Fermilab Center for Particle Astrophysics: Projects and Possibilities

May 13, 2008

Abstract

A vibrant Particle Astrophysics program at Fermilab is central to the Laboratory's mission and to its intellectual vitality, complementing the core program of accelerator experiments. Fermilab helped pioneer this field twenty-five years ago and today has an impressive program that includes theoretical astrophysics, ultra-high energy cosmic rays, dark matter detection, and optical cosmology. The Fermilab Center for Particle Astrophysics retreat in Fall 2007 reviewed this progress and explored a number of possible directions for future endeavors. In some cases, future projects will be natural progressions from existing experiments. In other cases, they involve new research areas that exploit the expertise and infrastructure that the Laboratory has developed. This document, written by the retreat participants, summarizes the range of exciting possibilities discussed and presents ideas for moving forward in several project areas. We have not attempted to prioritize Fermilab's future efforts within Particle Astrophysics; rather we present a menu of options which appear most fruitful to explore.

Fermilab Center for Particle Astrophysics Retreat

Twenty-five years ago, scientists at Fermilab helped develop the idea that one can learn about the small-scale physics that governs sub-atomic particles by studying the large scales that have traditionally been the province of astronomy. The fruits of this early labor have been harvested over the last decade. We now have strong evidence for physics beyond the Standard Model of Particle Physics in the form of non-zero neutrino masses, non-baryonic dark matter, dark energy with an energy density of $(10^{-3}\text{eV})^4$, and a second type of dark energy with an energy density of $(10^{25}\text{eV})^4$ (primordial inflation). Together, these elements compose a consistent accounting for the constituents of the universe and for the formation of structure within the universe—the new Standard Model of Cosmology. This new cosmological model sits squarely on the shoulders of new physics, much of which remains to be understood at a fundamental level:

- What is dark matter?
- What is causing the expansion of the universe to accelerate?
- Was an epoch of primordial inflation responsible for the origin of large-scale structure and did it leave observable imprints?
- What is the origin of the highest-energy cosmic rays?
- What are the neutrino masses and what is their impact on cosmic evolution?

For the future, addressing these fundamental questions will require new experiments in particle astrophysics coupled with accelerator-based experiments that probe these phenomena in complementary, mutually supporting ways. A number of national reports, from *Quarks to the Cosmos* to *the Quantum Universe* to *the Physics of the Universe* to *EPP 2010* have called out the critical importance of addressing these questions and their direct relevance to the goals of High Energy Physics. This document explores a range of possibilities and opportunities for new experiments in particle astrophysics that aim at uncovering fundamental physics.

To plan for the future, the Fermilab Center for Particle Astrophysics organized a retreat in the Fall of 2007. The retreat was attended by fifty people with a wide range of interests and backgrounds. Over the course of two full days, ten project areas were presented and discussed. Some of these are areas in which Fermilab has already established a successful program. Discussion in these areas centered on how to proceed as the scope of the experiments grows and the number of individual projects nationally decreases. Other topics are ones in which Fermilab has no current experimental involvement but which present excellent targets of opportunity.

In each case, the following questions were considered:

- Is the science compelling and world-class?
- Is it consistent with our fundamental science mission?
- (How) Can the science be funded?
- Will the project leverage Fermilab's human and infrastructure resources?
- Does it offer a natural role for Lab stewardship of and collaboration with its User community?

- Who will participate and lead?
- What are the time constraints on the national scale for joining and/or initiating the project?

Each of the following sections summarizes the presentation and subsequent discussion of a project. It is unlikely that Fermilab will be able to move forward on all of these fronts, but these projects are so exciting and powerful in their scientific reach that a future built on even a subset of them will do justice to our proud heritage in this field.

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Each section in this document describes a different project or set of projects covered at the retreat. There was considerable discussion before the retreat as to which fields should be included, but there is no intention here to prioritize projects. Each description of a project was written by its proponents, who used the presentation[1] and discussion at the retreat to inform their section.

[1] Presentations can be found at `http://astro.fnal.gov/Retreat07/What.html`.

Fermilab's first particle astrophysics project was the Sloan Digital Sky Survey, so our involvement in the field dates back to the mid-1990's. With responsibility for the DECam part of the Dark Energy Survey and partnership in the Supernova Acceleration Probe, Fermilab has a clear path forward. Nonetheless, understanding the scope of competing projects and how to leverage our skills and resources remain vital considerations.

Before the Dark Energy Survey was approved, the Experimental Astrophysics Group joined the (unsuccessful) PRIME infrared satellite proposal. Depending on the outcome of the SNAP proposal, opportunities in this regime – which probes the high redshift universe – may be an important component of the particle astrophysics program.

Weakly Interacting Dark Matter (WIMP) particles can be detected when they scatter off nuclei. Progress in this field has been rapid and Fermilab is heavily involved in two experiments, CDMS and COUPP. The rapid progress and compelling science means that the Lab must keep abreast of developments as it strives to maintain its leadership in the field.

In under a year, Fermilab scientists completed the GammeV experiment which excluded an important region of axion-like parameter space. There are several possible future projects the Lab might decide to join.

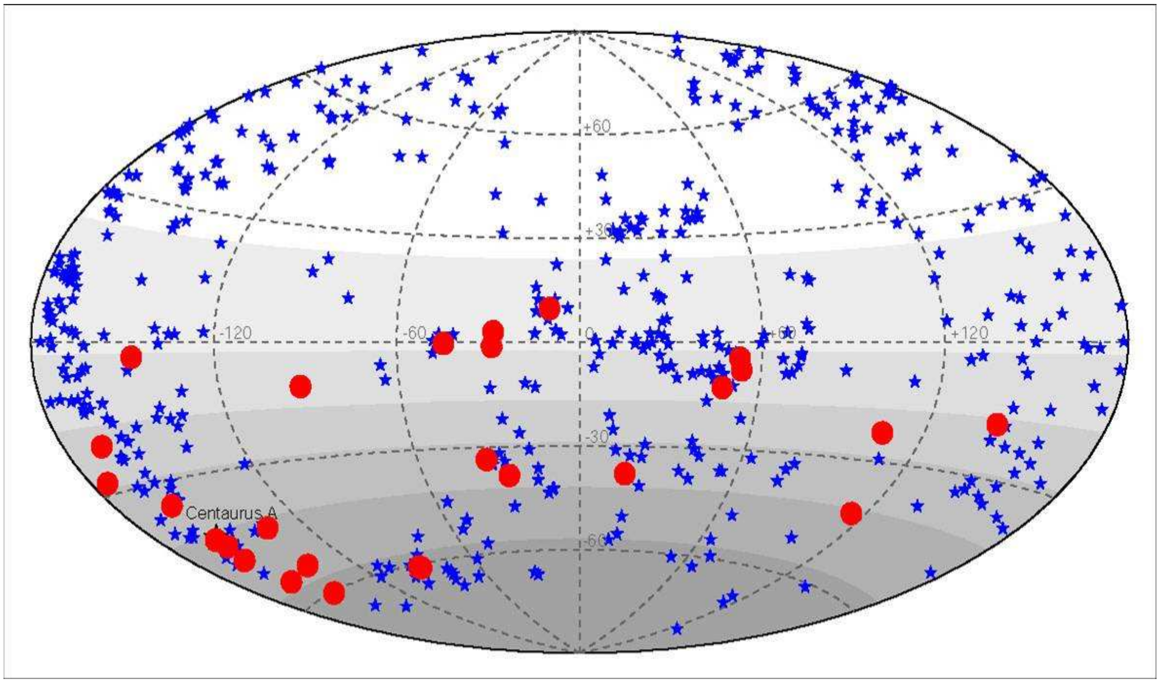

Figure 1: Map of the celestial sphere in equatorial coordinates. Colored circles with radius 3.1 degrees are centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN with redshift z less than 0.018 (corresponding to distances up to 75 Mpc) are from the 12th edition of the catalog of quasars and active nuclei by Veron-Cetty and Veron are indicated by the blue stars. Grey shading indicates larger relative exposure, which is maximum at the south celestial pole.

1 Ultra High Energy Cosmic Rays (UHECR)

1.1 Science

The Pierre Auger Collaboration is committed to determining how the highest energy cosmic rays are produced and how they interact. Data from the southern site exhibit a remarkably good correlation between cosmic ray arrival directions and the positions of nearby AGNs[10]. The correlation holds only for cosmic rays above the threshold energy for pion production (the GZK effect)[73], and the correlation is with the subset of AGNs closer than 75 Mpc. This correlation reinforces the interpretation that the observed steepening of the cosmic ray spectrum just below 10^{20} eV is indeed due to the GZK effect rather than a change in the average source spectrum.

The observed AGN correlation indicates that the sources of cosmic rays with energies above the photo-pion production threshold, can be detected individually. The trajectories of the particles are bent only a few degrees during propagation. It will be possible to identify which sources are strong emitters of these particles, which types are weak, and which types do not contribute. Because the density of AGNs is low, it is highly advantageous to aim at observing all nearby sources in all parts of the sky. Only with full-sky coverage and greatly enlarged aperture will it be possible to acquire adequate exposure to enough sources to be able to determine their nature and acceleration mechanism. If AGN are the sources of ultra-high energy cosmic rays, knowing which types of AGNs accelerate trans-GZK particles will be a major step toward understanding the acceleration process and the accelerator environments.

Competing models of the cosmic accelerators can be tested in more detail by measuring the spectra of individual sources. This is now known to be feasible with cosmic ray observations limited only by the amount of exposure to each source. Trans-GZK cosmic rays are a million times more energetic than the highest energy photons that survive intergalactic journeys through the microwave background radiation. By virtue of this long lever arm in energy, cosmic rays above the GZK threshold constitute a sensitive test of models for high energy astroparticle production.

Auger South does not have sufficient size to do sensitive spectral studies of individual sources above the GZK threshold. It records only about 30 such cosmic rays per year. To take an example, an array 7 times larger in the north will measure more than 2000 trans-GZK cosmic rays in 10 years. With this kind of exposure, Auger North can detect all sources within the GZK sphere if their numbers are comparable to AGNs in the VCV catalog. In addition, detailed spectra of the brightest sources are attainable. Since two of the 27 arrival directions in the data set of Auger South correlate with a single source (Cen A), an estimate is that 140 events might be observed from a single source by Auger North in ten years. Most detectable sources will have many fewer events, but still enough for rudimentary spectral comparisons and statistical studies. If AGNs are the sources, spectra from different sources of the same AGN class can be combined (after correcting for propagation effects) to test model predictions for different classes of AGNs collectively.

The AGN correlation together with the GZK feature implies that the highest energy cosmic rays are almost surely protons. Nuclei lighter than carbon photo-disintegrate rapidly in the cosmic microwave radiation at trans-GZK energies, so they could not get here from most of the correlating AGN sources, which are located out to about 75 Mpc. The magnetic field of the Galaxy should deflect protons at the GZK energy threshold typically by about 2 degrees on their way to Earth. There is uncertainty in this typical value, and the actual deflection must certainly vary with the arrival direction. It is implausible, however, that carbon or more massive nuclei (with charge Z=6 or greater) could correlate with source directions within the 3.2 degrees obtained in the AGN correlation. Including intergalactic fields and/or fields in the halo of our Galaxy can only strengthen the argument that the correlating trans-GZK particles do not have large electric charges. Careful analysis of the observed AGN correlation is currently underway. Preliminary results show that the assumption of Z=6 or greater conflicts with rotation measures and polarization studies of the galactic magnetic field. If these results hold under further investigation, they will establish that the trans-GZK cosmic rays are indeed protons.

Air shower measurements are especially interesting once the primary particles are known to be protons. The longitudinal and lateral distributions of electrons, positrons, gammas, and muons in the showers will probe properties of hadronic interactions at center-of-mass energies in excess of 300 TeV - currently unreachable with man-made accelerators. Remarkably, the measurements of air showers at Auger South are at variance with model expectations for proton cosmic rays, especially near and above the GZK energy threshold. The mean depth of shower maximum, $< X_{max} >$, does not rise with energy at the highest energies as is expected for cosmic ray protons. Moreover, the shower-to-shower fluctuations in Xmax are much smaller than expected for proton primaries using standard interaction models. Coupled with Auger evidence that muon production is greater than expected even well below the GZK threshold, these results point to unexpected properties of hadronic interactions at extremely high energies. The large aperture of Auger North will provide the high "beam luminosity" needed to study interactions at the extremely high energies where these effects become prominent.

Auger North will also be an observatory of ultra-high energy neutrinos. Its sensitivity will be in the EeV energy range and above, where the neutrino flux originating from the GZK effect is expected. With the increased exposure of Auger North, the detection of GZK neutrinos becomes likely, and astrophysical neutrinos directly from cosmic ray sources can be detected as well. The Auger Observatory can identify a neutrino-induced shower if the first interaction and the shower development happen deep in the atmosphere. A particle reaching the Earth at zenith angles close to the horizon has to traverse up to 36,000 g/cm^2 before reaching the ground. Hadronic primaries will interact and develop a shower with the electromagnetic component being absorbed through the first 2000 g/cm^2; only the muonic component remains. A neutrino shower can start close to the observatory and the electromagnetic component is still present. We have verified that the Auger Observatory is able to measure and reconstruct very inclined showers and that the electromagnetic and muonic components can be distinguished. Another way to detect neutrinos is through the decay of tau leptons over the array, the taus having been produced by interactions of Earth-skimming tau neutrinos. A nearly horizontal air shower is produced by the tau decay many kilometers from its point of production. There is no background for these neutrino signatures.

The plan for the future of the Pierre Auger Observatory includes the following[51]:

- Complete, and continue to operate the Auger South array.
- Complete and operate the low energy enhancements, bringing a continuous energy reach down to below 0.1 EeV.
- In response to the new physics being revealed by Auger South, we will consider possible modifications to the Southern Observatory to optimize further discovery. This might include sections with a higher and/or lower detector density or, possibly, a larger array.
- Complete the design, proposal, and construction of the Auger North Observatory. This requires stringent cost controls which are already part of the planning, for example, reducing the number of PMT's from three per detector to one, and spacing the detectors farther apart, which requires a new communications system design. Considerable R&D will be required to develop the low density, low cost array needed to increase exposure by at least a factor of five over the Auger Southern Site.

1.2 Fermilab's role

Fermilab has played, and continues to play, an essential role in the Auger Southern Observatory. This role has relied on both the technical expertise at Fermilab and the management expertise.The mechanical aspects of the surface detector were largely designed and developed at Fermilab, and the Project Management Office is at Fermilab. We anticipate playing similar roles for the Auger South enhancements and operations and the Auger North Observatory:

- Fermilabs skills at project management and accounting, honed on the successful construction and operation of the Auger South site, will be needed for the Auger North site.
- The Technical Division and Particle Physics Division are actively working on the mechanical and thermal aspects of the Auger North Cerenkov tanks and associated hardware. We anticipate this will continue.
- While the lead institutions for the Surface Detector electronics are not in the U.S., Fermilab is very well placed to advise and review the development of the components required. The expertise of the PPD and CD has been very useful in the past and we expect this to continue.

- The Computing Division is currently responsible for the Auger U.S. data mirror. We anticipate playing a more prominent role in the offline software, given our expertise from the Tevatron RunII and CMS. Auger has adopted many software tools and packages from high energy physics.

1.3 Why now?

Auger South is only the beginning of UHECR astronomy, not the end. It is the first credible observation of an anisotropy signal at the UHECR scale. Other groups[66] are actively studying our results. They are also likely to propose extensions. Although EUSO[3] has been quiescent, a comeback remains a possibility. These proposals will be evidently compared to ours. For these reasons, the Auger Collaboration will host a symposium on UHECR physics in Denver, May 2008. Fermilab is expected to play a leading role in these discussions.

1.4 Short Term Plan for Auger North

Research and development is underway to develop and demonstrate the technologies that will be needed for an Auger North site. The work is based on the differences in the needs between the two Auger sites:

- The northern site is colder, requiring thermally insulated water tanks. A vigorous development process is underway, led by Fermilab, to develop a new insulation technology for rotomolded tanks. It is planned to produce 21 tanks with this new technology and assemble an array in Colorado to test this technology and the other technologies being developed in the actual anticipated operating conditions.

- The site also lacks significant hills on which communications towers might be built, requiring a different communications system. The development of this system is underway, led by other US institutions, and will be a key part of the R&D array in Colorado.

- Some lessons learned from the southern experience have suggested improvements that might result in better long-term reliability or lower costs. An example of this is the complex, multilayer plastic liner developed for the Southern site. The possibility of a metallic layer to reduce transpiration and increase opacity even more is being studied. The Southern site operations indicate a single PMT can effectively replace the three PMT's used in the South, with commensurate cost reductions.

- Finally, technology has advanced, particularly electronics technology, resulting in an opportunity for considerable technical improvements and cost savings. Vigorous development efforts, most importantly in France, are underway to redesign the electronics package.

Substantial funding has been obtained for these activities. The US is presently seeking NSF and DOE support for its part in these activities. The assembly of the 21-tank R&D Array is planned to begin in Colorado as early as June, 2008.

2 Computational Cosmology

2.1 Science

Numerical simulations in cosmology[2] are rapidly becoming the primary tool for theoretical investigation of the complex physical processes that control the evolution of the universe on a wide range of scales, from star-forming regions and environments of supermassive black holes at the center of galaxies to large-scale cosmic structures. Theoretical progress is fueled by three main sources: (i) continuing steady increase in computing power of modern super-computers, (ii) recent breakthroughs in numerical approaches for modeling cosmic structures, and (iii) an explosion in the quantity and quality of the observational data.

The Theoretical Astrophysics Group at Fermilab has established a close collaboration with the numerical cosmology group at the University of Chicago and KICP led by Kravtsov. This collaboration led to the development of several state-of-the-art numerical codes for modeling the evolution of cosmic structures on a wide range of scales and at various moments in the history of the universe. Our primary simulation tool, the Adaptive Refinement Tree (ART) code, is an implementation of the Adaptive Mesh Refinement (AMR) technique. At present, the ART code is one of only two existing cosmological AMR codes, and is the most comprehensive in terms of the physical effects incorporated in it. We also have several other specialized simulation codes for specific-purpose simulations.

We aim to exploit this expertise to produce state-of-the-art cosmological simulations, which will simultaneously push the science forward and support upcoming experiments such as the South Pole Telescope (SPT), the Dark Energy Survey (DES), and the Supernova Acceleration Probe (SNAP).

The ability of these surveys to test fundamental physics and to constrain the nature of the dark sector hinges on accurate predictions of the observations given an underlying cosmology. Modern numerical simulations model key observational signatures with varying degrees of confidence, limited mainly by the complex astrophysics of galaxy formation. As surveys grow in size and scale, statistical errors drop, and systematic uncertainties in theoretical modeling become dominant. For some purposes, extracting information from the existing data is already limited by current simulations; this limitation will be a dominant source of systematic uncertainty for upcoming experiments in the near future.

To reduce this systematic uncertainty, computational cosmologists must produce simulations that are large enough to provide the requisite statistics, have enough dynamic range to capture small scale complexity, and include a wide range of physical processes. This last point is necessary because, although there is more dark matter than ordinary matter, the nature of the problem requires baryons as well. Most surveys probe baryons in the form of light-emitting galaxies or quasars; even those dedicated to gravitational lensing probe the dark matter tightly clustered with the baryons. So, the large, high resolution simulations required to extract information about, e.g., dark energy, need to include not only gravity but also, to handle the effects of the baryonic gas, hydrodynamics.

The needs of surveys aimed at understanding cosmological dark matter and dark energy go hand-in-hand with the needs of the broader astrophysical community, which is interested in solving the key astrophysical problems of star and galaxy formation. Since astrophysics is an observational (rather than experimental) science, theoretical modeling and numerical simulations form a crucial part of the process of astrophysical exploration.

[2] A task force charged with developing a long range plan for this effort submitted its report in August, 2007. The report can be obtained at `http://astro.fnal.gov/cci.pdf`. This section is based on that report.

2.2 Plans

In order to address computational cosmology challenges in the next several years, multi-million CPU time allocations *per project* will be required. The aim ultimately is to run hydro simulations on the scales which today are probed by N-body simulations (such as "Millennium Simulation").

To achieve these goals, we are building a medium-capability, high-capacity machine at Fermilab that will serve two purposes: (1) facilitate the R&D necessary to optimize current codes so that they will run efficiently at National Centers (NERSC, leadership DOE, Terascale NSF), and (2) provide the local resources for the efficient and timely analysis, archiving, and distribution of simulation results.

As of January, 2008, the Center has a 560 processor-core machine with 2GB of memory per core and 33TB of disk space. The funds for this machine were obtained from (i) a grant awarded by the Fermi Research Alliance, (ii) the Kavli Institute for Cosmological Physics at the University of Chicago, and (iii) the theoretical astrophysics group at Fermilab. We plan to continue to add to this cluster as funds become available. The ultimate goal is a 10,000 processor machine by 2012.

In a parallel effort, we plan to organize interested research groups nationally into a loose collaboration/consortium with common goals but diverse interests and methods. At present, the collaboration includes the Theoretical Astrophysics Group at Fermilab, KICP at the University of Chicago, and Steve Kuhlmann's group at ANL. We have also started discussions about coordinating efforts with LANL, KIPAC at SLAC, and LBL. We anticipate opening discussions with interested university groups.

At the November Physics Advisory Committee meeting, we presented the case for seeding a national collaboration in this area and siting at least some of the hardware here at Fermilab. The PAC recommended proceeding in this area, writing, *"It is now clear that large cosmological simulations are essential for further understanding of the growth of structure in the universe and for the interpretation of upcoming survey experiments aimed at addressing fundamental physics issues like the nature of dark matter and dark energy. The Committee thus strongly supports further investments in this area by the Laboratory."*

3 Cosmological 21 cm Surveys

3.1 Science

Observations of the 21cm line enable astronomers to survey the abundance of neutral hydrogen. By observing at different frequencies, they can obtain maps of the universe at different redshifts. In principle, this tool is much more powerful than its long wavelength cosmological cousin, the cosmic microwave background (CMB) because of the additional radial information. A CMB experiment which measures all the multipole moments out to some $l_{\rm max}$[3] can measure up to $l_{\rm max}^2$ independent modes, while a 21cm survey with the same angular resolution can get as many as $l_{\rm max}^3$ modes. CMB experiments are for the most part sensitive to physics at a single redshift ($z \simeq 1100$), while 21cm experiments could in principle obtain cosmological information about all redshifts from $0-100$. So the potential of 21cm experiments is enormous. Couple this with the current state of affairs – dozens of CMB anisotropy experiments have detected signals for over 15 years while no cosmological 21cm signal has yet been observed – and one gets an overwhelming sense of opportunity.

The science probed by a 21cm cosmological survey depends on the redshift/frequency range of the experiment as depicted in Fig. 2. Frequencies in the 120-200 MHz range are sensitive to the period of reionization at $z = 6-10$. The details of reionization are extraordinarily rich and depend on, for example, the primordial spectrum of inhomogeneities presumably set during inflation. Much higher frequency instruments might detect the structure of neutral hydrogen at low redshift, a structure which carries traces of the primordial Baryon Acoustic Oscillations (BAO). The angular and radial scales of the BAO are sensitive to properties of dark energy. Finally, a future very large 21cm project might probe the primordial neutral gas at redshift 50 [47], the distribution of which is sensitive to details of inflation and the neutrino mass.

We propose that Fermilab's first approach into this area be in the low redshift ($z = 0.5-2$) or high frequency ($0.5-1GHz$) range. The main science driver is detection of the BAO feature, which is attractive because it dove tails with our interests in dark energy and because high resolution is not needed to observe these large scale features. Thus, the telescope can be relatively small and inexpensive. This option seems more attractive than the reionization regime probed by 100 MHz receivers. There are already four reionization experiments operating: PAST in China, LOFAR in the Netherlands, and MWA and PAPER in Australia. It seems late for us to get involved in any of those at this stage or to start a new effort competing with these programs. By contrast, there is no operating 21 cm experiment aimed at the low-redshift BAO signal. If we establish ourselves in the high frequency/$z = 0.5-2$ range, we position ourselves to participate in the much larger Square Kilometer Array (SKA), and then ultimately in a primordial 21cm probe.

We propose joining the Intensity Mapping project [26], a low angular resolution precursor to the larger Hubble Sphere Hydrogen Survey (HSHS) [56], both of which aim to map the $z = 0.5-2$ universe. These maps will be the first of their kind of the universe in an entirely new band and hence might well turn up big surprises and change our view of the universe when it was a few billion years old. Even without any surprises, though, results from this survey will weigh in on the nature and properties of dark energy. Observations from the CMB and from the Sloan Digital Sky Survey virtually ensure that these maps will contain information about BAO, which in turn can be used to understand dark energy at these redshifts. The information we currently have about dark energy is restricted to $z < 1$. (Even luminosity distances out to the highest redshift supernovae at $z \simeq 1.5$ are primarily sensitive to dark energy at $z < 1$[4].) The radial extent

[3] The angular resolution of an experiment is $\theta_{res} \sim 2l_{\rm max}^{-1} \sim 1^\circ(100/l_{\rm max})$.

[4] Recall that the luminosity distance is an integral over z of the inverse Hubble parameter; that integral tends to

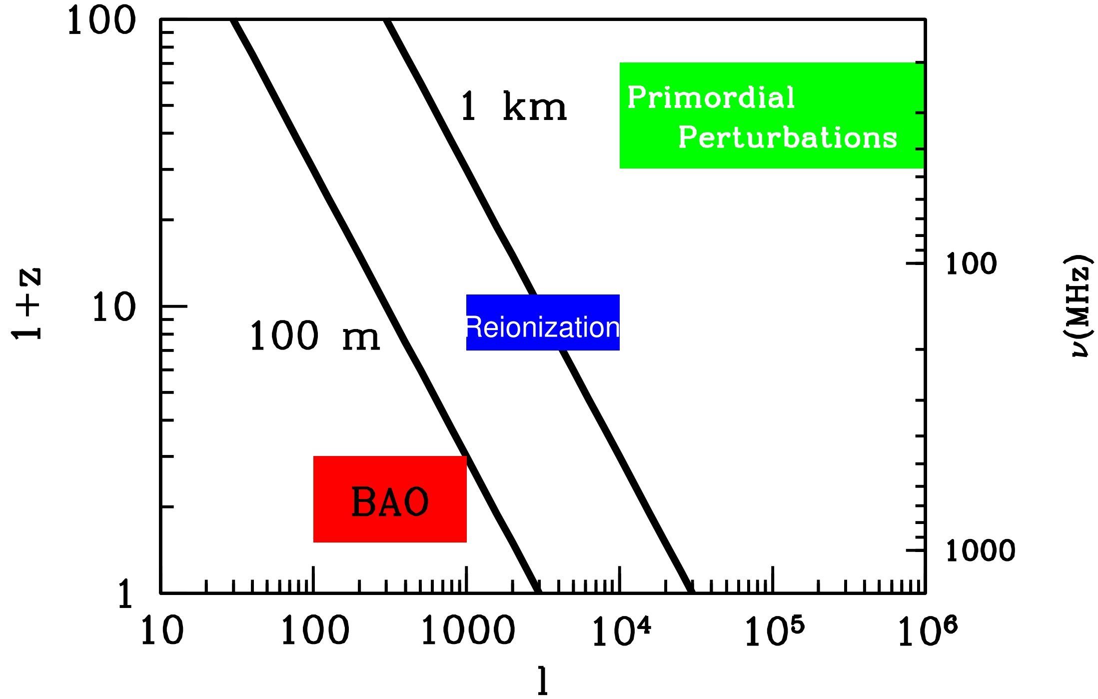

Figure 2: Redshift sensitivity and angular sensitivity of various cosmological 21cm experiments. Slanted lines depict the angular resolution possible for the given redshift when telescope separation is 1 km and 100m. Boxes denotes redshift/frequency and angular resolution needed to probe three types of physics: measuring the low redshift baryon acoustic oscillations, the epoch of reionization, and the primordial perturbations.

of the BAO feature at redshift 2 is a direct probe of the Hubble expansion rate at $z = 2$, and hence the energy density at that epoch.

3.2 Fermilab's Role

Although Fermilab has a history of interest in the cosmology that is accessible via radio astronomy, participation in an experimental program represents a new direction. The Intensity Mapping concept, however, utilizes state-of-the-art technologies that are well-known at Fermilab because of their applications in particle accelerators and detectors. The Intensity Mapping goal of looking at large scale structure departs from the goals of traditional radio astronomy in that the modest requirement on angular resolution and dramatic advances in digital signal processing now make it possible to access this science at a relatively modest cost.

Fermilab brings a number of strengths to any project of appreciable scale: engineering capability, a talented Computing Division, and Project Management skills. These would all be useful in the 21cm field, but here there are specific areas where Fermilab's expertise resonates with the needs of the projects. Specific contributions that we could make to the Intensity Mapping project (and beyond) include:

- **Project Management:** While Intensity Mapping is expected to be a modest sized project (with initial cost esimtate of $\sim$ \$5M), Fermilab's culture of project planning and cost discipline can be expected to be an important contribution to the success of the project.

- **RF Capabilities:** Fermilab engineers have extensive experience with r.f. systems that operate in a low signal-to-noise environment. Of particular relevance is more than 20 years experience in detecting and processing accelerator beam shot noise, the so-called Schottky signals. Fermilab engineers are particularly adept at computer aided design techniques that find the optimal solution without unnecessary trial and error.

- **Electronics:** The digital revolution has had a lesser known but immense impact on signal processing. Fermilab has been at the forefront of this field because of the unique requirements of accelerator r.f. systems. Fermilab engineers are also intimately familiar with handling digital data and computing in a firmware environment. The Fermilab computing division has the tools to create and test these firmware systems quickly and efficiently.

- **Mechanical Engineering:** One of the challenges of the Intensity Mapping project is system cost. Fermilab engineers have extensive experience in building large apparatus at low cost (neutrino experiments, for example). The antenna, support structure, and cable plant design are critical for the project and Fermilab engineers can be expected to improve on the innovative concepts that have already been developed.

- **Foreground Subtraction:** One of the biggest issues in the field is that emission from galactic and extra-galactic sources (so-called *foregrounds*) have amplitudes orders of magnitude larger than the neutral hydrogen signal. Much theoretical effort has been devoted to this problem of foreground subtraction, and the community is cautiously optimistic. The key observation is that foregrounds are smooth in frequency space while the neutral hydrogen signal varies quite rapidly in frequency (redshift) space. Gnedin [37] has worked on this and Dodelson has worked on the analogous problem in the case of the CMB [32]. They will work to identify optimal bandwidths and frequency configurations.

be most sensitive to the energy density at much lower redshifts than the observed z.

- **Cosmological Simulations:** Dodelson and Gnedin have initiated a cosmological computing initiative at Fermilab. With the help of several grants, they have built a cluster with 500 nodes and are aiming to continue to add to this cluster over the next five years. Gnedin's Adaptive Refinement Tree code is uniquely suited to studying the physics of neutral hydrogen at these redshifts and the synergy with an experimental program is extremely attractive. The simulations will test the robustness of the BAO signal.
- **Experimental Simulations:** The strong engineering resources and the scientific talent at Fermilab in the areas described above will enable an end-to-end simulation that will serve to solidify the case for the project feasibility and to identify any weaknesses that may be present.

3.3 Short Term Plans

We have submitted a proposal to the DOE Dark Energy Solicitation to carry out a concept study which will utilize scientific staff and engineers in collaboration with other institutions to develop an advanced design and cost estimate for the Intensity Mapping project. The goal is to obtain short term (one year) funding and also to plant the seeds necessary to encourage the DOE to join with NSF and international funding agencies to fully fund the experiment.

4 Cosmic Microwave Background Polarization

4.1 Science

Measurements of the cosmic microwave background (CMB) temperature and polarization anisotropy have played a central role in developing our current cosmological understanding of the universe, including the conclusion that the universe is currently dominated by some form of dark energy that is causing the expansion of the universe to accelerate. The CMB Task Force[22] has recommended a program of ground and space based experiments, along with technology development leading to receivers that contain a thousand or more polarization sensitive detectors.

The Planck satellite[58], with 63 sensors, will produce all-sky maps with improved sensitivity and angular resolution up to multipoles of 2500. This will enable tests of cosmological models, and improved measurements of parameters such as the dark-matter density and the slope of the primordial power spectrum. Planck data combined with galaxy survey data will be sensitive to neutrino masses down to 0.2 eV.

Ground based CMB experiments such as the South Pole Telescope (SPT)[59] will explore anisotropies with multipole values in the range of about 200 to 10000. At the higher multipole values, the CMB anisotropy is dominated by distortions such as those caused by the Sunyaev-Zel'dovich (SZ) effect. The SZ effect can be efficiently used to identify galaxy clusters independent of redshift, and the SPT, with 1000 sensors, can do this over a wide area. SPT data, combined with optical DES data, will provide a powerful probe of cluster evolution and a unique method to constrain the dark energy equation of state.

In the second phase of the SPT, polarization sensitive sensors will be installed, allowing for sensitive explorations of E-mode and B-mode patterns in the CMB. The SPT will be sensitive to B-mode polarization induced on small angular scales by gravitational lensing. This will provide an independent probe of the growth of large scale structure, constraining the dark energy equation of state and perhaps providing the strongest cosmological constraint on neutrino mass[43, 63].

Ultimately, the goal of this field is to develop a satellite with thousands of sensors to detect B-mode polarization on larger angular scales induced by primordial gravitational waves. These modes would provide a probe of the physics of inflation. Detecting them will involve a long program of understanding polarization foregrounds with ground-based experiments, as well as advances in sensor technology. A concept called "CMBPol" is being explored as a candidate Beyond Einstein Inflation Probe.

4.2 Near-term options

The Cryogenic Dark Matter Search (CDMS) experiment shares certain key technical features with the SPT experiment. Both measure energy using superconducting Transition-Edge-Sensors (TES), and SQUID amplifiers. The University of Chicago group is working with Argonne to develop polarization sensitive sensors for the second phase of SPT. One near-term option for a Fermilab group to get involved in CMB science would be to apply our technical expertise developed for the CDMS experiment to this upgrade and join the SPT scientific collaboration. There are several possibilities for how we could contribute, and settling on one would involve obtaining a better understanding of the project and discussions with the SPT collaboration. This could provide a natural way for us to start contributing to an existing CMB experiment.

Fermilab has experience building high precision calibration and monitoring systems for calorimeters. For the KTeV experiment, the Fermilab group designed and constructed such a system for the 3100-channel CsI electromagnetic calorimeter. Upcoming CMB experiments will place demanding requirements on a similar number of channels. Sensitivity to a B-mode signal, which is at least a factor of O(1000) smaller than the CMB anisotropy signal, will require fine control over instrumental drifts and nonlinearities, which can fake polarization signals.

Thus, another near-term option for Fermilab involvement would be to construct a calibration and monitoring system for upcoming CMB experiments such as SPT and QUIET, another polarization experiment. State-of-the-art systems use either cryogenic black-body sources, wire heat-sources (i.e. Joule heating), or electronic microwave sources, usually calibrated against a NIST-standard detector. To our knowledge, sources that can generate very small and controlled artificial polarized microwaves have not been constructed in the field.

While the microwave technology required is outside of Fermilab's experience, the goals and philosophy would be similar to those of the KTeV system and the learning curve for Fermilab will be modest. If the system can operate at ambient temperature, the infrastructure investment at Fermilab will also be modest. A possible initial investment would be in commercial microwave sources and diode receivers.

4.3 Longer-term goals

In the longer term, a collaboration between the University of Chicago, Argonne, and Fermilab could develop a powerful capability for developing and testing sensors, and constructing focal planes and other components. This could put us in a position to propose new experiments and to have a major role in future projects including CMBPol. The University of Chicago has a distinguished history in successful CMB experiments, and Argonne can contribute nano-fabrication facilities. Ways in which Fermilab can contribute include:

- Cryogenics
- Thermal modeling
- Test-stand operation: Both dilution-refrigerator based, as well as simpler 4K operations are possibilities.
- Warm electronics: Development for both sensor read-out and multiplexing.
- Support of the fabrication efforts: Use of SiDet for visual inspections and surgical repairs.
- Use of SiDet for focal plane assembly.
- Construction of cold hardware.
- Calibration and monitoring.
- DAQ
- Management of integration and operations.
- Data processing and cataloging.
- Theory, computation, and simulations.

For most of these items, Fermilab has successfully leveraged resources in comparable ways in support of the CDMS, KTeV, and other experiments.

4.4 Funding Options

In the long term, the science probed by CMB polarization – inflation and neutrino masses – is very consistent with the DOE's mission. Indeed, in *Physics of the Universe*[5], the agencies' response to *Quarks to the Cosmos*, the Interagency Working Group wrote, "The three agencies will work together to develop by 2005 a roadmap for decisive measurements of both types of CMB polarization." So pursuing this avenue of cosmological research is traveling along a path that has been "blessed."

In the short term, Fermilab, with the consent of the Directorate, has joined the CMBPol Mission Concept Study Team. Dodelson is co-I on a proposal submitted to NASA to organize a series of workshops in Summer 2008 which will produce detailed reports on the physics and technology of CMB polarization studies. Fermilab will host the workshop dedicated to Theory and Foregrounds. Total requested funds are $90k.

[5] `http://www.ostp.gov/html/physicsoftheuniverse2.pdf`

5 High Energy Gamma-Ray Astronomy

The primary goal of High Energy (HE, $E > 1$ GeV) and Very High Energy (VHE, $E \geq 100$ GeV) gamma-ray astrophysics is the understanding of the production, interaction, and propagation of energetic particles in the Cosmos, the so-called Nonthermal Universe. A first major breakthrough in HE gamma-ray astronomy came with the EGRET mission on board the Compton Gamma Ray Observatory, which demonstrated the richness of the HE Universe[48]. The GLAST satellite, to be launched in 2008, is following up on the success of EGRET and promises a second revolution in the field thanks to its greater exposure, field of view, angular and energy resolution. In the last decade VHE astronomy with ground-based detectors has also flourished. Although significant results have been achieved with extensive air shower detectors, Atmospheric Cherenkov Telescopes (ACTs) are currently the most sensitive instruments for detecting radiation in the VHE region [69].

Present experiments from both ground and space allow observations of a wide variety of interesting astrophysical sources including active galactic nuclei, compact binary systems, shell-type and pulsar supernova remnants and cosmic ray interactions with molecular clouds. Most of these objects are involved in the poorly understood process of Galactic and extragalactic cosmic-ray acceleration. Gamma rays are not deflected in cosmic magnetic fields, so they retain directional information providing a clear advantage over charged particles.

HE and VHE telescopes shed light on the last unexplored window of the electromagnetic spectrum. Any previous enlargement of the electromagnetic band has been accompanied by unexpected discoveries and has offered new tools for exploring extreme physical systems in the sky. It is remarkable that a large class of known HE and VHE sources has no recognized counterpart in other bands; they correspond to a new class of "dark" accelerators [12].

In addition to targets of astrophysical relevance, HE and VHE gamma ray astronomy also provides an opportunity to directly observe physics beyond the Standard Model. The best investigated and motivated possibility is the detection of high energy radiation from the annihilation (or decay) of dark matter particles. Other applications have also been envisaged, including bounds on or detections of violations of Lorentz invariance [21], discovery of axion or axion-like particles [40], and detection of primordial black holes evaporating via the Hawking radiation [53].

5.1 Indirect Detection of Dark Matter

Despite the compelling body of evidence in favor of the existence of dark matter (galactic rotation curves [23], galaxy clusters [76], gravitational lensing [67, 30, 29], the cosmic microwave background [64], light element abundances [52], and large scale structure [65]) the nature of the dark matter remains unknown. There are strong motivations which point to a connection between dark matter and the electroweak scale. A stable particle with an electroweak scale mass and couplings would naturally be produced in the thermal bath of the early universe in an amount similar to the observed dark matter abundance. While it is possible that this connection is only a coincidence, it may be an indication of the electroweak nature of dark matter interactions.

From a particle physics perspective, the hierarchy problem (i.e., the problem that the quadratic contributions to the higgs boson mass are expected to be unacceptably large) appears to require new physics at or around the electroweak scale. Furthermore, stringent constraints from electroweak precision measurements indicate that these new particles respect symmetries which limit their interactions. Such symmetries can also lead to the stability of one or more of the new particles, such as the lightest superpartner in R-parity conserving supersymmetry.

A stable, electroweak-scale particle that annihilates with a cross section leading to the measured dark matter abundance ($\sigma v \sim 3 \times 10^{-26}$ cm^3/s) could potentially produce a flux of gamma rays observable with ground or space-based telescopes [18]. The brightest source of dark matter annihilation radiation is expected to be the Galactic Center, due to its proximity and likely high dark matter density. This region is also significantly contaminated by astrophysical backgrounds, which will have to be effectively separated if any dark matter signal is to be identified. A careful subtraction of astrophysical backgrounds based on angular distribution and spectral shape is required to extract the dark matter annihilation radiation in the galactic or extragalactic diffuse gamma ray spectrum. For this reason, other "background-free" sources of dark matter annihilation radiation, such as dwarf spheriodal galaxies [34] or dark matter microhalos [31], have been considered despite the smaller gamma ray flux that is expected from these objects. Realistic chances of detections of these sub-structures thus rely on the fact that one or several of them serendipitously happen to be sufficiently near the Solar System.

In order to be an effective dark matter experiment, a next generation VHE gamma ray telescope will most likely require both a very large effective area and a very low energy threshold while maintaining effective rejection of non-photon events. In most models which address the hierarchy problem, the dark matter particle has a mass in the range of several tens to several hundred GeV. Most of the photons produced in dark matter annihilations, however, have considerably less energy than the dark matter particle's mass. Unless the dark matter is unexpectedly heavy, the sensitivity of a future gamma ray telescope to dark matter will depend critically on its energy threshold. Newer instruments should approach the 10 GeV level compared with the present-day $\mathcal{O}(100)$ GeV.

The location of the telescope is another important consideration. In particular, a Southern hemisphere site would enable the observation of the Galactic Center. From a Northern hemisphere site such an experiment would only be able to search for dark matter annihilations in dwarf galaxies and other substructures. Despite the advantage of no astrophysical backgrounds, these substructures are unlikely to produce enough gamma rays to be observable for the expected cross sections and distributions.

5.2 High Energy Astronomy Techniques

Not only is high energy astrophysics a good match to the scientific mission and interests at Fermilab, but the techniques also utilize the resources at Fermilab. Most of the techniques and detectors in space and on the ground are common to a high energy physics expertise.

There are two instruments aboard GLAST, the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). The LAT consists of a plastic scintillator veto to reject charged particles, a silicon strip tracker to get the direction of the high energy photon after it is converted into electron-positron pairs, and a CsI calorimeter to measure the energy of the incident photon. The plastic scintillator veto was produced at Fermilab as a service to the GLAST project. The GBM consists of an array of NaI and BGO detectors to trigger observations of gamma-ray bursts.

ACTs are large (10-30m diameter) optical reflectors with cherenkov cameras in the focal planes. Typically photomultiplier tubes (PMTs) are used as pixels to capture the faint cherenkov flash from high energy photon showers in the atmosphere. The fast timing of PMTs also allows efficient rejection of night sky glow.

The first highly significant observation of cosmic, high energy photons from the ground was reported in 1989 [70]. Since then consistent progress has been made with this technique, and now there are a number of observatories in operation around the world. HESS, an array of four 12m cherenkov telescopes in Namibia, is currently leading the field with an order of magnitude increase in the TeV source catalog [39]. MAGIC, a single 17m cherenkov telescope on La Palma in the Canary Islands, has made some impressive observations [49]. VERITAS, an array of four 12m telescopes similar to HESS at the base of Mt. Hopkins in Arizona, just celebrated first light in April, and is already close to publishing world-class results from data taken during construction [44].

5.3 The Future of High Energy Astronomy and Possibilities for Involvement

With the launch of GLAST in 2008, the visibility and knowledge in the field of high energy astronomy will improve. All GLAST data enters the public domain after one year. Analyzing and interpreting these data is one way for the FCPA to become involved in high energy astronomy. Support through the guest observer program may be possible. Although the first cycle of the guest observer program did not involve LAT data, and Fermilab scientific interests mainly revolve around data from the LAT instrument, future cycles of the guest observer program will include analysis of LAT data.

The following are potential areas of FCPA involvement in space telescopes:

- Submit a proposal for the second cycle of the guest observer program. A successful proposal could attract resources that would allow an analysis and interpretation of possible dark matter signals in the LAT data. One or more dedicated postdoctoral fellows funded through this NASA program would significantly increase the FCPA's visibility in the field.

- A next generation high energy space telescope will become attractive after the first GLAST data release. It is difficult to improve the sensitivity by increasing the collecting area of space telescopes. Increasing the energy resolution, angular resolution, or polarization sensitivity of future high energy space telescopes could become attractive, depending on the results from GLAST.

The current VHE astronomy groups are taking two paths to improving their detector sensitivity.

First, they are upgrading the existing detectors. HESS-II involves a 28m telescope in the center of the HESS array in an attempt to access showers with energies ≤ 100 GeV. The MAGIC-II plan is to build a second 17m telescope near the MAGIC telescope. Stereoscopic imaging of showers will improve the sensitivity of the MAGIC detector [25].

Second, there are two collaborations within the high energy astronomy community proposing to build new VHE observatories. In the United States, the Advanced Gamma-ray Imaging System (AGIS) collaboration includes scientists at the University of Chicago and Argonne National Laboratory. A similar collaboration, the Cherenkov Telescope Array (CTA) [38], exists in Europe. The main goal of these collaborations is to increase the sensitivity of ground-based techniques by gathering ~ 100 times more high energy photons. The parameter of focus is the footprint on the ground, and this direction requires $\sim 1\,\mathrm{km}^2$ arrays of cherenkov telescopes.

The key design parameters for observing a signal from dark matter annihilation are: sensitivity, including effective area, exposure time, and rejection of cosmic-ray backgrounds; energy threshold, including the collection and detection of cherenkov photons from air showers; and field of view, including off-axis optical aberrations and the cost of instrumentation. These km^2 arrays address the sensitivity requirement.

The AGIS collaboration formed in Summer 2007. The collaboration membership closes by early 2008, so a commitment to this project would have to be made quickly. Fermilab could make contributions to the field of ground-based, high energy astronomy. FCPA leadership on any one of the following projects would promote and advance VHE astronomy:

- Investigating wireless triggering techniques, much like those involved in the Pierre Auger project, could make a major impact on the AGIS design without a large amount of investment. Triggering a km^2 array can be expensive. Currently there are two groups involved with ideas that would require stringing fiber optic cables between the ~ 100 telescopes that would cover a km^2. This project could involve commercial wireless networking equipment. This project would directly lower the costs, and lower the deployment and maintenence difficulty. Once a large wireless network blanketing the array becomes attractive, this could naturally lead to moving data from each individual telescope, building the event data, reducing the image data, and distributing the reduced data.

- A more involved effort could focus on the camera used in AGIS. The VERITAS cameras were expensive, $\sim$ \$1500/channel, and assembly was time consuming and labor intensive. Research on this cost driver is critical to the success of AGIS. Investigation of light detectors such as multi-anode PMTs, CMOS, and silicon photon counters is ongoing. The group at the University of Chicago lead by Prof. Simon Swordy has a conceptual design for a multi-anode PMT camera design. The FCPA could investigate starting a partnership with the University of Chicago to design a low-cost, easily reproducible cherenkov camera. The University of Utah could also be a partner in this project, as they have 3m telescopes which they have offered as a test bed for cherenkov cameras in development.

Finally, there may be room for a dedicated instrument, trading observing time for collecting area, which could achieve the same sensitivity as the km^2 arrays at far lower cost. A drift scan of the Galactic Center with much lower energy threshold [13] is a more affordable option for studying dark matter annihilations in the Milky Way halo.

- A new instrument dedicated to studying dark matter annihilation could be developed. A low-cost drift scan of the Galactic Center could make an impact on the field of high energy astronomy. A straw man design has been developed as project DELTA, a Dark matter Experiment using a Low Threshold Array. This design involves three, fixed 20m spherical mirrors on the corners of a $\sim$80m equilateral triangle. A medium to large array of single-anode PMTs would image the air showers in the focal planes of these telescopes.

- A design study to reduce the energy threshold and improve the background rejection is required to advance this project beyond the concept stage. With material costs in the 3-20 million dollar range and as a project starting at Fermilab, this would require a larger Fermilab investment than involvement in the AGIS program. However, this project could produce science much sooner, and could have better sensitivity for dark matter annihilation signals. It is also a unique and rare opportunity in high energy physics to be able to make a large impact with modest material costs and little to no research and development.

High energy gamma-ray astronomy has been a rapidly progressing field for almost twenty years. This field will get a dramatic boost from GLAST and continue to grow for the next few decades with ground-based observatories. The Department of Energy has already invested in this field as a major partner in VERITAS. Fermilab could become involved, either as a major contributor to AGIS, or as a sponsor of a new experiment that could significantly advance high energy astronomy.

6 Optical Cosmology

Our view of the Universe is largely informed by ground-based observations made at optical wavelengths. The expansion of the Universe, its recent acceleration, and the domination of its matter content by dark matter are all discoveries made using the optical part of the spectrum.

6.1 Dark Energy

The search for understanding of the nature of dark energy drives the current experiments in optical cosmology. The question of the cause of the accelerating Universe is central to cosmology and to fundamental physics. The field is currently driven by observations of the Hubble expansion as a function of redshift, which requires large surveys to make progress. The surveys are either a) deep, long-duration time domain surveys, b) wide field spectroscopic surveys, or c) deep, wide field imaging surveys.

6.2 Optical Cosmology at Fermilab

The optical cosmology roadmap at Fermilab is paved with large imaging surveys.

In the language of the Dark Energy Task Force (DETF), the Sloan Digital Sky Survey (SDSS) was a stage II experiment that used the galaxy power spectrum in combination with the WMAP CMB power spectrum to confirm the existence of dark energy and begin to determine its properties. The Dark Energy Survey (DES) [9] is a stage III experiment that uses four methods to probe the equation of state of dark energy, w. SNAP [17] is a candidate stage IV experiment that envisions using two primary methods, supernovae and weak lensing, to measure dark energy, in particular the time variation of w, with a high degree of control over systematic errors. At the end of this roadmap we can expect to have a good idea of whether or not dark energy is a cosmological constant, and whether or not it should be described as a modification of general relativity. Along the way to those central questions are a rich set of astrophysical questions that must be answered.

The SDSS set the standard for high-quality astrophysical surveys in terms of data quality, calibration, reduction, and distribution. At Fermilab the primary technological skill we developed was that of large scale astrophysical data management techniques. In addition, Fermilab played major roles in telescope engineering. SDSS-II is scheduled for completion in July 2008, and Fermilab has chosen to not have the same strong and central presence in SDSS-III.

Fermilab is the host institution for DES and is playing lead roles in a number of project areas, including project management, the construction of the camera, simulations, survey strategy, and science. The current schedule calls for science data beginning in 2011. We propose to make the best use of an excellent data set by a) building up expertise in weak lensing, b) continuing development of clusters as a precision cosmology tool, c) taking the next logical step after the SDSS II SN project using the DES SN survey, and d) continuing development of photometric redshifts as a base science technology for all four DES key projects. All of these areas are fertile ground for the development of astrophysical expertise in high energy physicists joining the Particle Astrophysics Center. Technologically, the primary skill we are developing is CCD packaging, testing, and focal plane construction, every thing necessary for the construction of a large camera dewar.

SNAP is a large program and central to DOE's facilities roadmap to the next decade. Fermilab is committed to SNAP as the best JDEM candidate. We are currently contributing to SNAP in a number of areas such as front-end electronics, data acquisition electronics, calibration and CCD packaging and testing. On the science front, given the supernova experience gained from the SDSS II SN project and in the near future the DES SN survey, Fermilab should expect to make a strong contribution to the SNAP program of SN observations. However, building on the experience gained with weak lensing in the DES data set and existing expertise in large scale structure,and cluster statistics we would expect to make science contributions there also.

6.3 Natural Roles for National Labs

The natural roles for national labs lie in those areas that are not easily accomplished at a University. Generically in optical cosmology this comes in three areas: large-scale data processing, instrument construction, and project management. Telescope construction is left off because of two reasons: neither the production of optics nor the development of telescope support structures are natural to high energy physics labs while they are to national and private observatories. The same can be said about spacecraft bus integration: other lab-like organizations do the job.

In the arena of large scale surveys, the scale of instrument construction has increased to a level which is beyond the capabilities of most individual universities. In the arena of data processing, the supercomputing centers and the NASA-funded data centers are natural entities, but they are entrepreneurial, against which a DOE lab computing group can successfully compete or with which a DOE lab can collaborate. Project management expertise in today's DOE labs is high compared with universities for historical reasons.

6.4 Fermilab's special attributes

Fermilab itself has several unique features that can be brought to the table for current and future projects. First, it is perhaps the world's leader in the construction and maintenance of the new style of collaborations where DOE labs, NSF or DOE funded university groups, and private entities contribute roughly equally to a project. The SDSS and DES are examples of this organization type. Second, the development of the computational cosmology initiative is both scientifically interesting and central to the degree of success that projects like DES will have in interpreting their data. Third, Fermilab now has expertise in both the core areas of data management and CCD packaging/focal plane construction.

6.5 The Proposed Future

Clearly the highest priorities are ensuring that DES and SNAP are successful projects.

In DES that first means ensuring the resources to complete a high quality camera on the 2010 time scale. Secondly, we should make sure that we have active participation and leadership in the key DES science projects. We should also exploit the opportunity to pursue these science projects now with existing data sets like that of the SDSS or the Blanco Cosmology Survey (BCS) [50].

In SNAP we should move to take on one or more large responsibilities as the proposal writing begins in earnest with the expected announcement of opportunity in 2008. We certainly have the expertise to take on a role as a data center for SNAP, at the very least for the wide area survey. We have expertise to take on the focal plane, at the least CCD packaging. Even though focal plane construction for a space mission will most likely be a design and contract oversight project with an aerospace company actually cutting the metal, turning the screws, and shake and bake testing, having Fermilab scientists owning this central subsystem will both keep us central to the ongoing SNAP mission and at the forefront of focal plane construction. In the SDSS we learned data management and in the DES focal plane construction– continuing this path of expertise by working to take these responsibilites in SNAP is natural.

While the bulk of our resources will go to DES and SNAP, it is worth remaining cognizant of other opportunities in case those projects face roadblocks or in case additional resources become available. A Spanish consortium is moving forward on a project, PAU, that shares some of the scientific goals of spectroscopic surveys such as SDSS-III BOSS, namely to probe BAO. PAU would involve a wide-area imaging survey (on a new dedicated telescope) in a large number of narrow filters so that it can capture enough redshift information to compete with spectroscopic surveys; the Spanish group has expressed interest in Fermilab possibly participating/contributing to this project, exploiting the camera hardware experience developed for DES. This is just an example of a project that would take advantage of the technical expertise Fermilab has developed in building optical focal plane arrays.

Another possible intermediate-scale project would involve low-redshift supernovae. To be able to extract dark energy constraints with high confidence from the high-redshift supernovae that SNAP will observe, the DETF recommended an expanded program to study 500 low-redshift SNe Ia in detail. Members of the Nearby Supernova Factory are contemplating such an expanded program for the future and have expressed interest in Fermilab involvement, building on our successful operation and leadership of the SDSS-II Supernova Survey. This would be a relatively small resource-scale, intermediate time-scale project, but both it and PAU would require resources beyond those currently contemplated.

Finally, for the longer term, LSST [36] merits consideration for two reasons. First, it is squarely along the Fermilab optical cosmology roadmap from SDSS and DES both technically and scientifically, and second, it is likely to be a major DOE project. The LSST project has at various points approached Fermilab about joining the project and contributing in various ways; we have not joined the project as of yet, in large part because our resources are fully devoted to the projects above. If the focal plane hardware role for Fermilab in SNAP turns out to be "minimal", then that could potentially open up resources to contribute to the LSST focal plane as DES hardware work winds down.

7 Near Infrared Surveys

7.1 Infrared Landscape

Our view of the universe is largely informed by ground-based observations made at optical wavelengths. However, this wavelength region is only a tiny portion of the entire span of electromagnetic radiation from the universe. Notably the optical redshifts to the infrared at cosmological distances. Ground-based observations in the infrared are hampered by having to look through the earth's atmosphere. Additionally, IR detectors are more costly and have smaller formats than their optical counterparts. Nevertheless, a considerable amount of scientifically important information can only be obtained from observations in this region.

The IR spectrum can be divided into three regimes, on a basis of science, detector technology, and accessibility from the ground.

Near–IR ($1\mu - 5\mu$) - Radiation comes predominantly from stellar photospheres. Galactic extinction is much less than in the optical.

Mid–IR ($5\mu - 40\mu$) - Radiation comes from hot dust, cool supergiants, and protostars.

Far–IR ($40\mu - 250\mu$) - Radiation comes predominantly from cold dust, reradiating light absorbed from stars. Spiral galaxies and ULIRGS (Ultra-luminous IR galaxies) are prevalent.

Fermilab has strong science interests in observations made in the near–IR. When galaxies have a distance greater than redshift one the wealth of information in the optical about starlight and hydrogen gas lines are only observable in the near–IR. To the extent that we can predict that studying fundamental physics from cosmology will require reaching $z > 1$ we can predict that the near-IR is important to us.

The near-IR portion of the spectrum is partly accessible from the ground, whereas the mid- and far-IR portions are largely inaccessible and require one to observe from either high-altitude aircraft, long-duration balloons, or spacecraft. Observations from the ground are hampered in two ways: water vapor has a number of absorption features that cut out portions of the IR spectrum, and airglow emission from OH in the earth's atmosphere creates a background intensity that can be hundreds of times greater than that in the blue-green portion of the optical spectrum. Both effects increase in magnitude the further into the infrared one goes, and increases in background by factors of 100 are not unusual.

For these reasons current near-IR surveys are considerably less sensitive than their optical counterparts. For example, the 2MASS all-sky survey has a sensitivity limit that is 30 times less than that of the Sloan Digital Sky Survey. There is a huge benefit in observing from space in the near-IR. A modest space-based telescope with an aperture less than 1 meter can can survey an area of sky comparable in size and depth to the SDSS in just a 1 year mission. Figure 3 compares the sensitivity of a mission such as PRIME (a proposed small explorer satellite) with current ground-based optical and IR surveys.

7.2 Science

A deep imaging survey in the near-IR would enable multiple compelling science programs. For cosmological programs that involve measuring classes of objects over a wide range in redshift (such as a stage IV dark energy experiment), one wants to observe high-redshift objects in the near-IR to compare with their low-redshift counterparts observed in the optical. This motivation

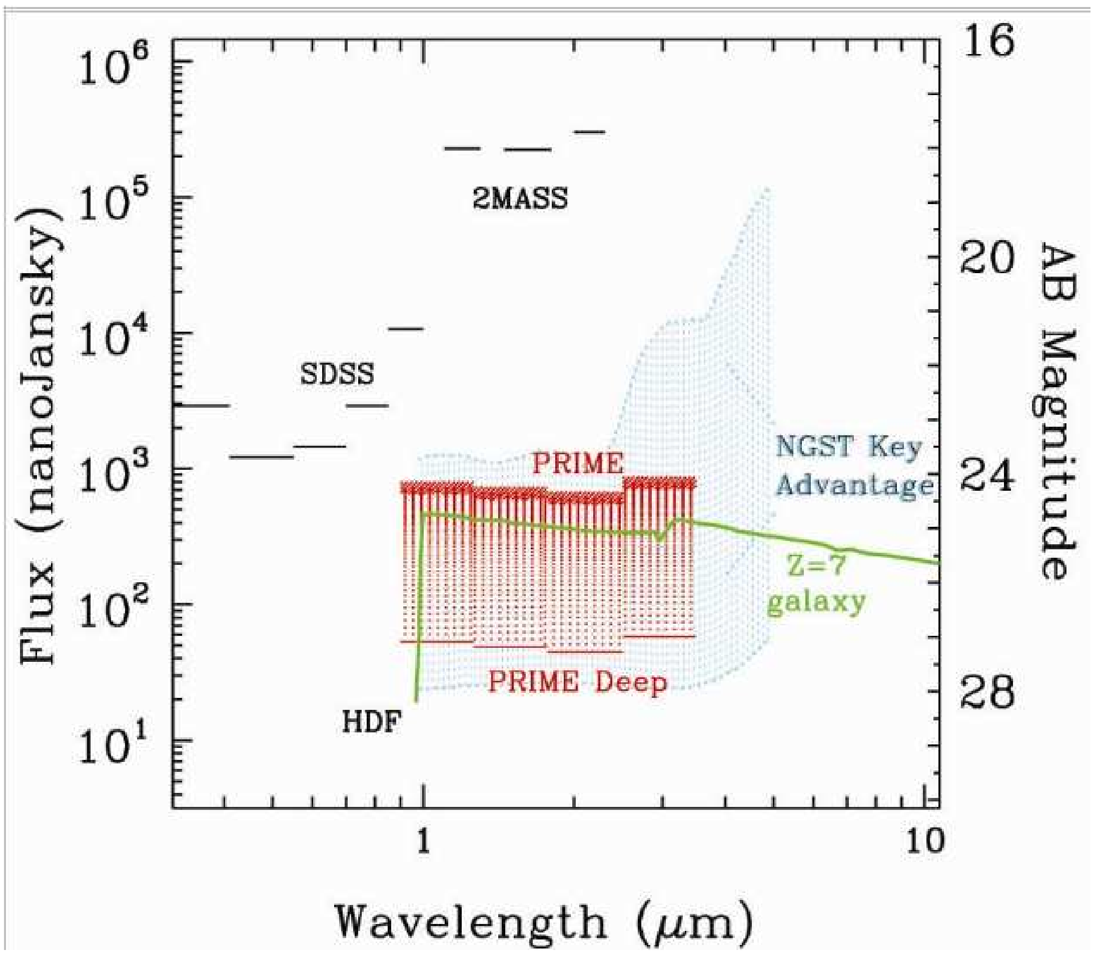

Figure 3: Sensitivity of a hypothetical PRIME-like IR survey compared with existing ground-based surveys.

has driven the design of SNAP [17], a dark energy experiment optimized to observe supernovae over the redshift range 0 to 1.7.

To achieve this goal, the satellite covers a wavelength range of 0.5 to 1.7 microns and reaches a sensitivity of AB=27. This performance allows SNAP to detect and measure all supernovae over the full redshift range at a wavelength that corresponds to the standard B (blue) band in the restframe of each supernova. The SNAP program consists of two surveys, one in the time domain for supernovae, the other a wide area survey that enables weak lensing and, to a lesser extent, cluster cosmology projects. No single mission design is optimal for all NIR science. A dark energy program that involves observing galaxy clusters out to a redshift of 2 would optimally observe all clusters in rest-frame R band and would reach to $AB = 25$ out to a wavelength of 2 microns. Such a program is more ideally suited to a mission like PRIME, which is a proposed Small Explorer mission, which has lower resolution but greater wavelength and sky coverage than SNAP. For programs that rely on having accurate photometric redshifts of galaxies, such as weak lensing experiments, the redshift accuracy can be greatly improved by combining optical with near-IR photometry. High-redshift objects such as quasars and Lyman-break galaxies at $z > 6$ are invisible in the optical and can only be detected in the near-IR. Closer to home, the peak in the spectrum of ordinary stars in nearby galaxies occurs in the near-IR. Galactic extinction from dust in the Milky Way, a hindrance to all-sky galaxy surveys in the optical, is minimized by observing in the near-IR. Low mass stars and brown dwarfs are best detected in the near-IR.

7.3 Opportunities

The following is a list of near-IR projects, both proposed and ongoing, and both imaging and spectroscopic. To compare the power of the imaging surveys, a representative figure is given for the limiting AB magnitude in the K band (2.4μ), unless otherwise indicated, for point sources. The AB magnitude provides the fairest comparison of sensitivity among different wavelength bands.

Ground based imaging surveys

2MASS - this all-sky survey is completed and provides a reference against which to compare other surveys. $AB = 16$ [62].

UKIDSS - large area survey (7,500 deg^2) in 4 filters. Claims to be the IR counterpart to SDSS. $AB = 20.4$ [68].

VISTA - This telescope will be used for a variety of surveys, including one, the VISTA Hemisphere Survey, to conduct a deep JHK survey to complement the DES. AB limit 20.

Space based imaging surveys

PRIME - dedicated near-IR survey. Originally proposed as a Small Explorer mission but turned down. Planned for resubmission. $AB = 24$.

SNAP - proposed experiment for JDEM mission. Joint optical and IR cameras. Current design has 3 IR filters to 1.7μ. Wide survey would cover 1000 sq. deg. $AB = 27$.

Space based spectroscopic surveys

ADEPT - Proposed experiment for a JDEM mission. 29,000 sq. deg., Objective prism spectroscopy of 100 million galaxies with $z = 1 - 2$, wavelength range $1.3 - 2.0\mu$.

Cosmic Inflation Probe - Proposed experiment for an Inflation probe. Objective prism spectroscopy of 10 million galaxies with $z = 2 - 5$, wavelength coverage $2.5 - 5.0\mu$.

For reference, two other approved missions will explore the near- and mid-IR regions:

JWST (James Web Space Telescope) - Four near- and mid-IR instruments. Narrow field of view for pointed observations [35].

WISE - all sky survey with $6 - 12$ arcsec resolution, wavelength range $3 - 23\mu$.

7.4 Fermilab and Near-IR Surveys

Fermilab is currently a participant in SNAP, and we take the position that SNAP is well designed as a near-IR survey. The current plan is to survey 1000 sq-degrees in the optical and near-IR.

In the long term the natural extension of this line of projects is an all sky near-IR survey, a complement to the optical ground-based all-sky surveys of LSST and Pan-STARRS. In the near term staying close to focal plane arrays and large scale data reduction centers positions us to choose our future.

7.4.1 Fermilab's Role

Fermilab's SNAP effort is currently 4-5 FTEs. Opportunities are open to expand our involvement into areas which include:

a. CCD packaging

b. Data management and software development

c. Calibration - planning

d. Ground infrastructure

e. Electronics

The first of these is specific to the optical regime while the remaining can be for NIR as well.

The above areas tap into strengths present at Fermilab but not necessarily at universities or in industry - e.g., CCD packaging draws on Fermilab's expertise in packaging silicon detectors for particle physics experiments. Of these, the two most promising areas for greatly expanding our involvement are in data management and in CCD packaging. Fermilab potentially could be a SNAP data center (see, for example, SAO and Chandra, http://chandra.harvard.edu/), which would require an expansion in our science pipeline, data management, data curation, and public interface roles. Likewise, Fermilab could increase its design and construction roles in CCD packaging outwards towards the full focal plane, a job that keeps us close to space based instruments.

Should SNAP not be approved, it would be worthwhile examining options for participation in a PRIME-like mission. It should be noted that ground experiments and some space experiments are chipping away at the periphery of the wavelength-sensitivity space that would be targeted by a PRIME-type mission, so the science case would need to be clarified.

8 Direct Detection of Dark Matter WIMPS

Observations of galaxies, superclusters, distant supernovae and the cosmic microwave background radiation tell us that ∼85% of the matter in the universe is not made of ordinary particles. Deciphering the nature of this dark matter is of fundamental importance to cosmology, astrophysics, and high-energy particle physics. A leading hypothesis is that it is composed of Weakly Interacting Massive Particles [45, 42], or WIMPs, that were produced moments after the Big Bang. WIMPs would have been in thermal equilibrium with quarks and leptons in the hot early universe and decoupled when they were nonrelativistic. Particle physics theories provide possible WIMP candidates. For example, many supersymmetric models predit that the lightest supersymmetric partner (LSP) is stable and interacts at roughly the weak-interaction rate, allowing it to decouple from ordinary matter in the early universe with a relic density comparable to the dark matter density [41]. Similarly, some models involving extra dimensions predict that the lightest Kaluza-Klein excitation is stable, with weak-scale mass and interaction cross sections [11, 60, 27].

If WIMPs are indeed the dark matter, their density in the galactic halo may allow them to be detected via elastic scattering from atomic nuclei in a suitable terrestrial target. The energy depositions and interaction rates are low, requiring that this type of experiment be located deep underground for protection from cosmic rays and requiring the use of radio-pure materials to shield against radioactivity in the environment. The current generation of direct detection experiments is now reaching the level of sensitivity needed to probe theoretical predictions in a way that is quite complementary to accelerator searches. The combination of LHC and WIMP-nucleus elastic-scattering experiments would check the consistency of the models and provide powerful constraints on the parameters. The low mass of the Higgs inferred from electroweak measurements points to a WIMP-nucleon cross section on the order of 10^{-45}–10^{-44} cm^2 [24].

A number of recent reports from the National Research Council (“Connecting Quarks with the Cosmos,” chaired by M. Turner [1]; “Neutrinos and Beyond,” chaired by B. Barish [4]) and HEPAP (“The Quantum Universe,” chaired by P. Drell [7]) have pointed out the high priority of direct detection experiments. In reviewing some of these findings, the OSTP Interagency Working Group’s “Physics of the Universe” report directed that in the area of dark matter “NSF and DOE will work together to identify a core suite of physics experiments. This process will include research and development needs for specific experiments, associated technology needs, physical specifications, and preliminary cost estimates” [6]. The central role that dark matter plays at the intersection of cosmology and fundamental physics was highlighted most recently in the NRC report “Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics,” chaired by H. Shapiro and S. Dawson [8]. To support this finding, the report recommends that an increased fraction of the US elementary particle physics budget be used to support dark matter direct detection experiments. The Particle Physics Project Prioritization Panel (“P5”), in a unanimously adopted report to HEPAP, recommended proceeding with dark matter experiments as among the top priorities in the HEP program, behind only the large programs at the LHC and R&D for the ILC [5]. Finally, the Dark Matter Scientific Assessment Group [2] has advised DOE and NSF to increase funding for the field to $10M/year and to support a variety of technologies aimed at direct detection.

8.1 Current Fermilab Dark Matter Experiments

When considering the scattering of WIMPs on nuclei, two types of coupling between the WIMP and a nucleon must be considered: spin-dependent and spin-independent [46]. The balance between the two types of coupling in supersymmetry depends on the flavor composition of the lightest particle and can strongly favor one or the other coupling. However, in the case of spin-dependent couplings, there is a cancellation between opposite-aligned spins in the target nucleus, while in the spin-independent case, all nucleons add coherently and boost the effective cross section by a factor proportional to the square of the number of nucleons (A). This amplifies the sensitivity of experiments using large-A nuclei to search for spin-independent scattering by a factor A^2. For this reason, the experimental community has focused most attention and resources on attempts to discover WIMPs via spin-independent interactions. However, it should be kept in mind that there are models in which these interactions are highly suppressed and spin-dependent interactions are dominant.

Direct detection results are beginning to significantly constrain both spin-independent and spin-dependent WIMP-nucleon scattering cross sections, as shown in Fig. 4 and Fig. 5. Recent results have not confirmed the DAMA claim of a WIMP signal based on annual modulation [19, 20]. The CDMS (E-891) and COUPP (E-961) experiments at Fermilab are on the forefront of this effort.

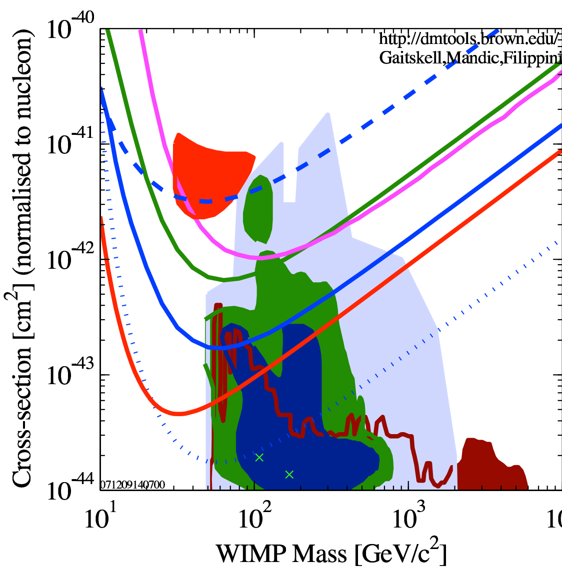

Figure 4: The colored curves are an ensemble of recent results from WIMP direct detection experiments showing upper limits on the **spin-independent** WIMP-nucleon cross-section (90% C.L.) versus WIMP mass. The colored regions in the lower part of the plot are taken from supersymmetric model predictions. The DAMA (1-4) 3σ signal region [19, 20] is shown in red. The best limits are currently from CDMS II and Xenon10. Also shown as a blue dotted curve is the expected sensitivity for CDMS II in Soudan. Note that the limits already probe a substantial region of MSSM phase space.

8.1.1 CDMS

The Cryogenic Dark Matter Search (CDMS) Collaboration [http://cdms.berkeley.edu], supported jointly by NSF and DOE, has pioneered the use of low temperature phonon-mediated detectors to

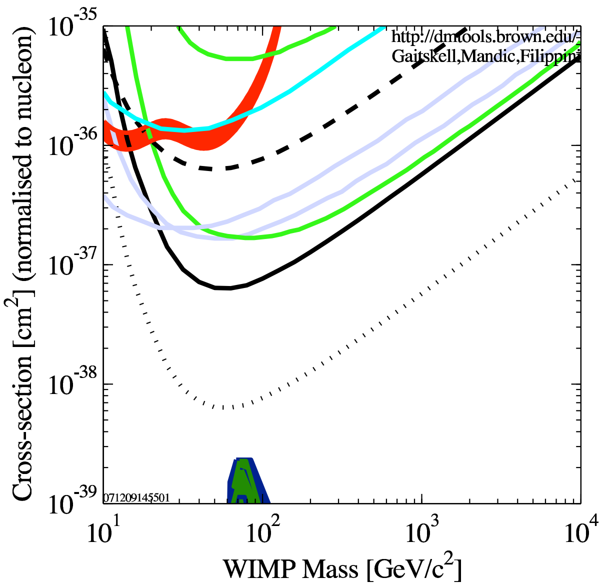

Figure 5: The colored curves indicate some of the recent results from WIMP direct detection experiments showing upper limits on the **spin-dependent** WIMP-nucleon cross-section (90% C.L.) versus WIMP mass. The colored regions at the bottom are taken from supersymmetric model predictions. The best limits are currently from CDMS II and COUPP. Also shown as a black dashed curve is the expected sensitivity for CDMS II in Soudan. Note that direct detection experiments cannot currently rule out any MSSM phase space for spin-dependent interactions.

search for the rare scattering of WIMPs on nuclei and distinguish them from backgrounds. The CDMS II experiment was constructed over several years (1998-2002) in the Soudan Underground Laboratory (2000 mwe) and has operated successfully since 2003. Current Fermilab scientists in CDMS II include Dan Bauer, Fritz DeJongh, Jeter Hall, Erik Ramberg and Jonghee Yoo. Mike Crisler and Roger Dixon were involved in the construction of the experiment.

Each CDMS data run so far has resulted in publications with the best limits in the world on the detection of WIMPs [14, 16, 15], and the current data run will be no exception. The experiment will continue to run with 4.5 (1.1) kg of Ge(Si) target mass at least through 2008, resulting in WIMP limits x10 better than those already published.

It is important to emphasize that CDMS II is the only direct detection experiment currently running without background events in the signal region. This is crucial for spotting the first few events of a WIMP signal. Indeed, CDMS II may have the reach to discover WIMPs in the coming year or two, before the Tevatron or the LHC see evidence for supersymmetry. Conversely, should supersymmetry be discovered at the Tevatron or LHC, CDMS II may clarify whether the lightest supersymmetric particle constitutes the dark matter.

8.1.2 COUPP

The Chicagoland Observatory for Underground Particle Physics is an experiment devoted to using bubble chamber technology for direct detection of dark matter. The COUPP collaboration includes the University of Chicago, Fermilab and Indiana University of South Bend. Fermilab physicists involved include Steve Brice, Peter Cooper, Mike Crisler, Martin Hu, Erik Ramberg, Andrew Sonnenschein and Bob Tschirhart.

The liquid used in COUPP bubble chambers is mildly superheated, such that it requires large energy density events like nuclear recoils to nucleate a bubble. Electron recoil events, which can be the dominant background in dark matter searches, are suppressed in bubble nucleation by about 10 orders of magnitude. The liquid currently being used, CF3I, provides sensitivity to both spin dependent and spin independent dark matter interactions.

The currently-operating bubble chamber has a 1-liter volume. It was designed and built at the University of Chicago and brought to Fermilab in 2005, where it has remained in operation in the NuMI near-detector hall (300 mwe) since 2005, with several shut downs for upgrades. Results from these runs have been shown at several conferences and submitted for publication. They provide the best limit on light WIMPs (below 30 GeV) interacting primarily by spin-dependent interactions on the proton. This sensitivity was achieved despite a very high background from radon gas decaying in the chamber in the early runs. The radon problem appears to have been solved by a recent upgrade, which should lead to greatly improved sensitivity.

8.2 Other Approaches to Direct Detection

The WIMP detection field has grown over the last several years, with the introduction of new technologies and a rapid increase in the number of university groups and national laboratories involved. There are now approximately fourteen research programs with operating experiments (DAMA/LIBRA, KIMS, CaF2-Kamioka, WARP, XENON-10, ZEPLIN-II, DEAP-I, XMASS, CDMS, CRESST, EDELWRISS, COUPP, PICASSO, DRIFT) and at least another three active R&D programs (ArDM, LUX, CLEAN). One clear trend in the last five years is the emergence of increasingly larger, more ambitious projects exploiting the properties of noble liquids. These projects are attractive due to the inexpensive, scalable detector designs, high material purities and, in some cases, very high levels of background discrimination that may be achievable.

Liquid noble gas technologies look like promising ways to positively identify the nuclear recoils on a per event basis. Several groups are progressing rapidly in developing this technology, but still need to reach key demonstration milestones of radiopurity, scintillation-light, ionization yield, and/or pulse-shape discrimination for nuclear recoils at low threshold. While these liquids may scale straightforwardly to large target masses, there are still technical challenges, such as trapped scintillation light from internal reflection and sufficient position resolution to limit the edge effects and, like all dark matter experiments, control of the radioactive background in a complex environment. Given the importance of the science, we believe it wise to support more than one large-mass technology to provide necessary cross checks on systematic effects. Indeed, this approach is in keeping with the OSTP [6] and DMSAG [2] reports, which refer to a suite of experiments.

8.3 R&D Towards the Future of Direct Detection at Fermilab

8.3.1 SuperCDMS

The SuperCDMS 25 kg proposal represents a x5 target mass increase over CDMS II. Combined with improved background rejection and location at the very deep (6000 mwe) site at SNOLAB, this experiment would represent another order of magnitude improvement in dark matter sensitivity. At present, the proposal has DOE CD-0 and Fermilab stage 1 approvals. Preparation for the SNOLAB phase of the experiment will overlap with continued running of CDMS detectors at Soudan. The first two Towers of SuperCDMS detectors will be run in the existing apparatus at Soudan in 2009, and the full payload of seven SuperTowers that make up the 25 kg experiment at SNOLAB will run in 2011-13.

The SuperCDMS detectors are 2.5 times more massive than the CDMS II detectors and have both improved rejection capability and decreased surface backgrounds. The projected exposure of 18,000 kg-days should reach a WIMP-nucleon cross-section of 1.3×10^{-45} cm^2 for a WIMP mass around 60 GeV/c^2 — a factor of $\sim$120 beyond the current published CDMS II limit.

By proceeding with the SuperCDMS 25 kg Experiment, Fermilab will be able to stay at the frontier of the WIMP searches and explore a crucial region of parameter space, in a way that is complementary to the LHC. SuperCDMS will be able to maximize discovery potential for WIMPS by remaining free of background events, a distinct advantage compared with most other technologies. Furthermore, since the SuperCDMS technology is a contender for a ton-scale detector at DUSEL, development work for a potential scale-up is also important.

8.3.2 COUPP

In October 2006, a proposal (http://www-coupp.fnal.gov) to upgrade to a 30-liter chamber was reviewed by the Fermilab PAC and approved by the director. A mechanical prototype of the 30-liter chamber is nearing completion. The PPD Mechanical Department is responsible for the design and construction of this chamber. The mechanical prototype will be used to develop the control and triggering algorithms and check all aspects of the operation that are not affected by radioactivity backgrounds. In parallel with the construction of the prototype, materials are being ordered for a high purity, low-background inner vessel. This will replace the lower purity parts used in the prototype and convert it into a fully functional WIMP detector. This detector should be ready to begin some physics running in the NuMI tunnel in mid-2008. If successful, it will be transferred to a deep underground laboratory. This detector will have an active mass of 60-80 kg and is expected to be the world's most sensitive device in searching for spin-dependent WIMP interactions. Depending on internal radioactivity backgrounds actually achieved, it may also be competitive for spin-independent interactions.

8.3.3 Liquid Argon

The noble-liquid technologies present new opportunities for Fermilab. If these technologies succeed, we will eventually have new ways to detect WIMPs with very small cross sections. Fermilab is strong in the engineering disciplines that these experiments will depend on (e.g. cryogenics, scintillation light detection and large-scale data acquisition), so our laboratory could have a very important role in these projects.

Given that CDMS and COUPP remain promising and certainly must be aggressively pursued to the next stage, expansion into the noble-liquid area would require additional resources. We believe that making modest, early investments in this area would be a very good idea for the laboratory, given the importance of the dark matter problem, the natural fit between liquid-noble detectors and the laboratory's existing technical capabilities.

A critical question for the noble liquid detectors is whether argon or xenon is the most promising target. The cross section for the scattering of WIMPs by spin-independent interactions is proportional to the square of the number of nucleons in the target, which for equal masses favors xenon over argon by about an order of magnitude if energy thresholds are low enough to avoid loss of coherence. On the other hand, argon offers the possibility of dramatically better background discrimination, due to the very large difference in scintillation pulse shapes for nuclear and electron recoils. Argon is also available in effectively unlimited quantities, and a thousand times less expensive than Xenon, which may become an important consideration for large chambers.

Commercial liquid argon is a distillation product of liquid air and Ar-39 is introduced into air by neutron interactions on Ar-40 at high altitude. Beta decays from Ar-39 would constitute a potentially large background for dark matter searches using liquid argon. Argon from underground sources, such as natural gas wells and subsurface waters, has the potential to be much lower in Ar-39 than atmospheric argon. Recently, a group at Princeton University and collaborators have demonstrated that at least two underground argon sources are more than ten times lower in Ar-39 than atmospheric argon (C. Galbiati et al., arXiv:0712.0381). Extraction of many tons of argon from these sources may be possible. Three Fermilab scientists (David Finley, Steven Pordes and Andrew Sonnenschein) have submitted a DOE proposal to work with Princeton on a systematic study of underground argon sources. The study will use a low-background liquid argon detector to be built at Fermilab and operated in the NuMI tunnel. If funded, this small-scale R&D proposal will be Fermilab's first venture into liquid-noble dark matter detection technology.

Recently, PPD's expertise and facilities have enabled considerable progress towards achieving high levels of purity required in liquid argon TPC's. This experience, along with R&D on light propagation and detection in liquid argon, would be important in development of liquid noble gas dark matter detectors.

8.3.4 Backgrounds

Direct detection dark matter experiments have reached a level of sensitivity corresponding to a few events per kilogram of target mass per year. This has already required a large effort to shield the detectors against gammas, electrons and neutrons from radioactivity. In addition, the experiments must be located deep underground to avoid neutrons produced in cosmic ray interactions.

Fermilab is well suited to become a center of low background material development and measurement, in such a way that it can improve the effectiveness of both of the current dark matter experiments and any future efforts. Several efforts have already been initiated by members of the CDMS and COUPP collaborations, although additional manpower would greatly accelerate progress in this area.

The primary source of radioactivity in the natural environment is long-lived U/Th isotopes, which yield alpha, beta and gamma particles from their decay chains. It is possible to screen materials for U/Th contamination by detecting the alpha particles emitted from surfaces. One of the most sensitive alpha detectors in the world is a wire chamber being developed by XIA LLC, based in Hayward, Ca. This unit has achieved a background level comparable to that achieved by the CDMS detectors. We are in the process of purchasing one of these prototype counters and will work with the company to develop it further. This work could benefit from the expertise of the wire chamber production facility in Lab 6.

A limiting background for all direct detection experiments is neutrons, since they produce the same nuclear recoil signature as the dark matter WIMPS we hope to detect. Mounting the experiments even deeper underground is sufficient to reduce neutrons from cosmic ray showers. However, neutrons also come from (alpha,n) and fission decays, both resulting from small amounts of U/Th isotopes surrounding dark matter detectors. This background will definitely be present in the next generation of experiments without extreme efforts to further reduce contamination. An interesting way to deal with the neutron background would be to surround the dark matter detectors with an active neutron veto that has high efficiency for detecting neutrons. The technology for loading liquid scintillators with elements like Li, B or Gd that have high neutron capture cross sections is well known. More recently, scintillating fibers have been developed that can also be loaded with such elements. It would be very interesting to design and construct a scintillating fiber calorimeter of modest thickness that could be an active neutron veto for the next generation of dark matter experiments. Fermilab has expertise in fiber detector development, with a dedicated fiber polishing and aluminization facility.

Fermilab's Lab 3 facility has recently been configured to provide clean room conditions for dark matter background investigations. There are two glove box units, one of which can supply an enhanced radon exposure for plate-out studies and another with a nitrogen atmosphere and air lock. This infrastructure will be very useful in investigating cleaning techniques and low-level screening. Lab 3 also provides a clean assembly area for both SuperCDMS and COUPP.

A Direct Detection of Axions

Axions were not discussed at the retreat so this section is included as an appendix.

A.1 Introduction

In the Standard Model, it appears that the strong interaction should violate CP; since this is not observed, the most popular explanation is that an additional symmetry prevents such a CP-violating term in the QCD Lagrangian. The soft breaking of that symmetry leads to the axion [54, 55, 71, 72], a viable cold dark matter candidate [74] if its mass lies in the range $10^{-6} < m_a < 10^{-3}$ eV.

Figure 6 shows the current bounds on the QCD axion. It is constrained to have a mass larger than about 10^{-6} eV (otherwise the expected production would overclose the universe) and less than about 10^{-3}eV (otherwise measurements from SN1987a would be troublesome). The coupling to photons, $g_{a\gamma\gamma}$ is excluded above 10^{-10} because otherwise certain stars would be expected to radiate their energy away in axions and not the observed photons. The width of the allowed band for QCD axions corresponds to details of different axion models and has yet to be probed experimentally.

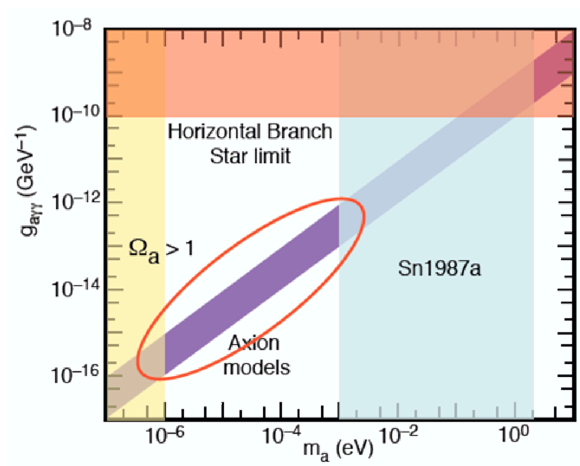

Figure 6: Current constraints on the QCD axion coupling to photons and mass.

A.2 Current experimental results

Current experimental limits on the axion come from a variety of different sources. Laser experiments including the recent results of the Fermilab GammeV experiment [28] probe a very strong coupling to photons that is not consistent with the QCD axion, but rather an axion-like particle. A solar telescope limit [75] from an experiment that points an LHC dipole magnet at the sun sets a limit near the star cooling limit, but well above the expected QCD axion coupling.

There have been narrow band probes at low QCD axion mass using microwave cavities including the currently running Axion Dark Matter eXperiment, ADMX [33]. ADMX consists of a tunable microwave cavity immersed in a high magnetic field. The idea is that a dark matter axion might enter into the cavity, interact with a virtual photon from the magnetic field, convert into a real photon, and cause a detectable signal to be amplified if the high-Q cavity is resonantly tuned to a frequency given by the kinetic energy, which in turns depends on the mass of the axion. ADMX is thus sensitve to a narrow mass range of axions provided the axion halo density is sufficient. The future of the ADMX experiment, as endorsed by the recent DMSAG report [2], includes upgrades that should allow for sensitivity into the QCD axion-photon coupling region for masses between 1 and 10μeV. This future includes two phases where the first (funded) is to incorporate very low noise amplifiers (SQUIDs) and the second (proposed) is to reduce noise even further by going to lower temperatures that would require a dilution refrigerator. With the ADMX program, the US is currently the leader in the dark matter detection of axion candidates. With these two additional phases complete, ADMX will be able to cover the region of interest for QCD axions in the first 1-10μeV decade, with the possibility of extending into the second 10-100μeV decade range if additional R&D is successful.

A.3 Possible new Fermilab directions

A.3.1 Enhanced laser Searches

A new idea [61] would extend the sensitivity of the GammeV experiment by using two coupled Fabry-Perot optical cavities on either side of the wall through which the axion-like particles would pass. This effort would require similar techniques as employed by the LIGO gravity wave experiment. Fermilab would be a candidate facility to host this experiment where magnet and cryogenic engineering and support would be especially beneficial. Advanced engineering such as stable mechanical support could overlap with efforts looking at the mechanical requirements for the International Linear Collider, ILC. Fermilab engineering could also provide electronics for the feedback control and readout electronics necessary for the experiment.

A.3.2 Microwave cavity searches

A second possible new direction would be for Fermilab to work on the yet-to-be covered QCD axion CDM region. In order to probe the QCD axion in a range where it is a viable dark matter candidate, Fermilab could join the ADMX project or perhaps develop techniques to cover a higher mass range than ADMX with its future upgrades will not be able to cover. Fermilab engineering with magnets and cryogenics could play a very large role. For example, there is a current program driven by the Muon Cooling effort for a wide bore magnet in which sits a RF cavity. RF cavity design work for the ILC could also be synergistic. To extend the reach toward higher masses, new cavities of smaller dimensions must be designed and produced in a way that recovers volumetric sensitivity. The existing Fermilab Magnet Test Facility has a VMTF test stand [57] that has the ability to support both a superconducting magnet and RF power, which could allow Fermilab to get started early by using the same or similar design of ADMX. In addition to magnets and cryogenics, Fermilab has expertise in electrical engineering including ASIC designers that have expertise in low noise sensors. There is also a group at Argonne that has developed low noise transition edge sensors that might be beneficial towards the effort.

A.3.3 Searches with crystal detectors

The third possible new direction is using crystal detectors to search for possible solar axions with relatively high masses (10^{-2} eV to 20 eV). Based on the accuracy of the standard solar model, we can estimate the axion flux at Earth. Solar axions may be converted back into photons in the strong Coulomb field of a nucleus by the Primakoff effect. Due to the crystal's highly periodic structure, the Bragg scattering pattern changes as the incident beam direction, greatly enhancing signal to noise. Such a search may be possible with either CDMS Ge crystals or the enriched

76Ge crystals employed by the Majorana double beta decay experiment. An R&D effort would be needed to optimize detection of energy deposits in the $1 - 10$ keV range.

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