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ASTROPARTICLE PHYSICS - A Personal Outlook

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ABSTRACT

At the request of the organizers, this talk surveys some of the hot topics discussed at this meeting, giving my *subjective views* on them. Subjects covered include the present age and Hubble expansion rate of the Universe - *inflation theorists need not yet abandon* $\Omega = 1$, theories of structure formation in the light of COBE and other data - *my favourite is a flat spectrum of initial perturbations subsequently amplified by mixed hot and cold dark matter*, neutrino masses and oscillations - *the only experimental indication I take seriously at the moment is the persistent solar neutrino deficit*, the lightest supersymmetric particle - *which may behave differently if conventional assumptions are relaxed*, and the axion - *much of the window between limits from SN 1987a and cosmology will be explored in an ongoing experiment.* Finally, I present a chronology of some possible interesting future experiments.

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1 Introduction

This lecture is concerned with the three questions raised by the Mayor of Toledo at the reception held during this conference:

¿De dónde venimos? Namely, what is the origin of the structure we see in the Universe?
¿Qué somos? Namely, what is the nature of the Dark Matter around us? and
¿Adónde vamos? Namely, what lies beyond the Standard Model?

2 On the Origin of Structure in the Universe

2.1 How Much Dark Matter?

Naturalness and inflation [1] suggest that the density averaged over the universe as a whole should be very close to the critical density, which marks the boundary between a universe that expands forever and one which eventually collapses, i.e. $\Omega \equiv \rho/\rho_c \simeq 1$. On the other hand, the matter we can see shining in stars, in dust, etc. amounts only to $\Omega \simeq 0.003$ to 0.01 [2], as seen in fig. 1.

The commonly-agreed concordance between big bang nucleosynthesis calculations [5] and the observed abundances of light elements suggests that $\Omega_{baryons} \lesssim 0.1$, as also seen in fig. 1. This concordance has recently been questioned, and it has even been suggested that big bang nucleosynthesis may be in crisis [3]. I do not share this view (see also [4],[5][6]). For one thing, I have long believed that all the systematic errors in the relevant physical quantities were not taken fully into account [7],[8],[9]. For another, I have less faith than some [3] in models of the chemical evolution of the galaxy (see also [5, 6]). Finally, I would prefer not to treat systematic errors as "top hats", as was done in [3], which cuts off the tails of the distributions, and leads to estimates of confidence levels that are difficult to interpret.

Also shown in fig. 1 is an estimate of $\Omega_{baryons}$ from X-ray observations of rich clusters [10], which tends to lie somewhat higher than the big bang nucleosynthesis estimate. However, the original rich cluster estimate was made in a pure cold dark matter model. It is modified in the type of mixed dark matter model to be discussed later [11], and could also be reduced if the clusters are not virialized. In any case, the possible discrepancy in fig. 1 is not very significant for values of H_0 in much of the favoured range discussed below.

The big bang nucleosynthesis estimate of $\Omega_{baryons}$ is comparable to the amount Ω_{halo} of matter that is suggested by observations of rotation curves [12] and the virial theorem to be contained in galactic haloes: $\Omega_{halo} \simeq 0.1$. Mathematically, the galactic haloes could in principle be purely baryonic, although they seem unlikely to be made out of gas, dust or "snow balls" [13]. As you know, there has recently been considerable interest in the possibility that haloes might be largely composed of "brown dwarfs" weighing less than $\simeq 1/10$ of the solar mass. The searches for such "failed stars" in our galactic halo via microlensing [14] of stars in the Large Magellanic Cloud in fact indicate [15] that only a fraction

$$f = 0.20^{+0.33}_{-0.14}\,[\text{MACHO}],\ < 0.5\,[\text{EROS}] \tag{1}$$

is composed of brown dwarfs [16],[17], assuming a simple spherical halo model, which would have a local density

$$\rho_{halo} = 0.3\ \text{GeV/cm}^3 \times 1.5^{0\pm 1} \tag{2}$$

The possibility has recently been reconsidered [18] that our halo is in fact significantly flattened, in which case the estimate (2) of the local density should be increased, and the brown dwarf fraction (1) correspondingly decreased. To be on the conservative side when discussing cold dark matter detection rates later in this talk, I will retain the spherical halo estimate (2).

It should be emphasized that, in the standard theory of structure formation reviewed in the next section, our halo *must* contain a large fraction of non-baryonic cold dark matter [19]. On the other hand, conventional infall models of galaxy formation suggest [20] that our halo is unlikely to be composed mainly of massive neutrinos, at least if their mass is chosen to yield $\Omega_{hot} \simeq 0.2$ as suggested in the next section. These observations follow from the need for cold dark matter to boost galaxy formation, whereas the phase-space density of neutrinos is severely restricted [21]. The dominant component of our galactic halo (2) should therefore be some form of cold dark matter.

Before addressing in more detail the nature of the non-baryonic dark matter, I will first comment on the age and Hubble expansion rate of the Universe, which have recently been the subject of some controversy [22]. Globular clusters seem to be at least 14 ± 3 Gyr old, and nucleocosmochronology suggests an age of 13 ± 3 Gyr [2]. Taken together, these constraints suggest that the Universe cannot be younger than 10 Gyr, and that a greater age would be more comfortable. The question is whether such an age is compatible with current estimates of the Hubble constant H_0 km/sec/Mpc, some of which are listed in Table 1. These may be combined [23] to yield the estimate

$$H_0 = 66 \pm 13 \tag{3}$$

where the central value is statistical, and the error is supposed to be realistic, particularly in view of the fact that any determination of H_0 involves the combination of many steps. For example, there has recently been a second determination based on Hubble Space Telescope observations [24] of Cepheid variables (which have their own intrinsic uncertainties), which must rely on other rungs in the cosmic distance ladder, such as the distance to the Large Magellanic Cloud, as well the extrapolation from Leo to the Coma cluster. Errors in all of these must be combined in order to arrive at the total uncertainty in H_0.

55 ± 8	Type IA supernovae	(Sandage et al.)
67 ± 7		(Riess et al.)
73 ± 13	Type II supernovae	(Schmidt et al.)
60 ± 10	Gravitational Lensing	(Lehar et al.)
70 ± 25		(Wilkinson et al.)
55 ± 17	Sunyaev – Zeldovich	(Birkinshaw et al.)
80 ± 17	Virgo Cepheids	(Freedman et al.)
69 ± 8	Leo I Cepheids	(Tanvir et al.)

Table 1 - Recent determinations of H_0 (in km/s/Mpc)

The range (3) is shown on the vertical axis of fig. 1, where we see that there is no incompatibility between the age of the Universe being 10 Gyr old and $\Omega = 1$ as wanted by inflation [1], as long as H_0 is in the lower part of the range (3). Therefore, I see no immediate need for inflation theorists to explore models in which Ω is significantly below unity [25], which do not, in any case, look very natural to me. Assuming that indeed $\Omega \simeq 1$, at least 90% of the matter in the Universe must be unseen non-baryonic dark matter.

2.2 Hot or Cold Dark Matter?

In addition to the above arguments based on contributions to Ω, non-baryonic dark matter is required for structure formation, because it enables density perturbations to grow via gravitational instability even before recombination, while perturbations in the conventional baryonic matter density are still restrained by the coupling to radiation. Which structures form when depends whether the non-baryonic dark matter was relativistic or non-relativistic at the cosmological epoch when structures such as galaxies and clusters began to form, which is the distinction between "hot" and "cold". Whether you favour hot or cold dark matter depends on your favourite theory of structure formation. If you believe that its origins lie in an approximately scale-invariant Gaussian random field of density perturbations, as suggested by inflationary models [26], then you should favour cold dark matter. This is because it enables perturbations to grow on all distance scales, whereas relativistic hot dark matter escapes from small-scale perturbations, whose growth via gravitational instabilities is thereby stunted [27]. Thus galaxies form later in a scenario based on Gaussian fluctuations and hot dark matter than they would in a scenario with cold dark matter, indeed, too late. For this reason, the combination of Gaussian perturbations with cold dark matter has come to be regarded as the "standard model" of structure formation. However, if you believe that structures originated from seeds such as cosmic strings [28], then you should prefer hot dark matter, because cold dark matter would then give too much power in perturbations on small distance scales.

Fig. 2 shows a compilation [29] of data on the power spectrum of astrophysical perturbations, as obtained from earlier COBE [30] and other observations of the cosmic microwave background radiation, and direct astronomical observations of galaxies and clusters. Subsequent to this compilation, data from the full 4 years of COBE DMR data have been made available [31]. These show no indications of non-Gaussian correlations [32], and are consistent with a scale-invariant spectrum [33], in agreement with inflationary models. However, models of structure formation based on cosmic strings would not predict non-Gaussian correlations observable in the present data, and would also yield a flat spectrum. Therefore, such models cannot yet be excluded, though I will not address them further in this talk [28].

The overall normalization of the perturbation spectrum is of interest to inflation theorists, since it specifies the scale of the inflationary potential in field-theoretical models. Parametrizing this by $V = \mu^4 \bar{V}$, where $\bar{V}$ is a dimensionless function of order unity, one finds that

$$\delta\rho/\rho \simeq \mu^2 G_N \tag{4}$$

Taking the normalization of $\delta\rho/\rho$ from the COBE data [30], one may estimate

$$\mu \simeq 10^{16} GeV \tag{5}$$

which is eerily close to the usual estimate [34] of the scale of supersymmetric grand unification. A related quantity of physical interest is the mass of the quantum of the inflationary field, the inflaton:

$$m_{infl} \simeq 10^{13} GeV \tag{6}$$

which may have implications for baryogenesis and neutrino masses, as discussed later. The scale (5) also determines the reheating temperature at the end of the inflationary epoch, which is of relevance to calculations of the potentially-dengerous relic gravitino abundance [35] in supersymmetric models.

The perturbations dicovered by COBE and experiments may in general be a combination of density (scalar) and gravity wave (tensor) fluctuations $A_{S,G}$, whose ratio depends on details of the inflationary potential:

$$A_S/A_G = \sqrt{4\pi G_N} H/|H'| \tag{7}$$

The ratio (7) exceeds unity if the inflaton field accelerates during inflation, as expected, but the COBE experiment is sensitive to the combination $\simeq 25\ A_G^2/2\ A_S^2$, so gravity waves could be important. Nevertheless, one usually assumes, as above, that scalar perturbations are dominant. A goal for future experiments is to disentangle the scalar and tensor contributions, and to measure the possible 'tilts' of their spectra:

$$n_{S,G} \equiv 1\ -\ (d/d\,ln\,\lambda)A_{S,G} \tag{8}$$

so as to map out the inflaton potential [36].

Fig. 3 compiles data on fluctuations in the cosmic microwave background radiation [37], and provides the basis for a discussion of the issues arising in these future measurements. The original COBE measurements at scales larger than the horizon at recombination are conventionally interpreted as due to the Sachs-Wolfe effect:

$$\delta T/T \simeq -\delta\phi/3 \tag{9}$$

where ϕ is the gravitational potential. There are by now many detections in the region within the horizon at recombination, where the first Döppler peak is expected to appear, with

$$\delta T/T \simeq v, \tag{10}$$

where v is the baryonic matter velocity. The existence of this first Döppler peak cannot yet be regarded as confirmed, but the outlook for models which do not predict it does not look very bright [38]. The COBE data alone yield an error of ±0.3 on the effective spectral index [33], whereas a combined fit to the available data indicates [39] the following range:

$$n \simeq 1.1 \pm 0.1 \tag{11}$$

Cosmic string models [28] are consistent with this and the apparently Gaussian nature of the fluctuations seen at large scales: a key test will be whether they still look Gaussian in the region of the first Döppler peak. Within the standard model of structure formation, the height of the this peak will be a measure of $\Omega_{baryons}$, and its location on the horizontal axis is sensitive to the total Ω: $l \sim 220/\sqrt{\Omega}$. Cold dark matter and related models predict further Döppler peaks, which can only be resolved with a higher-resolution experiment. Recall that the COBE resolution of a few degrees includes a comoving volume that will later contain several hundred clusters of galaxies: future experiments are aiming at resolutions of a fraction of a degree. The drop-off in fig. 3 visible at still smaller scales is due to the thickness of the last scattering surface.

The solid line which does not quite pass through all the points in fig. 2 is one calculated in the above-mentioned standard model of Gaussian scalar fluctuations and cold dark matter, assuming there is no tilt in the initial spectrum. Crucial tests of this and other models of structure formation will be provided by future measurements of the cosmic microwave background radiation and of larger-scale structure in the region of the bump in fig. 2, e.g., by the proposed

COBRAS/SAMBA satellite and the ongoing Sloan Digital Sky Survey. The present discrepancies from this curve indicate that there is less perturbation power at small distances than would be expected in this theory, compared with the COBE normalization at large distance scales.

This and other observations have suggested that it may be necessary to modify the pure cold dark matter model. Several suggestions have been offered, including a non-zero cosmological constant and a tilt in the spectrum of Gaussian perturbations away from scale invariance. However, the preferred scenario seems to be an admixture of hot dark matter together with the cold, resulting in the following cocktail recipe for the Universe [40]:

$$\Omega_{cold} \simeq 0.7\,, \quad \Omega_{hot} \simeq 0.2, \quad \Omega_{baryons} \lesssim 0.1 \tag{12}$$

The way in which this scenario works is illustrated in fig. 4. Hot dark matter alone would give a spectrum of perturbations that dies out at small scales, whereas hot dark matter does not. Combining the two, one can reconcile the relatively high COBE normalisation at large scales with the relatively small perturbations seen at small scales.

Fig. 5, which is adapted from [41], illustrates the performances of various dark matter models of structure formation, as compared to measurements on various different distance scales. We see that a pure cold dark matter model has severe problems at smaller scales. These may be somewhat alleviated by the introduction of biasing or a cosmological constant Λ, but there are still problems on galactic scales. A mixed dark matter model (12) with the hot dark matter provided by a single neutrino species of mass $\simeq$ 5 eV works quite well, except possibly for the density of clusters. The authors of [41] prefer for this reason a model with two neutrino species each weighing $\simeq$ 2.5 eV, which is also motivated by their interpretation of the LSND experiment [42]. However, I do not see the necessity for this embellishment of the mixed dark matter model, and remain to be convinced by the LSND data, as I discuss in the next section.

3 On the Nature of the Dark Matter

3.1 Neutrino Masses and Oscillations

Theorists have been saying for years that there is no fundamental reason why neutrino masses should vanish, and oscillations are inevitable if they are non-zero. However, for the time being, we only have the following upper limits on neutrino masses:

$$m_{\nu_e} < 4.5\,\mathrm{eV},\ m_{\nu_\mu} < 160\,\mathrm{KeV},\ m_{\nu_\tau} < 23\,\mathrm{MeV} \tag{13}$$

Cosmology in the form of big bang nucleosynthesis is close to strengthening the above upper limit on m_{ν_τ} to a fraction of an MeV [43], if the ν_τ is a long-lived Majorana particle.

There are many models for neutrino masses [44], which I will not discuss here. Instead, I will be inspired by the simplest see-saw mass matrix [45]:

$$(\nu_L, \bar{\nu}_R) \begin{pmatrix} m_M & m_D \\ m_D & M_M \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \tag{14}$$

where m_M and M_M are Majorana masses for the left- and right-handed neutrinos $\nu_{L,R}$, respectively, and m_D is a Dirac mass coupling ν_L and ν_R. All of $m_{M,D}, M_M$ are to be understood as matrices in flavour space. We expect M_M to be comparable (on a logarithmic scale) with the grand unification scale M_X, and the Dirac masses m_D to be comparable with the corresponding charge 2/3 quark masses $m_{2/3}$. We know from the experimental absence to date of neutrinoless double-β decay that

$$< m_{\nu_e} >_M \quad \lesssim \; 1/2 \text{ eV} \tag{15}$$

and diagonalization of (14) naturally suggests that

$$m_\nu \; \simeq \; m_D^2/M_M \tag{16}$$

for the known light neutrinos. If indeed $m_D \simeq m_{2/3}$, we may expect that for the three light neutrino flavours

$$m_{\nu_i} \simeq \frac{m^2_{2/3_i}}{M_{M_i}} \tag{17}$$

The heavy Majorana masses M_{M_i} are not necessarily universal, but (17) nevertheless suggests that

$$m_{\nu_e} << m_{\nu_\mu} << m_{\nu_\tau} \tag{18}$$

and the ν_τ mass could be in the range of interest to hot or mixed dark matter models if $M_{M_3} \simeq 10^{12}$ GeV.

To my mind, the most serious evidence for neutrino oscillations, and, by extension, for neutrino masses, is the persistent and recurrent solar neutrino deficit seen by four experiments [46], as compared with standard solar model calculations [47]. There was much heated debate at this meeting on the interpretation of these data [48], and on the uncertainties in the theoretical calculations. It seems to me that the crispest way of posing the dilemma is to plot the data in more than one dimension, for example in the two-dimensional representation of fig. 6 [49]. Taken at face value, all the experiments indicate a strong suppression of the Beryllium neutrinos, and a weaker suppression of the Boron neutrinos, compared with the predictions of [47]. This major feature is very difficult to explain in plausible modifications of this standard solar model, which tend to suppress the Boron neutrinos more than the Beryllium neutrinos, as also seen in fig. 6 [49]. Note in particular the dotted curve which corresponds a simply changing the central temperature of the Sun, as happens in low-opacity and simple mixing models. These cannot explain the data, if the latter are taken at face value. Some models which use different input nuclear cross sections [50] even fall below the low-temperature curve: they may explain the Boron deficit, but *a fortiori* they cannot explain simultaneously the Beryllium deficit, as seen clearly in this two-dimensional plot.

As we heard at this meeting [51], the helioseismologists are now making it very difficult even to reduce the central temperature of the Sun. They are able to verify that the sound speed, which is closely related to the temperature, agrees with the standard solar model to within about 1% down to about 5% of the solar radius. Indeed, the helioseismological talk here [51] included revised estimates of the Boron neutrino flux that were *even higher* than the standard solar model. One other possibility that was mentioned at this meeting was that slow convection could alter significantly the standard solar model predictions [52], but this remains to be demonstrated.

Two major new solar neutrino experiments will start taking data next year, namely Superkamiokande [53] and SNO [54]. The former will provide mind-boggling statistics for solar neutrinos, and for any supernova explosion inside our galaxy. The SNO experiment should be able to tell us whether the Beryllium neutrinos are really absent, or "merely" converted into another ν species, thanks to its aim of measuring both the charged- and neutral-current reactions. Many other solar neutrino experiments are on the drawing boards, including Borexino [55] which is also aimed at the Beryllium neutrinos, as well as HELLAZ [56] and HERON [57].

In my view, there *is* a solar neutrino problem, and novel neutrino physics is the most likely explanation, though certainly not yet established. The above-mentioned experiments may resolve the issue. To make a useful theoretical contribution to the continuing debate, I believe it is insufficient to point to some possible modification of the standard solar model without giving good reason to think that (a) it is consistent with *all* the constraints, including, e.g., those from helioseismology, and (b) it modifies the standard solar model predictions outside the quoted errors. To support any such claim, a valuable contribution should include some solid calculations.

If one does indeed take the solar neutrino deficit as an indication for novel neutrino physics, I am inclined to plump for mass mixing and oscillations rather than magnetic effects [58] (the required magnetic dipole moment seems very high, and I am not impressed by claims of a time dependence in the Homestake data), and prefer the MSW scenario to vacuum oscillations. In view of the prejudice (18), the most likely interpretation then becomes $\nu_e \rightarrow \nu_\mu$ oscillations, with

$$\Delta m^2 \simeq 10^{-5}\,\mathrm{eV}^2\,\mathrm{and}\, sin^2\theta \simeq 10^{-2} \tag{19}$$

provided by

$$m_{\nu_e} << m_{\nu_\mu} \simeq 10^{-3}\,\mathrm{eV} \tag{20}$$

Scaling m_{ν_μ} (20) up by m_t^2/m_c^2 (17), it is easy to imagine that there could be ν_τ dark matter with a mass around 10 eV. One of the most appealing aspects of this scenario is that it may soon be tested in accelerator $\nu_\mu \rightarrow \nu_\tau$ oscillation experiments, since it suggests that $\delta m^2 \simeq 100$ eV^2, and many models for ν masses further suggest a value of $sin^2\theta$ in the range accessible to the CHORUS [59] and NOMAD [60] experiments that are already taking data at CERN, or the planned COSMOS experiment [61] at Fermilab. If needed, increased sensitivity could in principle be attained with a next-generation detector [62].

This interpretation of the solar neutrino data also offers the possibility of an appealing scenario for cosmological baryogenesis [63]. After an inflationary epoch at the scale (5), the inflaton with mass (6) can decay into a massive ν_R state, which then decays out of thermal euilibrium. Diagrams of the type shown in fig. 7 may produce a lepton asymmetry [63],[64]

$$\epsilon = \frac{1}{2\pi(\lambda_L^+\lambda_L)_{ii}} \sum_j (\mathrm{lm}\left[(\lambda_L^+\lambda_L)_{ij}\right]^2) f\left(\frac{M_j^2}{M_i^2}\right) \tag{21}$$

where the λ_L are Yukawa couplings, (i,j) are generation indices, and f is a kinematic function of the ν_{R_i} masses M_i. The asymmetry ϵ is subject to subsequent reprocessing by electroweak sphalerons [65] to produce a baryon asymmetry. This scenario can be valid only if $m_{infl} > m_{\nu_R}$, which imposes a lower limit on the inflation scale (5) and/or a lower limit on the light neutrino mass (17).

In the longer term, ideas are afoot for long baseline ν oscillation experiments between Fermilab and Soudan II, between KEK and Superkamiokande, and between CERN and either the Gran Sasso laboratory and/or the NESTOR underwater detector now under construction [66]. In the case of the possible CERN-based experiments, the ν beam would be produced by a 120 GeV proton beam extracted from the SPS and directed along the planned transfer line to the LHC. This type of experiment would address principally the question of possible atmospheric ν oscillations raised by the Kamiokande experiment [67]. I am not yet convinced of the reality of this effect, and would like to see it confirmed with convincing statistics by a large experiment using a completely different experimental approach, as well as in Superkamiokande. Just for fun, let me mention the idea for what would surely be the ultimate earth-based ν oscillation experiment, namely to send a beam from CERN or Fermilab to Superkamiokande. This would involve digging a beam and decay tunnel inclined downwards at some 40 degrees, which would certainly amuse the civil engineers!

There is one final possibility of novel neutrino physics that I would like to address, namely the suggestion that neutrino oscillations may provide an explanation of the LSND data [42]. as you see in fig. 8, there is not much room for this explanation, given the constraints imposed by other experiments. Here again, I would like to see confirmation from a different experiment, as well as more data from the LSND experiment itself, particularly in view of the fact that there is no consensus yet on its interpretation [68]. Fortunately, we may not have to wait long, as the LSND group promises us more information in the near future [41], and reactor experiments should soon be able to explore the region of interest.

3.2 Lightest Supersymmetric Particle

My favourite candidate for cold dark matter [70], the lightest supersymmetric particle (LSP) is expected to be stable in many models, and hence present in the Universe as a cosmological relic from the Big Bang. This is because supersymmetric particles possess a multiplicatively-conserved quantum number called R parity [71], which takes the values +1 for all conventional particles and -1 for all their supersymmetric partners. Its conservation is a consequence of baryon and lepton number cancelation, since

$$R = (-1)^{3B+L+2S} \tag{22}$$

There are three important consequences of R conservation:

1. Sparticles should always be produced in pairs.
2. Heavier sparticles should decay into lighter ones.
3. The LSP should be stable, since it has no legal decay mode.

In order to avoid condensation into galaxies, stars and planets such as ours, where it could in principle be detected in searches for anomalous heavy isotopes [72], it was argued in [70] that any supersymmetric relic LSP should be electromagnetically neutral and possess only weak interactions. Scandidates in the future sparticle data book include the sneutrino $\tilde{\nu}$ of spin 0, some form of "neutralino" of spin 1/2, or the gravitino $\widetilde{G}$ of spin 3/2. The sneutrino is essentially excluded by the LEP experiments which measured the decay of the Z^0 into invisible particles, which have counted the number of light neutrino species: 2.991 ± 0.0016 [73], which does not leave space for any sneutrino species weighing less than $\frac{1}{2}M_Z$, and by underground experiments to be discussed in the next section, which exclude a large range of heavier sneutrino masses [74]. Since the gravitino is probably impossible to discover, and is anyway theoretically disfavoured as the LSP, we concentrate on the neutralino [70].

The neutralino χ is a mixture of the photino $\tilde{\gamma}$, the two neutral higgsinos $\tilde{H}^0_{1,2}$ expected in the minimal supersymmetric extension of the Standard Model, and the zino $\tilde{Z}$. This is characterized essentially by three parameters, the unmixed gaugino $m_{1/2}$, the Higgs mixing parameter μ, and the ratio of Higgs vacuum expectation values tan β. The phenomenology of the lightest neutralino is quite complicated in general, but simplifies in the limit $m_{1/2} \rightarrow 0$, where χ is approximately a photino state [75], and in the limit $\mu \rightarrow 0$, where it is approximately a higgsino state. As seen in fig. 9, experimental constraints from LEP and the Fermilab collider in fact exclude these two extreme limits [76], so that

$$m_\chi \gtrsim (10 \ \text{to} \ 20)\,\text{GeV} \tag{23}$$

Fig. 9 also indicates that there are generic domains of parameter space where the LSP may have an "interesting" cosmological relic density [77], namely

$$0.1 \lesssim \Omega_\chi H_0^2 \lesssim 1 \tag{24}$$

for some suitable choice of supersymmetric model parameters. Fig. 10 displays the calculated LSP density in a sampling of phenomenological models [78], [79] where we see that an interesting cosmological density is quite plausible for LSP masses

$$20 \text{ GeV} \lesssim m_\chi \lesssim 300 \text{ GeV} \tag{25}$$

For simplicity, this and most cancellations have made the simplifying assumption of universality in the spectrum of sparticles, and have also assumed that CP violation in the LSP couplings can be neglected. Studies exploring the relaxation of these assumptions have appeared recently. As seen in fig. 11a, it is much easier for the LSP to be a higgsino-like state if the universality assumption is relaxed [80],[81], and, as seen in fig. 11b, CP violation can relax the upper limit on the LSP mass [82].

4 On Searches for Cold Dark Matter Particles

In this section we first review some of the strategies that have been proposed to search for relic neutralinos, and then discuss cosmological axions. In considering interaction rates for any given relic χ, one should keep in mind the correlation between the overall cosmological density Ω_χ and the local halo density ρ_χ. The most reasonable assumption is that

$$\rho_\chi = (\Omega_\chi / \Omega_{cold})(1 - f)\rho_{halo} \tag{26}$$

where f, ρ_{halo} and Ω_{cold} are taken from equations (1, 2) and (12). It is not in general worthwhile calculating rates for detection rates for relics with uninteresting cosmological densities $\Omega_\chi << 1$, and certainly not if one assumes the local density to be ρ_{halo}.

4.1 Annihilation in the Galactic Halo

The first neutralino search strategy that we discuss is that for the products of their annihilations in our galactic halo [83]. Here the idea is that two self-conjugate χ particles may find each other while circulating in the halo, and have a one-night stand and annihilate each other: $\chi\chi \rightarrow \ell\ell, \bar{q}q$, leading to a flux of stable particles such as $\bar{p}, e^+, \gamma, \nu$ in the cosmic rays. Several experiments have searched for cosmic-ray antiprotons [84], with the results shown in fig. 12. At low energies there are only upper limits, but there are several positive detections at higher energies, which are comparable with the flux expected from secondary production by primary matter cosmic rays [85]. As also seen in fig. 12, relic LSP annihilation in our galactic halo might produce an observable flux of low-energy cosmic ray antiprotons somewhat below the present experimental upper limits [86]. This calculation was made fixing the supersymmetric model parameters so that $\Omega_\chi = 1$, and assuming that the local halo density (2) is dominated by neutralinos χ, and is subject to uncertainties associated with the length of time that the $\bar{p}$'s spend in our galactic halo.

Fluxes higher than those in [86] may be obtained if one considers neutralinos with $\Omega_\chi < 1$, because they have larger annihilation cross sections. This is a logical possibility, though it would mean that neutralinos would not be the only (or even dominant) cold dark matter component, if one retains the cocktail recipe (12). This would have the corollary that the assumed local density should be correspondingly reduced to some fraction of (2), with a quadratic effect on the $\bar{p}$ flux, which is proportional to ρ_{halo}^2. In any case, it is mathematically impossible for the halo density (2) to be saturated by neutralinos if the annihilation cross section is so large that $\Omega_\chi < \Omega_{halo} \simeq 0.1$. As already mentioned, in my view one should be careful when quoting rates and limits on neutralino parameters to check consistency with reasonable postulates on Ω_χ and Ω_{halo}.

The flux estimates of [86] may be interpreted as suggesting that

$$\rho_\chi \lesssim 10\, \rho_{halo} \tag{27}$$

and I do not believe it is possible to be much more precise at the present time. NASA and the DOE have recently approved a satellite experiment called AMS [87], which should be able to improve significantly the present upper limits on low-energy antiprotons, and may be able to start constraining significantly supersymmetric models.

Finally, I note that it is also possible to derive limits on supersymmetric models from the present experimental measurements of the cosmic-ray e^+ [88] and γ fluxes [89], but these are not yet very constraining.

4.2 Annihilation in the Sun or Earth

A second LSP detection strategy is to look for $\chi\chi$ annihilation inside the Sun or Earth. Here the idea is that a relic LSP wandering through the halo may pass through the Sun or Earth [90], collide with some nucleus inside it, and thereby lose recoil energy. This could convert it from a hyperbolic orbit into an elliptic one, with a perihelion (or perigee) below the solar (or terrestrial) radius. If so, the initial capture would be followed by repeated scattering and energy loss, resulting in a quasi-isothermal distribution within the Sun (or Earth). The resulting LSP population would grow indefinitely, à la Malthus, unless it were controlled either by emigration, namely evacuation from the surface, or by civil war, namely annihilation within the Sun (or Earth). Evaporation is negligible for χ particles weighing more than a few GeV [91], so the only hope is annihilation. The neutrinos produced by any such annihilation events would escape from the core, leading to a high-energy solar neutrino flux ($E_\nu \gtrsim 1$ GeV). This could be detected either directly in an underground experiment, or indirectly via a flux of upward-going muons produced by neutrino collisions in the rock. (By the way, LSPs in the core of the Sun do not affect significantly its temperature, and hence have no impact on the low-energy solar neutrino problem.)

The high-energy solar neutrino flux produced in this way is given approximately by the following general formula [92]:

$$\begin{aligned} R_\nu = \quad & 2.7 \times 10^{-2} \, f \, (m_\chi/m_p) \left(\frac{\sigma(\chi p \to \chi p)}{10^{-40}\,\mathrm{cm}^2}\right) \\ & \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\ cm}^{-3}}\right) \left(\frac{300\ \mathrm{km\,s}^{-1}}{\bar{v}_\chi}\right) \times F_\nu \end{aligned} \tag{28}$$

assuming that proton targets dominate capture by the Sun. Here f is a kinematic function, $\sigma(\chi\, p \to \chi\, p)$ is the elastic LSP-proton scattering cross section, ρ_χ and $\bar{v}_\chi$ are the local density and mean velocity of the halo LSPs, and F_ν represents factors associated with the neutrino interaction rate in the apparatus.

There is an analogous formula for the production of upward-going muons originating from the collisions in rock of high-energy solar neutrinos, and rates in a sampling of supersymmetric models are shown in fig. 13. While some models are already excluded by unsuccessful searches, most are not [79]. We see in fig. 14 that searches for solar signals usually constrain models more than searches for terrestrial signals, though this is not a model-independent fact [79]. As seen in fig. 15, in the long run it seems that a search for upward-going neutrino-induced muons with a 1 km^2 detector could almost certainly detect LSP annihilation [93], if most of the cold dark matter is indeed composed of LSPs.

Before leaving this subject, I would like to recall that MSW oscillations may also be important for high-energy solar neutrinos, as seen in fig. 16 [94]. Until the possible neutrino mass and oscillation parameters are pinned down, this introduces another ambiguity into the above analysis. For the time being, it would be conservative to quote upper limits on fluxes assuming that the neutrinos arriving at the detector are those for which the detector has the smallest efficiency.

4.3 Dark Matter Search in the Laboratory

The third LSP search strategy is to look directly for LSP scattering off nuclei in the laboratory [95]. The typical recoil energy

$$\Delta E < m_\chi v^2 \simeq 10 \left(\frac{m_\chi}{10\,\mathrm{GeV}}\right) \mathrm{keV} \tag{29}$$

deposited by elastic χ-nucleus scattering would probably lie in the range of 10 to 100 keV. Spin-dependent interactions mediated by Z^0 or $\tilde{q}$ exchange are likely to dominate for light nuclei [96], whereas coherent spin-dependent interactions mediated by H and $\tilde{q}$ exchange are likely to dominate scattering off heavy nuclei [97]. The spin-dependent interactions on individual nucleons are controlled by the contributions of the different flavours q of quark to the total nucleon spin, denoted by Δq. These have now been determined by polarized lepton-nucleon scattering experiments with an accuracy sufficient for our purposes. Translating the Δq into matrix elements for interactions on nuclei depends on the contributions of the different nucleon species to the nuclear spin, which must be studied using the shell model [96] or some other theory of nuclear structure [98]. The spin-independent interactions on individual nucleons are related to the different quark and gluon contributions to the nucleon mass, which is also an interesting phenomenological issue related to the π-nucleon σ-term [99]. Again, the issue of nuclear structure arises when one goes from the nucleon level to coherent scattering off a nuclear target. It is in particular necessary to understand the relevant nuclear form factors, which are expected to exhibit zeroes at certain momentum transfers [100].

We will not discuss here the details of such nuclear calculations, but present in figs 17 and 10 the results of a sampling of different supersymmetric models [79]. We see in fig. 17 that the spin-independent contribution tends to dominate over the spin-dependent one in the case of Germanium, though this is not universally true, and would not be the case for scattering off Fluorine [96]. In fig. 10 we plot the scattering rates off ^{73}Ge, where we see that there are many models in which more than 0.01 events/kg/day are expected, which may be observable [78]. The direct search for cold dark matter scattering in the laboratory may be a useful complement to the searches for supersymmetry at accelerators [96].

Fig. 18 shows as solid lines upper limits from searches for elastic scattering in the laboratory, for spin-dependent rates:

$$\begin{aligned} &\sigma_p^{dep} \lesssim 0.3\,\mathrm{pb} \text{ for} \\ &20\,\mathrm{GeV} \lesssim m_\chi \lesssim 300\,\mathrm{GeV} \end{aligned} \tag{30}$$

in part (a), and for spin-independent scattering rates:

$$\begin{aligned} &\sigma_p^{ind} \lesssim 3\ 10^{-5}\,\mathrm{pb} \text{ for} \\ &20\,\mathrm{GeV} \lesssim m_\chi \lesssim 300\,\mathrm{GeV} \end{aligned} \tag{31}$$

in part (b) [101]. Also shown in fig. 18 as dashed lines are corresponding upper limits from indirect searches of the type discussed in the previous subsection. These may appear more stringent, but involve more uncertainties, as already discussed. Please note also that limits may also be obtained from studies of tracks in ancient Mica [102], and from searches for inelastic excitations by relic particles [103].

It should also be emphasized that the significances and relative importances of these different search strategies are sensitive to the usual assumption of universality in the sparticle masses. This point is made in fig. 19, whose panel (a) shows results in a sampling of "universal" models, whilst panel (b) shows what happens in a sampling of "non-universal" models [80], [81]. The latter have yet to be explored so systematically.

4.4 Axions

The axion [104] is my second-favourite candidate for the cold dark matter. As you know, it was invented to guarantee conservation of P and CP in the strong interactions. These would otherwise be violated by the QCD θ parameter, which is known experimentally to be smaller than about 10^{-9} [105]. The θ parameter relaxes to zero in any extension of the Standard Model which contains the axion, whose mass and couplings to matter that are scaled inversely by the axion decay constant f_a. The fact that no axion has been seen in any accelerator experiment tells us that

$$f_a \gtrsim 1\,\mathrm{TeV} \tag{32}$$

and hence that any axion must be associated with physics beyond the scale of the Standard Model.

Axions would have been produced in the early Universe in the form of slow-moving coherent waves that could constitute cold dark matter. The relic density of these waves has been estimated as [106]

$$\Omega_a \simeq \left(\frac{0.6\times 10^{-5}\,\mathrm{eV}}{m_a}\right)^{7/6} \left(\frac{200\,\mathrm{MeV}}{\Lambda_{QCD}}\right)^{3/4} \left(\frac{75}{H_0}\right)^2 \tag{33}$$

which is less than unity if

$$f_a \lesssim 10^{12}\,\mathrm{GeV} \tag{34}$$

In addition to these coherent waves, there may also be axions radiated from cosmic strings [107], which would also be non-relativistic by now, and hence contribute to the relic axion density and strengthen the limit in equation (34).

The fact that the Sun shines photons rather than axions, or, more accurately but less picturesquely, that the standard solar model describes most data, implies the lower limit

$$f_a \gtrsim 10^{7}\,\mathrm{GeV} \tag{35}$$

This has been strengthened somewhat by unsuccessful searches for the axio-electric effect [108], in which an axion ionizes an atom. More stringent lower bounds on f_a are provided by the agreements between theories of Red Giant and White Dwarf stars with the observations [109]:

$$f_a \gtrsim 10^{9}\,\mathrm{GeV} \tag{36}$$

Between equations (34) and (36) there is an open window in which the axion could provide a relic density of interest to astrophysicists and cosmologists.

Part of this window is closed by the observations of the supernova SN1987a. According to the standard theory of supernova collapse to form a neutron star, 99% of the binding energy released in the collapse to the neutron star escapes as neutrinos. This theory agrees [110] with the observations of SN1987a made by the Kamiokande [111] and IMB experiments [112], which means that most of the energy could not have been carried off by other invisible particles such as axions.

Since the axion is a light pseudoscalar boson, its couplings to nucleons are related by a generalized Goldberger-Treiman relation to the corresponding axial-current matrix elements, and these are in turn determined by the corresponding Δq [113]. Specifically, we find for the axion couplings to individual nucleons that

$$\begin{aligned} C_{ap} = \; & 2[-2.76\,\Delta u - 1.13\,\Delta d + 0.89\,\Delta s \\ & - \cos 2\beta\,(\Delta u - \Delta d - \Delta s)]\,, \\ C_{an} = \; & 2[-2.76\,\Delta d - 1.13\,\Delta u + 0.89\,\Delta s \\ & - \cos 2\beta\,(\Delta d - \Delta u - \Delta s)] \end{aligned} \tag{37}$$

Evaluating the Δq at a momentum scale around 1 GeV, as is appropriate in the core of a neutron star, we estimate [114] that

$$\begin{aligned} C_{ap} &= (-3.9 \pm 0.4) - (2.68 \pm 0.06)\cos 2\beta \\ C_{an} &= (0.19 \pm 0.4) + (2.35 \pm 0.06)\cos 2\beta \end{aligned} \tag{38}$$

which are plotted in fig. 20.

As in the case of LSP scattering, the uncertainties associated with polarized structure function measurements are by now considerably smaller than other uncertainties, in this case particularly those associated with the nuclear equation of state. A particular focus of attention here has been the suggestion [115] that nucleon spin fluctuations in the supernova core might suppress substantially the axion emission rate. In fact, sum-rule considerations [116] suggest that this suppression may be less important than first thought, though there is some shift in the open part of the axion window [117].

The good news here is that an experiment [118] is underway which should be able to detect halo axions if they live in at least part of this window.

5 Prospects

We have every reason to think that the near future will be a very exciting period for astroparticle physics. As seen in Table 2, many experiments are underway, under construction, or being actively planned, which will contribute to resolving the fundamental issues in this field. On the side of astrophysics and cosmology, we have every reason to hope that a verified "Standard Model" of structure formation will soon emerge, and that the nature of the invisible 90% or more of the matter in the Universe may soon be resolved. On the side of particle physics, we have every reason to hope that the resolution of these astrophysical and cosmological issues will take us beyond the current Standard Model of particle physics, a strait-jacket from which accelerators have not yet been able to extract us. As is seen in Table 2, it may in fact be the next generation of accelerator experiments that creates these twin revolutions in astroparticle physics.

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	Cosmology / Gravitation	*ν physics*	*Accelerator experiments*	*Non-accelerator experiments*	*Issues*
1996	NAUTILUS, AURIGA	CHORUS, NOMAD, SNO, SKK	LEP 2	Axion, AMANDA, Baikal,	HDM
1997	AGAPE, DUO	Chooz, San Onofre		DUMAND II, NESTOR	LSND
1998		BOREXINO	B factories	AMS	Solar ν
1999	Sloane Survey	KEK/SKK, ICARINO			CDM matter–antimatter
2000	LIGO, VIRGO, GEO, TAMA	HERON, HELLAZ			susy, Higgs
2001	COBE′	COSMOS, MINOS			Atmospheric ν's
2002					
2003	COBRAS– SAMBA				inflation/cosmic string
2004			LHC		
2005	40 t sphere	NOE, ICARUS	pp AA PA	BAND	
2006					
2007					
2008					
2009			LHC/LEP		
(2015)	LISA		ep ? eA		gravitational waves

Table 2 - Chronology of some possible future interesting experiments and the astroparticle physics issues they may resolve.

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they are likely to be white dwarfs or neutron stars, whose progenitors must have weighed $\simeq 2$ or more solar masses in order to have burnt out already: see also F.C. Adams and G. Laughlin, astro-ph/9602006. However, in this case, one would expect to see also a population of visible objects with masses between 0.1 and 2 solar masses. Even taking these new MACHO results at face value, there is still expected to be a substantial local density of non-baryonic cold dark matter particles: see, e.g., M.S. Turner, E.I. Gates and G. Gyuk, astro-ph/9601168.

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Figure Captions

Fig. 1 - The (Ω, H_0) plane, adapted from [2], which exhibits no serious discrepancy between the average measured value of $H_0, \Omega = 1$, and an age for the Universe of 10^{10} years. This plot also shows the estimates of the present baryon density $\Omega_{baryons}$ obtained from visible features in the Universe, from Big Bang Nucleosynthesis and from rich clusters. All the indications are that $\Omega_{baryons} \lesssim 0.1$, so that at least 90% of the matter in the Universe is non-baryonic dark matter.

Fig. 2 - A compilation of data on the primordial perturbation spectrum [29], compared with a cold dark matter simulation assuming an initially scale-invariant spectrum of Gaussian fluctuations. The wave number $k \propto 1/d$, where d is the distance scale of the perturbation.

Fig. 3 - Compilation of data on fluctuations in the cosmic microwave background spectrum [37], which provides the basis for a discussion of theoretical ideas and observational issues in measuring fluctuations in the cosmic microwave background radiation. The harmonic number $l \propto 1/d$.

Fig. 4 - Illustration how a mixed dark matter scenario [40] may reconcile the large-scale perturbations seen by COBE [30],[31] with the relatively small magnitude of the perturbations seen at small scales.

Fig. 5 - A sketch indicating the relative successes of different models of structure formation, as compared with different types of astrophysical and cosmological data.

Fig. 6 - A planar presentation [49] of the solar neutrino deficits seen in different experiments, compared with a selection of different solar models.

Fig. 7 - Diagrams which may produce a lepton asymmetry in heavy neutrino decay, which may subsequently be partly recycled by sphalerons into a baryon asymmetry [63],[64].

Fig. 8 - Confrontation of the LSND data [42] with constraints on neutrino oscillation parameters provided by other experiments.

Fig. 9 - The cosmological relic density of the neutralino χ [70] may well (shaded regions) lie in the range of interest to astrophysicists and cosmologists [77], namely $0.1 \lesssim \Omega_\chi \lesssim 1$.

Fig. 10 - Relic density of supersymmetric particles, calculated in a sampling of different models [78], together with the estimated scattering rate on ^{76}Ge.

Fig. 11 - Some results of relaxing the usual restrictive assumptions made in analyses of supersymmetric relic particles: (a) the supersymmetric relic is more likely to be a higgsino if scalar masses are not universal [81], and (b) it may be heavier if there are large CP-violating phases[82].

Fig. 12 - The results of experimental searches for cosmic-ray antiprotons [84], compared with the secondary fluxes expected from primary matter cosmic rays [85] and a supersymmetric model [86]. The lower points with error bars are what should be obtainable with the AMS experiment [87].

Fig. 13 - The flux of upward-going muons expected from $\chi\chi$ annihilation inside the Sun in a sampling of supersymmetric models [79].

Fig. 14 - A comparison of the muon fluxes from the centre of the Sun and Earth, as found in a sampling of supersymmetric models [79].

Fig. 15 - A detector with an area of one square kilometer is likely to able to detect upward-going muons from relic annihilations [93].

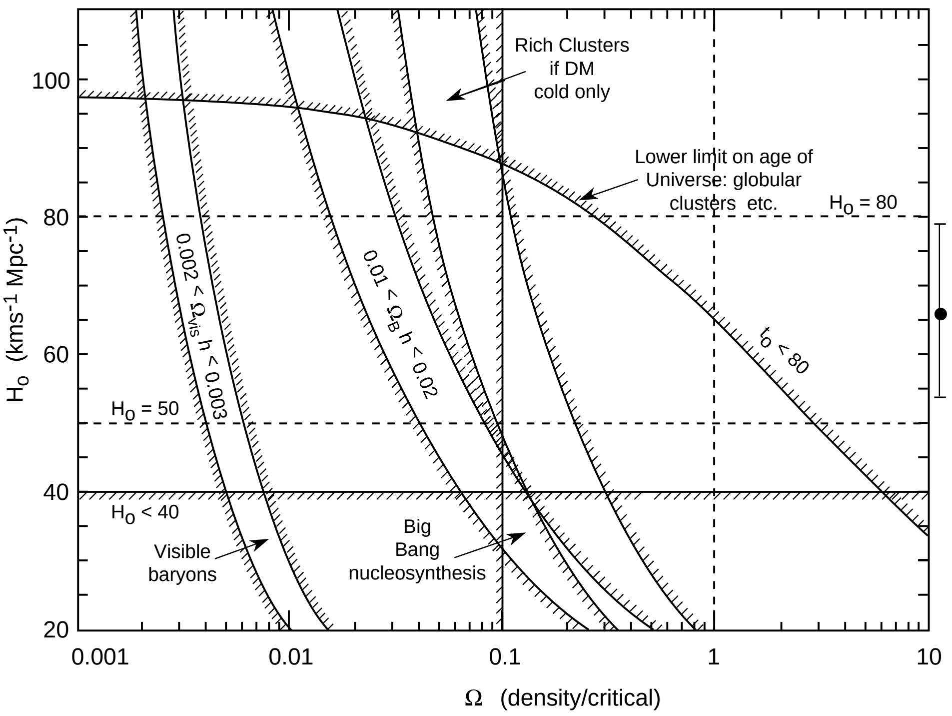
Fig. 16 - High-energy solar neutrinos produced by relic annihilations inside the Sun may be sensitive to matter-enhanced oscillations [94].

Fig. 17 - A comparison of the spin-dependent and spin-independent interaction rates of relic neutralinos χ with Germanium in a sampling of supersymmetric models [79].

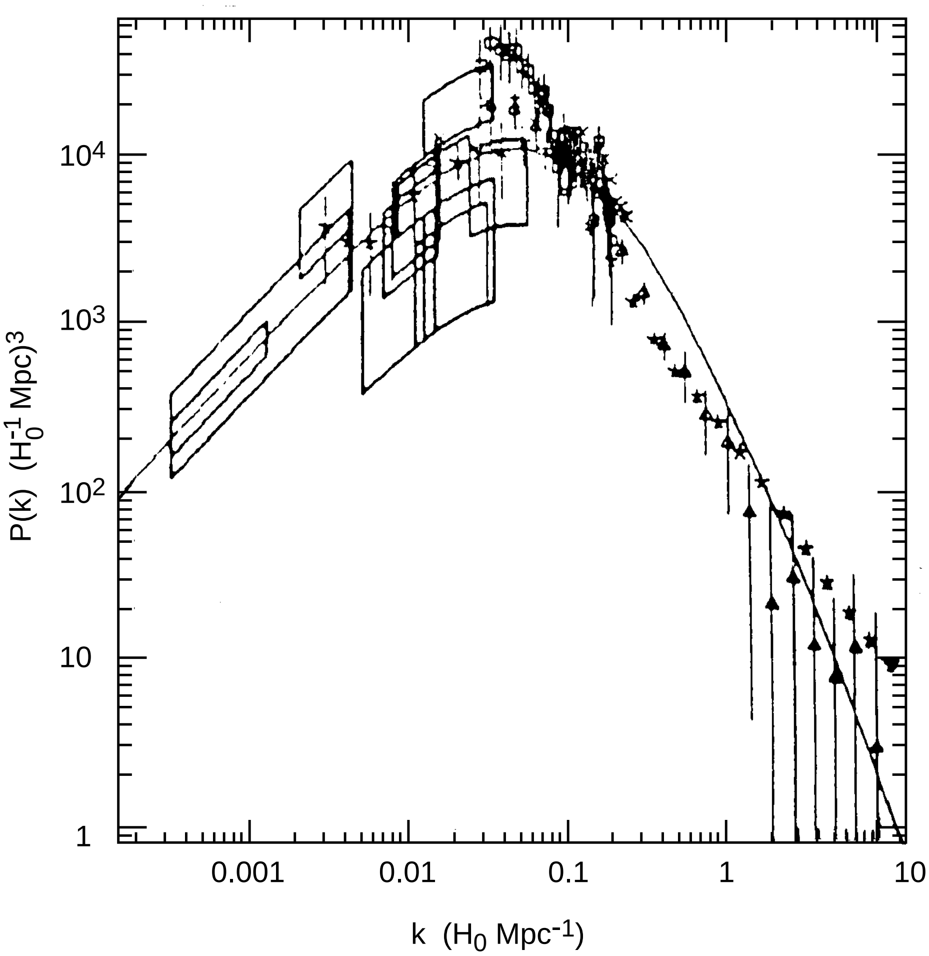
Fig. 18 - A compilation of present upper limits on dark matter scattering via (a) spin-dependent and (b) spin-independent interactions [101].

Fig. 19 - The sensitivities of direct and indirect searches for dark matter in (a) "universal" models, and (b) "non-universal" models [81].

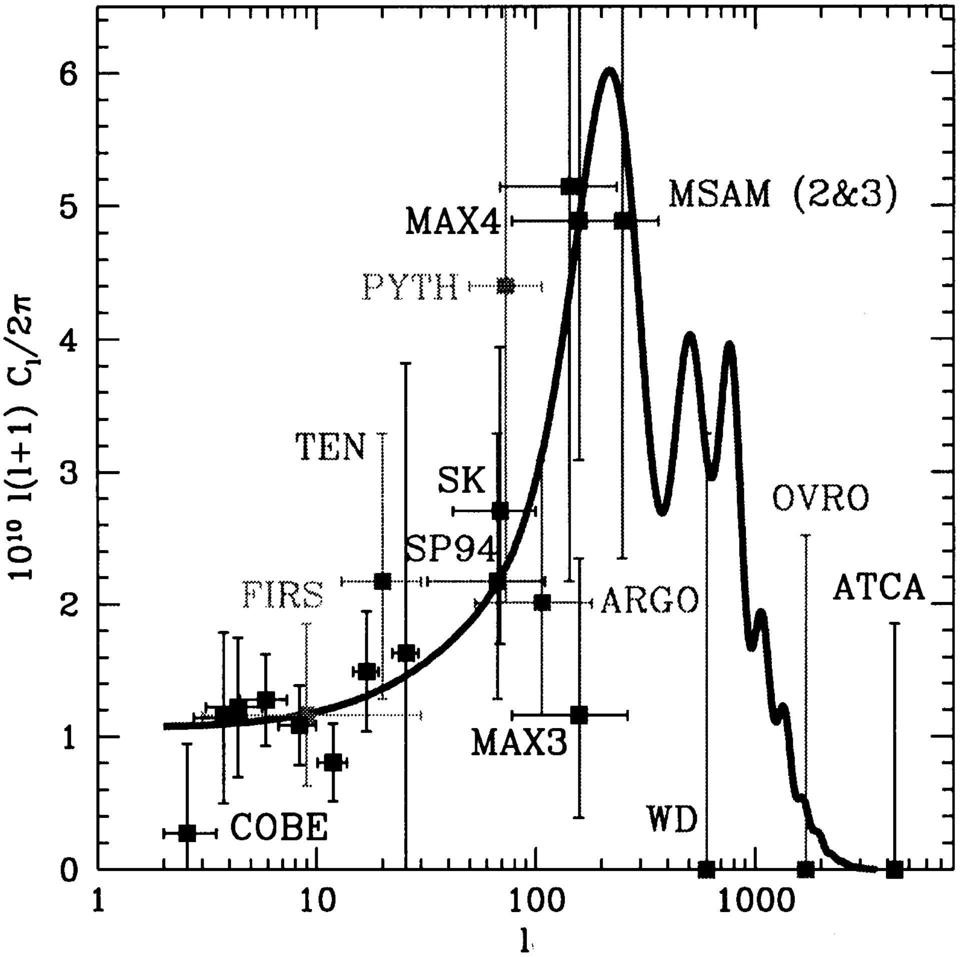
Fig. 20 - Axion couplings to the nucleon, as determined in [114] using polarized structure function data.



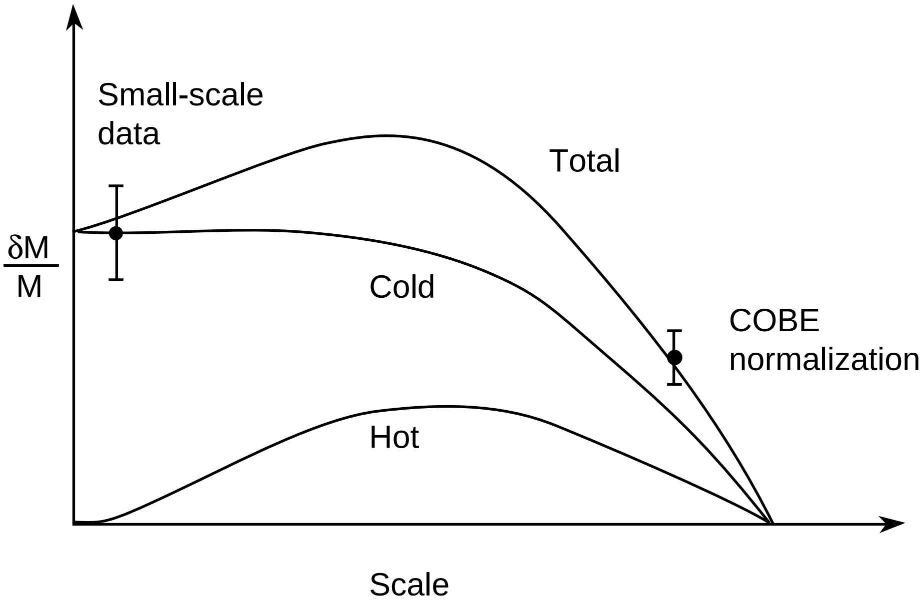
Rich Clusters
if DM
cold only
Lower limit on age of
Universe: globular
clusters etc.
H_o = 80
t_o < 80
$0.002 < \Omega_{vis} h < 0.003$
$0.01 < \Omega_B h < 0.02$
H_o = 50
H_o < 40
Visible
baryons
Big
Bang
nucleosynthesis
100
80
60
40
20
H_o (kms^{-1} Mpc^{-1})
0.001
0.01
0.1
1
10
Ω (density/critical)



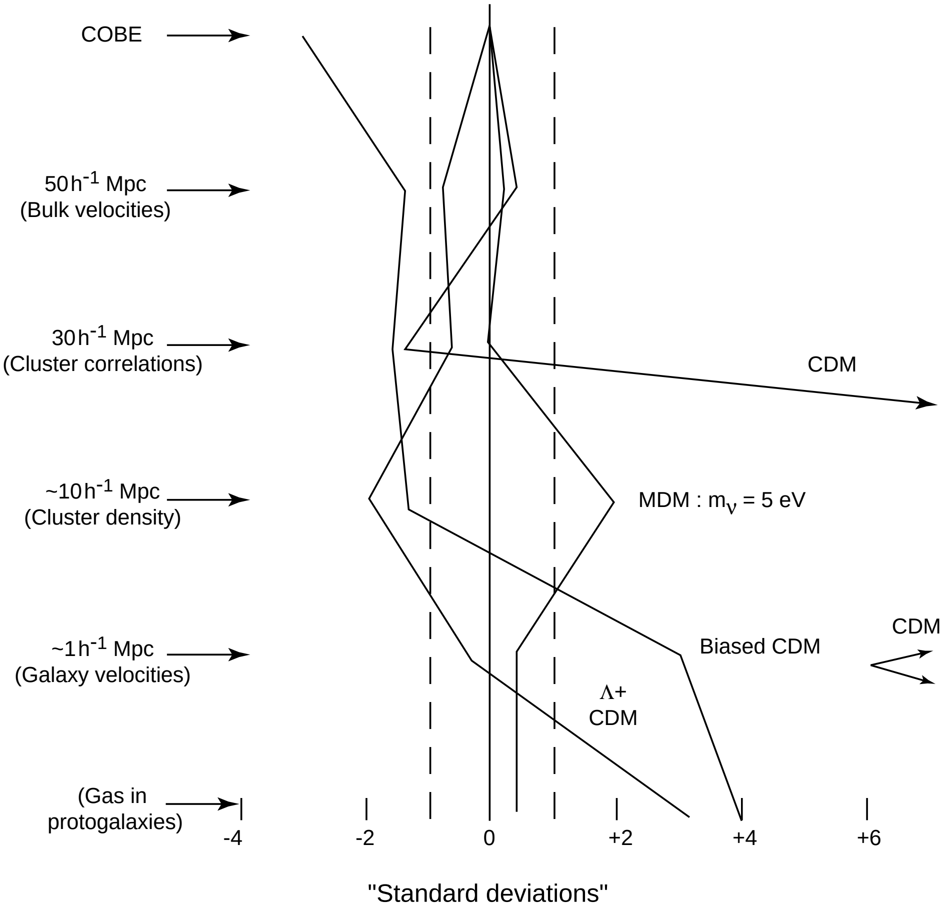
P(k) $(H_0^{-1}\ \mathrm{Mpc})^3$
10^4
10^3
10^2
10
1
0.001
0.01
0.1
1
10
k $(H_0\ \mathrm{Mpc}^{-1})$

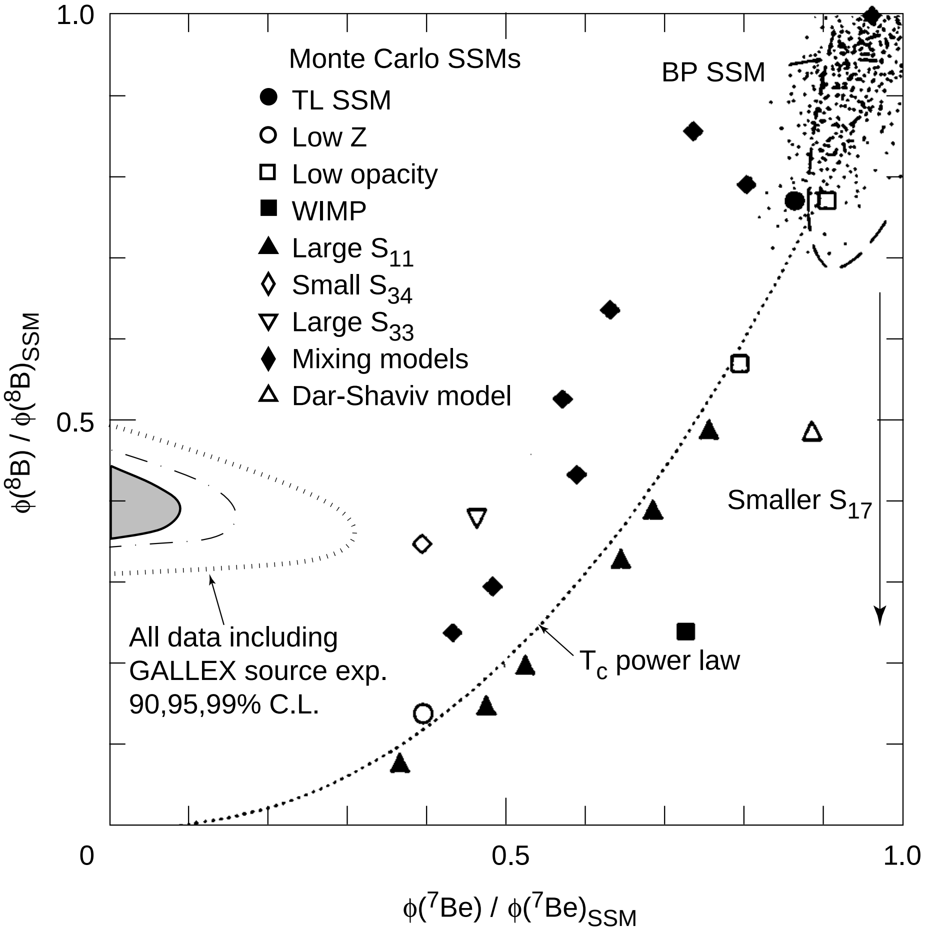


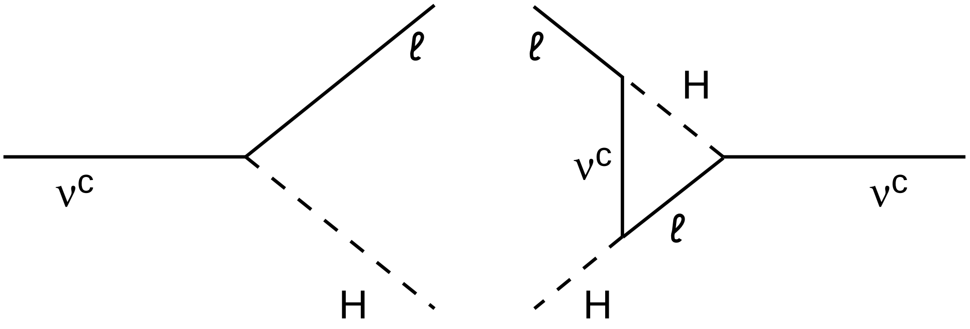
$10^{10}\, l(l+1)\, C_l/2\pi$
l
0
1
2
3
4
5
6
1
10
100
1000
COBE
FIRS
TEN
SP94
SK
PYTH
MAX4
MSAM (2&3)
ARGO
MAX3
WD
OVRO
ATCA

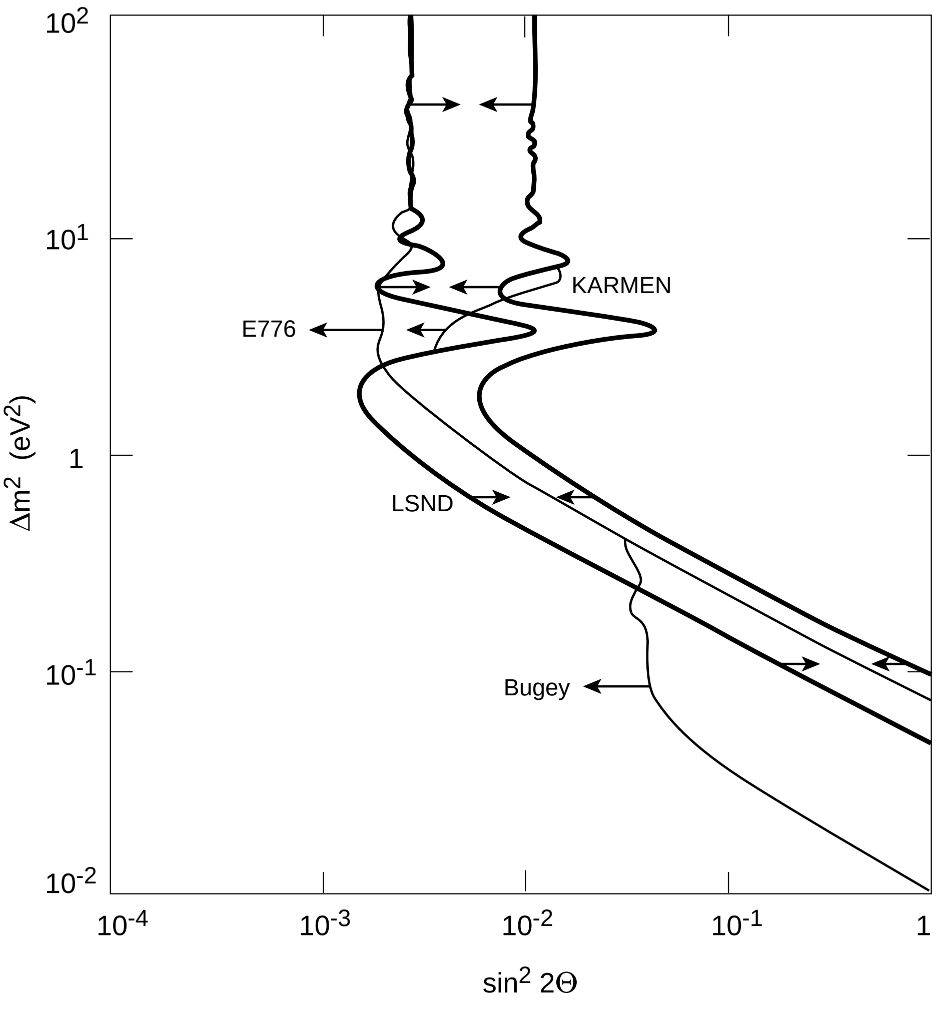


Small-scale
data
Total
$\frac{\delta M}{M}$
Cold
COBE
normalization
Hot
Scale

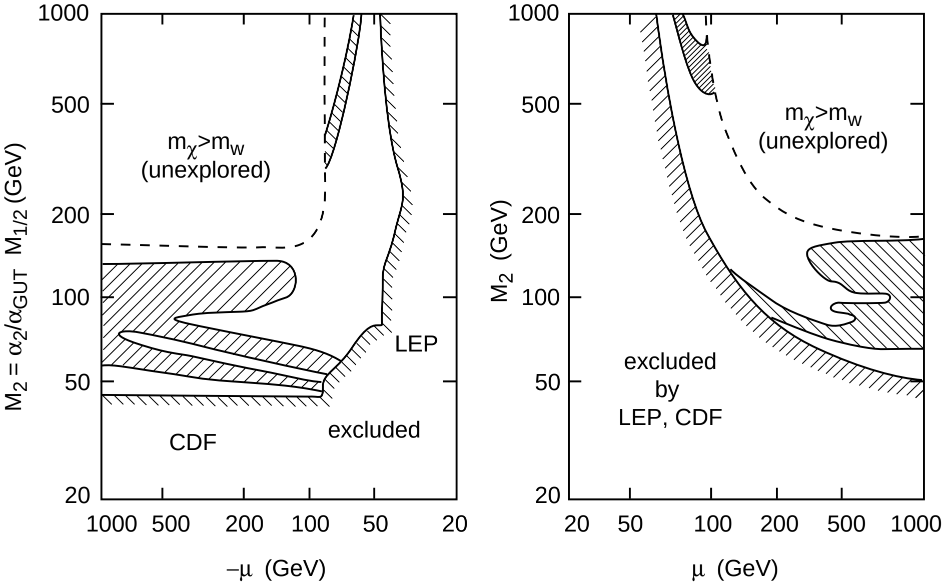

COBE
$50h^{-1}$ Mpc
(Bulk velocities)
$30h^{-1}$ Mpc
(Cluster correlations)
$\sim10h^{-1}$ Mpc
(Cluster density)
$\sim1h^{-1}$ Mpc
(Galaxy velocities)
(Gas in
protogalaxies)
CDM
MDM : $m_\nu = 5$ eV
Biased CDM
CDM
Λ+
CDM
-4
-2
0
+2
+4
+6
"Standard deviations"


Monte Carlo SSMs
● TL SSM
○ Low Z
□ Low opacity
■ WIMP
▲ Large S_{11}
◊ Small S_{34}
▽ Large S_{33}
◆ Mixing models
△ Dar-Shaviv model
BP SSM
Smaller S_{17}
T_c power law
All data including
GALLEX source exp.
90,95,99% C.L.
$\phi(^8B) / \phi(^8B)_{SSM}$
$\phi(^7Be) / \phi(^7Be)_{SSM}$
1.0
0.5
0
0.5
1.0

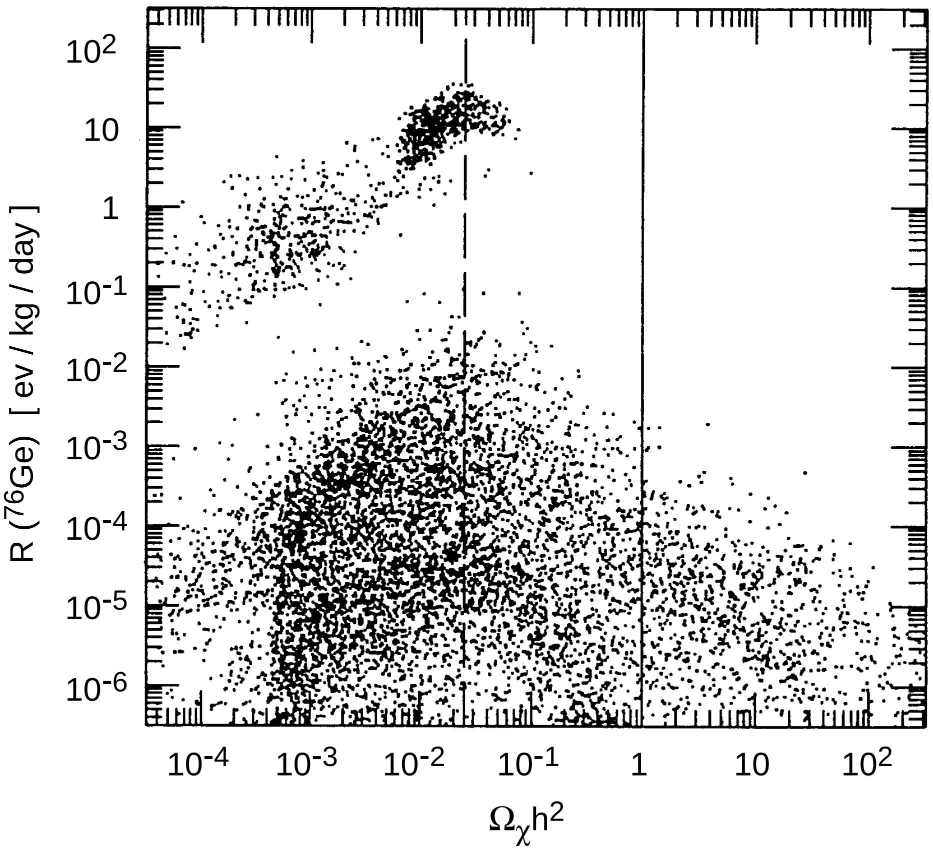

ℓ
ν^c
H
ℓ
H
ν^c
ν^c
ℓ
H



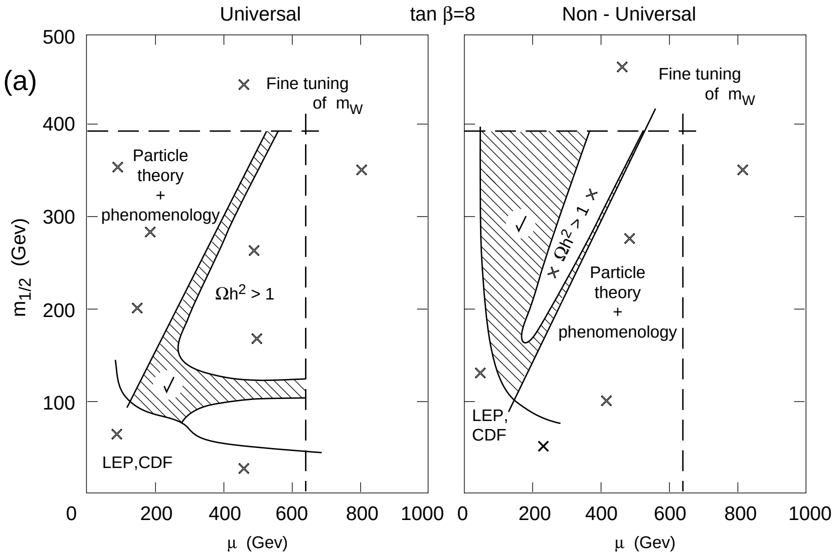
10^2
10^1
1
10^{-1}
10^{-2}
Δm^2 (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$
KARMEN
E776
LSND
Bugey

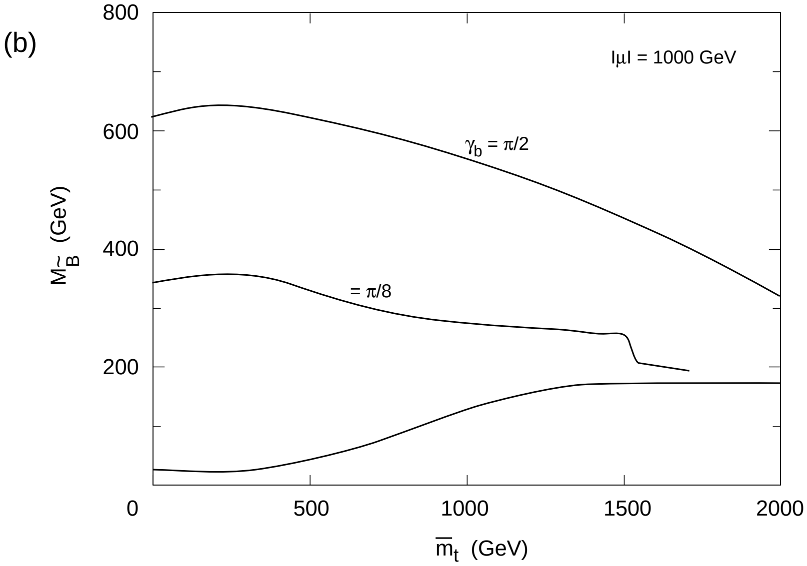


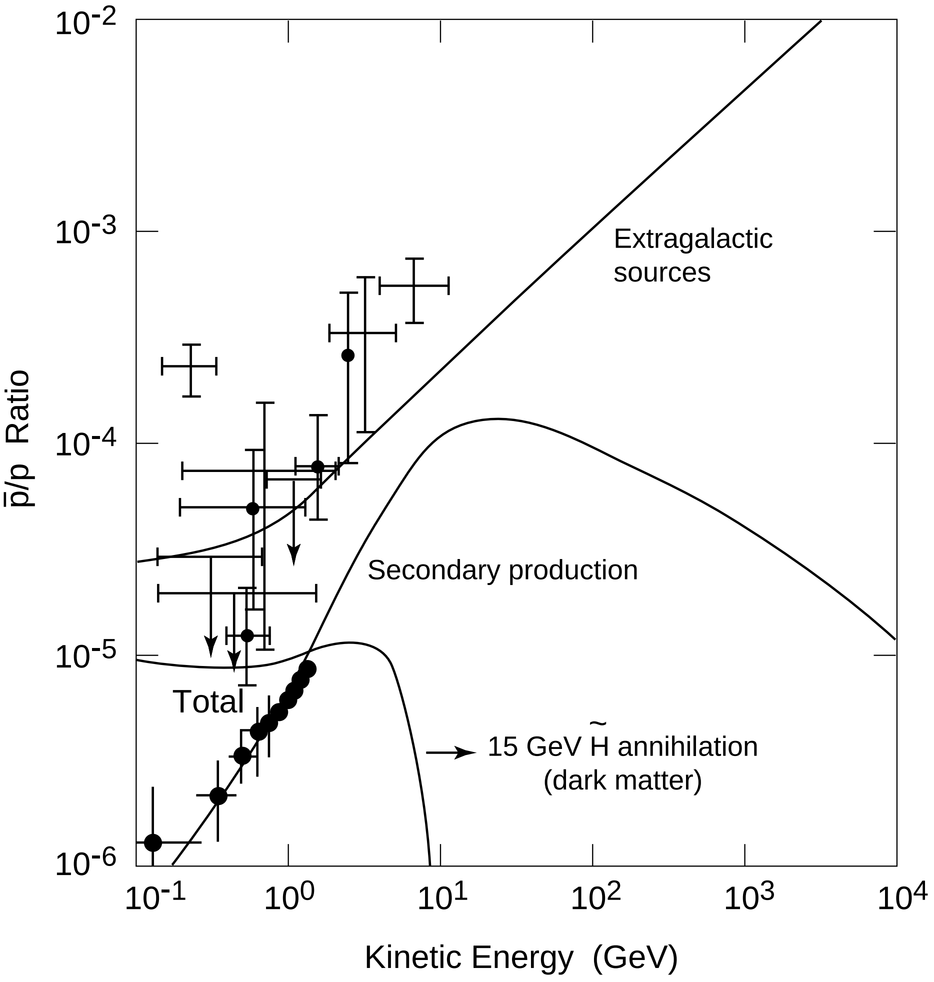
m_o = 150 GeV, m_A = 200 GeV, m_t = 190 GeV, $\tan\beta$ = 2



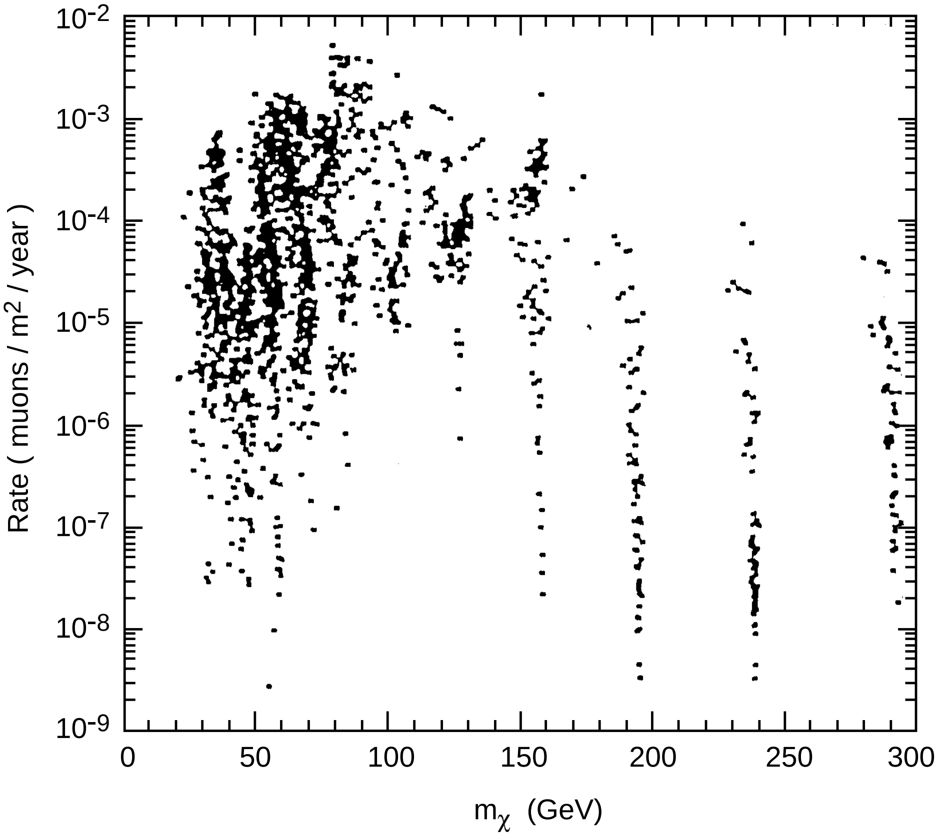
R (^{76}Ge) [ev / kg / day]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$\Omega_\chi h^2$


(a)
Universal
tan β=8
Non - Universal
500
400
300
200
100
0
200
400
600
800
1000
m1/2 (Gev)
μ (Gev)
Fine tuning of mW
Particle theory + phenomenology
Ωh2 > 1
✓
LEP,CDF
LEP, CDF

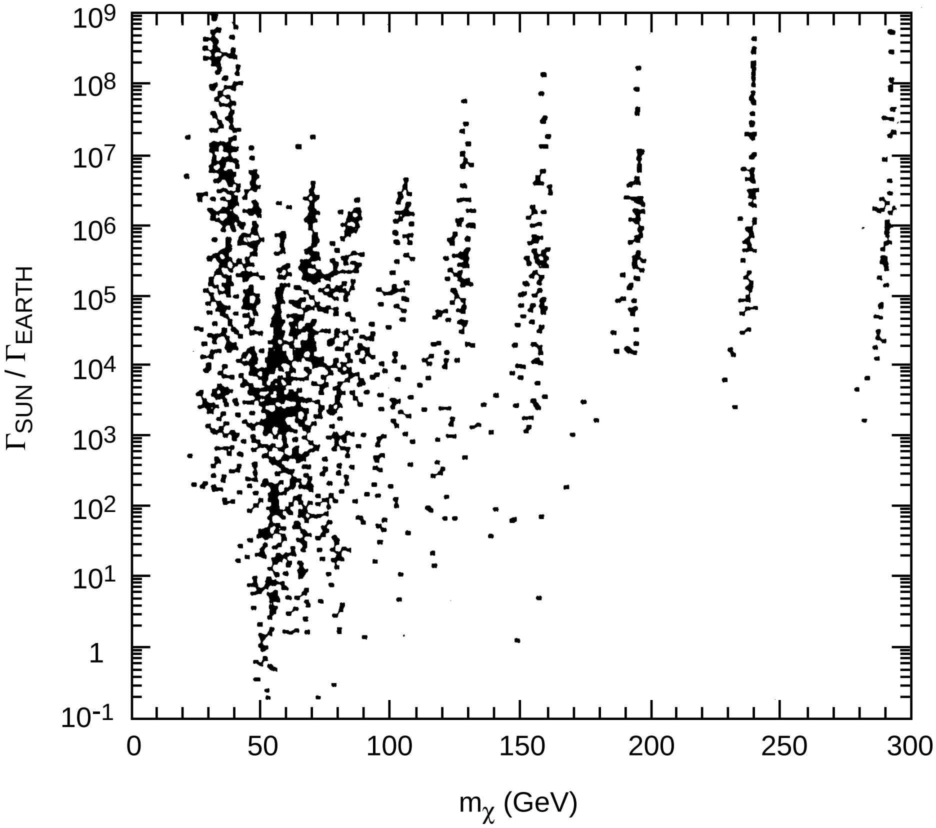

(b)
800
600
400
200
0
500
1000
1500
2000
IμI = 1000 GeV
γb = π/2
= π/8
M~B (GeV)
m̄t (GeV)

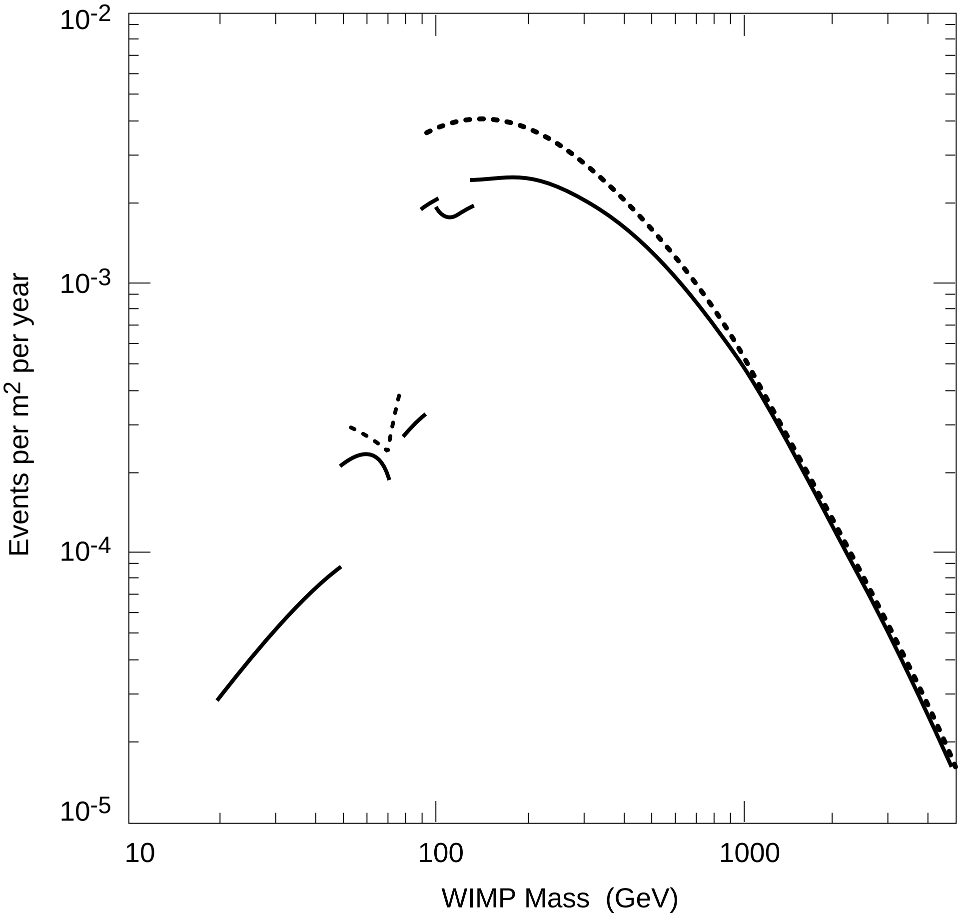


10-2
10-3
10-4
10-5
10-6
p̄/p Ratio
10-1
10^0
10^1
10^2
10^3
10^4
Kinetic Energy (GeV)
Extragalactic sources
Secondary production
Total
15 GeV H̃ annihilation (dark matter)

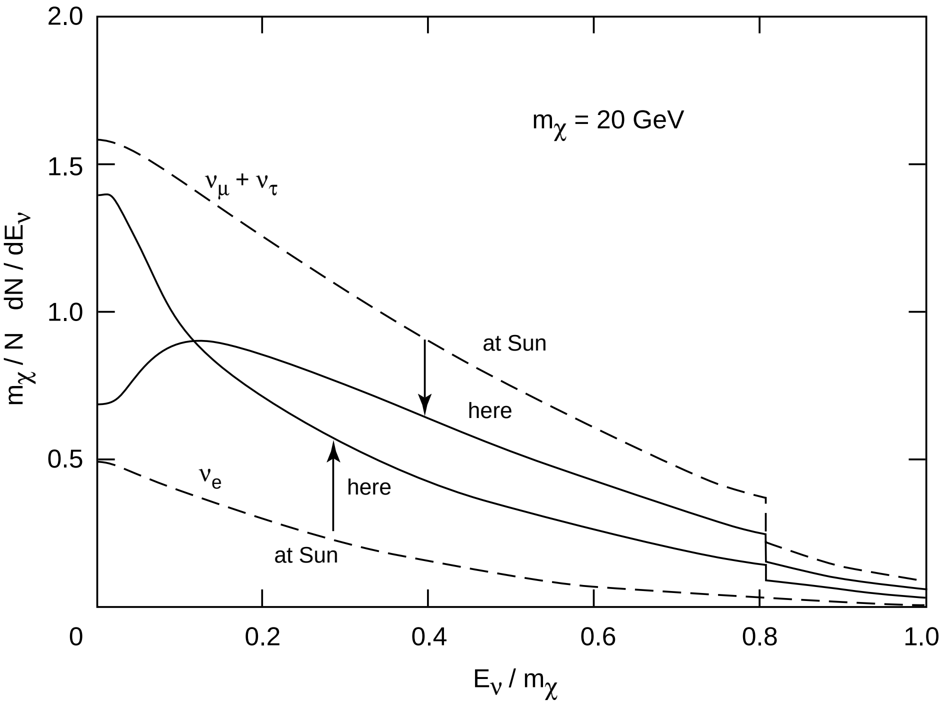


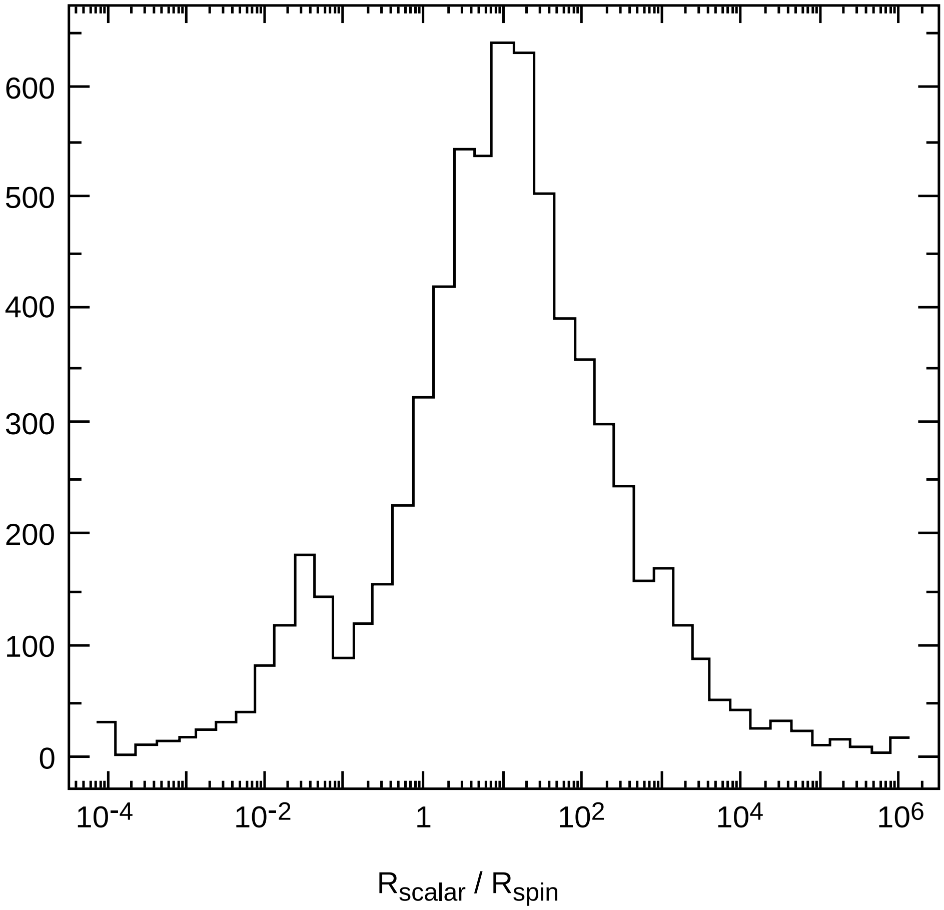
Rate (muons / m^2 / year)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
50
100
150
200
250
300
m_χ (GeV)

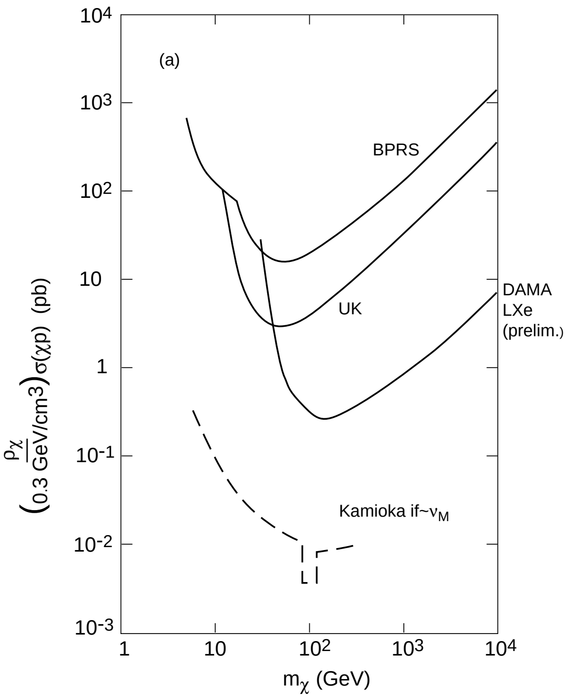

10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^-1
Γ_SUN / Γ_EARTH
0
50
100
150
200
250
300
m_χ (GeV)



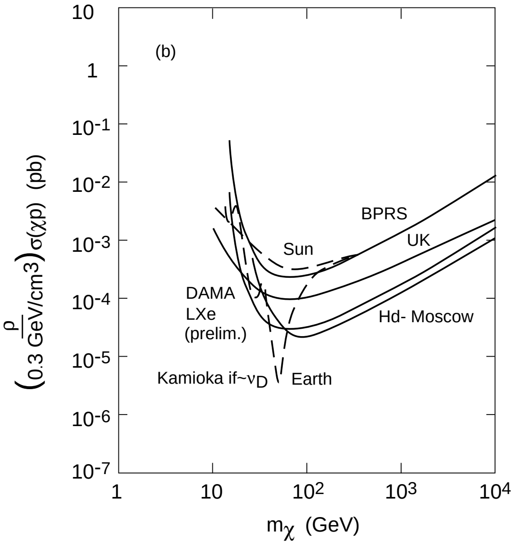
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Events per m^2 per year
10
100
1000
WIMP Mass (GeV)


m_χ = 20 GeV
$\nu_\mu + \nu_\tau$
at Sun
here
ν_e
here
at Sun
m_χ / N dN / dE_ν
E_ν / m_χ
0
0.2
0.4
0.6
0.8
1.0
0.5
1.0
1.5
2.0

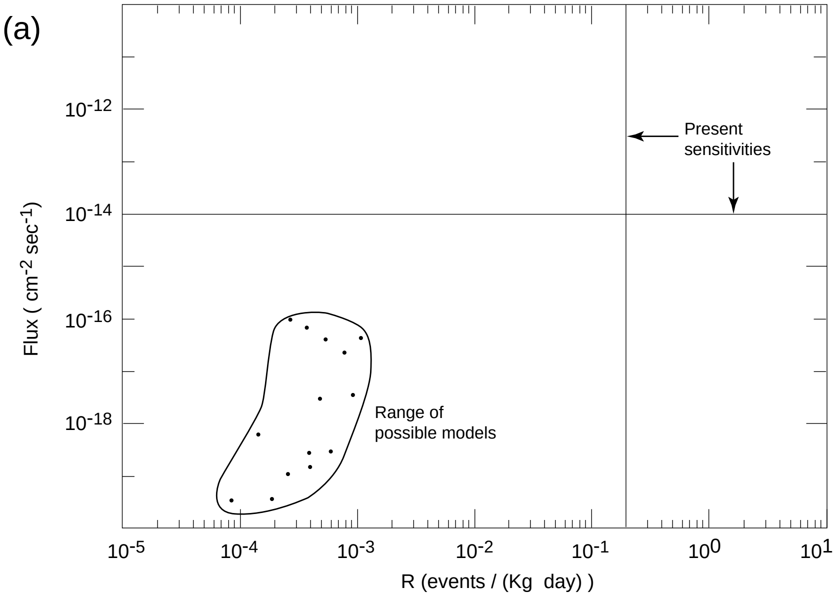

600
500
400
300
200
100
0
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
R_{scalar} / R_{spin}

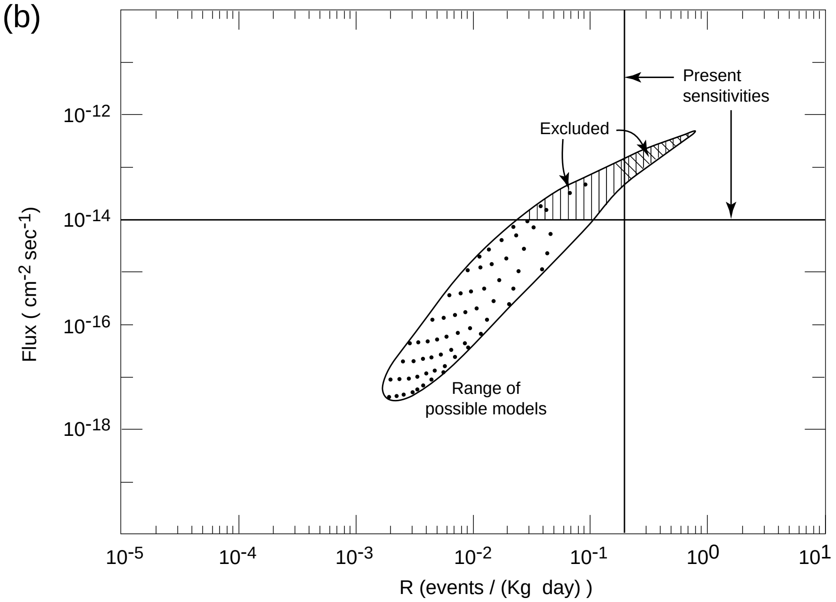


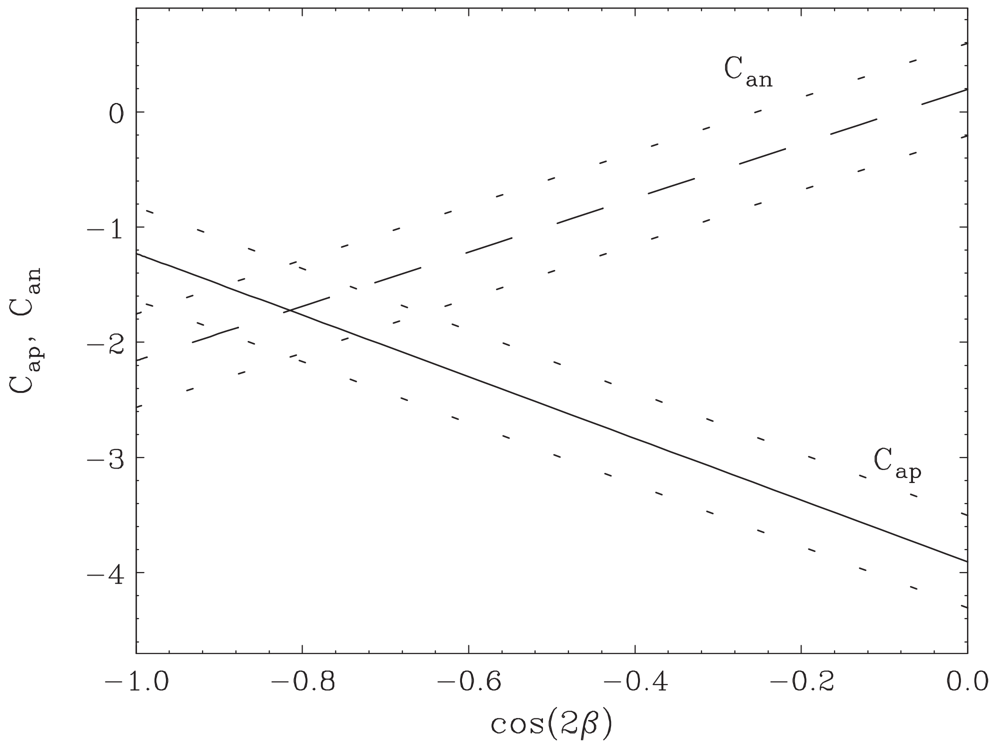
(a)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
$\left(\frac{\rho_\chi}{0.3\ \mathrm{GeV/cm3}}\right)\sigma(\chi p)$ (pb)
BPRS
UK
DAMA
LXe
(prelim.)
Kamioka if~ν_M
1
10
10^2
10^3
10^4
m_χ (GeV)

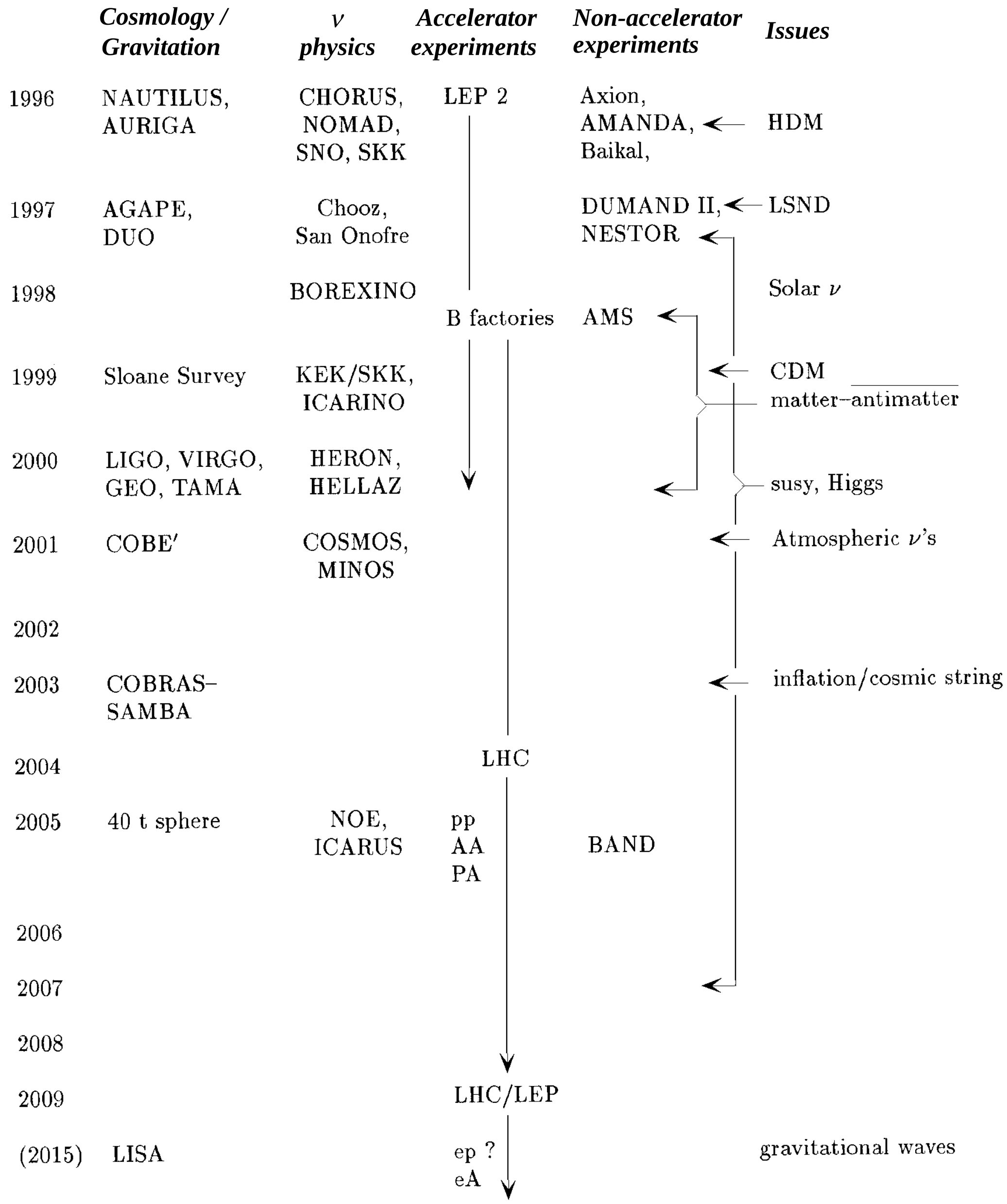


(b)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\left(\frac{\rho}{0.3\ \mathrm{GeV/cm3}}\right)\sigma(\chi p)$ (pb)
BPRS
UK
Sun
DAMA
LXe
(prelim.)
Hd- Moscow
Kamioka if~ν_D
Earth
1
10
10^2
10^3
10^4
m_χ (GeV)


(a)
Flux (cm-2 sec-1)
10-12
10-14
10-16
10-18
Present
sensitivities
Range of
possible models
10-5
10-4
10-3
10-2
10-1
100
101
R (events / (Kg day))


(b)
Flux (cm-2 sec-1)
10-12
10-14
10-16
10-18
Present
sensitivities
Excluded
Range of
possible models
10-5
10-4
10-3
10-2
10-1
100
101
R (events / (Kg day))


C_an
C_ap
C_ap, C_an
0
−1
−2
−3
−4
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
cos(2β)



	Cosmology / Gravitation	*ν physics*	*Accelerator experiments*	*Non-accelerator experiments*	*Issues*
1996	NAUTILUS, AURIGA	CHORUS, NOMAD, SNO, SKK	LEP 2	Axion, AMANDA, Baikal,	HDM
1997	AGAPE, DUO	Chooz, San Onofre		DUMAND II, NESTOR	LSND
1998		BOREXINO	B factories	AMS	Solar ν
1999	Sloane Survey	KEK/SKK, ICARINO			CDM matter–antimatter
2000	LIGO, VIRGO, GEO, TAMA	HERON, HELLAZ			susy, Higgs
2001	COBE′	COSMOS, MINOS			Atmospheric ν's
2002					
2003	COBRAS– SAMBA				inflation/cosmic string
2004			LHC		
2005	40 t sphere	NOE, ICARUS	pp AA PA	BAND	
2006					
2007					
2008					
2009			LHC/LEP		
(2015)	LISA		ep ? eA		gravitational waves