The Dark Universe: The Search for Dark Matter and the Nature of Dark Energy

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In these lectures we discuss the evidence for dark matter in the universe and in galaxies. The search for WIMP dark matter is discussed in detail, including the current search. We describe the ZEPLIN II detectors constructed at UCLA and now underground at Boulby Laboratory. Future search with one ton detectors (Super CDMS, ZEPLIN IV, etc.) at SNOLAB is described. The dark energy first reported at the 1998 Dark Matter conference in Los Angeles is discussed. The current evidence supports an Einstein Cosmological Constant source. Future prospects for the study of the equation of state are described. Precision dark matter determination will be needed.

1. INTRODUCTION

The direct searches for dark matter particles are some of the most difficult experiments ever made as well as the most important. The detection of dark matter could:

(a) Resolve the issue of the existence of dark matter compared to the concept of modifying gravity in some way (MOND)
(b) Provide the discovery of supersymmetry, a profound advance in elementary particle physics
(c) Lead to the understanding of the dynamics of dark matter in our Halo (streams, flow, Halo model)
(d) Lead to a precision determination of the dark matter needed to study the equation of state and dark energy

Over the past 15 years many techniques have been developed to search for dark matter. We classify these detectors as

(A) Non-discriminating
(B) Discriminating

In the beginning detectors of type A searched for dark matter and made modest progress. With the advent of type B detectors great improvements in the search has already been made.

This review article will first outline the evidence for dark matter and possible properties in the Milky Way. We will then concentrate on the current detectors of type B, review the current search results and discuss the future prospects.

In Table 1 we give a brief history of cosmology in the 20^{th} and 21^{st} century.

Table 1 Brief History of Cosmology in the 20th and 21st Century

1915-1917	Einstein: General relativity and Cosmological Constant ( )
~1921	Friedman Equation for expanding universe
~1924-25	Hubble discovers **galaxies**: M31
~1929	Hubble discovers Red Shift: expanding universe
~1933	Zwicky discovers galactic clusters have missing mass later galaxies have **dark matter**
~1958	Gamov et al propose Big Bang leaves behind 3 relic radiation
~1964-65	Panzias/Wilson discover CMBR
~1970s-80s	Growing evidence for Hot Big Bang: nucleosynthesis of light elements H, D, H_e….
~1990	COBE observes fluctuation in CMBR
~1998	2 groups report accelerating universe $\rightleftharpoons$ **dark energy** (?)
~2003	WMAP date gives proof of dark matter 0 = 13.7By, 0 =1, ~ 0.7
~2006	**First round of dark matter experiments!**

The report will rely strongly on the proceedings of the 5th Symposium on Source and Detection of Dark Matter and Dark Energy in the Universe, held at Marina del Rey, February 2004 and previous meetings.

2. THE EVIDENCE FOR DARK MATTER

In 1993 F. Zwicky studied the galaxies in the COMA cluster and noted that the rotation velocities were too large for the system to be stable and bound. He suggested there must be missing mass in the cluster [2]. Today we know that these clusters are dominated by dark matter. The mass is not missing but is dark [3].

The rotation velocity or stars in undeveloped galaxies also indicate that there is dark matter in galaxies [3]. Perhaps the most convincing evidence comes from the WMAP data that shows [4]

$$\Omega_0 = 1.02 \pm 0.002$$

and

$$\Omega_m \approx 0.29 \pm 0.05$$

Baryons cannot account for this value of $_m$. Therefore there must be appreciable non-baryonic dark matter in the universe.

3. DARK MATTER IN THE MILKY WAY GALAXY: HALO UNCERTAINTY AND STREAMS

In order to detect dark matter particles we must have an understanding of the flux of particles through any given detector on earth. Therefore we must understand the halo of dark matter for our galaxy [1]. In addition some models give clumps of dark matter, others give causes of dark matter [5]. These effects can increase or decrease the rate of interaction in an earth-bound detector. At the recent Marina del Rey meeting we devoted an entire session to the knowledge of our halo [1].

The halo model is very important when attempting to compare different types of experiments, say, direct search and annual variation searches [6]. There is no doubt that the ultimate test for the existence of dark matter will be the observation of an annual variation signal [7]. However there is a strong debate among the experiments as to whether this annual variation signal should be carried out with discriminated events (reduced background) or with raw data (large background). We will show an example of the former from simulation of the ZEPLIN II detector later in this article.

There are also models of dark matter caustics by P. Sikivie and colleagues that can give the opposite sign of the annual variation to that expected in the standard isothermal sphere model [5]. At the Marina del Rey meeting two notable contributions were given by Anne Green and Larry Krauss [1].

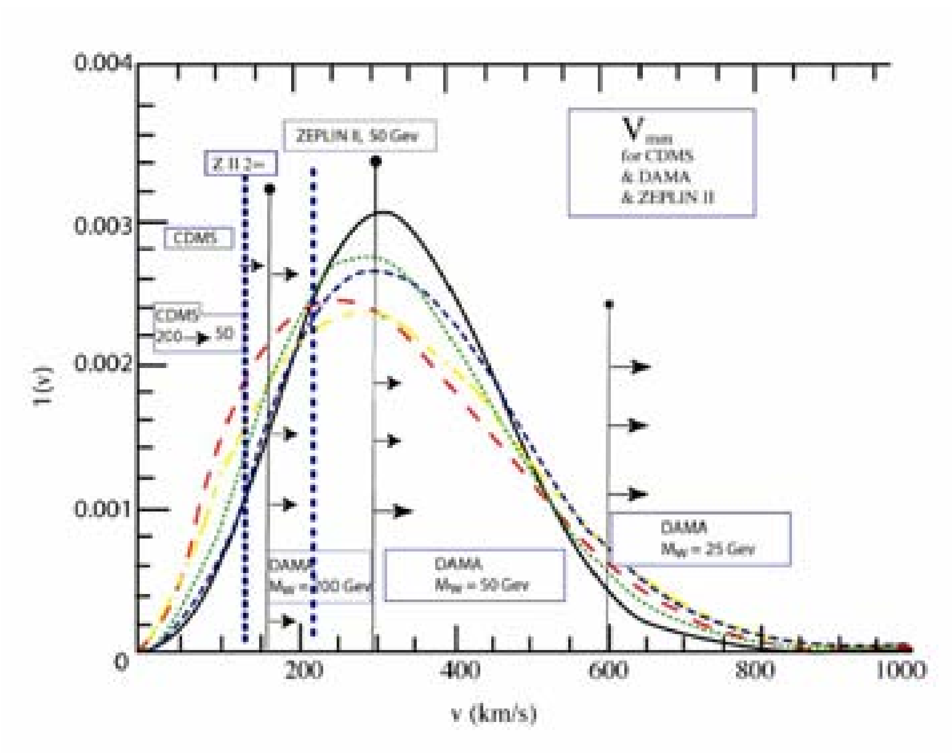

Fig. 1. Schematic of the halo velocity distribution with minimal velocities for CDMS, DAMA and ZEPLIN II; the figure is modified from A. Green, P.R.D. 68, 023004 (2003) (Reference 6).

In Fig. 1 we show the kinematics of the halo velocity distributions for various detectors [8]. In Fig. 2 we show the work of L. Krauss and colleagues that compares annual variation signals to direct search signals for a large variety of halo models [1]. Note that the variation is not very large. We will discuss this later in the article when the current results of direct searches is described.

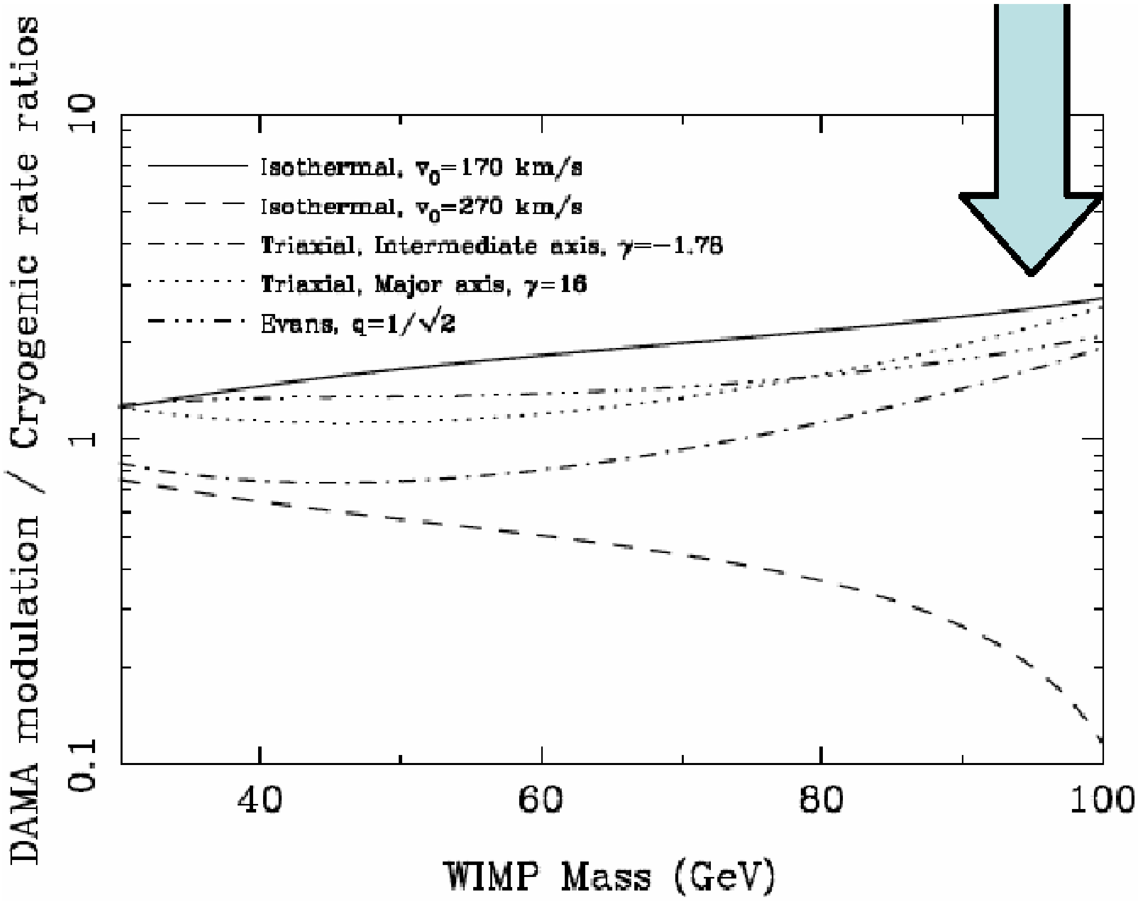

Figure 2. Work of L. Krauss and colleagues in different halo models [1].

4. METHODS FOR THE DIRECT SEARCH FOR DARK MATTER PARTICLES

The direct search for dark matter particles is among the hardest experiments ever undertaken in science [9]. Backgrounds exist for cosmic rays, natural radioactivity even at great depths underground. Early reviews can be found in Ref. 10. Therefore the next generation detector will almost certainly use a method to discriminate against background as well as an active veto shield to reduce the neutron flux from cosmic ray induced events even at great depths underground.

The types of detectors can be generally classed as

1. Cryogenic
2. Liquid Xenon, Neon or Argon
3. Other methods such as bubble chamber or non-discriminating detector.

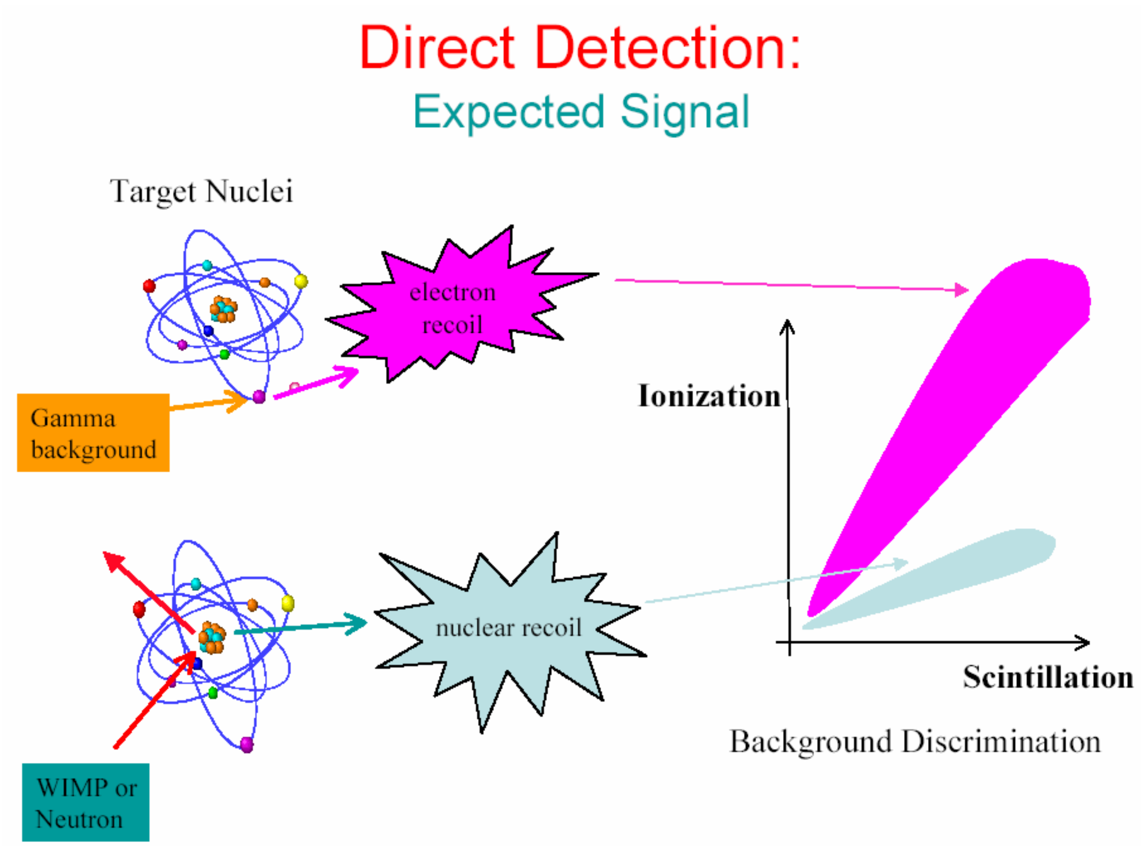

Figure 3. Concept of discrimination in a liquid Xenon detector (H. Wang/UCLA).

To get some sense of the number of detectors [2] and time scale we give a partial list in Table 1 [11]. The concept of discrimination of background is illustrated in Fig. 3 for a liquid Xenon type detector.

4.1. Cryogenic Detectors

For more than 15 years several groups around the world have been studying the possibility of constructing a low temperature detector to measure the recoil energy of the nucleus having been hit by a WIMP [3]. Since this energy is in the range of kiloelectron volts the detector must act as a bolometer to measure the "heat" produced by the recoil [14]. Three groups have now made such detectors using this technique. These groups are:

CDMS

Edelweiss

Cresst

All three groups have now reported limits in the in the search for dark matter particles. So far the nucleus of choice has been Ge or Si. However the Cresst group has worked with $Al0_2$ as well as CaW mixtures.

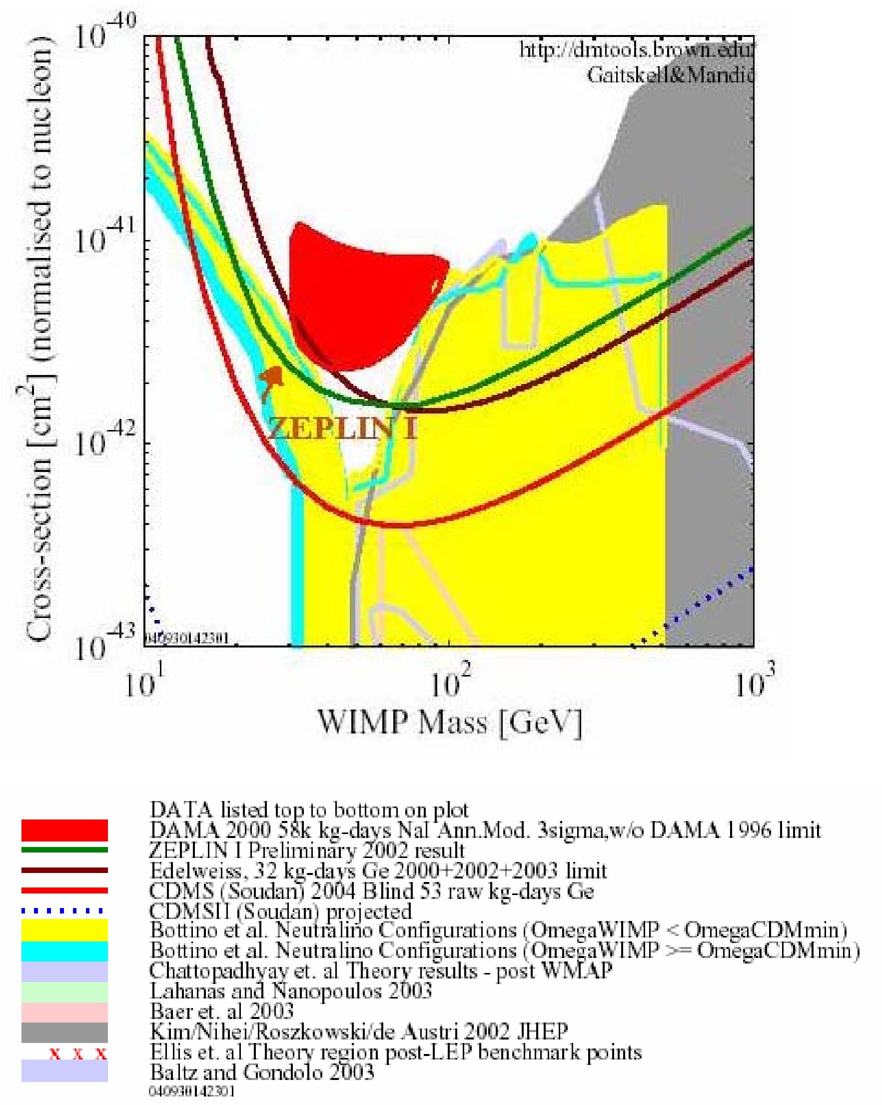

Fig. 4. Current limits on dark matter search (R. Gaitskell summary).

The best limits that have been set by these detectors came from the CDMS II detector operated at the Soudan underground laboratory [18]. These limits are well below the claimed signal by the DAMA group as shown in Fig. 4. All of these detectors are being upgraded to larger mass and 2005 will be a big year for these types of detectors.

4.2. Liquid Noble Gas Detectors: Xenon, Argon and Neon

Another promising method to detect dark matter is to use the scintillation light produced in Noble gas liquids [12]. The process is very well known since excimer lasers use a similar concept. For example the very first excimer laser was made in Russia in 1970 using liquid Xenon. A key part of this method is to apply an electric field to the detector to drift out any electrons that are produced at the recoil vertex as a basis to discriminate against background [12] [Fig. 3, 5].

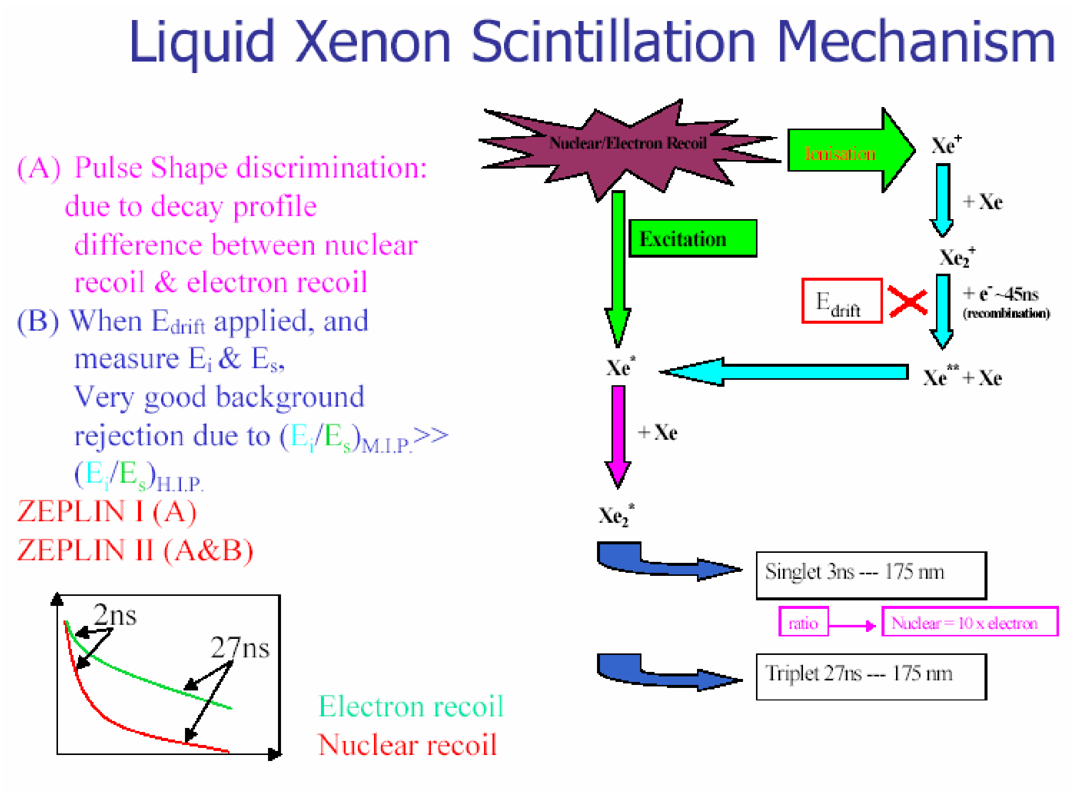

Fig. 5. Schematic of signals in a liquid Xenon detector [12].

This method was just invented by our group within the ICARUS collaboration and is the basis for the ZEPLIN II, III, IV and XENON, as well as XMASS detector [11]. In Fig. 5 we show the basic concept of this method. In Fig. 6 we show the schematic of the ZEPLIN II detector and the complete detector being tested at RAL [19]. The XENON detector uses a similar design [1][20].

More recently there have been studies of the use of liquid Argon (WARP) and liquid Neon (Clean) as WIMP detectors. One virtue of the use of liquid Xenon is the existence of different isotopes with different spins, thus testing the spin dependence of the WIMP interaction.

The ZEPLIN I team detector has reported a limit in the WIMP search using a partial discrimination method of pulse shape analysis. Of all the current detector concepts the one most easily expanded to the one ton scale seems to be liquid Xenon. The US/UKDMC team is designing the XEPLIN IV/MAX [12] detector that will have a mass on the range of one ton. Currently it is not clear if there will be a single one ton detector or four 250 kg detectors.

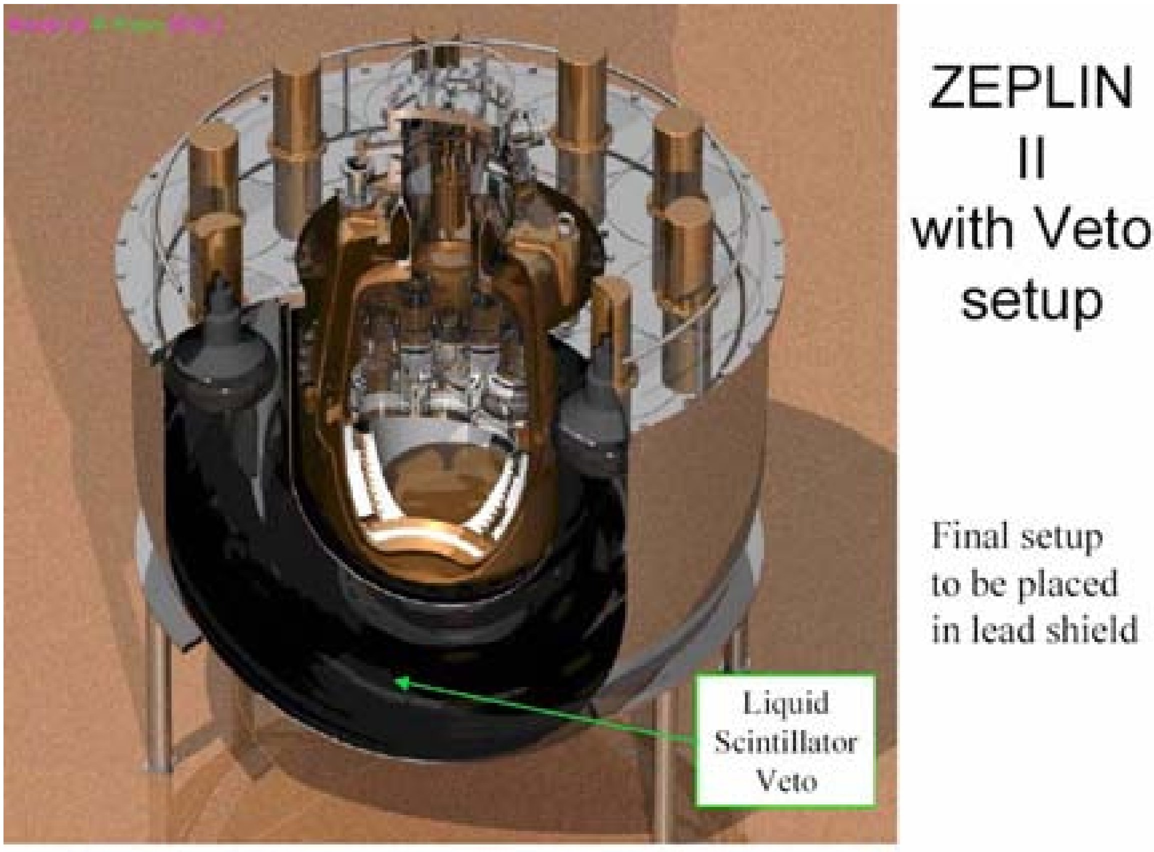

Fig. 6. Schematic of ZEPLIN IV Detector (see [12] for example).

A schematic of the one ton ZEPLIN IV/MAX detector is shown later in this paper.

The goal of the one ton detectors is to reach the cross-section level of absorb 10^{-9} to 10^{-10} pb. Current calculations of the cross-section for SUSY WIMPS (see Fig. 7) indicate that a discovery of dark matter is likely to be made in this cross-section range [14].

4.3. Other Types of Detectors

There are many other ideas for large WIMP detectors. We only discuss two here.

One concept is GENIUS, which will use one ton of 76Ge (also to be used for double decay search)[see Table 3 for references]. While this detector has no discrimination it is to be produced of ultrapure material so that there is little or no radioactive background. The detector is submerged in a large bath of liquid Nitrogen to shield out neutrons from cosmic rays.

Another concept is to construct a “bubble chamber” to detect WIMPS by the formation of bubbles in the detector. More information on this novel scheme can be found in Ref. 1 (see papers in the 2004 Dark Matter meeting).

TABLE 3. STATUS OF THE SEARCH FOR DARK MATTER PARTICLES

Detector	Search Method	Exposure kg/day	Possible signal events	Limit events/kg/day	Comment
DAMA	Annual variation of non-discriminating data			Effective 1 – 0.3 90% CL	Not confirmed
CDMS I (SLAC) 2000	Direct interaction		13	0.4	Events consistent with neutrons
CDMS I (SLAC) 2002	Direct interaction	28	20	0.35	Events consistent with neutrons
Edelweiss 2002 2003	Direct interaction Direct interaction	10 20	0 2	0.2 0.2	Events consistent with neutrons
ZEPLIN I	Direct interaction (pulse shape analysis)	300	Null	0.1	Background substration

~ 360 (before new CDMS II) kg/d data

1) The DAMA results suggest a signal at 0.8 events/kg/day (for standard halo model)
2) The CDMS group carries out a joint fit to CDMS/SAMA data, signal ruled out at > 98% CL.

Table 4. One Ton Dark Matter Detector Proposals

Detector	Material	Method	Proposal	Current Prototype
GENIUS (LNGS) (a)	Ge	Ultrapure detector in LNGS	1997	10kg GENIUS test detector
ZEPLIN IV (Max) (Boulby/SNOLAB) (b)	Xe	2 phase discriminating detector	~1999	ZII/III Detectors at Boulby
Super CDMS (SNOLAB) (c)	Ge/Si	Ionization and Phonons	~2001	CDMS II
XMass (Japan) (d)	Xe	2 phase (?)	~2000	prototype
Xenon (LNGS) (e)	Xe	2 phase Detector	~2001	prototype
WARP (LNGS) (f)	Ar	2 phase (possible larger than one ton)	~2003	prototype

References

a. H.V. Klapdor-Kleingrothaus et al, Z. Physics A 359, 351 (1997).
b. D. Cline, H. Wang et al, UCLA DM 2000, published in Proceedings.
c. R. Gaitskell et al, 2001 Snowmass Proceedings.
d. Y. Suzuki, hep-ph/008296.
e. ZENON Collaboration, NSF Proposal 0201740, 2001.
f. C. Rubbia talk, UCLA DM 2004, to be published in the Proceedings.

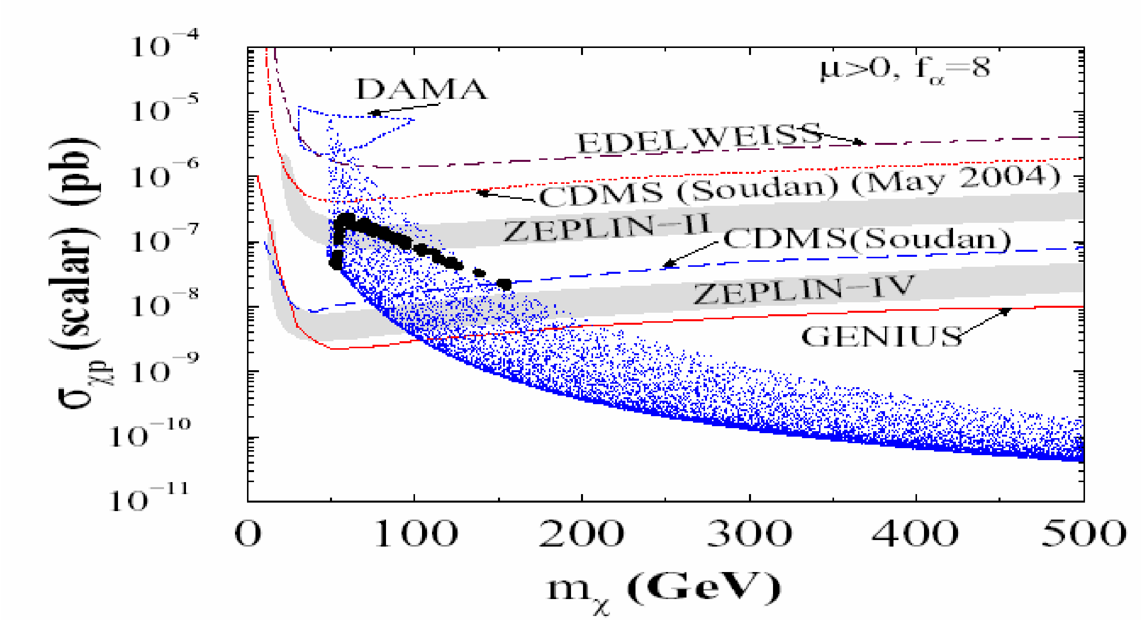

Fig. 7. Expectations for SUSY WIMP cross-sections by Pran Nath and colleagues.

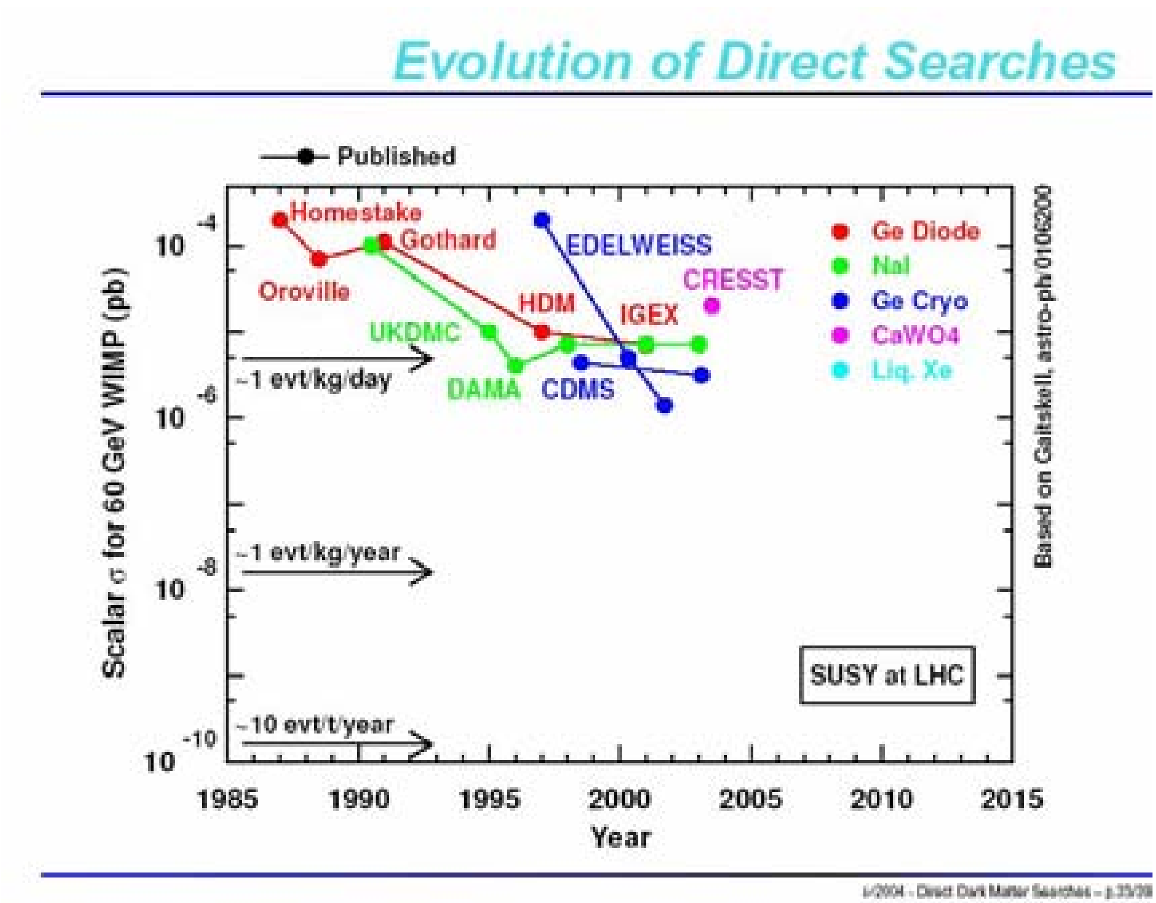

Fig. 8. History of the search for dark matter particles (R. Gaitskell).

The experiment collected 52.6 kg days of data with one event being recorded fully consistent with the estimated background. This limit is also shown in Fig. O [20]. As can be seen from Fig. O the bulk of the DAMA region is in conflict with several experiments. At the Paris Neutrino (04) meeting the first results from CRESST were shown (Fig. P) that also seem inconsistent with the DAMA allowed region.

There is one small region of the DAMA allowed region that may not yet be excluded as was pointed out by Gelmini and Gondolo [private communication], who assumed an arbitrary flow of dark matter the maximize the onward variation signal and minimize the direct search limit. A small region in mass near 8 GeV was found (Fig. 10) that could fit all the data. In this case the Na target in DAMA (not the I target) was assumed to be struck. This region can be observed in CDMS II by analyzing the Si data or by lowering the threshold.

In essence except for this fine tuned region the entire cross-section region down to ~10^{-6} pb has been eliminated.

5. STATUS OF THE SEARCH FOR DARK MATTER PARTICLES

A serious search for dark matter particles started around 1995 with the use of NaI detectors at several locations. Fig. 8 traces the history of this early search. In Table 2 we provide a list of the leading detectors being used for the search [11]. By the end of 2003 there were considerable data on this search summarized in Table 3 [1]. In addition the CDMS I group carried out a joint fit of their data and the DAMA data, and claimed these data were inconsistent to 98 percent confidence level. Fig. 4 shows the limits on the dark matter search at the time of the DM04 February 2004 meeting [1]. One month later the new results from CDMS II at the Soudan underground laboratory were presented [11].

6. FUTURE DETECTORS IN THE TON SCALE AND SENSITIVITY

There were many new estimates for the SUSY DM cross-section range given at the DM04 symposium. In Fig. 7 we show one that was published elsewhere by P. Nath and colleagues [14]. Note in these types of calculations that the most likely region of discovery is between 10^{-7} - 10^{-8} pb cross-section but that the signal could be as low as 10^{-9} – 10^{-10} pb. See also Ref. 1 for similar estimates.

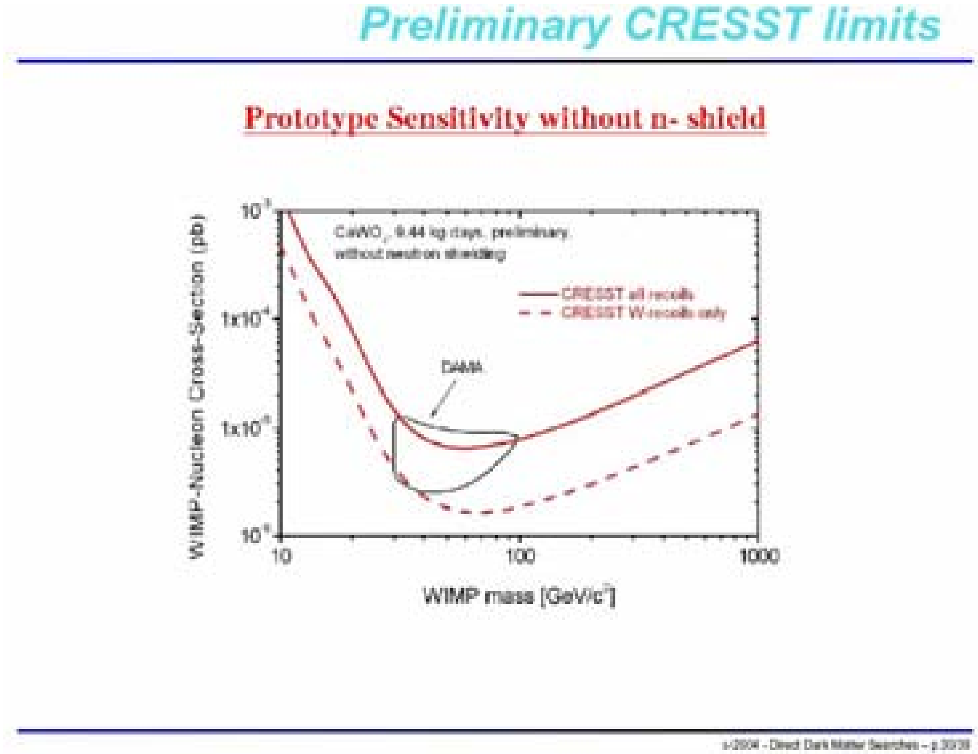

Fig. 9. Results for CRESST II shown at the Paris Neutrino 04 meeting , to be published in the proceedings.

While the next generation of detectors will likely reach 10^{-7} or even 10^{-8} pb (CDMS II, ZEPLIN II, Edelweiss II, etc.) there is no certainty that even 10^{-8} pb can be reached. For this case much larger detectors in the one ton range will be needed. Even if a tentative signal is observed at 10^{-8} a much larger detector will be needed to confirm this signal.

A new, third-generation of detectors is being studied for this case. We consider the example of ZEPLIN IV/MAX here for such a detector [12]. In the case that a single one ton detector is to be constructed the detector will require some new concepts beyond that employed in the ZEPLIN II/III detectors. Of course the data from these detectors will be crucial to the understanding of how such a detector will work underground.

We show one schematic design of the ZEPLIN IV/MAX detector in Fig. 11 [21]. The expected reach of ZEPLIN IV/MAX is shown in Fig. 12. Table 3 lists most of the worldwide proposed one ton detectors.

A summary of the expected reach of the other one ton detectors is shown in Fig. 13 (by R. Gaitskell) as a function of time. It is quite possible in the case of supersymmetry that SUSY dark matter could be discovered before the LHC discovers SUSY.

7. DISCOVERY OF DARK ENERGY

At the 1998 Dark Matter meeting held at Marina del Rey two groups (Supernova Cosmology Group; High Z team) reported results for the first time that the universe is accelerating. In Fig.14 we show the schematic of the method (see references 24, 25).

8. STUDY OF THE EQUATION OF STATE FOR DARK ENERGY

The study of dark energy requires us to understand the equation of state:

$$\omega(z) = P / p = f(z)$$

In Table 5 we indicate some of the developments in this field. During the period 2002-2003 there were several fits to data (26, 27, 28). In the simplest case we assume no Z dependence and measure $\omega_0 = P / p$. For $\omega_0 = -1$ we have the example of the cosmological constant.

Table 5

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1) In 1998 evidence for an accelerating universe was presented using SN1a data by 2 groups at Marina del Rey meeting
2) This was confirmed in ~2000
3) In 2003 WMAP study of CMBR gave

$\Omega_{DM} = 0.27 \;\; \tau_0 = 13.7 By$

$\Omega_0 = 1 \pm (.03 \;\; now\, .01) \;\; \Omega_\Lambda = 0.7$

$\omega = -1 \; is \; \Lambda$ (Einstein's cosmological constant)

4) New results from SN1a, CMBR give first constrained on the equation of state of the dark energy:

   $\omega = -1.2^{+.3}_{-.4}$ Tonrey [27]

   $\omega = -1^{+.13}_{-.19}$ Reiss et al [26]

5) New methods to measure involve clusters ratio galaxies … $\omega = -1^{+0.1}_{-0.2}$ consistent with No Z dependence [Fig. 16]
6) By 2006 we expect better results ~ 500 SN1a and on error of 0.05

   DM/DE 2006 Expect new DM/DE results

7) In the long range new telescopes like LSST/SNAP may improve but only if $_{DM}$ is known within precision.

Fig. 5 shows how the Z dependence of the DE that determines . The current results are summarized in Fig. 15 and suggest that a cosmological constant (- -1) is favored.

Future precision measurements (Fig. 17) require precise $_{DM}$ measurements as well.

9. SUMMARY

The direct search for dark matter particles within the supersymmetry model is reaching a critical stage. The next generation of detectors could discover these particles as we have shown in this review. In any case another generation of one ton class detectors will be required to either confirm and explore the discovery or to confirm the search down to $10^{-9} - 10^{-10}$ pb.

One key test for dark matter will be the observation of an annual variation of the signal of discriminated events. See Ref. 1 for a discussion of the annual variation signal.

This is undoubtedly an exciting time in the 70 year search for the origin of the missing mass just identified by Zwicky in 1933.

The discovery of dark energy in 1998 is of great importance. Current measurements suggest this is likely due to an Einstein cosmological constant effect.

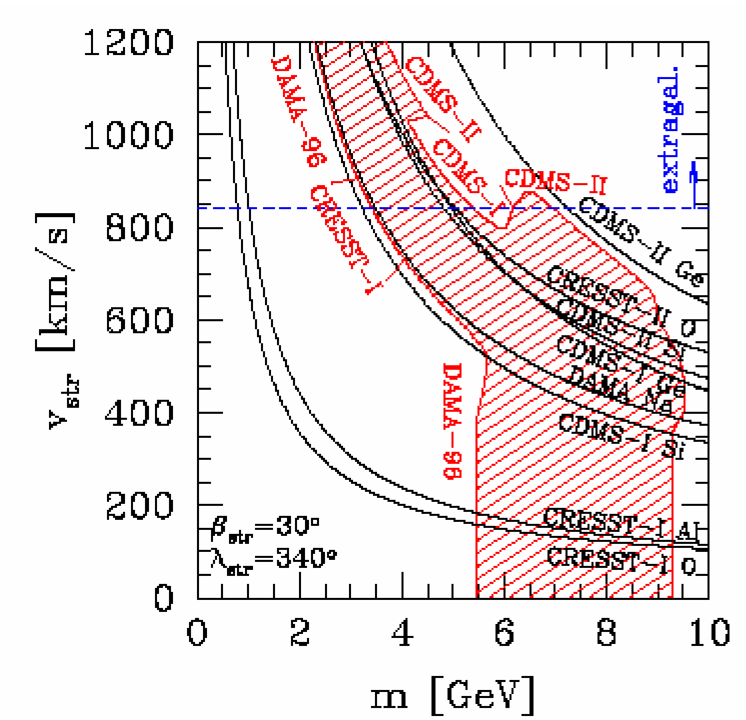

Fig. 10. Recent work from Gelmini and Gondolo, assuming a fine tuned dark matter flow.

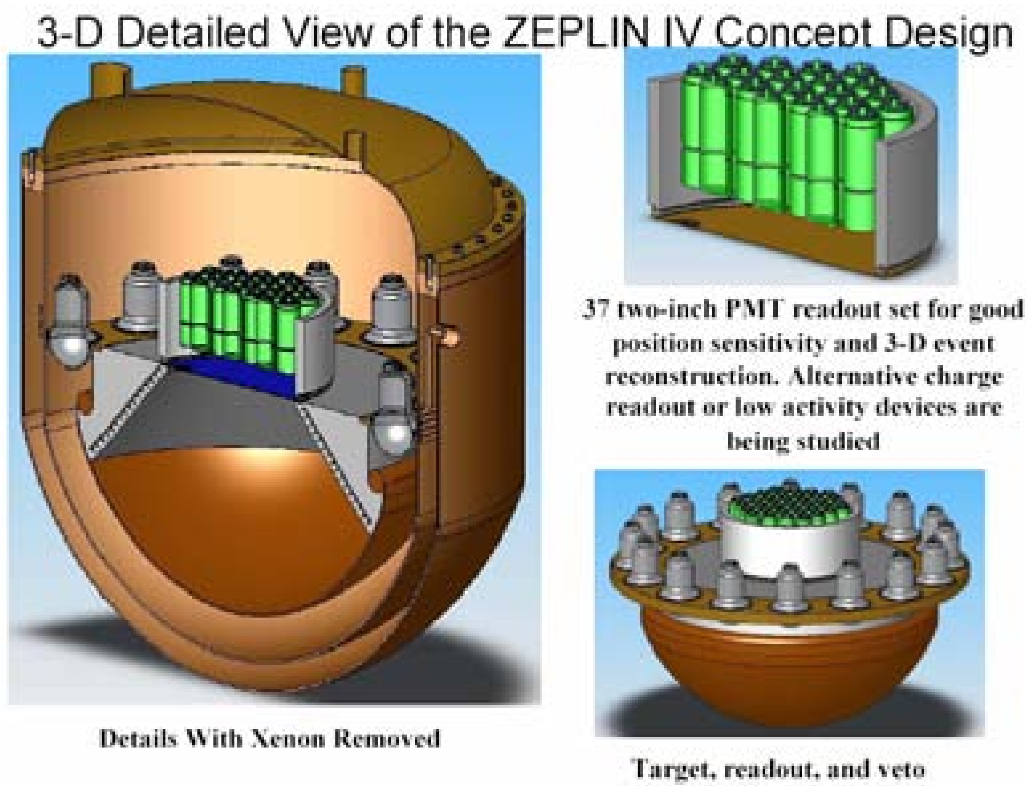

Fig. 11. Schematic of one version of ZEPLIN IV/MAX (H. Wang, private communication).

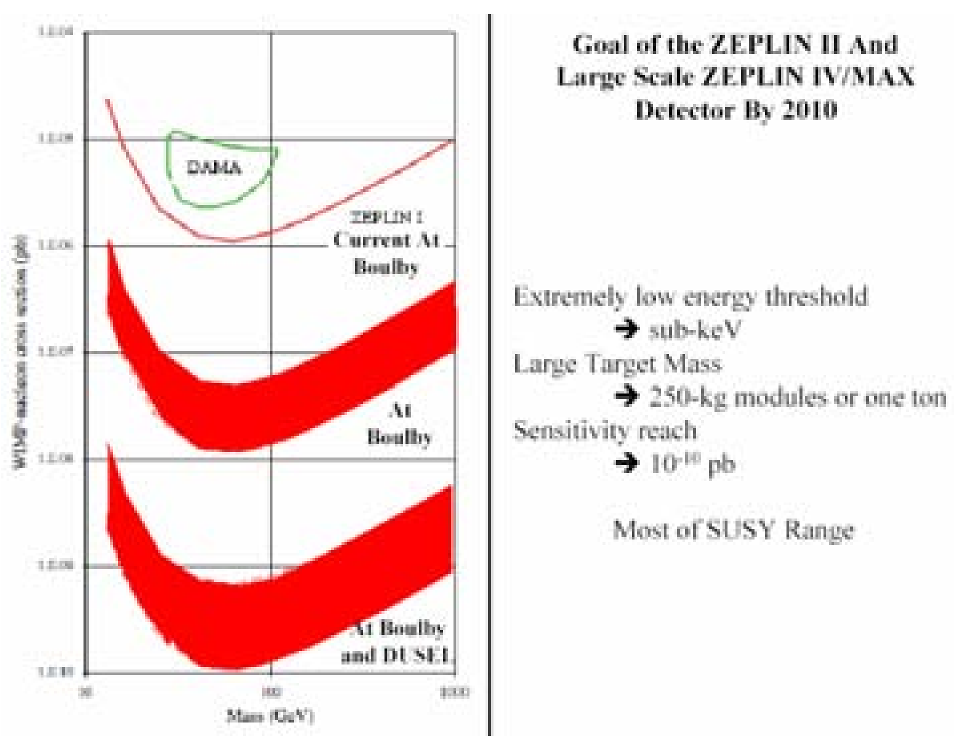

Fig. 12 ZEPLIN II and IV goals.

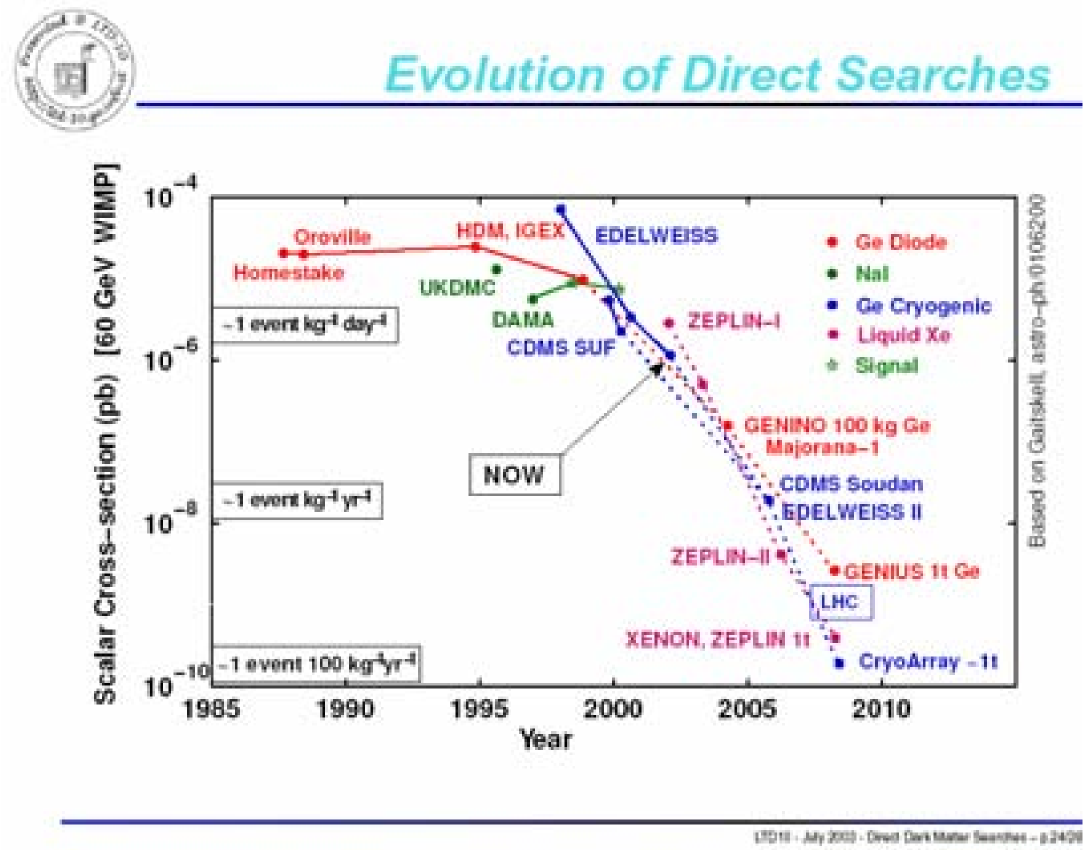

Fig. 13. Schematic of the possible future of the dark matter search (R. Gaitskell).

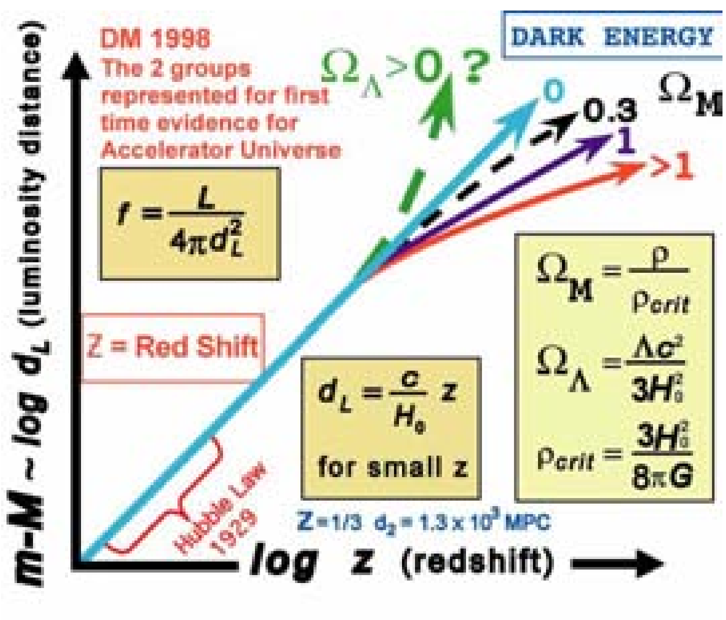

Fig. 14. Measurement of the magnitude difference for SN1A from expectations of Hubble's Law as a function of red shift can determine the dark energy in the universe.

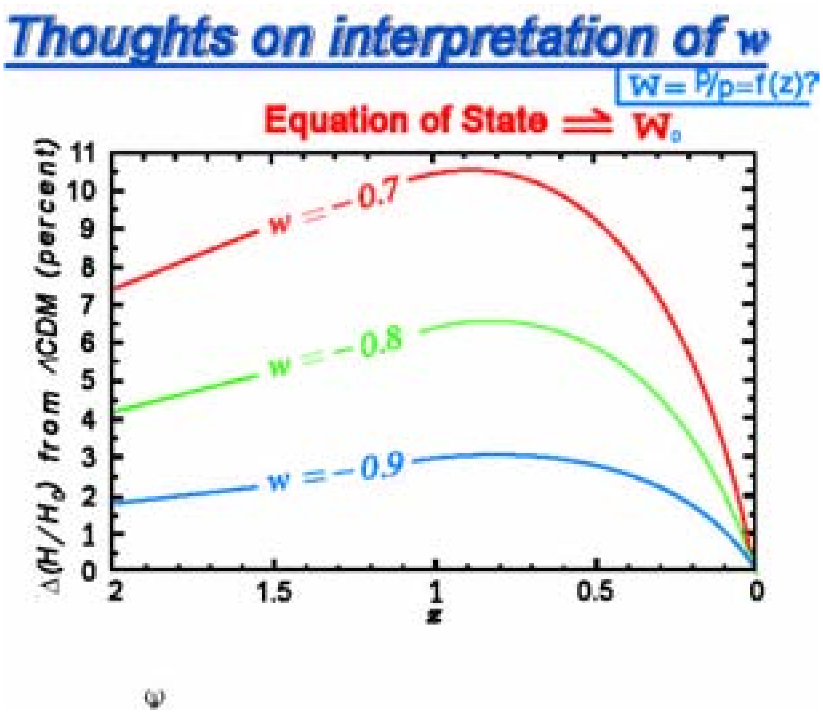

Fig. 15. The red shift dependence for different values of . Current data favor a value near –1.

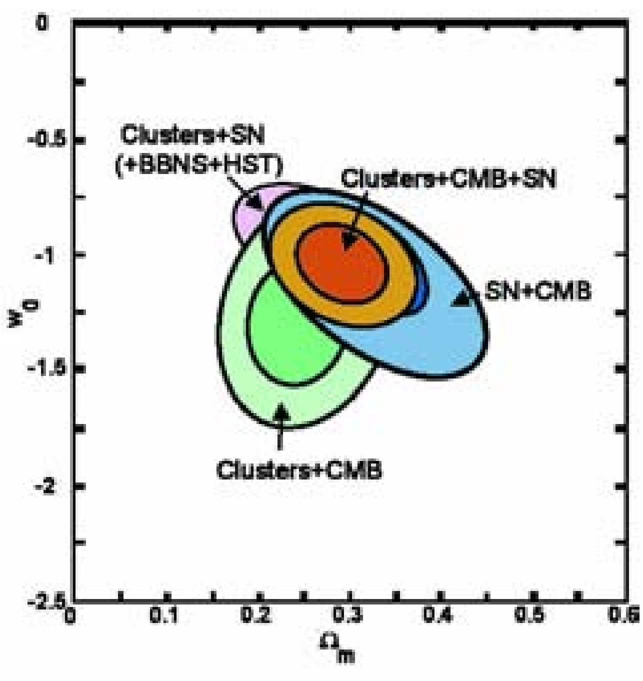

Fig 16. The 68.3 and 95.4 persent confidence limits in the ($_{m}$, $_{0}$) plane for the various pairs of data sets and for all three data sets combined. A constant dark energy equation of state parameter is assumed.

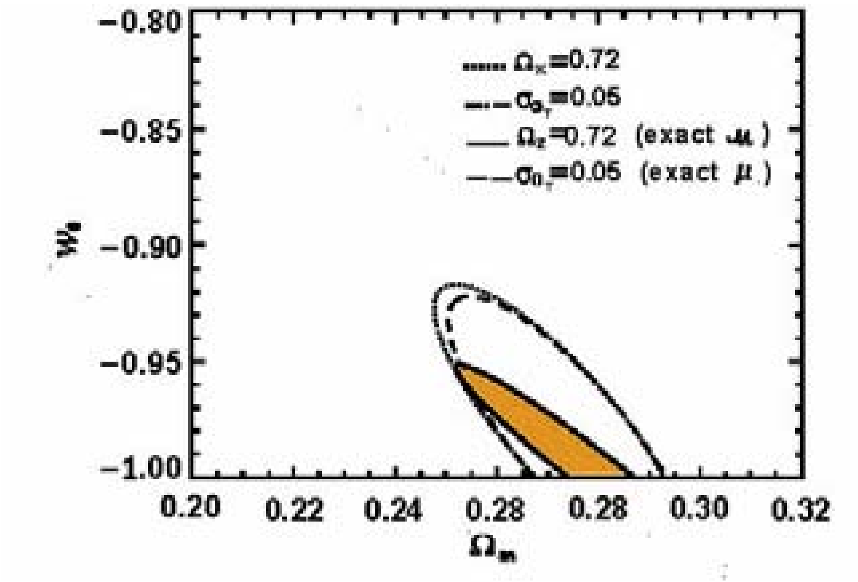

Fig. 17. 68.3% confidence regions for ($_{m}$, $_{0}$) in the one-year SNAP scenario assuming exact knowledge of X, i.e. no prior knowledge on the geometry. The filled region (solid line) assumes exact knowledge of *M*, the dasked line within the filled region assumes also a prior knowledge with $_{m}$ Gaussian around the true value and $_{m-prior}$ =0.05. The dotted and dash-dotted lines assume no prior knowledge of *M*, without and with $_{m}$ prior, respectively.

References

1. See the Proceedings of the 5th Symposium on Sources and Detection of Dark Matter and Dark Energy in the Universe, 2004.
2. F. Zwicky, Helv Phys Act 6 (1933) 110.
3. C. Rubbia and W.K. Ford, Ap J 159 (1970) 379; D.H. Rogstad and G.S. Shostak, Ap J 176 (1972) 315.
4. C.L. Bennett et al, Ap J Suppl 148 (2003) 1.
5. P. Sikivie, Phys Lett B 432 (1998) 139.
6. A. Green, Phys Rev D 68 (2003) 023004; C. Copi, L. Krauss, Phys Rev D 67 (2003) 103507; J.F. Navarro, C.S. Frank and S.D.M. White, Ap J 462 (1996) 563; B. Moore et al, Ap J Lett 499 (1998) L5.
7. K. Freese, J.A. Frieman and A Gould, Phys Rev D 37 (1988) 3388; G. Gelmini and P. Gondolo, Phys Rev D 64 (2001) 023504; F.S. Ling, P. Sikivie and S. Wick, Diurnal and Annual Modulation of Cold Dark Matter Signals, UFIFT-HET-04-6.
8. D.B. Cline, Direct Search for Dark Matter Particles with Very Large Detectors, from the Proceedings for Beyond the Desert 2003, Springer Proceedings in Physics v. 92, Hans Klapdor-Kleingrothaus, ed., 2004.
9. M.W. Goodman and E. Witten, Phys Rev D 31 (1985) 3059; A. Drukier, K. Freese and D.N. Spergel, Phys Rev D 33 (1986) 3495; I Wasserman, Phys Rev D 33 (1986) 2071.
10. J.R. Primack, D. Seckel and B. Sadoulet, Ann Rev Nucl Part Sci 38 (1988) 751; P.F. Smith and J,D, Lewin, Phys Rep 187 (1990) 203; G. Jungman, M. Kamionkowski and K. Griest, Phys Rep 267 (1996) 195.
11. D. Cline, Scientific American, 288:3 (2003), 50-59.
12. D. Cline, A. Curioni, A. Lamarina et al, Astropart Phys 12 (1999) 373-377.
13. A. Bottino et al, Phys Rev D 69 (2004) 037302.
14. U. Chattopadhyay and P. Nath, hep-ph/0405157.
15. D.S. Akerib et al, (CDMS Collaboration), Phys Rev D 68 (2003) 82002.
16. A.Benoit et al, Phys Lett B 545 (2002) 43.
17. L. Stodolksy and F. Probst, talk at Dark Side of the Universe, Ann Arbor, May 2004.
18. CDMS II; see Table 3.

19. D. Cline, Y. Seo, H. Wang et al, “Status of ZEPLIN II and ZEPLIN IV Study”, *Nuclear Physics B, Proceedings Supplements, 5th International Symposium on Search and Detection of Dark Matter and Dark Energy in the Universe*, ed. by D.B. Cline (Elsevier, Amsterdam 2003), 229-232.
20. XENON Detector; see Table 3.
21. See for example D. Cline, “ZEPLIN IV: A One Ton WIMP Detector”, a paper given at the Dark 2002 meeting, Capetown, January 2002, to be published in the proceedings of DARK 2002, Springer, Heidelberg, 2002, eds. H.V. Klapdor-Kleingrothaus and R. Viollier, 492-498.
22. Private communication from H. Wang.
23. GENIUS; see Table 3.
24. S. Perlmutter et al, ApJ 517 (1999), 565.
25. A.G. Riess et al, ApJ 116 (1998), 1009.
26. A.G. Riess et al, ApJ 607 (2004), 665.
27. Tonry et al, ApJ 594 (2003), 1.
28. M. Tegmark et al, Phys. Rev. D 69 (2004b), 103501.