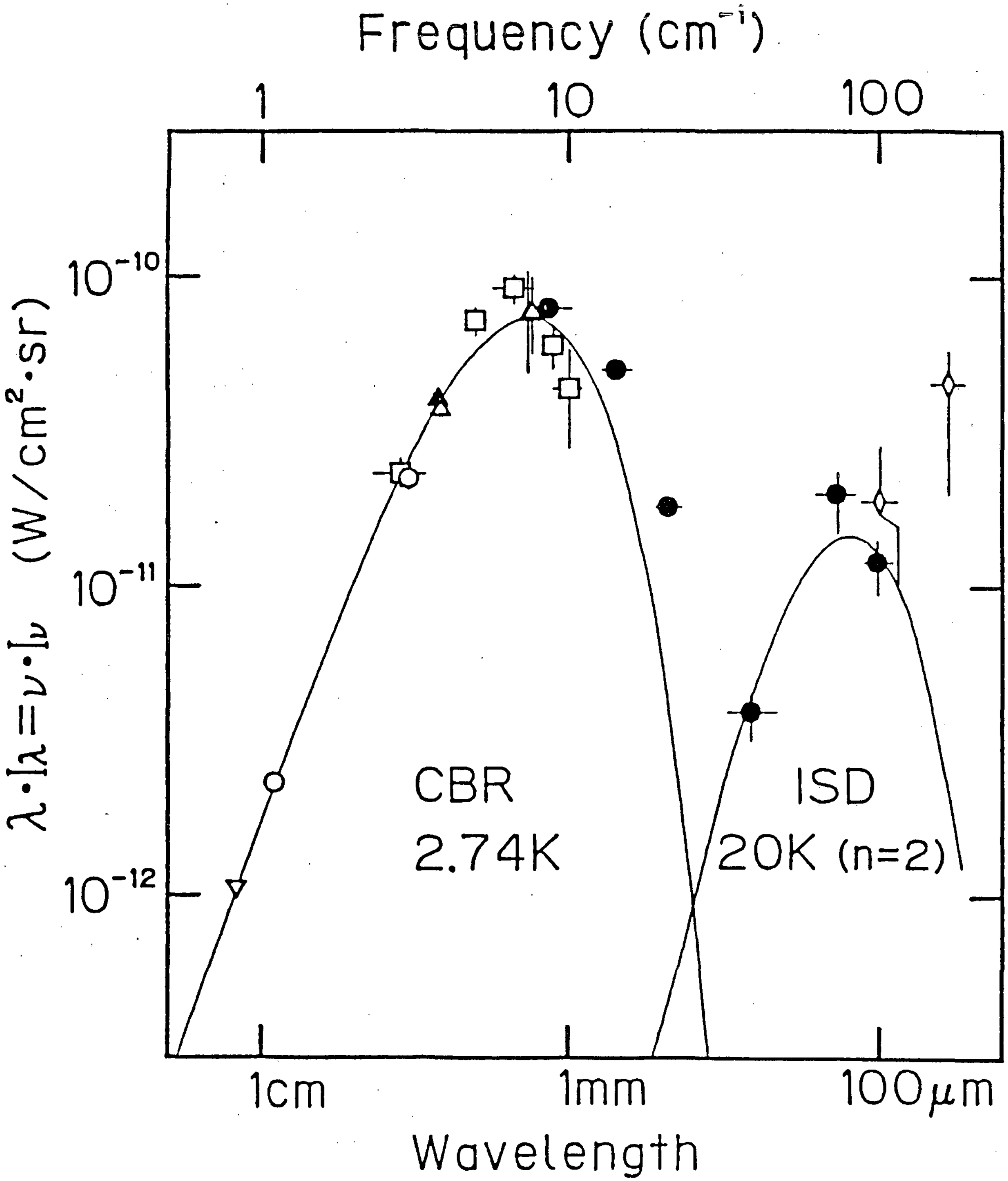


Figure 3.5a: The observed spectrum of the astrophysical background. The fluxes obtained by Matsumoto et. al. 1988 are indicated by ●

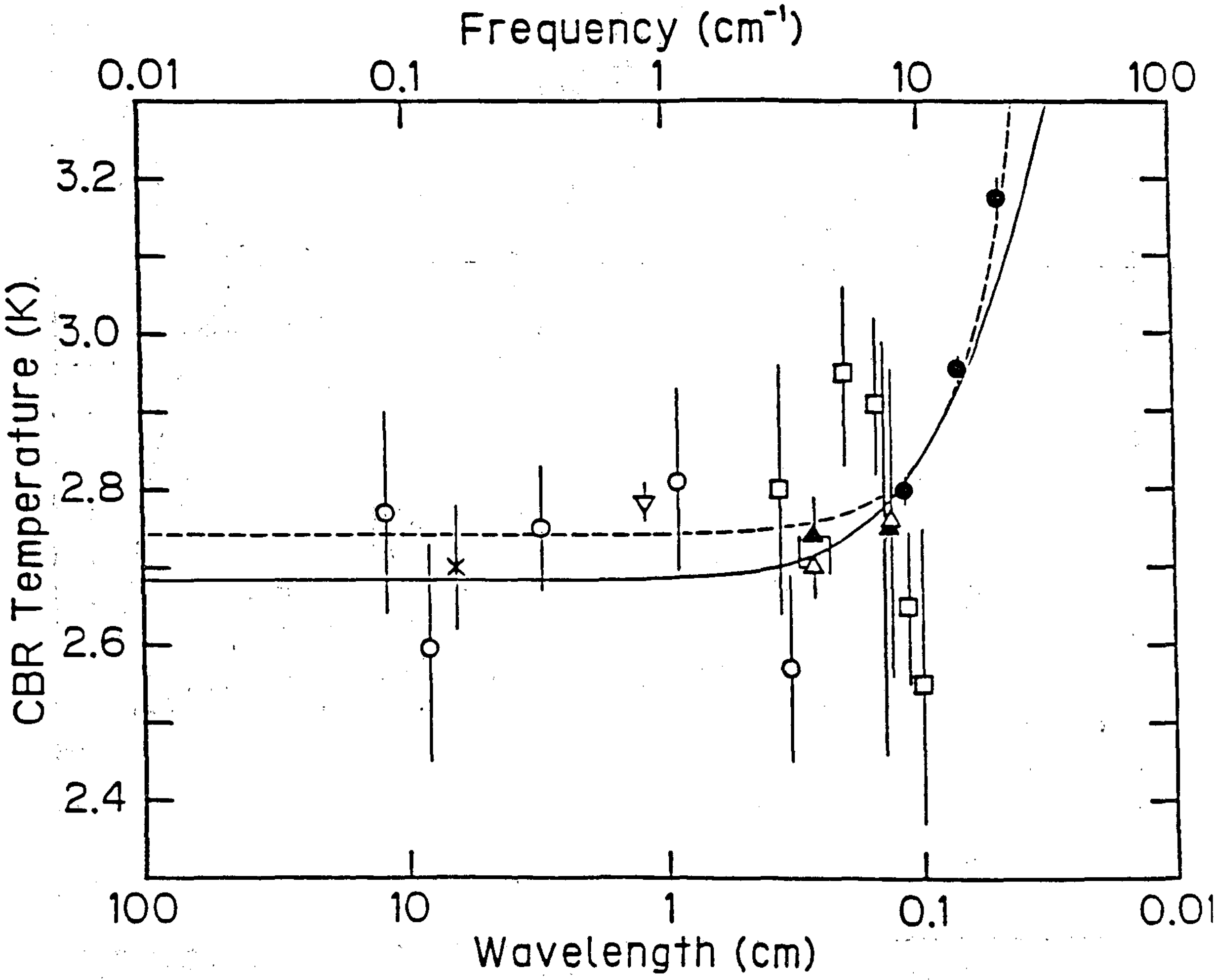
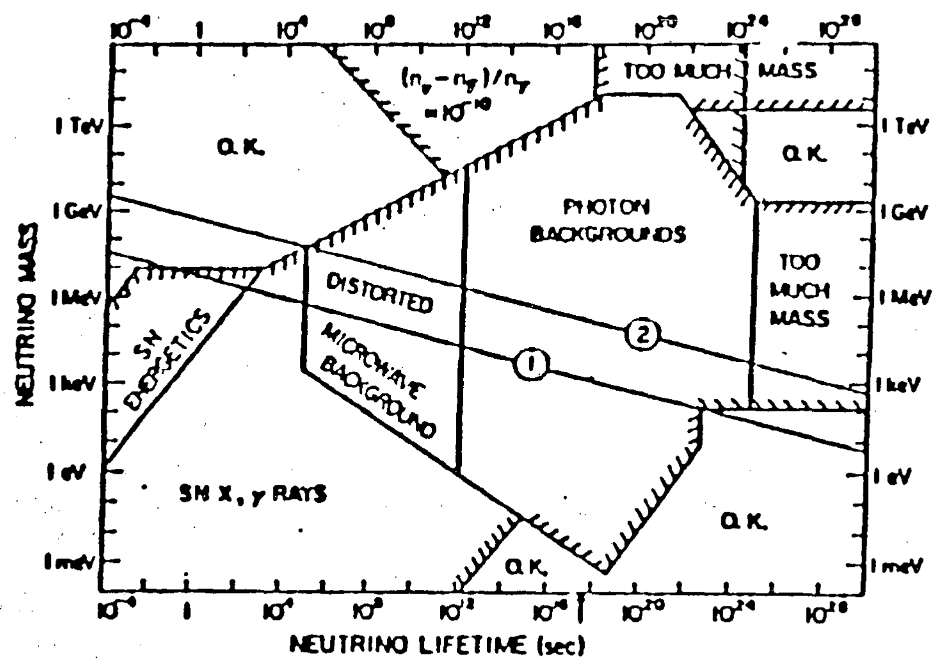


Figure 3.5b: The equivalent blackbody temperature vs. wavelength.
(● Matsumoto et. al. 1988, Δ Meyer and Jura 1985, O Smoot et. al., 1985, ▲ Crane et. al. 1986, ∇ Johnson and Wilkenson, 1987 and X Mandolesi et. al. 1986)

a)



b)

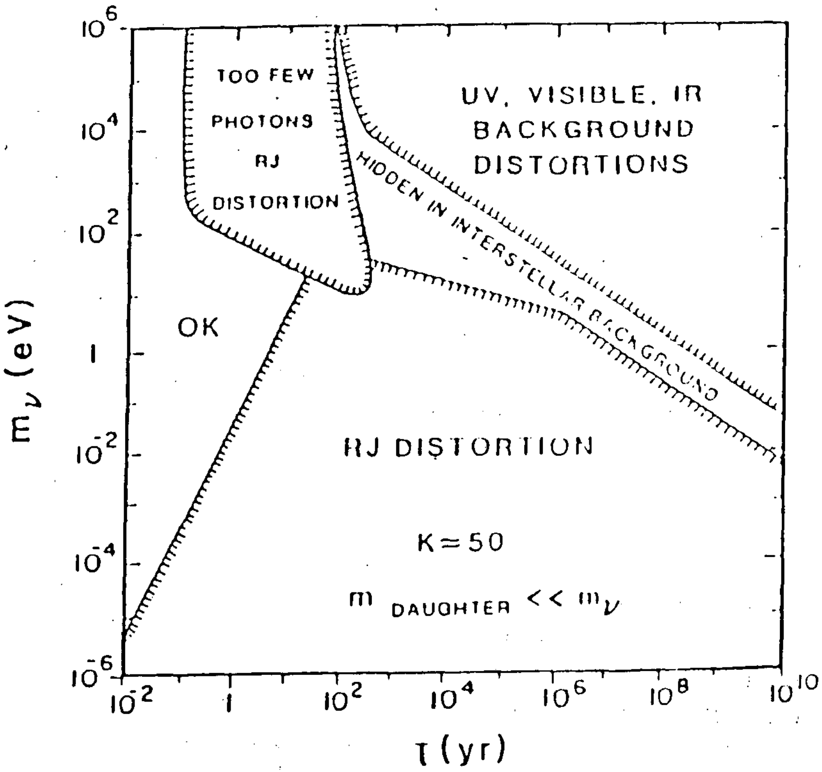


Figure 3.6:
a) Limits on neutrino mass and lifetimes [Turner, 1981].
b) Observationally excluded values of mass and lifetime for particles which decouple when the number of interacting species is ~50. [Silk and Stebbins, 1983].

The results are summarized in Fig. 3.7. Apart from a large dipole component, the cosmic microwave background is very uniform. The only positive evidence for anisotropy is claimed by Davies et al. [Davies, 1987] who are working in the 8^o range.

These results are extremely important for our understanding of cosmology. The observed dipole component allows us also to measure our movement with respect to the expanding frame of the universe. In the absence of recent rescattering, variations of the effective temperature gives us information on the uniformity of energy density at the recombination era. This is relevant in two respects. As explained in Section 2.1.1, the mere fact that regions of the sky separated by more than a few degrees have the same temperature to fairly high accuracy implies that a naive extrapolation backwards with a standard equation of state is untenable. These points should not have been in causal contact and therefore cannot have the same temperature. This difficulty led to the invention of the concept of inflation. The uniformity of the background also severely constrains [Silk, 1984] our scenarios for the formation of the large scale structure of the universe by gravitational collapse of density fluctuations. Although models with cold dark matter can circumvent present limits, temperature fluctuations $\Delta T/T$ of at least 10^{-6} are expected in these kinds of models because of the gravitational red or blue shift that density fluctuations should produce (Sachs-Wolfe effect [Sachs and Wolfe, 1966]). The region of maximum sensitivity is expected to be in the degree range since below 15 arc minutes the finite thickness of the last scattering surface washes out possible anisotropies.

This kind of measurements will be significantly improved by COBE which will give a complete map of the sky with 7^0 resolution. Various balloon experiments are being planned, with telescopes of 1 m diameter. By using very sensitive detectors, measuring at several wavelengths to substract the atmospheric and galactic components, and making maps down to 15 arc minutes, they may approach the $\Delta T/T = 10^{-6}$ landmark.

The implications of these measurements for particle physics are also important. We have seen that the isotropy may hint at a phase transition in the early universe. The density fluctuation of the photon field put limits on the quantum fluctuations in this inflation era. Moreover, if toplogical singularity such as cosmic strings have been generated in the early universe, they may be seen in maps of the cosmic microwave background. Cosmic strings would appear as linear temperature jumps across the sky.

3.1.1.2 The hard X-ray and γ-ray diffuse background.

The other window in electromagnetic waves on the early universe is the region between 100 keV and 100 GeV. Indeed an extragalactic diffuse flux is observed [Fichtel and Trombka, 1983]. It is more or less spatially uniform and the spectrum (Fig. 3.8) displays a conspicuous bump around 2 MeV.

The origin of this diffuse flux which extends down to the last region is still unclear. Although contribution of active galactic nuclei (quasars, QSO, and Seyfert galaxies) is certainly important in the low energy region, an additional component may be needed. If it is real, the bump at a few MeV may be difficult to explain. Various models based on the red shifted decay of particles have been proposed: the suggestion of Stecker [Stecker and Wolfendale, 1984] that they are due to π^0's produced on matter-antimatter annihilation runs onto the causal difficulties of matter-antimatter symmetric universes (see below section 3.2.2.2). Scenarios based on

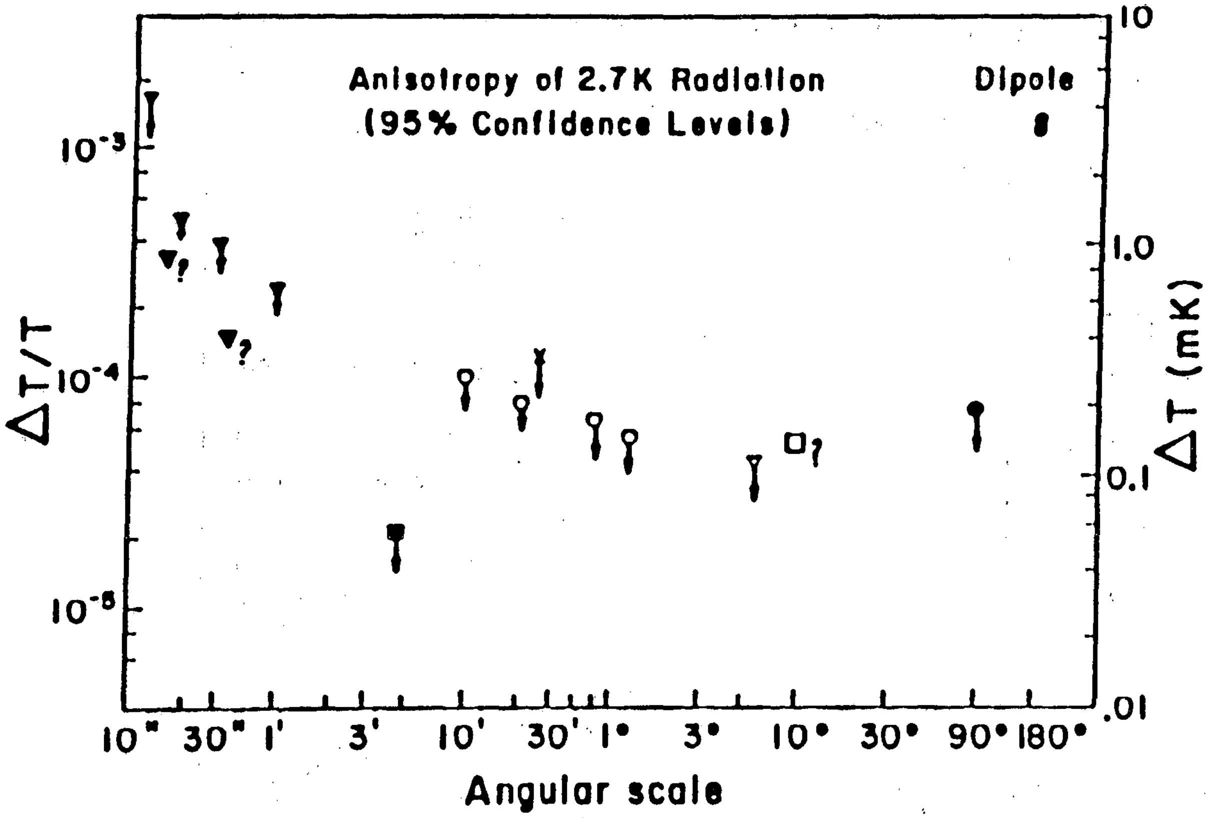


Figure 3.7:
Experimental results on the anisotropy of the Cosmic Microwave Radiation. [Wilkinson, 1986]

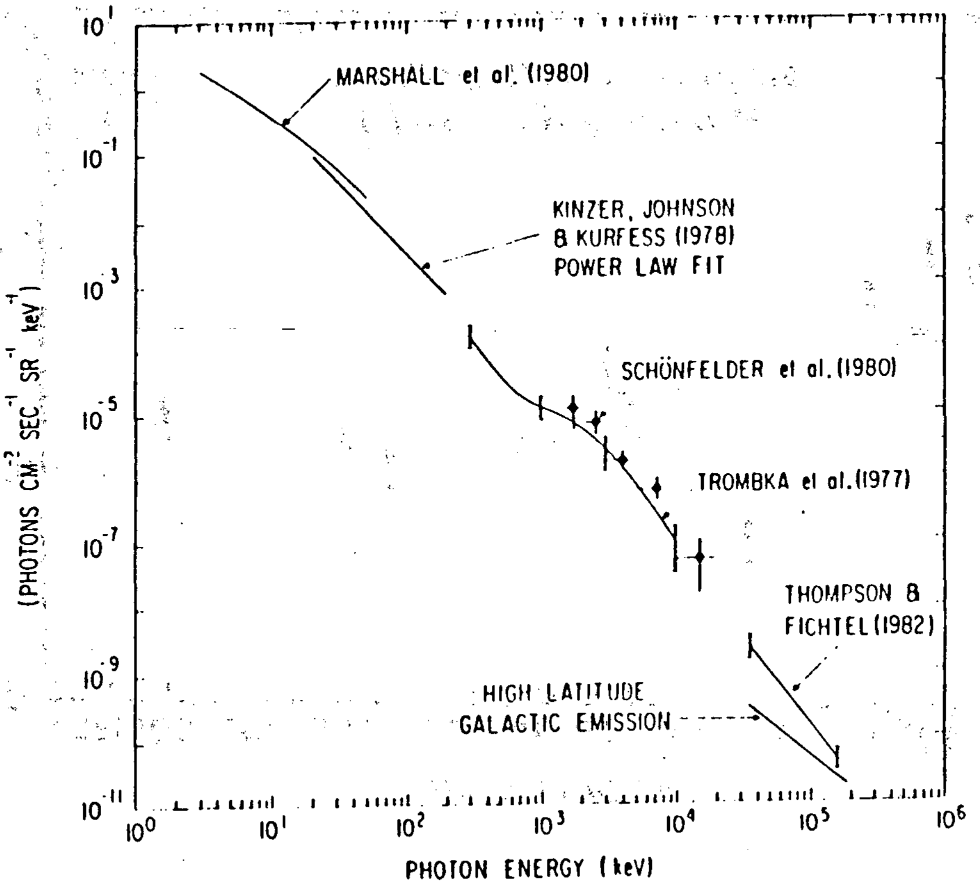


Figure 3.8:
Diffuse background photon flux as a function of photon energy. [Trombka and Fichtel, 1983]

gravitinos [Olive and Silk, 1985], decaying dark matter [Daly 1987] etc., have been proposed with no compelling reason so far.

Experimentally, some new information [Fichtel, 1982] should be brought by the gamma-ray observatory (GRO) which should be finally launched in 1990. At the minimum, it should increase the statistics on quasars in the hard X-ray and γ-ray region. This will put models based on superposition of active galactic nuclei [Bignami et al., 1979] on stronger footing. Transfer of technology from particle physics, for instance, the development of high pressure drift chambers made by the Berkeley group [Sadoulet et al., 1987, 1988a, 1988b; Parsons et al, 1988] may allow a fine scale (arc minute) measurement of the granularity which may hint at either a relatively local origin (AGN's) or a high red-shift phenomenon.

3.1.2 Neutrinos

Large neutrino fluxes are also expected from the early universe.

3.1.2.1 2 K cosmological background.

The same high energy processes which lead to the 2.7 K photon background should also produce neutrinos. However, they decouple from photons and matter around a temperature of 2 MeV and they are not reheated as the photons are by the e^+e^- annihilations (e.g. [Weinberg, 1972]). One expects therefore their temperature to be

$$\left(\frac{4}{11}\right)^{1/3}$$

the temperature of the photons, that is about 2 K.

There is no serious doubt about the existence of such a flux. Its detection would be, however, a marvelous confirmation of the Big Bang theory. The only problem is that there are no good ideas how to detect these very low energy neutrinos (see e.g., [Langacker, 1983]).

3.1.2.2 The MeV region.

Another cosmological background is expected from the supernovae which have exploded all along the life of the galaxies. In particular, it is usually expected that at the time of galaxy formation, a large number of supernovae went off. The fluxes are large but may be difficult to distinguish from the atmospheric flux and the radioactive decays inside the earth crust and nuclear plants.

3.1.2.3 The GeV region.

Although not strictly cosmological in origin, high energy neutrinos are expected from annihilation of dark matter particles if they exist. This will be discussed in more details in Section 4.

3.1.3 Other relics

There are potentially other relic particles coming from the early universe. Magnetic monopoles are natural candidates in grand unified theories. We refer the interested reader to recent reviews such as that of Turner [Turner, 1983]. Figure 3.9 summarizes the present flux limits. Note that the mica limit depends on the assumption that magnetic monopoles will be bound to nuclei. The IMB result depends on the hypothesis that monopole catalyzes proton decay. Larger experiments are

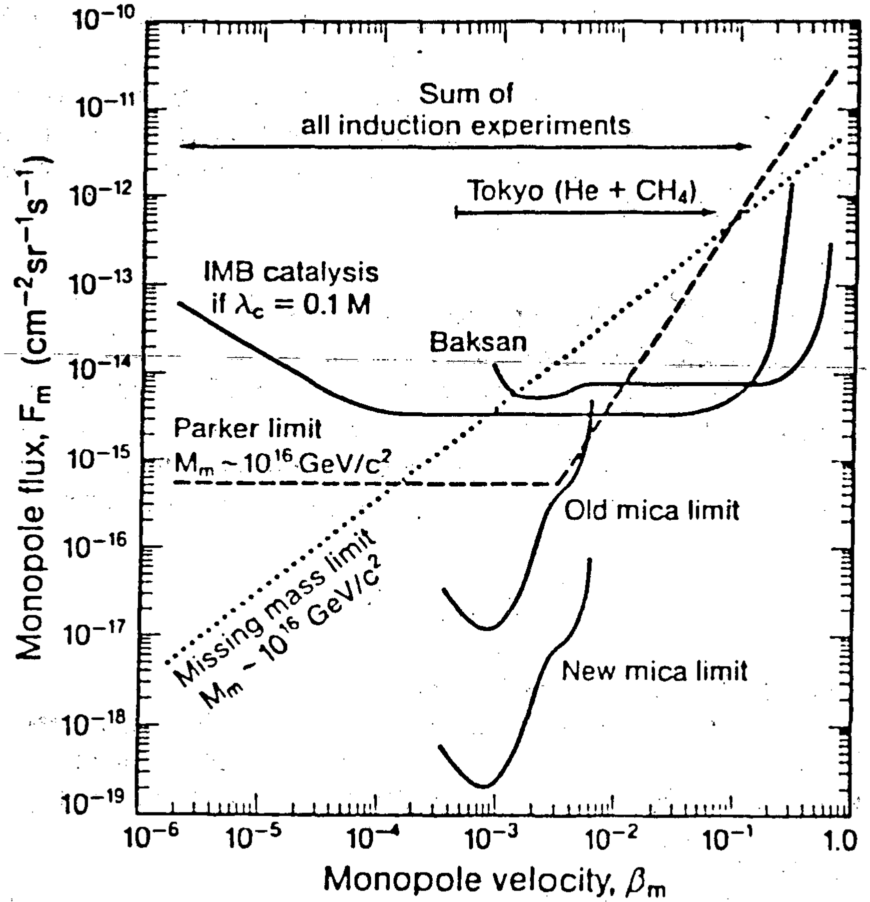


Figure 3.9: Monopole flux limits vs. monopole velocity for several direct searches (solid curves) and indirect astrophysical arguments (dashed curves).

being constructed with magnetic detectors of large size and the MACRO detector. The latter combines three techniques: liquid scintillators, gaseous detectors to see the Drell effect, and track-etch layers. When it is completed, its large area (72×12 m^2) should allow to go below the Parker limit for monopoles which ionizes sufficiently (i.e., for $\beta \geq 10^{-4}$).

Gravitational radiation can be generated in the early universe, for instance by the collapse of cosmic strings. This stochastic gravitational background could be detected by monitoring extremely accurately the arrival times of radio pulses from a spatial grid of rapidly spinning neutron stars [Backer and Hellings, 1986]. The present limits are just above the predictions and the Princeton and Berkeley group is trying to increase its measurement capability.

3.2 Chemical Composition of Present Universe

A second major source of information about the early universe is the chemical composition of the present universe. Photons and cosmological neutrinos (cf. their mass is much below 1 eV) represent today a negligible factor of the energy density. Dark matter will be discussed in Section 4. Here we limit our remarks to the number of baryons and the amount of antimatter in the universe.

3.2.1 Baryons: Primordial nucleosynthesis

The primordial abundances of the elements (^{4}He, ^{3}He, ^{7}Li) give the ratio η between the number of baryons and the numbers of photons and hence, since the photon density is known from the measurement of the microwave background, it fixes the mean density of baryons in the universe and its ratio Ω_b to the critical density.

3.2.1.1 The basic physics.

We summarize here the well known result [e.g., Weinberg, 1972]. Above a temperature of 100 keV, there is practically no nucleosynthesis, in spite of the fact that the binding energy of most nuclei is much higher. This is due to the fact that the density is not large enough for reactions to proceed by any other process than two-body collisions and that deuterium, which is then a necessary step in the synthesis, is dissociated by high energy photons.

When the temperature is low enough, this bottleneck disappears and very rapidly the light elements D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li and ^{7}Be are formed. Figure 3.10 gives a calculation by Wagoner [Wagoner, 1973]. The reactions stops at Li and Be, because there are no stable nuclei above that energy which can be formed by two-body processes. The universe will have to wait for stars to be formed to see the formation of carbon by the merging of three alpha particles.

The resulting primordial abundances of the various elements depends critically on the ratio η of baryons to photons which determines the temperature at which the synthesis starts, and the ratio of the neutron density to the proton density. The latter is a function of the freeze out temperature at which the thermodynamical equilibrium between the neutron and the proton cannot be maintained, because the inverse beta decay reactions are too infrequent. The ratio is then fixed at

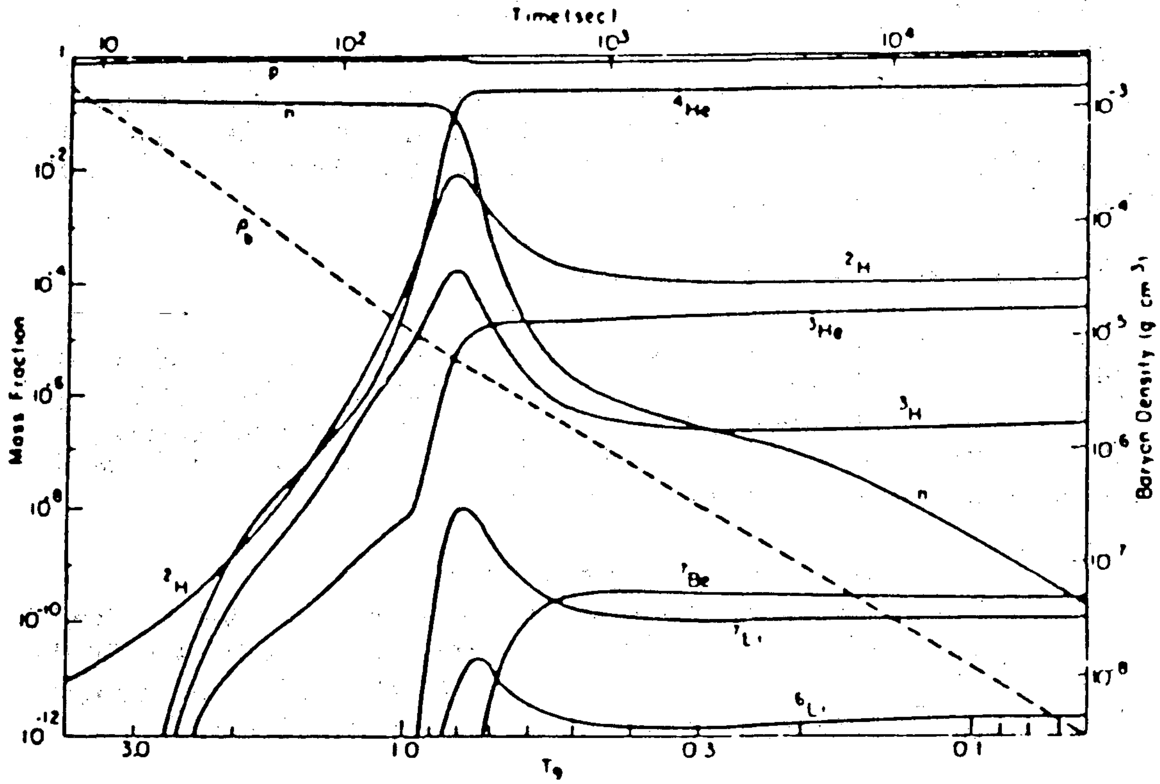


Figure 3.10: Evolution with time (and temperature) of the primordial abundances and the baryon density ρ_B calculated by Wagoner (1973). One can notice that D comes from the neutron absorption reaction by protons $n + p \rightarrow D + \gamma$ occurring at $T < 10^9$ K. A large part of D is subsequently transformed into ^3He, ^4He and ^7Li (+^7Be).

$$\frac{n}{p} = \exp\left(- \frac{\Delta m}{kT_{\text{freeze out}}}\right)$$

where Δm is the mass difference between the neutron and the proton. This number will be subsequently modified slightly by the n decay. The freeze out temperature is determined primarily by the expansion rate of the universe, which is a function of the number of relativistic species at the time of freeze out.

Figure 3.11 ([Yang et al., 1984], see also [Delbourgo-Salvador, 1985]) gives typical results in the standard model: the universe is assumed to be homogeneous at the time of nucleosynthesis and no subsequent release of energy was strong enough to lead to strong photodissociation..

3.2.1.2 The experimental situation.

Measuring the primordial abundances is difficult. Especially for D, ^{3}He and ^{7}Li the concentration are extremely small and the signal weak. Moreover, the determination of D depends on the small isotopic shift $\Delta\lambda/\lambda$ corresponding to velocities of 80 km/s [Fig. 3.12]. Not only does this require good spectrometers, but the shift could be simulated by velocities in the observed clouds which can easily encompass these values. [See e.g., Gry et al., 1983]. The determination of ^{3}He in that way, would be even more difficult with an isotopic shift of 17km/s.

An even more fundamental difficulty is that it is difficult to find primordial gas which has not been reprocessed in stars: D_2 is destroyed, helium can be produced and ^{7}Li can evolve in the two directions. The experimenter is looking for sites where the abundances are likely to be primordial. Unfortunately, the more desirable a site, the more difficult are the observations. The intergalactic medium is the best candidate and gas clouds are known to exist. They produce the large number of absorption bands (the so called Lyman alpha forest cf Fig 3.13) seen in the blue wing of Lα emission of the quasars. (Fig. 3.12) Unfortunately, the complexity is such that there is little hope, for the time being, to unravel the deuterium signal.

At the risk of larger contamination, higher densities may be obtained in the interstellar medium. Absorption lines can then be observed in the emission spectrum of a star. The current deuterium determination uses this method [Vidal-Madjar, 1983].Radio emission lines can also be used for the same measurement [Blitz and Heiles, 1987].

Emission lines from H_{II} region ionized by a close hot blue star can also be used, but the percentage ionized atom has to be estimated, yielding additional uncertainties. This is the main method used for ^{4}He [Kunth and Sargent, 1980]. In the same regions, ^{3}He is also ionized and give rise to a radio emission. This leads to the main determination of the ^{3}He abundance[Rood, 1984].

Still taking more risks for distortion of the primordial spectrum, stellar atmospheres can be used, especially those of old stars (Pop II) which have a very small amount of convection. The present estimates of ^{7}Li are based on that method [Spite and Spite 1982].

Finally, the solar system can be used and abundances can be determined relatively easily in the solar wind, planetary spectra and meteorites. But the risk for destruction and fractionation effects are bigger and many authors view these determinations as uncertain.

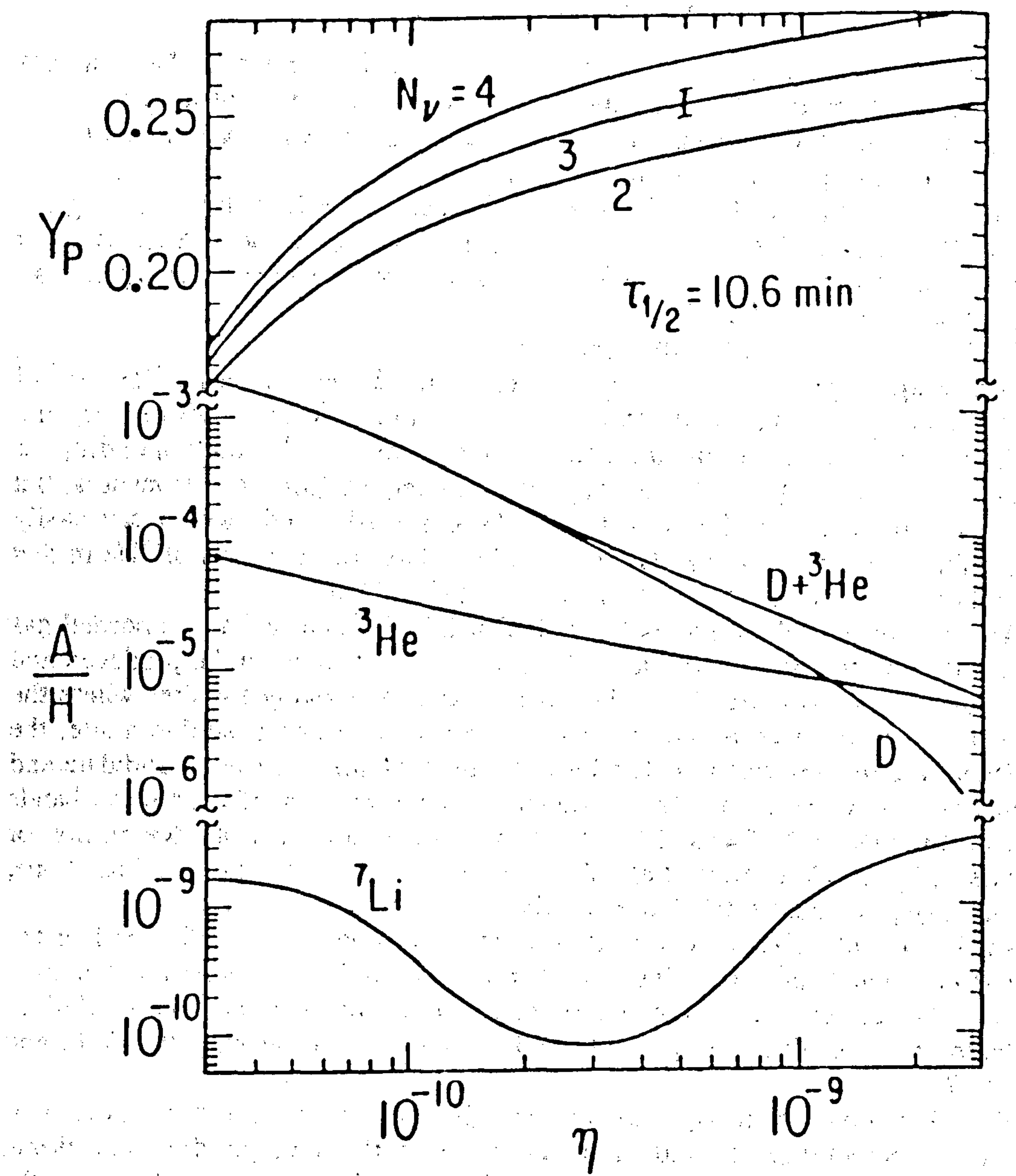


Figure 3.11: The predicted primordial abundances of ^4He (by mass), D, ^3He, and ^7Li (by number relative to H) as a function of η for $\tau_{1/2}$ =10.6 minutes; for ^4He the predictions for N_ν = 2,3,4 are shown, and the size of the "error" bar shows the range in Y_p which corresponds to $10.4 < \tau_{1/2} < 10.8$ minutes. Note the changes in the abundance scales. [Yang et. al., 1984].

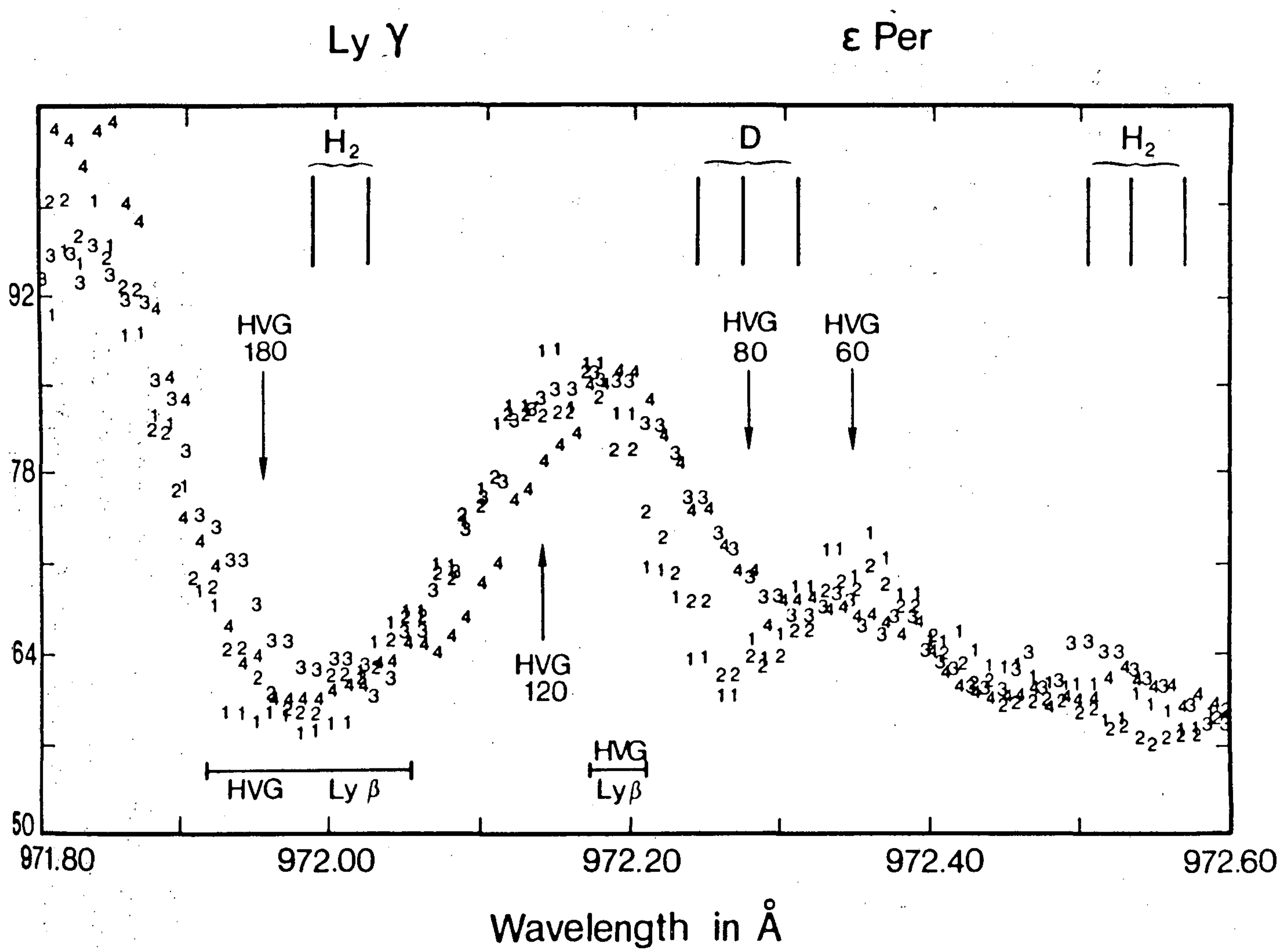


Figure 3.12: Lyman γ profile of ε Persei. The observations are separated in 4 sets (marked 1, 2, 3, 4), the mean time interval between two successive sets is 4h. Note that a time variation is now also evident at -60 km s-1. [Gry et al., 1983]

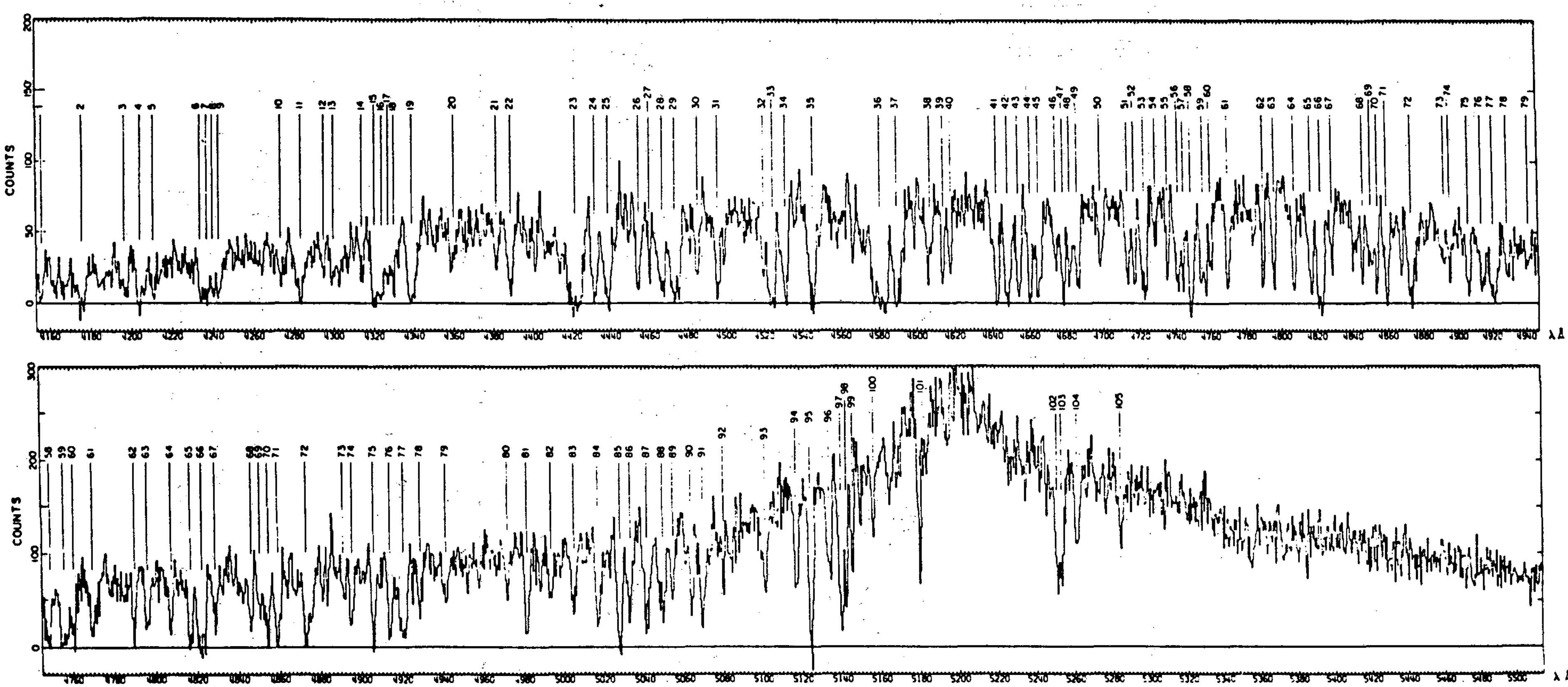


Figure 3.13: The Lyman α forest: Spectrum of PKS 2126 - 158, showing four overlapping, independent observations covering the range 4153 - 6807 Å. Each bin is equivalent to 25.78 km s^{-1} (the wavelength axis is logarithmic). The zero intensity level in each observation is indicated by horizontal lines [Young et al. 1979],[Sargent and Young 1980].

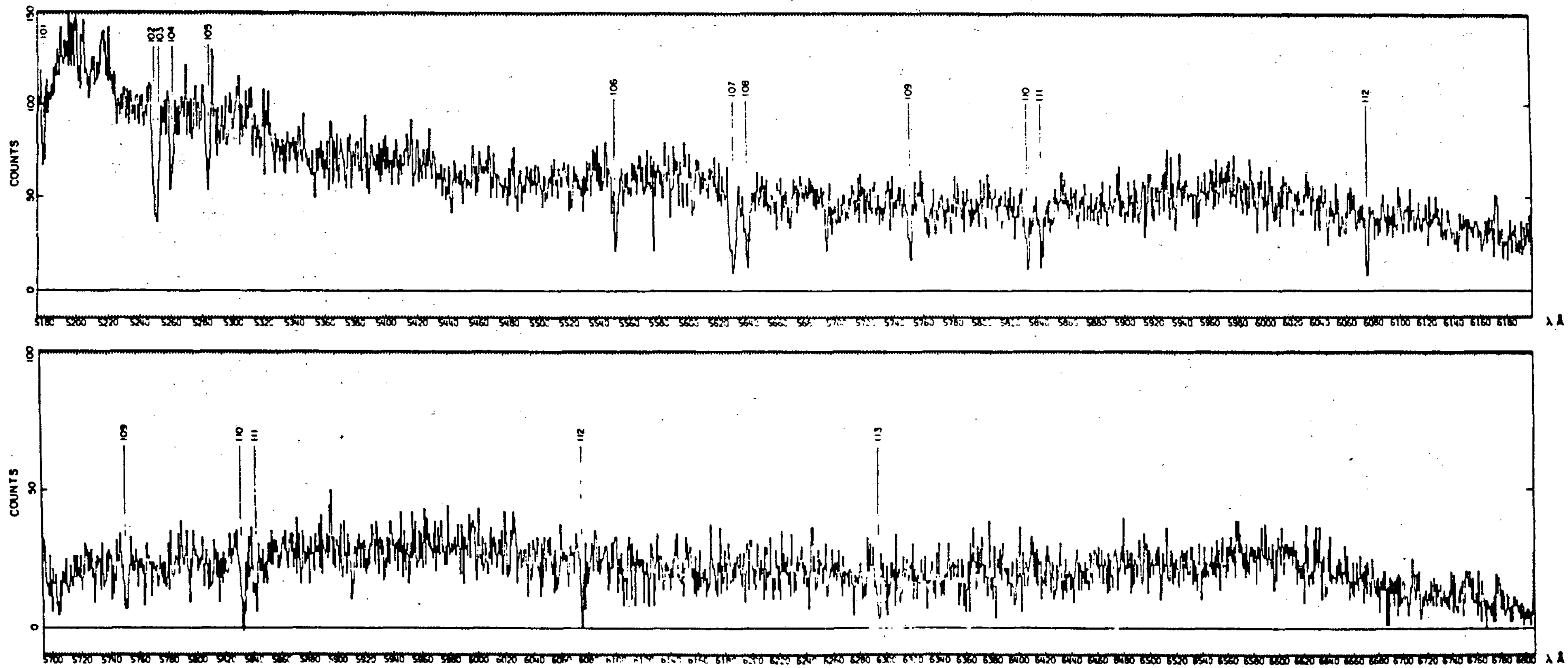


Figure 3.13: - continued.

In this experimental situation where some reprocessing has to be tolerated, it is tempting to try to correct for it by correlating the observed abundances of light elements to the abundances of heavier elements, such as C or O ("metals" in the astronomer jargon) and to extrapolate to zero metallicity. This is the method used by Kunth and Sargent for ^{4}He. However, experimentally the correlation is weak and site dependent variations may be dominant. It has been argued that ^{3}He+D should be relatively independent of reprocessing [Yang et al., 1984] since D will be mainly converted into ^{3}He. However, no experimental confirmation has been given in the form of an anticorrelation between ^{3}He and D.

Table 3.1 attempts to summarize the above discussions and the current results. When compared to the curves of Fig. 3.11, they lead to a estimate for η of

$$1.5\ 10^{-10} \leq \eta \leq 6\ 10^{-10}$$

or

$$5\ 10^{-3} \leq \Omega_b h^2 \leq 2\ 10^{-2}$$

where as usual, h is the Hubble constant in units of 100 km/s/Mpc. The ^{7}Li result is very important in such a determination and a word of caution is necessary. The ^{7}Li abundance is usually much more important in young stars (Population I) [Hobb, 1987] and although it seems established that ^{7}Li increases with metallicity [Vauclair, 1988], a complete model of the evolution of ^{7}Li in stars does not exist. Note also that since we know that deuterium is destroyed, the higher range of deuterium is preferred leading to low value of Ω_b.

In the next ten years, these results will be certainly improved by the Hubble space telescope and the far UV satellite FUSE. Note that it is unlikely that first generation of spectroscopes aboard the space telescope have enough resolution for disentangling deuterium in the Lα forests. Meanwhile, patient work on the ground to understand the ^{7}Li evolution and to attempt to measure $\frac{D}{H}$ in the radio may lead to significant progress.

3.2.1.3 Importance for cosmology and particle physics.

Primordial nucleosynthesis is, after the 2.7 K microwave background, the most dramatic confirmation of the Big Bang model.

The experimental results fix the ratio η of photons to baryons. This is, of course, central to the problem of dark matter. If indeed $\Omega_b h^2$ is smaller than $2 10^{-2}$, the larger values obtained in gravitational studies ($\Omega \geq 0.2$) implies the existence of **non -baryonic** dark matter. The uncertainties mentioned above prevent this argument from being totally compelling. Other scenarios have been explored to turn this argument around, by dropping the assumption of homogenity with a segregation of neutron at the time of the quark-hadron transition ([Applegate et al., 1987] or [Fuller et al., 1987]) or by postulating a bright era which destroys helium by photodissociation after the nucleosynthesis ([Dimopoulos et al., 1987]). It is possible to obtain $\Omega_b = 1$ at the price, however, of over producing ^{7}Li and ^{6}Li. Because of that, these scenarios do not seem to be viable.

Another important aspect of η is that it is given by the baryogenesis mechanism (see below section 3.2.2).

Primordial Abundances

Elements		Intergalactic	Interstellar Optical	Interstellar Radio	Stellar Atmosphere	Solar System	Results By Mass	Results By Number
Deuterium	NOW		COPERNICUS H_{II} region UV Lyman $\frac{\Delta\lambda}{\lambda} \cong 80$ km/s Difficulties: High velocities clouds Reprocessing	D_I Line (~1m) in direction of galactic anticenter. Difficulties : Long	Unreliable because destroyed $T > 10^5$ K	Solar wind meteorites Spectrum of planet	$\frac{D}{H} = 2\,10^{-5} - 2\,10^{-4}$ ↓ Evolution $6\,10^{-4}$	$10^{-5} - 10^{-4}$ ↓ $3\,10^{-4}$
	FUTURE	Lyman α Forest But not first generation of HST					$\frac{^3H_e + D}{H}$	More constant $3 - 12\,10^{-5}$
H_e^3	NOW			H_{II} regions $^3He^+$ 3.46 cm	-//-	-//-	$\frac{^3He}{H} = 2\,10^{-5} - 3\,10^{-4}$	$0.6\,10^{-5} - 10^{-4}$
	FUTURE		FUSE: Blue wing of ^{4}He Lyman (60 nm) $\frac{\Delta\lambda}{\lambda} \cong 17$ km/s					
H_e^4	NOW		H_{II} regions in compact blue galaxic. (Young/low metallic) Difficulty : Ionization correction factor Correction for evolution		Fit to HR plot in - Population II stars - B stars		$0.22 < Y = \frac{m\,^4He}{m_H} < 0.25$	
	FUTURE	-//-	+ Better angular resolution + Fuse (H_e^3/H_e^4)					
L_i^7	NOW				Population II stars $\lambda = 671$ nm Difficulty: convection		$5\,10^{-10} = 1.5\,10^{-9}$	$1\text{-}2\,10^{-10}$
OTHER					^{7}Be not observed B observed			

Table 3.1

Finally, as displayed in Fig. 3.11, the amount of ^{4}He depends on the number of relativistic species around 2 MeV. In particular, it depends on the number N_ν of species of neutrinos of mass much below 1 MeV. The more species, the larger will the energy density and the expansion rate be, leading to a higher decoupling temperature and n/p ratio. As a consequence, more helium is produced. Current measurement of ^{4}He constrains the number of families to be smaller than 5. It is interesting to note that this number is similar to limits obtained by three different methods:

a) Collider experiments obtain limits

$$N_\nu \leq 3\text{-}6 \quad \text{(depending on the top mass)}$$

by comparing the production rates of W and Z boson [Colas, 1988].

b) e^+e^- experiments (ASP, MAC, CELLO) do not see events of the type

$$e^+e^- \rightarrow \gamma + \text{undetectable particles.}$$

This lead to the limit

$$N_\nu \leq 8 \qquad \text{[Grivaz 1988]}$$

c) In the case of the supernova SN1987a, we can compare the energy observed in neutrinos as measured with the proton decay detectors in the maximum energy release expected ([Ellis, 1987], [Schaeffer, 1987]). Taken at face value, these numbers imply

$$N_\nu \leq 4.$$

3.2.2 Matter - antimatter

A major puzzle in the Big Bang cosmology is the very small amount of antimatter in the universe. Naively, since the laws of physics are to a good approximation symmetrical under charge conjugation, we would expect to observe an equal number of protons and antiprotons.

3.2.2.1 Experimental evidences.

a) Antimatter can be searched directly in cosmic rays. The best evidence would be the observation of heavy antinuclei which could only be formed in a star of antimatter. None has been observed so far. A new balloon experiment EXAM is in preparation and should greatly improve these limits.

It is also possible to look for antiproton in the cosmic rays. This is a less stringent test since $\bar{p}$ can be produced in cosmic ray interactions. However, the very low energy region cannot be populated by $\bar{p}$'s from the pp interactions, because of kinematic effects: $\bar{p}$'s produced centrally in the collision have a minimum momentum in the laboratory. Figure 3.14 show the present data on the ratio of p to p together with expectations from cosmic ray interactions. This ratio is used to correct for the deceleration of cosmic rays by the solar wind and magnetic field ("solar modulation"). The fluxes are generally higher than expected. Particularly worrying was the point of Buffington et al. [1981] at very low energies which was many orders of magnitude above the naive prediction. Recently, the low energy flux was remeasured by two groups, and the Buffington result showed to be in error [Ahlen, 1987a]. The remaining excess may be attributed either to instrumental effects or to other mechanisms, such as the annihilation of dark matter particles [Silk and Srednicki, 1984, Stecker et al., 1987,Rudaz and Stecker, 1988]. In any case, the amount of $\bar{p}$ in the cosmic rays is smaller than 10^{-3}.

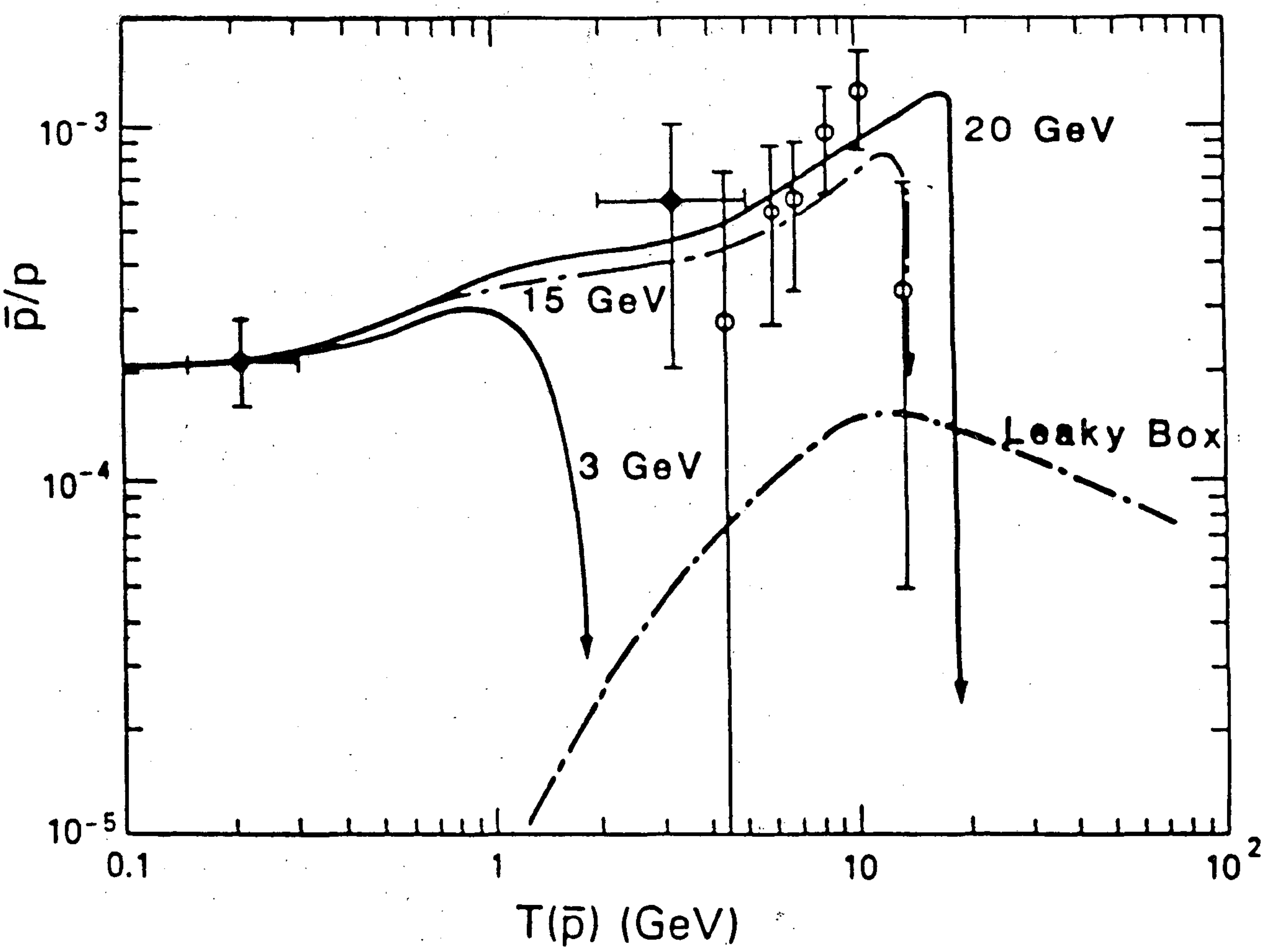


Figure 3.14: Present data on the ratio of $\bar{p}$ to p [Ahlen et al 1987a]

Another method is to look for positrons in cosmic rays. Figure 3.15 shows that there are indeed more positrons than expected. However, it is as easy to produce e^+ by pair production, for instance, and thus this evidence is hardly compelling.

b) The indirect evidence for absence of antimatter in our neighborhood is probably stronger. Matter-antimatter annihilation would produce γ rays. None are seen to be emitted by the planets and the observed flux in the diffuse extragalactic background shows that there is no significant amount of antimatter in at least a 20 Mpc radius (the distance of the Virgo cluster).

3.2.2.2 Relation to particle physics.

How can we explain this absence of antimatter? Two lines of argument have been proposed.

a) In a symmetric cosmology, it has been argued that some segregation mechanism could emerge (e.g. [Omnes, 1969]). These types of models face two difficulties. No convincing physical process has been proposed. Moreover, there are serious problems with causality if the segregation occurred early enough so as not to affect nucleosynthesis. Scales of 20 Mpc were outside the horizon and could not have evacuated antimatter in a coherent fashion. Recent scenarios based on inflation [Stecker and Wolfendale, 1984] are hardly convincing.

b) It seems much more natural to explain the absence of antimatter by a slight cosmological asymmetry. If the number of quarks exceeded the number of antiquarks by some 10^{-10}, all pairs would annihilate in the early universe and we would be left with only the small excess (e.g. [Barrow, 1983]). Note this argument relates the initial asymmetry to the ratio η of the number of baryons to the number of photons today. Sacharov has given the general conditions for such a mechanism to work. There should be a force which violates baryon and lepton number conservation, C and CP. In addition, the process should occur out of thermodynamical equilibrium.

A prototype for such a model is the SU(5) grand unified theory [Ellis et al, 1979], where a heavy gauge boson X is suppose to have slightly different couplings to qq and $\bar{q}\ell$ than its antiparticle $\bar{X}$.

$$X \rightarrow qq \quad (f) \qquad \bar{X} \rightarrow \bar{q}\bar{q} \quad (\bar{f})$$
$$X \rightarrow \bar{q}\ell \quad (1\text{-}f) \qquad \bar{X} \rightarrow q\bar{\ell} \quad (1\text{-}\bar{f})$$
$$f \neq \bar{f}$$

However, this model fails in two aspects: the proton should be unstable with a lifetime of 10^{29} - 10^{32} years, which is practically ruled out by proton decay experiments. Moreover, the CP violation term is too small and the predicted η is much too small.

More complex models can be built, in particular with several Higgs, in such a way that this process is still operational while the experimental limits in the proton lifetime and the electric dipole of the neutron are not exceeded. In such models the constraint on η from cosmology is usually used to fix some parameters on the model.

In conclusion, in the framework of asymmetric cosmologies, the absence of antimatter in our neighborhood and the value of η are powerful constraints on the physics at very high energy. Unfortunately, so far no unambiguous experimental test has been proposed to check if this line of argumentation is correct.

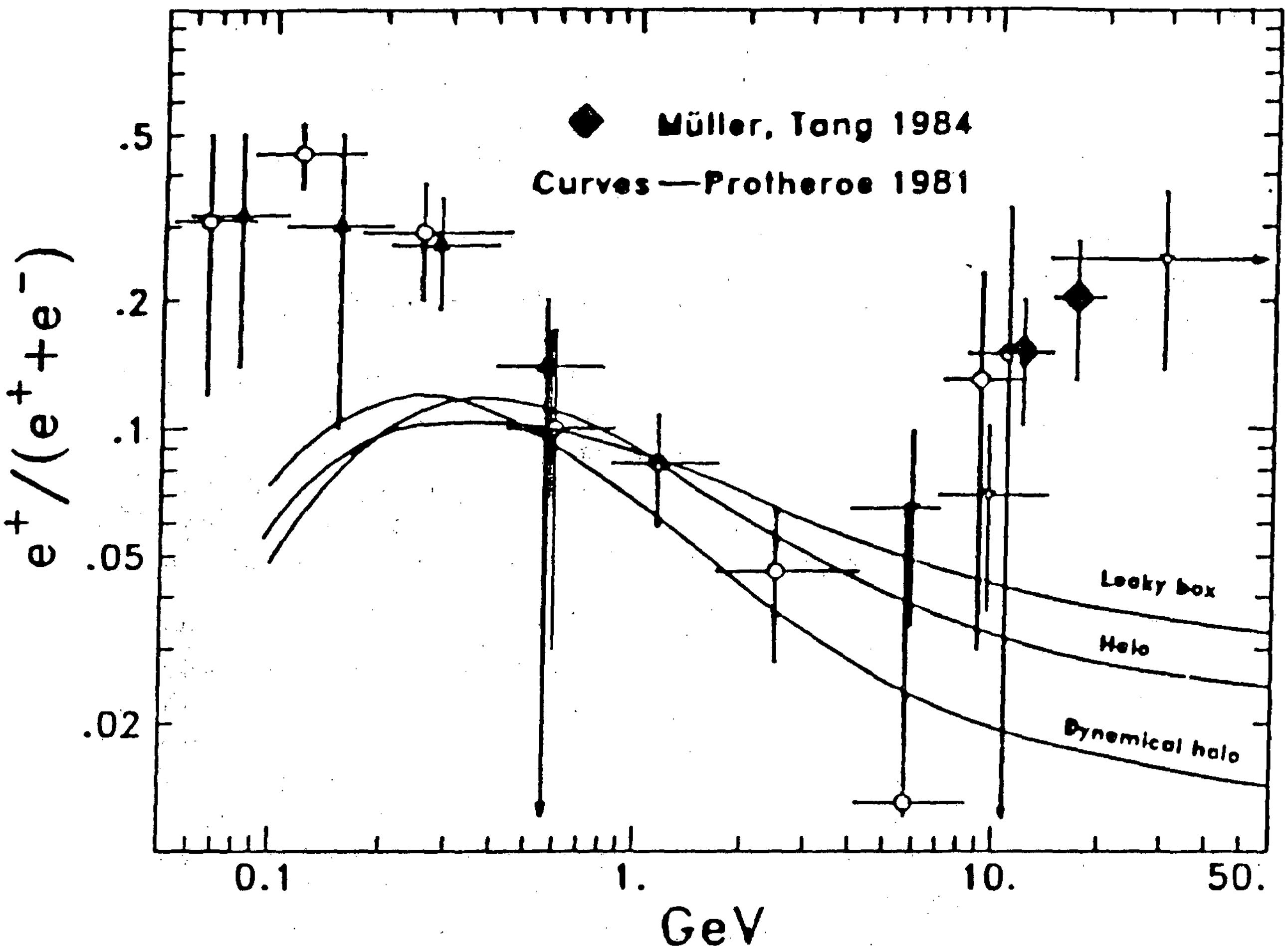


Figure 3.15: Positrons in cosmic rays

3.3 Large Scale Structure and Streaming Motions.

We finally analyze a third type of information which we have about the early universe: the present large scale structure of the universe which surrounds us and the large scale motions which seem to be superimposed on the Hubble flow.

3.3.1 The facts.

For sometime (since about 1923), we have known that stars are grouped in galaxies of 10^{11} solar masses or so. They have different morphologies with spirals dominating outside clusters, and ellipticals present mainly in the center of clusters (see e.g. [Shu, 1982] for an introduction). They are believed to have been formed around a red shift of four (from the maximum red shift of quasars, which are believed to be active galactic nuclei). The galaxies are themselves grouped in clusters of 10^3 galaxies which themselves form superclusters of 10^{15} solar masses. The upper end of this hierarchical structure appears to be still forming. It is only by going to very large distances that the universe can be considered uniform and isotropic. How large these distances have to be, is for the time being, unknown. Two recent results indicate that significant structure may exist to distances of at least 100 h^{-1} Mpc.

De Lapparent et al [1986] have recently analyzed the three-dimensional distribution of galaxies in a small region of the sky centered around the Coma cluster (Fig. 3.16). The third coordinate is given by the red shift of the galaxy and is, of course, smeared out by peculiar velocities. This explains why the central structure of the Coma cluster is elongated (as a "finger of God" as cosmologists like to say). The resulting structure is reminiscent of bubbles or of a sponge. This may be confirmed by the analysis (in progress) of the neighboring strips. In some other cases (Perseus) filaments seem to be prominent. The amazing feature is the existence of voids of 30 h^{-1} Mpc!

Another recent spectacular result is that of Dressler et al. [1987a]. They conclude from the analysis of deviation from the Hubble flow of elliptical galaxies that most of the galaxies in a radius of 50 h^{-1} Mpc have a large streaming velocity of 700 km/s with respect to the comoving of the microwave background(Fig. 3.17). They interpret their result as a common infall to a "great attractor". Numerous technical problems have been raised with the accuracy of the distance indicators used, the biases and the obscuration from our galaxy. For instance, the great attractor happens to be in a region that we cannot see. Therefore, this result still needs some confirmation. However, if it is correct, it will have very profound consequences for our understanding of large scale structure.

3.3.2 Implications

There are basically two pictures which have been proposed to explain the formation of galaxies and of the large scale structure. One model relies completely on the growth of density fluctuations, while the second proposes that gigantic explosions have formed the bubbles we see today. After the explosion, of course, the evolution is governed by gravitational instabilities as in the first model.

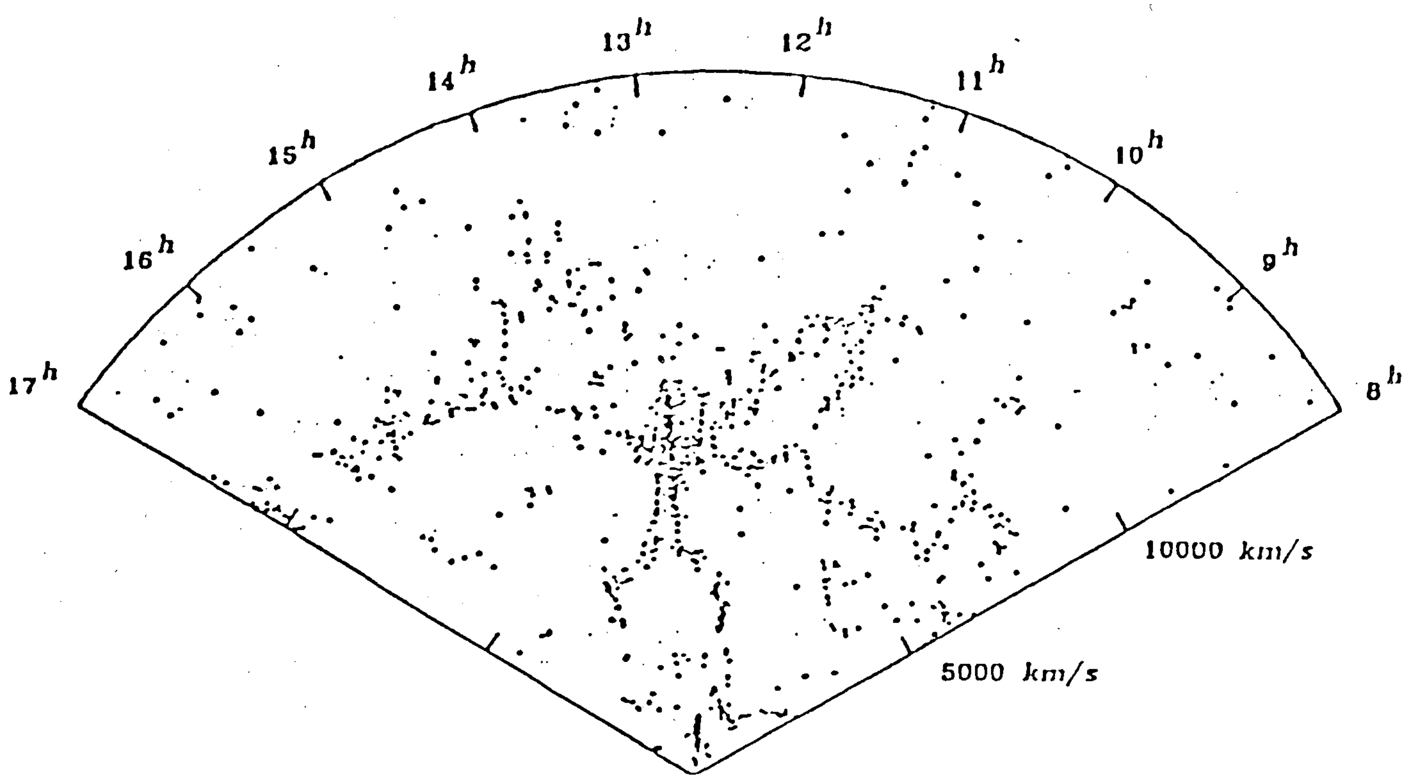


Figure 3.16: Distribution of galaxies around the Coma cluster (26.5 < α < 32.5) [de Lapparent et. al., 1986]

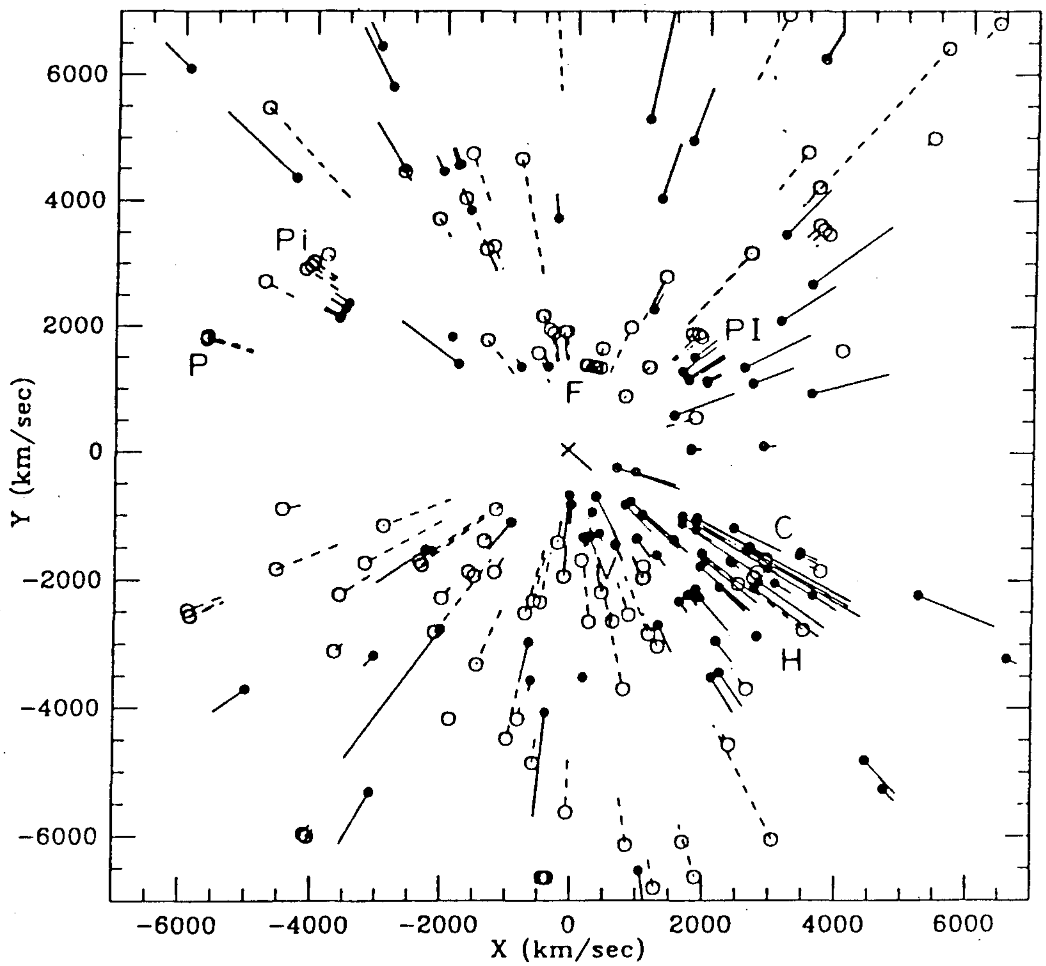


Figure 3.17: Streaming velocities of galaxies within a radius of 50 h^{-1} Mpc with respect to the comoving frame of the microwave background. [Dressler et al., 1987a]

3.3.2.1 Gravitational unstability .

The basic idea is that density fluctuations of spatial dimensions large enough to escape erasing by acoustic propagation are unstable under gravity and will grow (see e.g. [Weinberg, 1972] Section 15.8, or [Peebles, 1980]). In order to describe the present structure, we have to answer three types of questions:

a) **What is the origin and the probability distribution of the initial density fluctuation?** Inflation answers most naturally this question; it predicts uncorrelated quantum fluctuations of magnitudes related to the details of the inflationary episode, with a specific power spectrum as a function of spatial frequency (the so called Zeldovich spectrum). Topological singularities such as cosmic strings lead to phase correlation and contain more arbitrariness.

b) **What is the value Ω?** For the same reasons that those explained in Section 2.3., the growth of density fluctuations is a strong function of Ω. For Ω smaller than 1, the growth stops when $z \approx \Omega^{-1}-1$. This may superficially explain why the observed "bubbles" have not collapsed onto their point of contact. Large Ω would lead to higher peculiar velocities and would be definitely needed if the large scale motions are confirmed.

c) **What is the carrier of the density fluctuations?** This question has been the focus of research in this field for the last six years. Let us attempt to summarize the results (cf. [Primack, 1986] and references therein).

Baryons alone cannot do it, in scenarios where the fluctuations are "adiabatic", that is, where photons and baryons fluctuate together (before recombination). If the density fluctuations are due to quantum fluctuations, this is the most natural hypothesis. In that case, the limits on the 2.7 K background of anisotropy will give an upper limit to the matter density fluctuations at the time of recombination. This limit is so small that whatever the value of $\Omega < 2$, there is not enough time to form galaxies. A way out is to suppose that the fluctuations occur only in the matter field and that the radiation density is constant ("isothermal " or "isocurvature", because at high z the radiation density is dominant), (e.g., [Peebles, 1987]). In the framework of particle physics, there is no natural reason for this to happen, but the only limits on matter density fluctuations at recombination come from the Sachs-Wolfe effect and are therefore relaxed.

Unless we call for this unnatural scenario, it is necessary therefore to **add at least one additional component.** In current models, it is either dark matter or cosmic strings. This second possibility offers so many parameters that it has essentially no predictive power. We therefore limit our remarks to the case of dark matter.

The basic idea of the **dark matter models** for galaxy formation is that while baryons are "locked" with photons and while photon diffusion (Silk damping) erases fluctuations on small scales, the dark matter component can still grow fluctuations. After recombination, when the baryons decouple from the photons, they fall back in the potential wells thus created. The details depend on the mass of the dark matter particles.

Hot dark matter models consider the case where the dark matter particle is relativistic at a temperature of 1 keV. This would be the case for a light neutrino of mass in the region of 30 eV. The streaming of the dark matter particle transports energy far and therefore erases density fluctuations up to medium scales. The larger scale structures collapse first and superclusters form before galaxies. This seems to be in contradiction with the observation. N-body computer simulations (e.g. [Frenk et al., 1983]) show that either there is not enough time to form galaxies, or too much structure at large scale is generated in such scenarios.

Much better agreement is obtained with **cold dark matter,** where dark matter particles are nonrelativistic at the time where galaxy size fluctuations begin to grow ([Primack, 1984]). There is no suppression. In order to be compatible with $\Omega = 1$, an additional ansatz is required (for a review see [Primack, 1986]): galaxies have to be "biased" so that they do not trace mass and appear on largest fluctuation peaks. In that case, a fair description is obtained of the age of galaxies, the galaxy correlation functions, the bubbly structure, and some important features of the galactic halos (flat rotation curves, Tully Fisher relation). Problems remain in this scenario at a large scale where fluctuations as given by the Zeldovich inflation spectrum do not seem to be large enough. As a result, cluster correlation functions and the large scale streaming motion claimed by Dressler et al. cannot be reproduced. We should also remark that although some plausibility arguments exist, no real explanation of the "biasing" has been provided.

3.3.2.2 Explosions.

A second type of model relies on explosions to create the present large structure [Ostriker and Cowie, 1981]. However, the amount of energy necessary is staggering and no purely astrophysical mechanism has been found to work. Recently, it has been proposed [Ostriker, Thompson and Witten, 1986] that superconducting string could produce the necessary energy flux.

3.3.3 Relation to Particle Physics

In any case, it seems that galaxy formation requires at least an additional component than ordinary matter, dark matter, explosions, topological singularities, etc. In the dark matter scenarios, a cold dark matter model seems to be preferred over the light neutrino model, but the argument will stay far from being compelling until the remaining difficulties of the model at large scales are solved.

4. Dark Matter

4.1 The Problem of Dark Matter

As we have seen in section 2.3 there is rather strong evidence for dark matter , and there is a general consensus on its existence. On the other hand, there is a heated debate on its nature, and the conclusion is not yet clear.

4.1.1 The debate.

• *Baryonic dark matter.* This view is usually held up by astronomers (e.g.[Bahcall, and Casertano, 1985]. We know that some dark matter has to be baryonic. There is some indication that there is dark matter in the vicinity of the sun from the study of star oscillations across the disk of the galaxy. We also expect dark "ashes" from star evolution: white and brown dwarfs, neutron stars, black holes etc.

In addition, as Bahcall and Casertano remarked, the fact that velocity curves become flat inside the luminous disk implies a conspiracy between dark matter and stellar matter. However, this argument is not as strong as these authors have claimed because such a conspiracy is obtained quite naturally in cold dark matter violent relaxation scenarios [Blumenthal and Primack, 1984].

• *Non-baryonic dark matter.* Mainly cosmologists and particle physicists will argue that dark matter can hardly be baryonic. The strongest argument is based on nucleosynthesis. As we have seen conventional nucleosynthesis indicates that at most

$$\Omega(\text{baryons}) < 0.15$$

(enlarging significantly the range that we quoted in section 3.2.1.2)while at large enough scale

$$\Omega(\text{gravitational}) > 0.15.$$

The basic question is to decide whether this is a marvellous agreement between absolutely independent (and somewhat uncertain) methods or a significant disagreement. The tenants of this school will argue that the trend of the data is in the direction of a disagreement. Since the deuterium is destroyed, the natural trend is to overestimate Ω(baryons) while most of the determinations of Ω(gravitational) are not sensitive to inhomogeneities and are therefore underestimations.

The second argument presented will be that since Ω is so close to 1 and varies very fast if it is different from 1, it is tempting to have it equal to 1 (e.g. using inflation). In that case, if none of the unorthodox scenarios of nucleosynthesis with Ω(baryon)=1 are successful, we need non-baryonic dark matter.

It is also very difficult to prevent baryons from shining or absorbing radiation [Hegyi and Olive]. If dark matter was in the form of intergalactic gas and not ionized, we should observe a strong absorption trough in quasar spectra, and this is not the case[Gunn-Peterson, 1965]. The L_α forest which is observed (see Fig 3.13) can be accounted for with only $\Omega_b \approx 10^{-3}$. If it is ionized, we would then observe strong X-ray emission. Similarly, if the gas was in the galaxy halos, it would radiate and it is difficult to understand why it would have collapsed. The only solution seems to hide baryonic dark matter in condensed objects. It could be in the form of lots of small stars which have not ignited ("jupiters"). This requires a somewhat artificial peak at low mass in stellar mass distribution. To hide it in the remnants of large stars is even less likely. Such a scenario cannot easily explain the presence of low metallicity population II stars in the galactic halo since star death releases material in space which would contaminate these stars and increase their metallicity.

Finally, as we have seen, our present galaxy formation requires an additional component. However, this component does not need to constitute dark matter (e.g. cosmic strings), and the present models with non baryonic dark matter are not entirely successful. This last argument is therefore not very strong.

If the above arguments are correct, dark matter has to be constituted of some kind of non-baryonic primordial objects. Among the various hypotheses, black holes, quark nuggets etc. massive particles seem to be the most natural candidates.

4.1.2 The hypothesis that dark matter is made out of particles.

In fact, the hypothesis that dark matter consists of a non-baryonic particle species is much less vague that could be supposed *a priori* and in most cases, is directly testable. In the following sections we are discussing in what ways it is testable, and it can be argued that proving or disproving this hypothesis is one method to bring clarity to the debate.

•*Hints for particle physics* . There are lots of candidates for dark matter particles. Grand Unified Theories predict massive neutrinos but unfortunately do not give the scale. Supersymmetry which is introduced in order to stabilize the theory of strong interactions, leads to a new family of particles, and the least massive particle should be stable. Depending on the parameters, it could be the photino $\tilde{\gamma}$,the higgsino $\tilde{h}$, the zino $\tilde{z}$ or more likely a mixture of the three, or the scalar neutrino $\tilde{\nu}$. Another class of model [Peccei-Quinn, 1977] propose a new massive particle, the axion, to solve the CP problem in strong interactions. Numerous other models exists and there is therefore no lack of theoretical suggestions.

The experimental limits obtained in the laboratory are providing some constraints. The present neutrino mass upper limits of the ν_e , ν_μ or ν_τ (20eV, 250 keV, 70 MeV) are not excluding the cosmologically interesting region. As far as supersymmetry is concerned, $e^+ e^-$ experiments give a lower limit for the $\tilde{e}$ of 54 GeV/c^2 [Hearty et al., 1987] and the CERN collider experiments constrains the mass of the $\tilde{q}$ or the $\tilde{g}$. Unfortunately, this is not related directly to the mass of the least massive superpartner. Laboratory experiments have excluded the first version of the axion model, but have left open the possibility that it is "invisible" [Dine,Fischler and Srednicki, 1981].

• *Hints from astrophysics and cosmology.* Cosmology and astrophysics give additional hints. For the axion, constraints can be obtained from the theory of star evolution [Dearborn et al., 1986]. If their couplings were too large, helium ignition will be prevented in red giants. The requirements that the energetics of the Large Magellanic Cloud supernova SN1987a are not too much disturbed lead to even better limits ($m_a \leq 9\ 10^{-5}$ eV [Mayle et al 1987], or may be an order of magnitude higher [Deckel and Raffelt, 1988]) not too far from the cosmological constraint that the axion density does not overclose the universe ($m_a \geq 2\ 10^{-5}$ eV).

As we have seen in Section 2.1.1, an important argument (e.g. [Lee and Weinberg 1977]) relates the present density of dark matter particles to the interaction cross section. If this hypothetical particle, which we call δ, not to be tied to any specific model, was once in thermal equilibrium with quarks (q) and leptons (l), presumably through the reactions

$$\delta \bar{\delta} \leftrightarrow q \bar{q}, l \bar{l}$$

then their present density in the universe is a function of their annihilation rate at the time they went out of equilibrium (the "freeze-out" time). The argument is simple: Let us first assume that there is no initial asymmetry and the number of δ's is the same as the number of their antiparticles. If this annihilation rate is much faster than the rate of expansion of the universe, they will all disappear and they cannot constitute the present dark matter. If, on the other hand, the rate is too small, the expansion quickly dilutes the δ's, which soon cannot find an antiparticle to annihilate with, and their abundance will now be too large. Note that the axions are specifically excluded from the foregoing discussion because they have never been in thermal equilibrium with the rest of the matter in the early universe. When applied to the specific case of Dirac massive neutrinos, this argument constrains the mass of the neutrino to be either smaller than $30 eV/c^2$ or larger than $2 GeV/c^2$ if we want Ω_ν to be smaller than 1.

More generally, for δ masses above 300 MeV/c^2, the freeze-out temperature is about a twentieth of the rest mass of the particle, and the annihilation cross section is approximately equal to

$$\sigma v = 10^{-26} / (\Omega_\delta h^2) \ cm^3/s,$$

where Ω_δ is the current ratio of the δ average density to the critical density and h is the Hubble constant in units of 100km/s/Mpc. **This result corresponds to a weak interaction cross section**, as expected for supersymmetric particles, while nowhere in the argument, has any assumption of this kind has been made. This could be a numerical coincidence, or a precious hint that something like supersymmetric particles is responsible for the dark matter.

If we then combine this number with the limits on scalar fermions from accelerators, we find that

$$m_\delta \geq 3 \ GeV/c^2$$

or so. In any case, the argument gives a normalization point to the interaction strength of the model considered. If there is an initial asymmetry between the δ and its antiparticle, similar to what presumably happens for baryons and antibaryons, the above rate is a lower limit, and

$$\sigma v \geq 10^{-26} / (\Omega_\delta h^2) \ cm^3/s.$$

Finally, cosmology provides weak evidence against a low mass dark matter particle (cf. [Primack 1984] and the references therein). We have seen that the scenarios of galaxy formation involving hot dark matter such as light massive neutrinos are not successful. Either the galaxies are formed too late, or there is too much structure. Moreover, too light particles are not expected to accrete on to low mass objects, and there are indications that dwarf spheroidal galaxies contain a fair amount of dark matter. It can even be shown that if the densities observed in these objects are correct, a generalization of the Liouville theorem requires [Faber and Lin, 1983] that

$$m_\delta \geq 500 \text{ eV/c}^2.$$

4.2 Detection Schemes for Light Dark Matter Particles

The hints provided either by particle physics experiments or by astrophysics and cosmology are precious to orient the work of the experimentalist trying to test directly the hypothesis that dark matter is made out of particles. We describe first the attempts to detect axions and light neutrinos.

4.2.1 Detection of axions.

If axions form the dark halo of our galaxy, it is possible to detect them by converting a tiny fraction of the ambient axions into photons in a precisely tuned microwave cavity [Sikivie, 1983,1984,1985] . The axion couples to two photons proportionally to its mass, and if one of these photons is supplied by the magnetic field, the other is emitted into the cavity and excites it. If the magnetic field is large enough and the quality factor Q of the cavity high enough (10^6), the axion may be detectable . The result of the current search at Brookhaven National Laboratory only rules out the presence of an axion halo at 200 times the expected density as shown in Figure 4.1 ([De Panfilis et al 1987] and update from the collaboration circulated on February 16,1988.). The Sikivie group in Florida is preparing a similar experiment. Because of the large number of frequencies to scan and the necessity of changing the technology roughly every octave of frequency, this search will be long and painful. But other schemes such as the process

$$a+e \rightarrow \gamma+e$$

([Krauss et al., 1985], [Slonozewski, 1985], [Sikivie, 1986]) do not appear as sensitive. In principle it is possible to detect axions from the sun, but none have been seen so far [Avignone et al., 1987]. A scheme has been proposed to build an axion "helioscope" which would be sensitive down to mass of 1 eV [Von Bibber et al., 1988]. However, such experiments require the axion to be both emitted, and cannot reach the range interesting for dark matter.

4.2.2 Light neutrinos.

Unfortunately, as we have seen, for the time being, there are no good schemes to detect light massive neutrinos [Langacker, 1983].

4.3 Detection of Weakly Interactive Dark Matter Particles

4.3.1 The general picture.

We have shown in section 4.1.2 that if the particles δ have been in equilibrium with quarks and leptons at high temperature, the annihilation rate is fixed at the time of freeze out and is bounded from below

$$\sigma v \gtrsim 10^{-26} / (\Omega_\delta h^2) \text{ cm}^3/\text{s}.$$

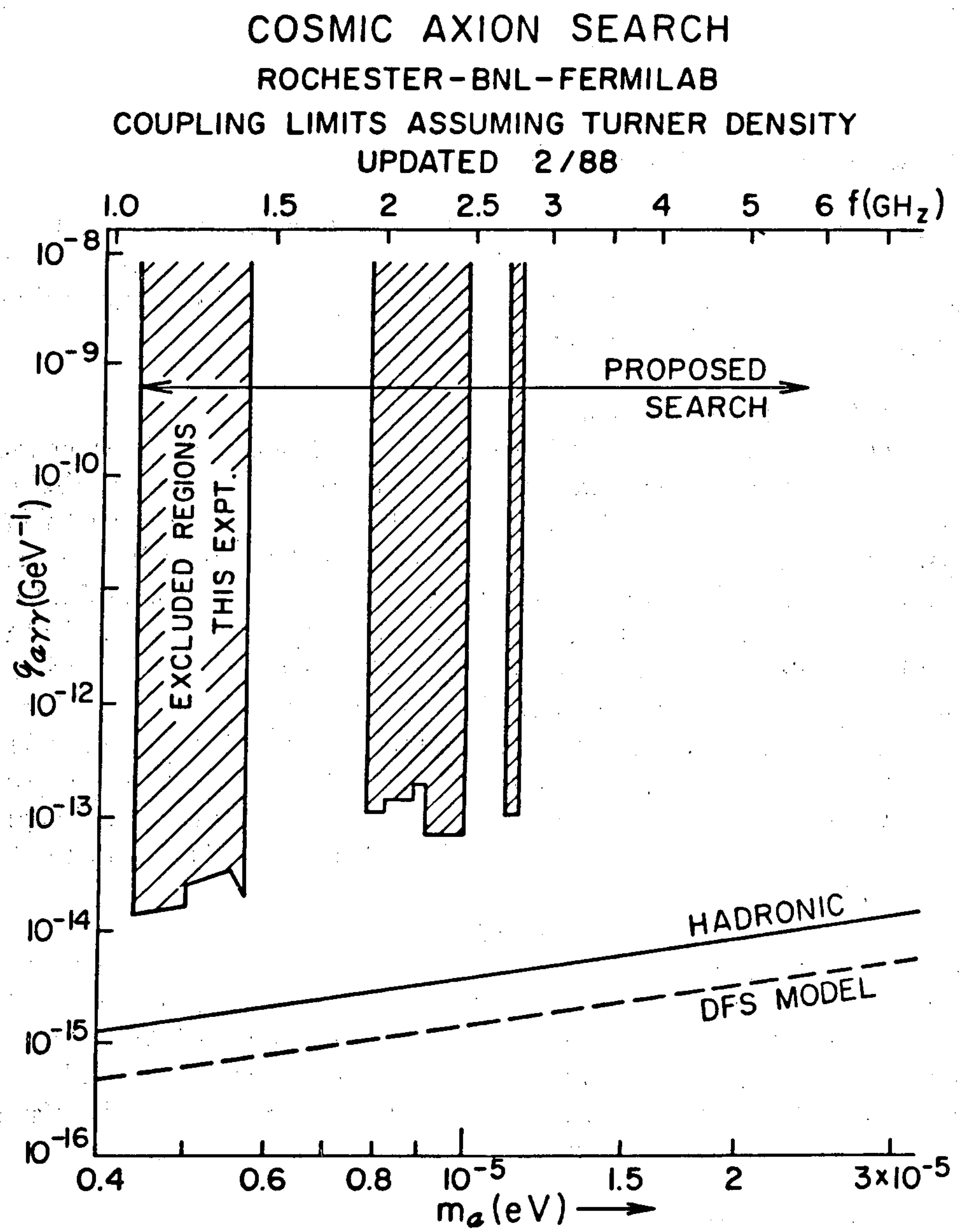


Figure 4.1: The Cosmic Axion Search [De Panfilis et al 1987]

Through the standard methods of field theories, this annihilation cross section at a specific energy can be related to other processes. This is schematized in Figure 4.2. Given the form of the effective Lagrangian (e.g., vectorial, axial vectorial, etc.) it is possible to extrapolate from the freeze-out energy to very low energies and predict the annihilation rate today in the halo of our galaxy. The annihilation products can then be observed in cosmic rays, giving rise to gamma ray lines a low-energy flux of antiprotons and positrons[Silk and Srednicki 1984, Stecker and Rudaz 1987]. As we said in Section 3.2.2.1, the apparent excess of antiproton at low energy has not been confirmed [Ahlen et al. 1987a]. However the uncertainty on the confinement time of antiprotons in the halo of the galaxy does not allow to deduce anything significant on dark matter.

In the opposite direction, it can be extrapolated to high energy, where experiments of the type,

$$e^+e^- \rightarrow \gamma + \text{no detected particle}$$

(ASP, MAC , and CELLO) provide limits on the cross section for $e^+e^- \rightarrow \delta\,\bar{\delta}$.

New experiments at the colliders and at SLC (e.g., the measurement of the Z^o width) will provide vital constraints on particle models. If evidence for supersymmetry were discovered at the Tevatron, an immediate question would be whether the least massive supersymmetric particle could be responsible for the dark matter.

Given the same matrix element, the annihilation cross section can be related by crossing to the elastic cross section of δ on ordinary quarks. If the quark channel represent a signifcant fraction of the annihilations, we expect an elastic cross section

$$\sigma \gtrsim 10^{-38}\text{cm}^2/\,(\Omega_\delta\, h^2).$$

This elastic cross section leads to two consequences:

•The δ can be trapped in the sun and in the planets, modifying their core temperature and leading to enhanced annihilations which may be detectable as a high energy neutrino flux ([Krauss et al., 1985],[Silk et al., 1985]). Ellis et al. [1987b] review the present experimental situation. No powerful constraint is set yet. In the case of the sun, one consequence might be to explain the solar neutrino problem ([Press and Spergel, 1985], [Gilliland et al., 1986]

•The elastic scattering rate of halo δ on ordinary matter in the laboratory may be large enough to be detectable ([Goodman and Witten, 1985]).

We devote the rest of this section to the discussion of this direct detection of dark matter particles.

4.3.2 Dark matter detection through elastic collisions.

4.3.2.1 *Rates and Spectrum of energy deposition.*

Let us first remark that although fairly model independent, the above arguments contain loopholes and it is possible to have a zero elastic cross section at low energy, for instance in the case of pure p-wave scattering (e.g. for AV or VA couplings), or of no coupling to the up and down quarks. This is, however, unlikely and does not occur in existing models.

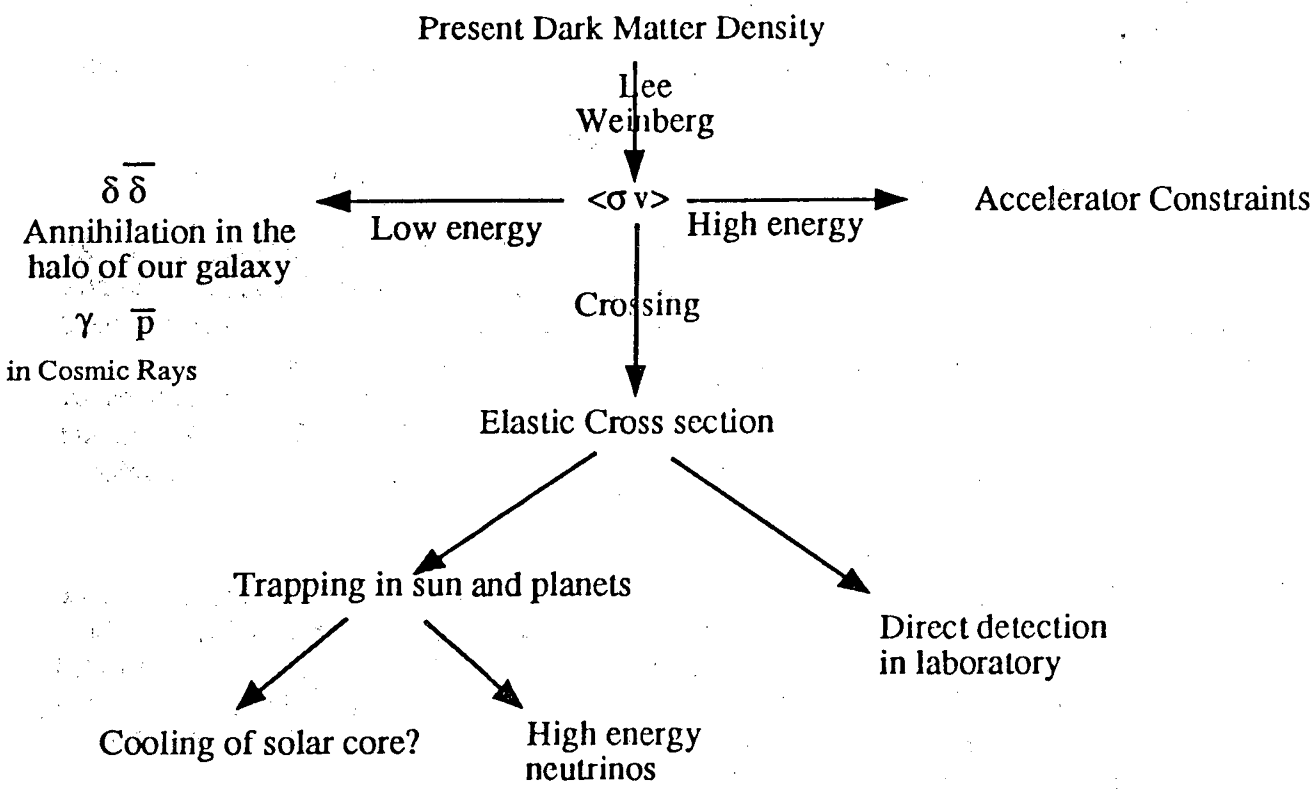


Figure 4.2: The Dark Matter Search

Secondly, let us assume that there is no initial asymmetry between the number of δ's and $\bar{\delta}$'s. In that case, $10^{-38}cm^2/(\Omega_\delta h^2)$ is not a lower limit but the approximate value of the cross section on p or n.

For heavier targets, we have to take into account an additional complication that we omitted for clarity from the previous discussions. The δ's will have velocities of the order of 10^{-3}c and the resulting small momentum transfers correspond to de Broglie wave length much bigger than the size of the nucleus. Therefore, coherent effects are important, as first noted by Goodman and Witten[1985]. For some types of matrix elements (e.g. the vectorial current $\bar{u}\gamma^\mu u$) the coherence adds up the relevant nucleon charges, and cross sections will go essentially as the square of the atomic number of the target nucleus. Unfortunately, for other couplings (such as the axial one $\bar{u}\gamma^\mu\gamma_5 u$, which is the case of standard photinos), it is the spin which is the additive quantum number and the final cross section is proportional to s(s+1) where s is the nuclear spin of the target. The coherent effects are then minimal and there is no elastic scattering on spin zero nuclei which make up the major part of natural silicon and germanium.

For favorable targets (e.g. boron), the event rate would be of the order given by Fig 4.3a. We assumed $\Omega_\delta h^2=1/4$, a root mean square velocity of 300km/s and a halo density of 0.7 10^{-24} g/cm^3.Note that because σ_{el} is roughly constant, the rate goes down as $1/m_\delta$ if m_δ is comparable to the mass of the target.

A second case, which is more favorable, is that of an additive quantum number proportional to A, or the number of protons or neutrons(as for heavy neutrinos). The rate is much bigger (Fig 4.3b) but still decreasing as $1/m_\delta$.

As a last archetype of what could happen, we should consider an initial asymmetry between the number of δ's and their antiparticles. The annihilation cross section can be much bigger than the Lee-Weinberg limit. Figure 4.3c gives the example of a heavy neutrino coupling with the full Z^0 strength. The rates are much bigger and as we will see, already double β experiments put limits on such models of dark matter.

It is also easy to compute the energy deposition and Figure 4.4b shows the predicted energy deposition in eV. These two calculations clearly identify the two major technical challenges of the proposed experiment:

- The need for very low thresholds (100eV) for detectors of a few kilograms and therefore of rms noise less or equal to 20eV.

-The need for very low radioactive background.

We now review these experimental challenges.

4.3.1.2 *Backgrounds and signatures*

We have to distinguish between three background sources:

1. Cosmic rays can be vetoed and are harmful mainly through their indirect effects, spallation products and neutron production by muon capture, which can generate relatively large radioactive backgrounds in the detector. Dark matter search experiments may then have to be located deep underground.

2. The main background will come presumably from the residual radioactivity in the detector elements and in their surroundings. Internal radioactivity of the detectors

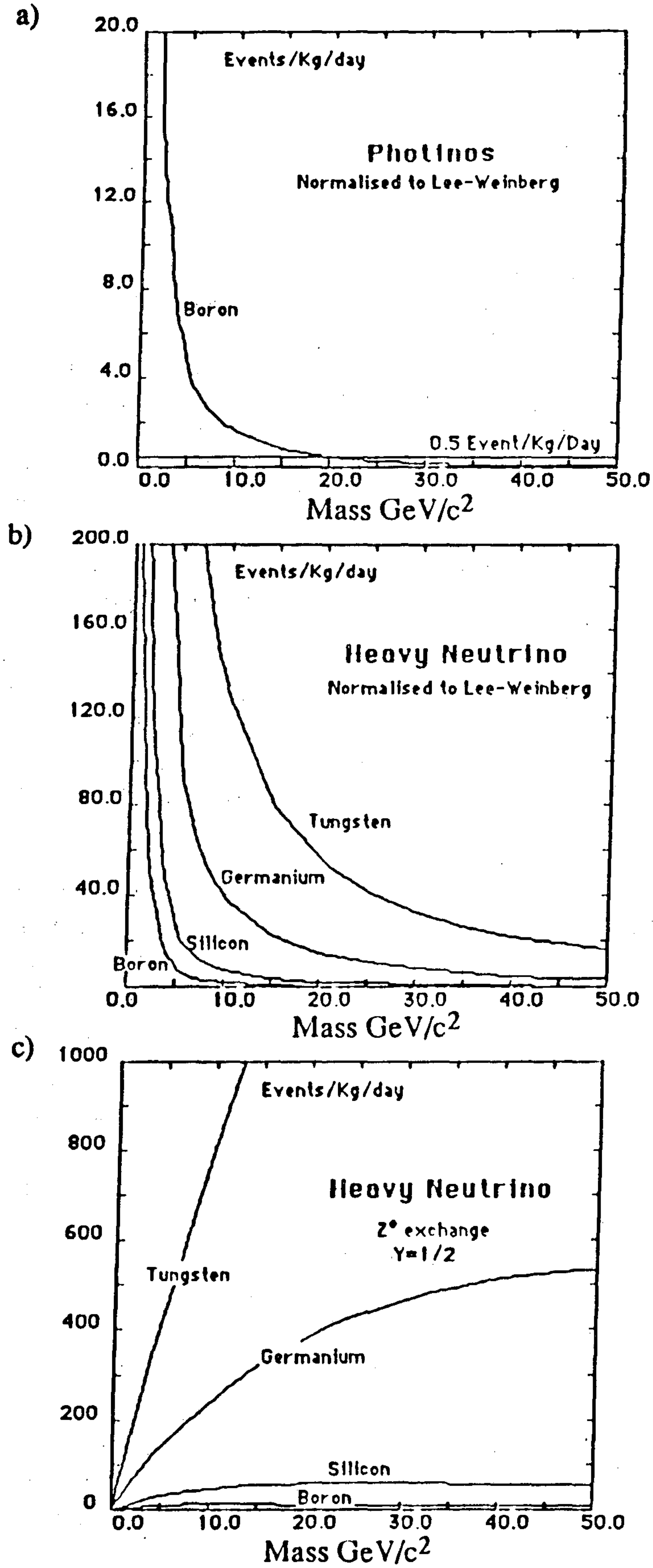


Figure 4.3: Interaction rates on various targets for three archetypes of dark matter models

is expected to be negligible if crystals such as Ge, Si, and maybe B are used.On the other hand, spalliation products such as ^{68}Ge ([Caldwell et al., 1988] or tritium [Martoff, 1987] produced during the time when the detectors elements were exposed to the cosmic radiation at the surface of the earth, may be quite disturbing because the decay energy is in the range of interest.

The main source of background will presumably come from the surroundings (refrigerator, dewar, shield). Short range particles, α's and β's can be eliminated completely in a position-sensitive detector by imposing a fiducial region. Fast neutrons from U and Th decays or μ captures, are potentially dangerous but can be thermalized easily with 40cm of water. Slow neutrons which may create γ rays can be absorbed by a borated shield. By far the most difficult background to deal with is the γ rays from lines, n γ reactions and β bremsstrahlung. They produce a flat Compton background which may be quite difficult to decrease appreciably even with an active veto.

The potentially most dangerous mechanism is the feed-down from high energy to low energies because of defects of the detector: bad collection efficiency, dead regions, edge effects etc...This could produce in some instances an energy spectrum peaked at low energy, like the expected signal. Localization of the interaction is essential to set up fiducial regions in the detector and reject events in region of doubtful sensitivity.

3. Close to the threshold, the upper end of the electronics noise may also simulate a dark matter signal.

These three types of effects are seen in the double β decay experiments of LBL/UCSB [Caldwell et al., 1988] and PNL/USC [Ahlen et al., 1987b] . These two groups have background rates of the order of 0.5 to 1 event/kg/keV/day at 20 keV(Fig 4.5). This level of radioactivity is quite compatible with the expected Compton background, but may also be partially due to dead regions in the detectors. The peaks and rises observed below 20keV are related to specific instrumental problems (radiogenic components in the detector, microphonics), which both groups think can be cured. The two collaborations are currently attempting to decrease their thresholds. This state of the art is quite encouraging since these experiments were not designed for these low energies, and the background performances of these detectors are still improving rapidly showing that the limit of technology is not yet reached.

Should a low energy signal be observed, how can one be sure that it is due to dark matter interactions and not to a misunderstood behavior of the detector?

1. The most unambiguous evidence would be a change in the event rate and the spectrum of energy deposition with the time of the year. This annual modulation is demonstrated in Figure 4.4a .The reason is simple ([Drukier et al., 1986], [Freese et al., 1987]). The halo has not collapsed significantly and is predicted to have a very small overall angular velocity. On the other hand, the sun goes around the galaxy and therefore through the halo at 225km/s and the earth is adding(subtracting) half of its velocity to the sun velocity in the summer(winter). Both the mean energy deposition and the rate should then vary by about $\pm 7\%$. In order to observe such an effect at 3 σ, about 3700 events are needed and therefore very large mass detectors (of the order of

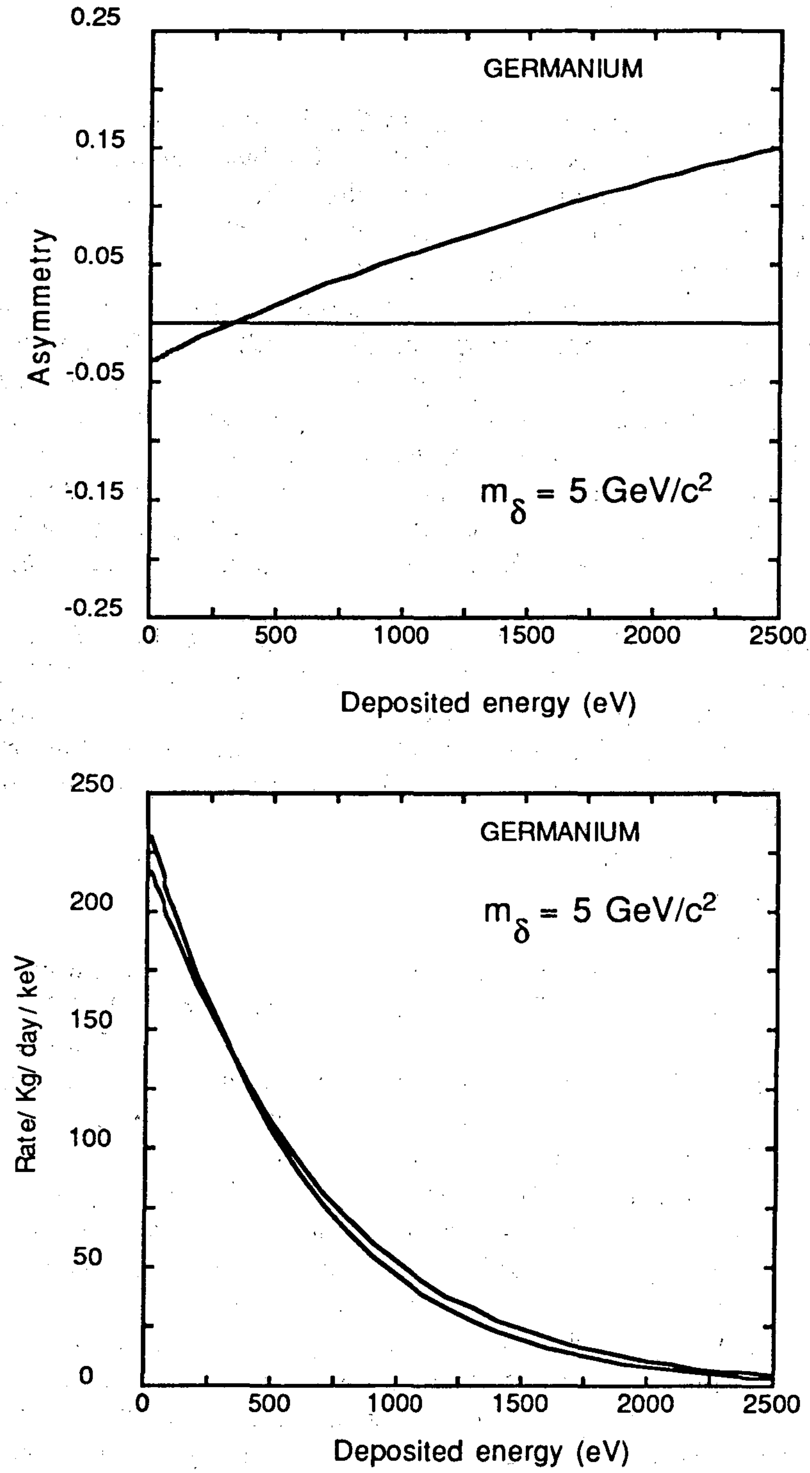


Figure 4.4: Energy deposition in germanium

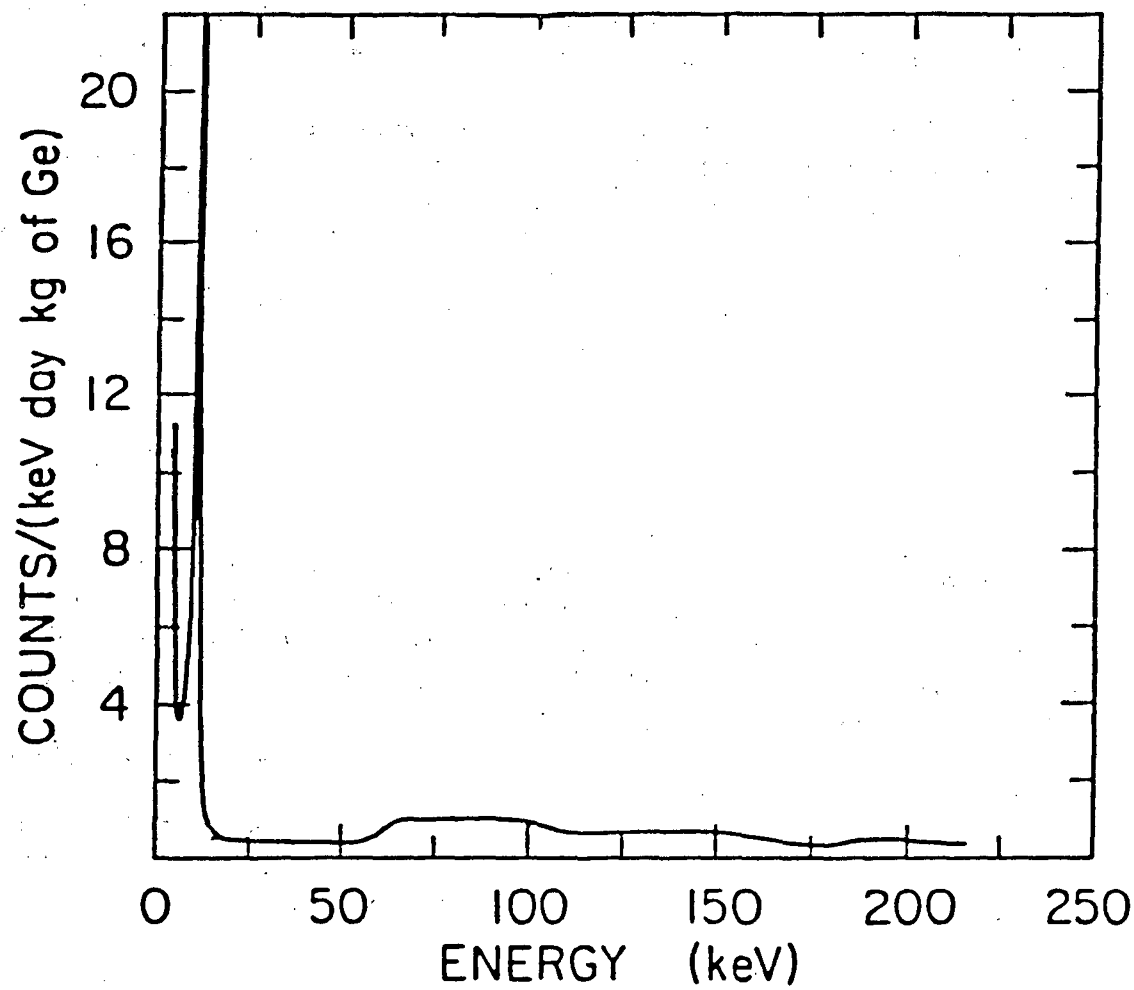


Figure 4.5: Background observed at low energy by the LBL-UC Santa Barbara group in a germanium detector. The background of the USC-PNL group [Ahlen et al. 1987b] is similar.

10 kg) will be required for the unambiguous detection of supersymmetric particles in a reasonable amount of time (two years).

2. The measurement of the direction of the scattered nucleus would be another powerful discrimination tool [Spergel, 1987]. Because of the rotation of the sun inside the halo, dark matter particles will come preferentially from one direction. However this is extremely difficult.

3. The shape of the spectrum is an important datum. To take a simple example, spectra in germanium contaminated by ^{68}Ge show gallium, zinc and copper X ray lines between 8.9 and 10.6 keV which cannot be confused with a potential signal for a detector with appropriate energy resolution. Such a line would be however fatal for a "threshold" detector.

4. Another important handle is the behavior as a function of the material. The average energy deposition is given by

$$\frac{m_\delta^2 M < v^2>}{(m_\delta + M)^2}.$$

Targets made of different materials will effectively allow the measurement of the mass of the δ particle. A neutron induced signal can readily be identified through this mass measurement and Compton energy deposition is independent of M. However, the cross section and the impurity level will vary with the element, and the rate may be too small for some of them, complicating the interpretation.

5. As emphasized above, an important discriminant against background is the spatial distribution of the energy in the detectors.

6. An important signature would be to know that the interaction has occurred on a nucleus and not on an electron as would be the case for β or γ interactions. This, in principle, can be deduced from a simultaneous measurement of ionization and heat.

In conclusion, although we cannot turn off the source nor locate its direction, there is a fair number of tests which could be used to validate a signal! As is usual for difficult experiments, a maximum amount of redundancy has to be included in the design.

4.3.3 Detection methods

4.3.3.1 *Energy deposition mechanism* .

Let us consider a detector made out of gas (e.g. a proportional chamber) or of a solid crystal (e.g. a germanium detector). Dark matter particles are expected to interact elastically with the nucleus in the target, and the energy is deposited in the gas or the crystal by the recoiling nucleus. However, the struck atom is usually not ionized after the primary collision and only transfers part of its energy to ionization in subsequent collisions with other atoms in the medium. This process is not very efficient because of the mass mismatch between the nucleus projectile and the electron target. The resulting pulse height in an ionization detector of a slow nucleus is much smaller than that of an electron of the same kinetic energy. Sadoulet et al [1988b] have reviewed the experimental situation for germanium and silicon. Although there is a clear need for remeasuring the ionization yield at low recoil energy, the current data are consistent with Lindhard's theory [Lindhard 1963] and for instance in germanium a Ge nucleus of 12 keV has the same ionization yield as an electron of 4 keV. Most of the energy is dissipated in excitations, mechanical movements and eventually heat. This explains why even if the quanta of energy involved in the ionization process (electron-ion pairs in a gas with binding energies of typically 10 eV, electron-hole pairs in semiconductor ionization detectors involving energies of the order of 1 eV) seem small compared to the deposited energies (hundreds of eV), the ionization yield will be small.

4.3.3.2 *Gaseous Ionization detectors* .

Proportional chambers are well developed detectors. In a time projection configuration, the imaging capability may be important for background rejection as shown by the experience of double beta experiments using this type of device ([Iqbal et al 1986], [Elliott et al 1986]). At low pressure (e.g.≈ 30 torrs) it should be possible to recognize a β of 10 keV from its range (≈2 cm), and as proposed by Rich and Spiro (private communication 1988) a recoiling nucleus may also leave a "track" and it may be possible to measure its direction. The energy range where this scheme works remains to be experimentally identified. However, this technique faces a number of problems: (a) In spite of the fact that detection of a single electron is technically feasible, the effective threshold may be around a few keV and the resolution will be poor. Thus, proportional chambers may be mostly useful for high m_δ. (b) Another serious problem comes from the background rate in proportional chambers which, without any precautions, is extremely high (≈ 1 count per second and per meter of wire without any precaution) compared to the required level, and it is not clear that radioactivity is the only responsible mechanism. At the level of a few detected electrons metastable states and electron extraction from the walls may play an important role and may be more difficult to control. Nothing is known and development is necessary. (c) Finally, the need to have several kilograms of gas leads to rather voluminous set-ups, and an active veto around the detector may be impractical and expensive.

4.3.3.3 *Solid state Ionization detectors* .

Semi-conductor ionization detectors suffer from the same problem of low energy transfer efficiency to ionization leading to a loss of sensitivity below 10 KeV [Sadoulet et al., 1988b]. For large germanium detectors of mass 1 kilogram, the state of the art noise [Caldwell et al., 1988] is around 450 eV rms which, because of the large number of standard deviations (6 or 7) necessary to overcome the noise, leads to ≈3 keV threshold for electrons. For a recoiling nucleus which ionizes much less, the effective threshold will be ≈12 keV, too high when $m_\delta < 10$ GeV/c^2. However, these detectors exist and provide the only presently available limits. Because of the high thresholds, they are currently only useful to reject models with both large m_δ large interactions rates of the type of our third archetype. For instance, Caldwell et al [1988] have recently improved the limit of Ahlen et al [1987b] for heavy Dirac neutrino, excluding masses down to 13 GeV/c^2. It is possible to decrease these thresholds by going to silicon [Sadoulet et al., 1988b] and using smaller detector elements. This may allow us to test within a year the hypothesis that dark matter trapping is responsible for the deficit of boron solar neutrinos.

A major drawback of this technology is that only two materials can be used, silicon and germanium. It is only in these materials that one can obtain the large region free of carriers (depletion depth) necessary for sizeable detectors of at least several cubic centimeters. Unfortunately, these materials are predominantly spinless and it would be necessary to enrich targets in ^{29}Si or ^{73}Ge to be sensitive to Majorana particles; moreover, at least for the naive quark model axial couplings (e.g Goodman and Witten [1985]), the expected interaction rates for these isotopes with spin are not favorable. If the EMC determination of these couplings is correct, the situation may be better [Ellis et al., 1987b].

4.3.3.4 *Cryogenic detectors* .

In an effort to decrease the energy detection threshold, it seems natural to attempt to use quanta of smaller energies than those involved in ionization processes: Cooper pairs in a superconductor have binding energies of the order of 10^{-3} eV and phonons in a crystal at 100 mK have energies of 10^{-5} eV. If efficient detection schemes using broken Cooper pairs ("quasiparticles") or phonons can be implemented, the small energy of quanta involved will lead to very low thresholds. In order to prevent thermal excitation of the quanta to be detected, such detectors have to be maintained at very low temperature, typically much below one Kelvin, and are thus called cryogenic detectors.

The potential of such methods for dark matter searches and other applications has been recognized for some time ([Cabrera et al., 1985], [Cabrera et al., 1987], [Drukier et al., 1986]. These detectors can be classified into two main categories: detectors of quasiparticle in a superconducting crystal and phonons detectors in a insulator. I have recently reviewed the development situation in [Sadoulet, 1988] which contains an extensive list of references.

1. Quasiparticle Detectors Cooper pairs in a superconductor have binding energies ranging from 4.10^{-5} eV (Ir) to $3 \cdot 10^{-3}$ eV(Nb) and the deposition of even a modest amount of energy in a superconductor leads to a large number of broken Cooper pairs (quasiparticles). Two methods have been proposed to detect them: if the detector element is small enough, the superconductivity will be broken by the energy deposition. This is the idea behind Superheated Superconducting Granules (which dates back from [Bernas, 1967]). The detector is made of many small spheres of a few microns diameter. If they are immersed in a magnetic field, the transition of a single sphere from the superconducting to the normal state can be detected through the suppression of the Meissner effect. The method has been demonstrated, but faces a number of technological problems to achieve a high, uniform sensitivity (see [Sadoulet, 1988] and references therein, and [Pretzl, 1987]) and in spite of the significant progress recently achieved, it may lack the desired redundancy for dark matter searches. Variations of the above method which use superconducting film have been suggested [Neuhauser et al 1987].

A potentially much more sensitive and accurate method of detecting quasiparticles is to make them tunnel through an insulating barrier between two superconductors (SIS junctions). Recently very encouraging results have been obtained by Twerenbold and Zehnder at SIN [1986,1987] and the von Felitzch group in Munich [Krauss et al., 1986a]. .Although photo-lithographic techniques may be used very effectively, outstanding problems still have to be solved in the manufacturing of low leakage and sturdy junctions and the trapping of quasiparticles in a smaller gap superconductor as proposed by Booth [1987] .

2. We now turn to the detection of phonons which represent even smaller quanta of energy. One of the oldest methods for detecting energy is calorimetry, where the absorbed energy ΔE results in a measurable temperature rise ΔT

$$\Delta T = \frac{\Delta E}{C},$$

where C is the heat capacity. If this is done at low enough temperature for C to be very small, the method can be in principle very sensitive and able to detect individual particles [Niinikoski, 1974],[Cabrera, 1985] , [Fiorini and Niinikoski, 1984]). In practice, a small thermistor is fixed to or implanted in a high quality crystal which acts as an absorber and its resistance gives the temperature. This is a detector of **thermalized** phonons and, because of their discrete nature, the detector will experience thermal energy fluctuation. Standard optimum filtering methods [Moseley et al., 1984] taking into account, in addition, the Johnson noise in the thermistor give a statistical uncertainty on the energy

$$\delta E = \xi \sqrt{k T^2 C}$$

where ξ depends on the responsivity dR/dT of the thermistor. At temperatures above 100 mK the best thermistors investigated so far are doped semiconductors leading to $\xi \approx 2$. This thermal limit has nearly been achieved by McCammon et al. ([1987] and references therein) for a small crystal of 10^{-5} gram of Si. The base-line energy fluctuation at 100 m°K was measured to be 4.5 eV r.m.s., a very impressive result.

The above formula indicates the obvious route for extrapolation to larger devices ([Cabrera et al., 1985] , [Fiorini and Niinikoski, 1984]). Since C is proportional to the mass, and for an insulator proportional to $(\frac{T}{T_D})^3$ where T_D is the Debye temperature,

$$\delta E \approx \xi \, T^{5/2} M^{1/2}$$

and a large augmentation in mass can in principle be compensated by a modest decrease in temperature. Extrapolating from the results obtained by McCammon and coworkers, it should be possible, if the thermistor responsivity is maintained at low temperature, to get at 15 m°K less than 10eV rms noise for crystals of 320g of boron, 200g of silicon, 100g of germanium! But 15m°K is relatively easily obtained by modern dilution refrigerators and cooling down a few kilograms is technically feasible. This line of thought has led many groups to develop bolometric detectors. However, there are still significant problems with enlarging calorimeters operated at low temperature.

It should be noted, however, that very likely the picture outlined above is fundamentally incorrect. At low temperatures, the absence of thermal phonons will prevent phonons originating from the interaction from thermalizing efficiently, and the energy of a significant number of them is expected to stay relatively high, around a few milli-electron-volts [Maris, 1986], [Neuhauser et al., 1986] . Such phonons will be ballistic, that is, will travel in straight lines for relatively long distances and bounce off surfaces, and the concepts of temperature and heat capacity are inadequate to describe such a system. These effects are well known to solid state physicists for large energy depositions, and have been recently unambiguously demonstrated in the context of particle detection (Peterreins [1987]). Instead of being a nuisance, ballistic phonons may ease the detection job. Instead of the heat capacity of the global crystal, what counts now is the efficiency of energy collection and the crystal acts as a phonon guide. Because of this fast propagation, these phonons may allow timing on several faces of the crystal. This requires a fast rise time of the sensor signal. In addition, the fact that energy propagates in preferred directions ("focussing") may allow the localization of the event within one millimeter by pulse division between several sensors.These ideas are quite attractive, especially in the context of dark matter detector where large volumes are necessary. However, it remains to be proven that such detectors can be implemented. Two kinds of sensors are being studied, highly doped semiconductor thermistors which should be sensitive to high energy phonons (e.g., [Wang et al., 1988]) and superconducting film and tunnel junctions [Neuhauser et al., 1986].

An interesting variant of this method which uses protons has been suggested for liquid ^{4}He [Lanou 1987].

4.3.3.5 *Simultaneous measurement of ionization and heat.*

The simultaneous detection in a cryogenic detector of the ionization and phonon components, in principle, allow us to give an unambiguous signature for an elastic scattering off a nucleus ([Krauss et al., 1986b], [Sadoulet, 1987b]). In that case, the ratio of the ionization energy to the total energy released will be 2 to 4 times smaller than for an electron interaction involving the same deposited energy, and only a rough measurement of the ionization yield may be necessary. This attractive method requires the combination of two difficult techniques at very low temperature. It may be, however, the real justification for the development of cryogenic detectors.

4.3.4 Outlook

In the short run, it is likely that the main limits on the existence of massive dark matter particles will be obtained through improvement in the threshold of "conventional" solid state detectors, and may be, with low pressure proportional chambers, the two technologies which are well developed.

In the long term, cryogenic detectors may become the instruments of choice, if they can be made to work for large masses, because of the low thresholds, the variety of materials they should allow and may be the signature of a nuclear interaction. These detectors face, however, a long development because of the complexity of the solid state physics and materials technology which has to be mastered, and the inconvenience of ultra low temperature refrigerators. Note that these detectors have also very interesting applications in particle physics [Cabrera et al., 1987] and in other fields [Sadoulet, 1988c]. So their development is well motivated and they provide another example of the experimental connections between particle physics and cosmology!

More generally, in spite of the fact that these searches for dark matter particles will take a long time and a lot of effort, they are very much worthwhile. Dark matter is one of the most central scientific problem of our times. It could be considered a scandal that we do not understand the nature of what constitutes more than 90% of the universe. And if indeed, we could prove that the dark matter is non-baryonic, this would be the ultimate Copernician revolution. Not only are we not at the center of the universe, but we are not made of the "stuff" which the universe is made of.

5. Conclusion

In this rapid survey, we have attempted to outline the many areas of contact between particle physics and cosmology.

In recent years, cosmology has made significant advances and is now a highly promising scientific field. Not only have the theoretical and phenomenological links to traditional astrophysics and particle physics been strengthened in the past decade, but also the number of groups getting into "experimental" cosmology has increased, and there has been a significant influx of scientists to the field .

Particle physics depends almost totally on cosmology for information about very high temperatures, and some of the most central puzzles in cosmology may have their solutions in particle physics. They share very fundamental scientific goals which they attack in a complementary way. Traditional accelerator experiments survey systematically a limited region of energy; non-accelerator experiments attempt by very precise measurements to check at low energy the consequences of the physics at very high energy and cosmology provides hints of the global nature of this physics.

Taking a slightly wider view, we are witnessing the emergence of a new field: **Particle Astrophysics**. It includes cosmology, gravitational physics and high energy astrophysics and lies at the convergence point between particle physics and astrophysics (Fig 5.1). The growing transfer of technology and experimental methods from one field to another can only be beneficial, and from the point of view of a cost-to-benefit analysis, particle astrophysics is very attractive, allowing in many cases small teams to make fundamental contributions. The progress of the field depends critically on the development of sophisticated detectors, and despite the fundamental nature of this new science, it could have significant benefits for other scientific fields and have a large technological spin-offs. Finally, because of the appeal of the questions tackled, the field attracts many graduate students and fascinates the public at large.

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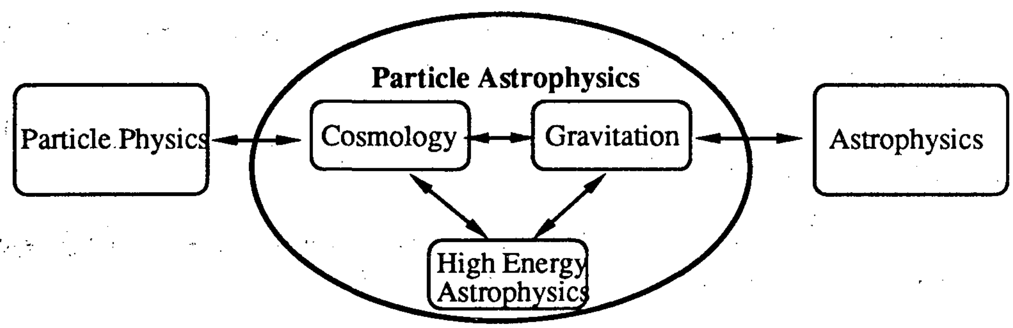

Figure 5.1 : A new field Particle Astrophysics

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UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720