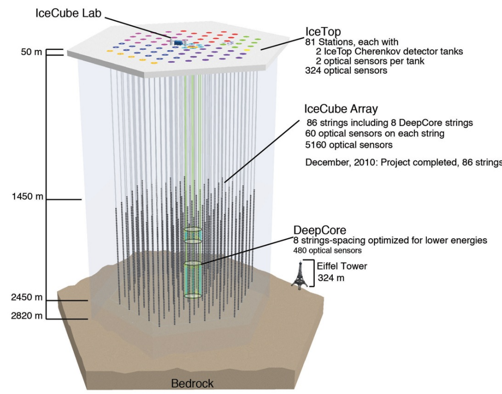
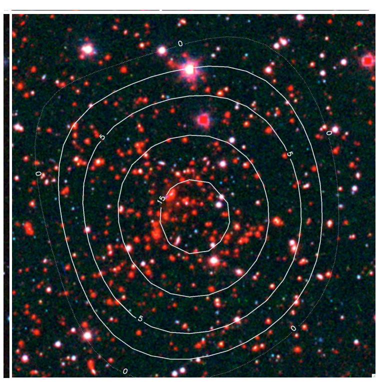
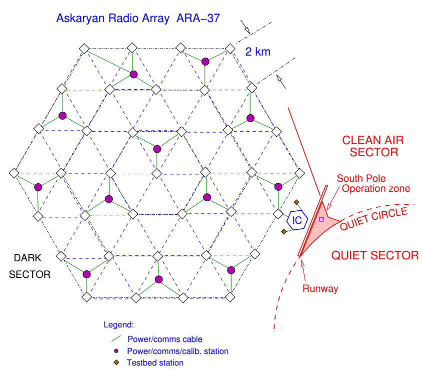
Report from the Workshop

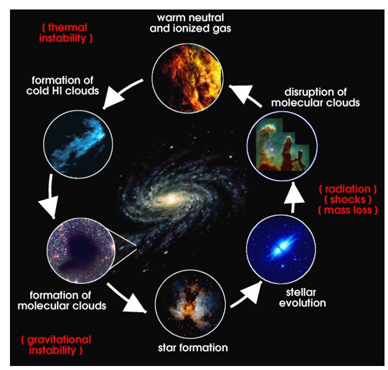
"Astrophysics from the South Pole: Status and Future Prospects"

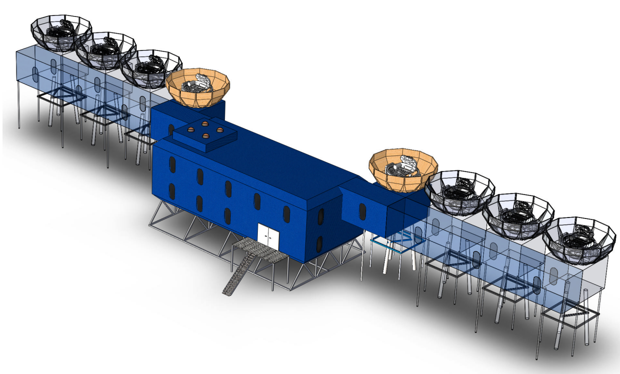
Held in Washington DC April 4–5 2011

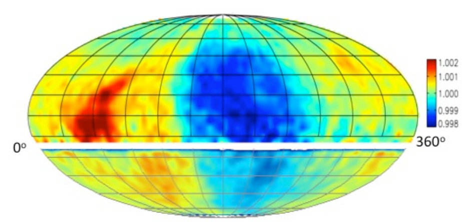












Edited by: Clem Pryke, Albrecht Karle and Craig Kulesa

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1 Executive Summary

The NSF-operated Amundsen-Scott South Pole Station has a rich past, a vibrant present, and a bright future as a site for cutting-edge astrophysical observations. From the pioneering (and sometimes heroic!) early days a world-class research program has emerged spanning areas from precision measurements of the Big-Bang to searches for ghost-like ultra high energy particles from the most extreme environments in the present day Universe. With the recent completion of the state-of-the-art New Station, and the extremely large IceCube project, it is timely to consider the status of the astrophysical program and what the future may hold. To this end a workshop was organized in Washington DC on April 4/5 2011[1]. This report summarizes the material presented at that workshop and the following discussions with special emphasis on the infrastructural implications of the visions for the future. It was intended to feed informally into the review process now accomplished by an NRC convened committee[2].

Astrophysical observations from the U.S. Amundsen Scott South Pole Station have been underway for several decades, and to date represent the majority of ground based astrophysical work in Antarctica. The site offers two very special characteristics—the ice below and the sky above.

The ice below is two miles thick, and extremely clear, making possible neutrino telescopes of unprecedented scale and sensitivity. Building on the AMANDA experiment the IceCube collaboration has recently completed by far the largest and most sensitive neutrino telescope on Earth. Neutrinos are ghostly sub-atomic particles which interact hardly at all with the ordinary matter which makes up stars and planets—it is only by building truly vast detectors that we have any hope of catching and measuring them. On the other hand it is precisely this incredible penetrating ability which makes them so important to study—once born in distant cosmic accelerators of truly awesome power they easily escape from the site of their production and cross the vast reaches of intergalactic space to reach us here at Earth. By studying these elusive particles we can learn about the most extreme environments in the Universe. Many kinds of other science are also being carried out with the IceCube detector and its associated IceTop array including cosmic ray studies and searches for lower energy neutrinos produced in supernova explosions.

The sky above South Pole has proven to be ideally suited to observations in the millimeter waveband where the Cosmic Microwave Background (CMB) is the dominant signal. It turns out that the entire sky is glowing brightly in microwaves, and that these are the stretched out remnants of the blinding white light of the Big-Bang fireball itself. By studying this incredibly ancient light we have learned an amazing amount about the origin, content and ultimate fate of the entire Universe. Since the late 1990's the South Pole has been at the forefront of the global quest to study the CMB, repeatedly delivering world class scientific results. At this time two major efforts are ongoing: the 10 meter SPT telescope is finding massive galaxy clusters at unprecedented distances to measure the history of comic expansion, while the BICEP/SPUD program is searching for the faint signature of hyper inflation a tiny fraction of a second after the beginning of time.

[1] See `http://find.spa.umn.edu/~pryke/southpolemeeting/`

[2] `http://www.nap.edu/catalog.php?record_id=13169`

Over the years many other types of astronomy have been done from the South Pole and at the moment a set of small new experiments are opening up fresh opportunities. These include using South Pole as a staging post to develop, and then deploy, autonomous experiments to still higher sites on the Antarctic plateau. Other ideas are to study the cosmic web of intergalactic matter, and infrared astronomy with robotic adaptive optics.

This report details each of these major research areas with emphasis on future ideas and directions. The final section summarizes the infrastructural implications of these visions for the future of astrophysics at the South Pole. The most pressing needs identified are for higher bandwidth satellite data transmission and a new laboratory building to replace the aging MAPO facility.

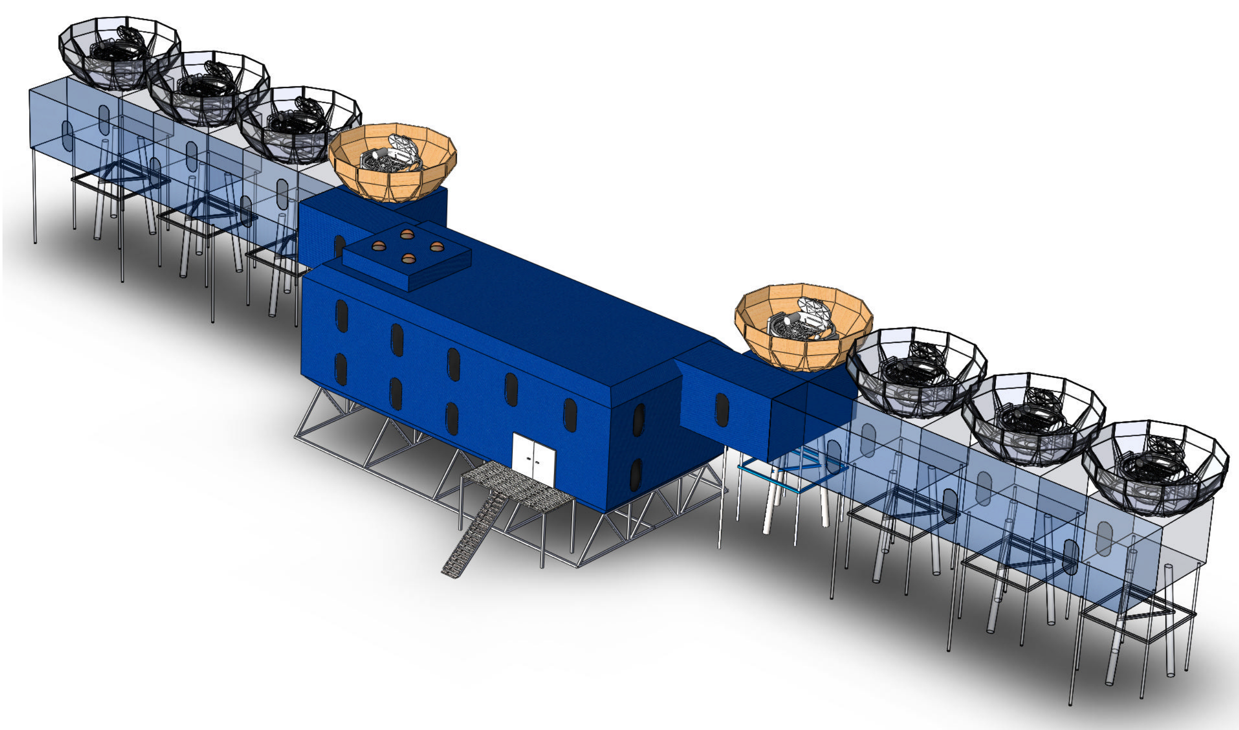

Figure 1: A rendering of a possible replacement for the MAPO observatory building at South Pole. As an example an array of CMB telescopes are shown attached. However, the building, and its modular extension towers, would be flexible and suited to many kinds of astrophysical observations.

2 Cosmic Microwave Background

The Cosmic Microwave Background is an "after-glow" of the Big-Bang—relic thermal light left over from the "fireball" of the early Universe. Around 400,000 years after the beginning the expanding Universe had cooled sufficiently to make the transition from opaque plasma to transparent neutral gas, so at that time the "fireball" light became free and has been streaming through the Universe ever since. After the discovery by Hubble that the Universe is expanding, and the suggestion that it began in a Big-Bang, researchers started looking for this after-glow radiation—dubbed the Cosmic Microwave Background or CMB. It was found, partially by accident, by Penzias and Wilson in 1963, earning them the Nobel Prize.

It was soon realized that the glow of the CMB should have small variations in brightness (anisotropies)—the seeds that grew into the galaxies and clusters of galaxies in the present day Universe. After many attempts, these very faint variations in the glow were first convincingly detected by the COBE spacecraft in 1992. In the last two decades CMB research has been an increasingly hot area with a series of South Pole experiments leading the field.

2.1 Previous CMB Experiments at the Pole

The Universe has expanded by a factor of about one thousand since the CMB was released—stretching these light-rays with it from the optical all the way down to microwaves with wavelength of around 2 mm. At these frequencies water vapor is extremely opaque so one must seek the driest site possible to make observations from the ground. It is a curious fact that although the ice is two miles thick at South Pole the rate of accumulation is incredibly slow—it is actually an "ultra desert". It is also quite high (10,000 feet), and hence the total amount of water vapor between the ground and outer-space is as low as at almost any site on Earth. In addition Pole has the unique feature that there is one day-night cycle *per year* leading to extremely stable atmospheric conditions, particularly in the deep winter (see Section 5). In the late 1980's researchers realized the incredible potential of the site for CMB research and a series of pioneering experiments were carried out. However the environmental conditions are of course very challenging and it took some time for the proper techniques and strategies to be worked out—for an excellent review of the early years see [1].

Python: was a 0.75 m off-axis telescope with a fast chopping primary. It was first operated in late 1992 and quickly detected CMB anisotropy on degree scales, confirming the COBE results less than a year after their release [2].

DASI: The Degree Angular Scale Interferometer was a 30 GHz array installed in fall of 1999. It was one of the final projects of CARA—The Center for Astronomical Research in Antarctica. DASI was a highly successful project discovering multiple acoustic peaks of the CMB power spectrum in early 2001 (as featured on the front page of the New York Times—see Figure 2 and reference [3]), and the polarization of the CMB in mid 2002 (as featured on the cover of Nature Magazine [4]).

ACBAR: In late 2000 the ACBAR receiver was deployed on the 2.1 m VIPER telescope and made measurements over the next five winter seasons leading to ground breaking results on the small scale structure of the CMB [5].

QUaD: For the 2005 winter season the QUaD experiment was installed on the telescope mount previously used for DASI and made fine scale polarization measurements through the

"All the News That's Fit to Print"

The New York Times

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Listen Closely: From Tiny Hum Came Big Bang

By JAMES GLANZ

WASHINGTON, April 29 — Two detectors in Antarctica have discovered minute patterns in a glow from primordial gases, possible traces of the cosmic match that ignited the Big Bang and led to the creation of the universe 14 billion years ago, astronomers announced here today.

The patterns, astronomers said, were probably created by microscopic processes — energy fluctuations at the quantum scale — that were at work when the universe was a tiny fraction of a second old and smaller than a human fist.

The new observations do not see the quantum fluctuations directly, but instead have found traces of colossal waves, much like sound waves, that the fluctuations probably set in motion, roiling the young universe.

The results rest on the most detailed observations ever made of a glow from the hot gases of the early universe. That glow, called cosmic microwave background radiation, carried an imprint of those waves to the detectors on Earth.

The news comes as a relief for astronomers, some of whom started to worry last year that their basic picture of the origins of the universe might be flawed, after detailed observations failed to find the wave patterns.

"We see the structure of the universe in its infancy," said Dr. John Carlstrom, a University of Chicago astrophysicist who leads the team operating the Degree Angular Scale Interferometer, or DASI (pronounced daisy), a microwave detector at a South Pole research station operated by the National Science Foundation.

Dr. Michael Turner, a cosmologist

Continued on Page A8

Scientists Hear the Tiny Hum They Say Ignited the Big Bang

Continued From Page A1

at the University of Chicago who was not involved in the measurements, said that the precise time the fluctuations took place remained to be determined by future measurements, but that the process was likely to have taken place in a fraction of a second comparable to a decimal point followed by 32 zeros and a 1.

"We are living in the most exciting time ever in cosmology," he added.

Besides DASI, which also involved astronomers at the California Institute of Technology, the announcement today included the so-called Boomerang team. This group flew a balloon-borne detector around Antarctica, and includes astronomers from the United States, Italy, Canada and Britain. Antarctica is excellent for such observations because the air is thin and dry and does not strongly absorb microwave radiation.

Dr. John Ruhl of the University of California at Santa Barbara presented results today for the Boomerang team. The announcements took place at a meeting of the American Physical Society.

The Antarctica studies were buttressed today when another group of researchers reported that they had made less distinct observations of the wave patterns from the United States. That team, called Maxima, includes astronomers at the University of Minnesota and the University of California at Berkeley.

The leading theory of how the universe could have exploded out of the primordial nothingness, known as the theory of inflation, predicts that the quantum fluctuations should have rattled the universe in such a way that it resonated like a vast organ pipe, with one main tone, or wavelength, and a series of overtones or harmonics.

Last year, the Boomerang team detected the main tone but found no clear evidence for the overtones, raising the possibility that the inflation theory could be wrong. Since much of the information about the fluctuations, like their relative intensity and spectrum, would reside in the characteristics of the overtones, those results raised the prospect that few remnants of the initial spark might be found.

Today, the three teams announced that they had seen two of the overtones for the first time. In musical terms, the observations saw the first two harmonics above the main tone.

"We do see two more bumps and wiggles out there," Dr. Ruhl said. "We can move to the question of, 'What do these bumps and wiggles tell us?' "

Dr. Max Tegmark, a cosmologist at the University of Pennsylvania, said that while the new results were still far from absolute proof of the inflation theory, their agreement with the theory was uncanny and would cast doubt on alternative models. "It's even scary that things agree this well," he said. "This is a very bad day for the competition."

Some other scientists, including Dr. Andrew Lange of Caltech, a leader of the Boomerang group, said the results strikingly showed that cosmologists understood the composition and behavior of the universe in the first few hundred thousand years of its life. It was then that the sound waves were humming through the young cosmos; astronomers believe the microwave background radiation was emitted as the universe cooled below a critical temperature when it was about 400,000 years old.

"We've really been waiting for the other shoe to drop," Dr. Lange said in reference to the lengthy search for the overtones. "What we're confirming for the first time is a very generic prediction of modern cosmology."

Although astronomers said much more detailed observations, including the discovery of further overtones, would be required to define the quantum fluctuations and to verify inflation, the results are likely to be seen as major victories for two scientists in particular.

The first, Dr. Alan Guth of the Massachusetts Institute of Technology, developed the germ of the inflation model in 1980, a theory he has called "the ultimate free lunch" because it shows how the entire universe could have exploded out of nothing and impressed the quantum fluctuations on the cosmos.

The results also provide major support for ideas closely associated with Dr. David Schramm, a Chicago cosmologist who died in a plane crash late in 1997. Dr. Schramm and his colleagues worked out a theory, unrelated to inflation, using trace elements created in the Big Bang explosion to gauge the amount of ordinary matter in the universe.

Those values agree closely with the amounts deduced from the intensity of the sound wave overtones; that intensity is affected by the sloshing of matter in the sound waves' peaks and troughs.

On the other hand, the results also leave cosmologists with some deep and perhaps troubling questions.

For example, the new observations confirm that most of the cosmos seems to be made of so-called dark matter and dark energy, possibly particles or energy lurking somewhere in space but still never detected directly. Dr. Turner, of Chicago, said skeptics might well term that picture "the absurd universe, or the preposterous universe."

Sir Martin Rees, an astrophysicist at Cambridge University, said scientists were left with the question of whether fundamental physical laws would someday explain that strange mixture of ingredients, or whether the precise amounts were a sort of accident of how the universe came into being — something like snowflakes, each of which has a hexagonal symmetry but carries a pattern that is otherwise unique.

"It may well turn out that the underlying laws do not give us these numbers, any more than they give the detailed pattern of a snowflake," Sir Martin said.

'Listening' to the Origin of the Universe

Measurements of a faint, pervasive radiation throughout space bolster a theory of the universe's origin

THE MEASUREMENT

MAIN TONE

HARMONICS

TEMPERATURE

1 0.5 0.3 0.25 0.2

ANGULAR SCALE (DEGREES, OR AMOUNT OF SKY)

Tiny fluctuations in the temperature of wide stretches of sky carry the imprint of a wave of sound like one resonating from an organ pipe. The main tone is a tall peak, and the overtones, or harmonics, have smaller peaks. This "ringing" is predicted by the theory of inflation.

INFLATION THEORY AND THE BIG BANG

INFLATION

Intense, fluctuating energies fill a tiny point, setting it ringing.

It rapidly expands, stretching the fabric of space as well as the fluctuations ...

...which ignites the Big Bang, creating a hot, dense soup of particles. The expanding universe continues to resonate as it cools.

Several hundred thousand years later, light waves decouple from matter and carry the imprint of the energy fluctuations across the universe.

The light waves expand with the universe and can be detected as faint ripples of hot and cold spots called background radiation.

Sources: Dr. John Carlstrom, Dr. Wayne Hu, University of Chicago

The New York Times; Radiation chart courtesy of University of Chicago

Figure 2: *Left*: The New York Times announces DASI temperature results in 2001. *Right*: Nature Magazine features DASI polarization results in 2002.

next three winter seasons. The results published in 2008 remain the best to date in this highly competitive field [6]—they will presumably finally be surpassed in the next couple of years by the billion dollar Planck space mission. Photographs of QUaD and the other experiments mentioned above are shown in Figure 3.

2.2 The South Pole Telescope

The stunning success of South Pole CMB experiments detailed in the previous section, followed by the confirmation of those experiments' results with the WMAP satellite, left CMB researchers with the obvious question of: "What next?" The two areas of CMB research with clear potential for exciting science that had not yet been fully exploited were the very small-scale temperature anisotropy—including the potential to discover distant clusters of galaxies through the thermal Sunyaev-Zel'dovich (SZ) effect—and the B-mode polarization power spectrum. The small-scale temperature signals were the primary motivation for building the 10-meter diameter South Pole Telescope (SPT).

Why study the small-scale CMB? One of the strongest motivations is to investigate the nature of the Dark Energy. Using CMB results and studies of distant supernova it was discovered about ten years ago that the Universe is expanding ever more rapidly, and that the driver of this accelerated expansion is some form of energy density with negative pressure. The nature of this energy remains a complete mystery. The only means we have of obtaining information about Dark Energy is to measure its effect on the expansion history of the universe and the growth of structure. A census of the abundance of massive clusters of galaxies as a function of redshift can measure both of these effects and produce constraints on the Dark Energy equation of state complementary to constraints from purely geometrical

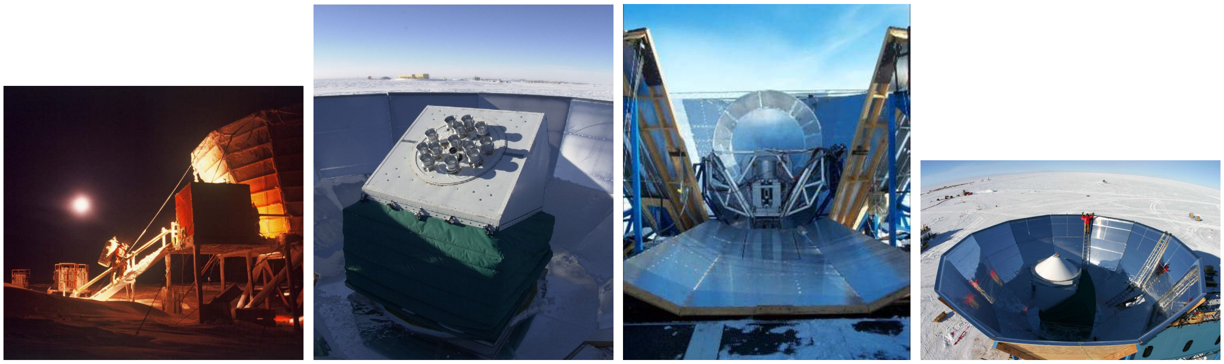

Figure 3: Previous South Pole CMB Telescopes, left to right: Python, the first CMB experiment to operate in winter at South Pole, DASI in early 2000 before its first winter, ACBAR on the VIPER telescope, and QUaD in 2005.

probes such as the apparent brightness of supernovae.

The SZ effect is perfectly suited to performing such a survey, because the brightness of the effect is independent of redshift, so clusters are equally easy to find at $z = 2$ as they are nearby (provided one has sufficient angular resolution), and, furthermore, because the total SZ effect from a cluster is a measure of its total thermal energy and should faithfully trace the cluster's mass, which is what cosmological models can predict. However, to find enough clusters for a cosmologically interesting survey, a large increase in sensitivity was needed over existing CMB instruments. The SPT (shown in figure 4) was designed with these dual goals of sensitivity and resolution—also keeping in mind the control of systematics needed to properly measure such small signals. The conservatively illuminated 10-meter dish gives a 1 arcminute beam at 150 GHz, which is well matched to distant clusters, and the 960 element, three-color bolometer array in the current camera provides unprecedented instantaneous sensitivity in the frequency range of interest to CMB and SZ studies.

The 2500 square degree SPT-SZ survey has occupied the first four years of the telescope's life and is being completed this current austral winter (2011). This survey has already produced many important galaxy cluster results including: the first ever clusters discovered through their SZ signature [7], the first cosmological constraints from an SZ-selected catalog of clusters [8], discoveries of the two most massive clusters above $z = 1$ [9], and tests of the ΛCDM cosmological model and Gaussian initial conditions from the most massive clusters in the survey [10].

Of course, an arcminute-resolution instrument with unprecedented sensitivity at these frequencies also opens up discovery space well beyond searches for galaxy clusters. The SPT-SZ survey has also produced the first ever detection of secondary anisotropy in the CMB power spectrum [11], the first millimeter-wave (mm-wave) detection of the clustering of the cosmic infrared background [12], and has discovered a new population of strongly lensed, high-redshift star-forming galaxies [13]. In all, over a dozen scientific articles on SPT data have appeared in refereed journals in just the past two years—Figures 5–8 show some examples.

Figure 4: The 10-meter South Pole Telescope (SPT). In the foreground are the Dark Sector Laboratory building and the BICEP telescope.

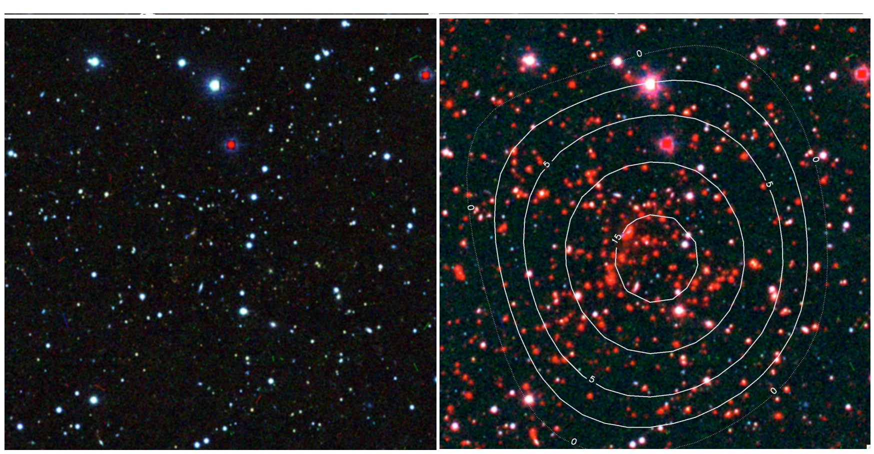

Figure 5: Optical (left) and near-infrared (NIR, right) images of the most massive high-redshift galaxy cluster yet discovered, SPT-CL J2106-5844, at z=1.13. Contours in the NIR image show the Sunyaev-Zel'dovich signal from SPT data, in which this extreme object was first identified. Despite its extreme mass, this cluster is extremely faint in the optical because it is at such high redshift.

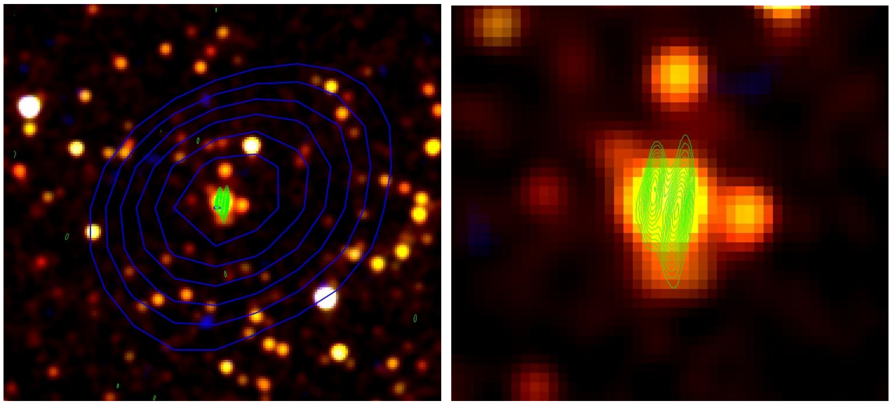

Figure 6: Millimeter-wave, sub-millimeter, and near-infrared observations of SPT-S 053817-5030.8, a typical strongly lensed dusty galaxy discovered by SPT. The background image is near-infrared data from the Spitzer Space Telescope, which is primarily sensitive to light from the lensing galaxy rather than the background source; blue contours are 1.4 millimeter (220 GHz) data from the SPT; green contours are high-resolution interferometric data at 850 microns (350 GHz) from the Submillimeter Array (SMA) on Mauna Kea. The zoomed-in image clearly shows multiple images of the background source in the SMA data, coincident with the Spitzer image of the lensing galaxy, confirming that this source is strongly lensed.

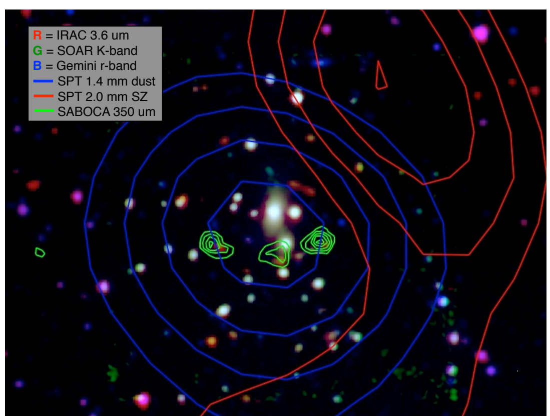

Figure 7: Composite millimeter/submillimeter/near-infrared/optical image of SPT-S J233229-5358.5, a high-redshift dusty galaxy that has been strongly lensed by a massive galaxy cluster along the line of sight. Red contours show the SZ decrement from the cluster in the 2mm (150 GHz) SPT band, partially filled in by the background source flux; blue contours show the source flux in the 1.4mm (220 GHz) SPT band (where the SZ spectrum crosses zero, so there is no signal from the cluster); green contours show the source flux resolved into multiple strongly lensed images by the SABOCA 350um camera on the APEX telescope. The background colors show the cluster galaxies and the much redder high-redshift source.

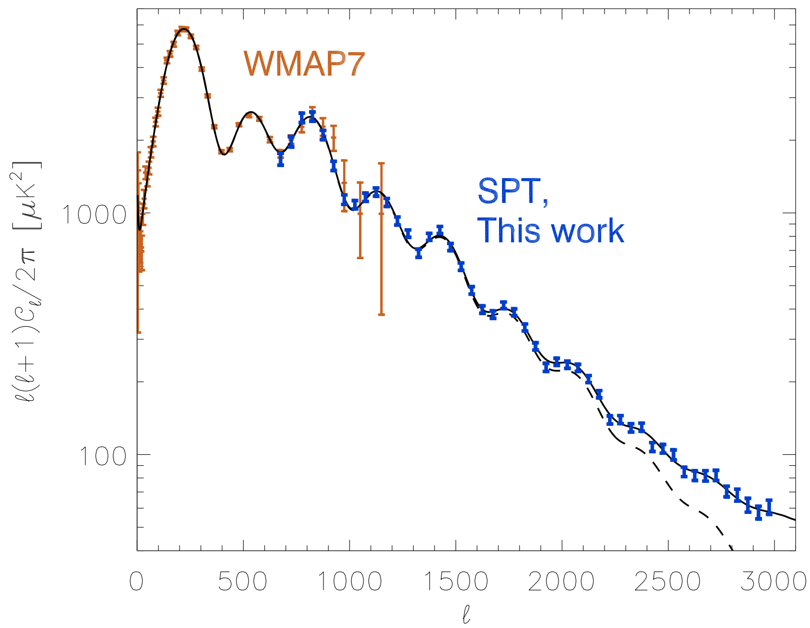

Figure 8: The SPT bandpowers, WMAP bandpowers, and best-fit ΛCDM theory spectrum shown with dashed (CMB) and solid (CMB+foregrounds) lines. The combination of these two telescopes alone is now sufficient to characterize the CMB power spectrum to a precision unimaginable just a few years ago. (Reproduced from [14].)

The immediate future of the SPT will be devoted to measuring the polarization of the CMB as described in section 2.4 below. Beyond that ∼5-year window, there are a number of technological advances that could enable the SPT to become an even more powerful discovery tool at mm and sub-mm wavelengths. The current focal plane is divided between pixels observing in different bands, and the pixels are separated by roughly an Airy diameter. Advances in detector design could produce a focal plane that is fully sampled at multiple frequencies simultaneously. In the meantime, the SPT is also poised to contribute to a worldwide effort aimed at probing black hole physics at the scale of the Schwarzschild radius. The Event Horizon Telescope, a mm/sub-mm VLBI array, has already made measurements down to $4R_S$ with only three baselines separated by a few thousand km. The addition of the SPT to this array will drastically improve the resolution and enable probes of fundamental physics.

2.3 The BICEP/BICEP2/Keck-Array Program

The final frontier of CMB science is the most exciting of all—the search for gravity waves spawned a tiny fraction of a second after the beginning of time in a process dubbed "Inflation". Inflation posits that the entire observable Universe was once a tiny subnuclear volume which underwent superluminal expansion around 10^{-32} seconds after the beginning. This theory explains many of the observed features of the CMB, and the Universe as a whole, but deals with fundamental physics at an energy scale scale far beyond anything we can ever reach with terrestrial particle accelerators. Inflation injects gravity waves into the fabric of space and looking for a faint "B-mode" signature they may induce in the polarization pattern of the CMB is the best hope for gaining further insight. This quest is regarded as fundamental physics of the highest priority— globally there on the order of ten experiments pursuing this important goal.

BICEP1 was deployed to South Pole in the fall of 2005 and was the first experiment specifically designed to search for the "smoking gun" of Inflation in CMB polarization. Since the predicted signature is a large scale effect—patterns with characteristic size of several degrees—a small telescope has adequate resolution. A small telescope also offers compelling advantages in the control of contaminating effects. Even miniscule levels of pickup from the ground or other areas of the sky would swamp the absolutely tiny signals of interest, but with a small telescope it is practical to have a comprehensive co-moving screen to completely prevent such contamination from entering the telescope. In addition it is possible to rotate a small telescope about the line of sight which gives additional powerful rejection of false signal.

Figure 4 shows the BICEP telescope shield on the DSL building to the left of SPT while Figure 9 shows results from BICEP1 released in 2009—in the lower panel we see that, while there is still some way to go, BICEP1 leads the global chase down to the sensitivity level where the exciting gravity wave signal may lurk.

To keep pushing down in sensitivity in 2009 BICEP2 replaced BICEP1. BICEP2 uses new antenna coupled TES detectors and is *field proven to be a factor of twelve* more sensitive than BICEP1. Figure 10 shows the ground breaking BICEP2 focal plane while Figure 11 compares maps made by BICEP1 using three seasons of data versus BICEP2 with only half a season—BICEP2 is already pushing further down into the noise in search of the elusive inflationary signal.

Sensitive though BICEP2 is, still more sensitivity is required. To leverage the substantial investments already made in the BICEP program, in the fall of 2010 the initial three receivers of the SPUD array were deployed on the mount originally built for DASI. Figure 12 shows two views of this newest telescope system. In the 2011/12 season the SPUD array will be expanded to its full complement of five receivers. BICEP2/SPUD is already the most sensitive CMB polarimeter ever deployed—more sensitive even than the billion dollar Planck space mission—keeping South Pole out in front in the global quest for Inflation.

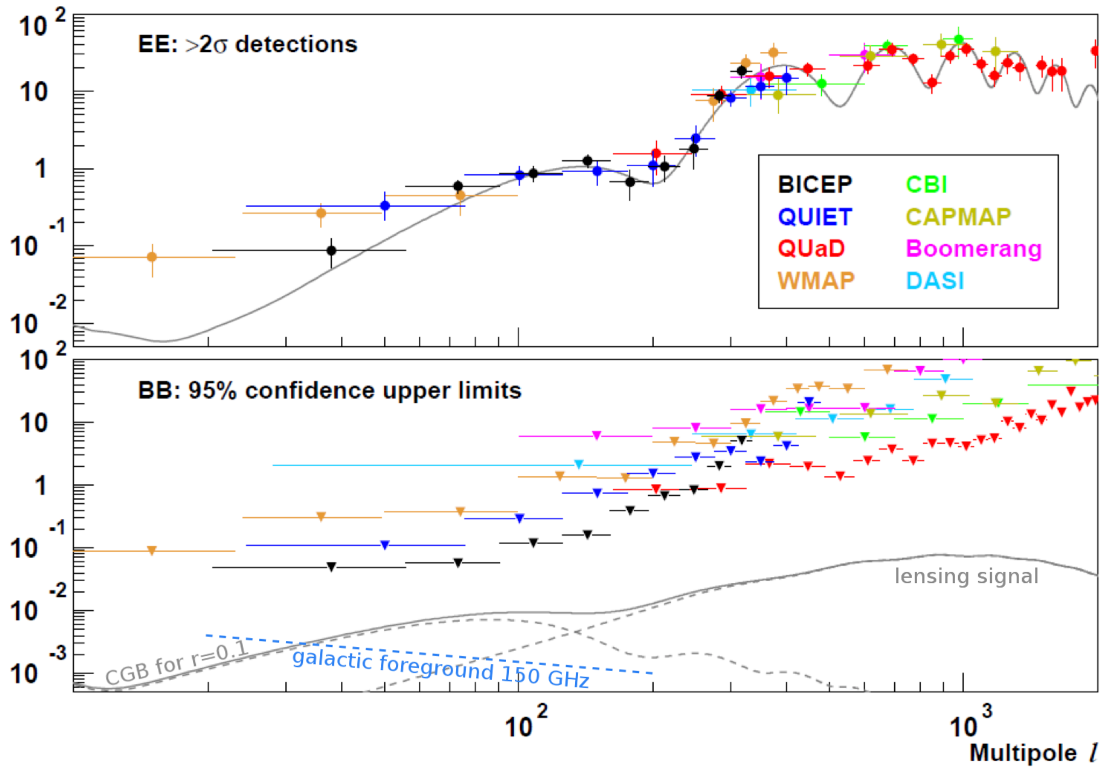

Figure 9: Current results on CMB polarization (reproduced from [15], with the addition of more recent points from the QUIET experiment). Note that the world's current best measurements and limits are from BICEP1 (and its sister experiment QUaD). The dashed grey lines in the lower figure indicate B-mode signals from lensing and from gravity waves with $r = 0.1$; the solid grey line is the sum of these two signals. The dashed blue line indicates predicted levels of Galactic contamination (both synchrotron and dust) at 150 GHz.

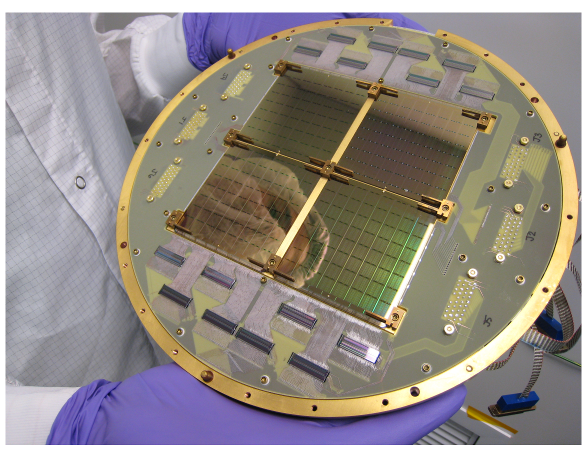

Figure 10: The BICEP2 focal plane, with 512 TES detectors operating at 150 GHz. Each of the four sub-arrays is a silicon wafer with superconducting lithographed microwave circuitry that forms the beams and defines the spectral band. This is a major advance from previous generations made possible by a technology development program at NASA-JPL and NIST.

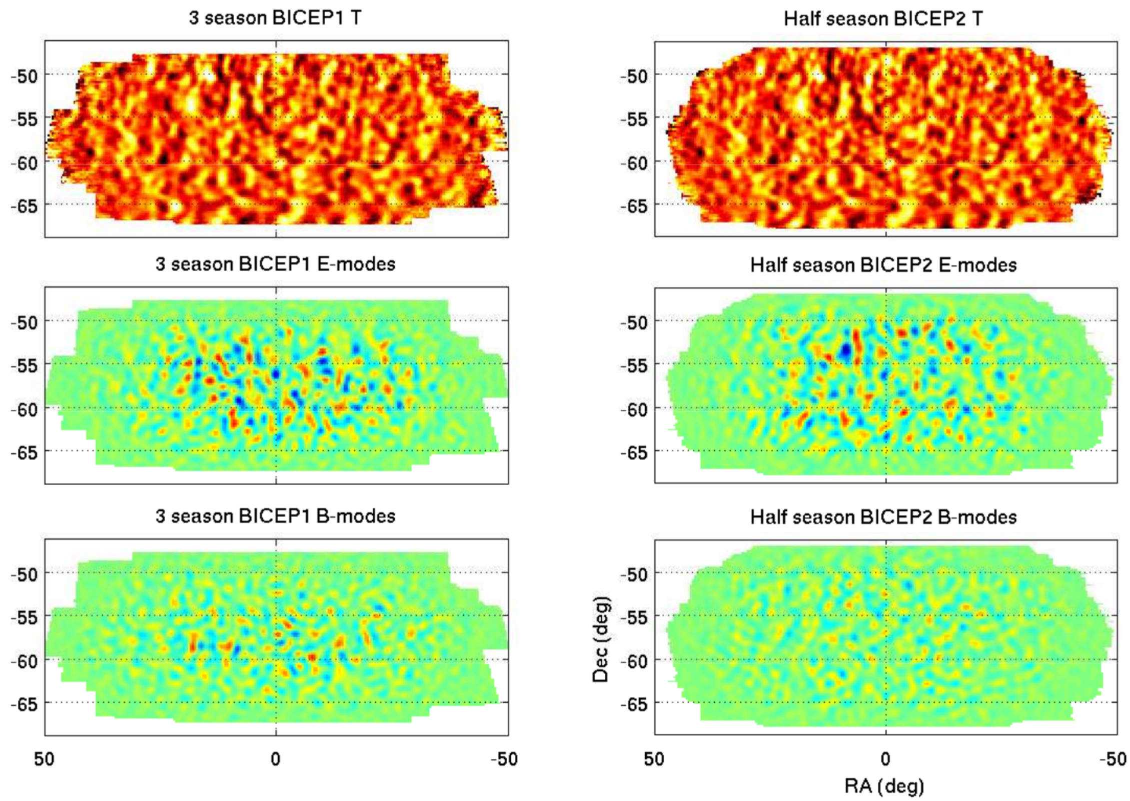

Figure 11: A comparison of BICEP1 and BICEP2 maps. The BICEP1 maps are made with three full seasons of data, while the BICEP2 maps contain approximately half of the first season. *Top row*: Temperature maps on a color scale of ± 150 μK—the signal-to-noise in these maps is very high and they are close to identical. *Middle and bottom rows*: Apodized E-mode and B-mode maps filtered to the angular scale range $70 < \ell < 280$ on a color scale of ± 8 μK. While it is not visually obvious, the E-mode maps show the expected degree of correlation. The half-season BICEP2 B-mode map already has lower noise than its three-season BICEP1 equivalent, illustrating the large mapping speed gain and indicating that any systematic induced floor lies at a still lower level.

Figure 12: *Left*: SPUD team in February 2011. *Right*: SPUD observing in the deep Antarctic night.

2.4 Upcoming SPT Polarimeter

As mentioned above a new polarization sensitive receiver for the SPT has been under development for several years, with deployment planned for the 2011-2012 austral summer. This will bring the excellent angular resolution of SPT to bear in the polarization arena, making exquisite measurements highly complementary to those of BICEP/SPUD, and teaching us more about dark matter, dark energy, neutrino masses, and the epoch of Inflation.

In addition to the possible inflationary B-mode signal there are several other forms of CMB polarization. The basic E-mode spectrum measured by DASI and QUaD is shown in the upper panel of Figure 9. Gravitational lensing by structure along the line of sight between us and last scattering converts some of this primordial E-mode polarization into a B-mode signal; this lensing induced signal is expected to peak at angular scales of a few arcminutes—a scale many times smaller than the inflationary signal and a good match to the SPT's one arcminute beam at 150GHz. SPTpol will measure this signal for the first time, and use it to probe physics that affects the growth of that structure, in particular the action of dark energy and neutrino mass. In addition SPTpol will compete and collaborate with SPUD in the quest for the inflationary B-mode signal—this science goal is of such overriding importance, and the technical challenges so extreme, that it makes perfect sense to attack it simultaneously with these very different instruments.

The SPTpol receiver is based on novel polarization-sensitive bolometric detectors developed at Argonne National Laboratory (ANL) and the National Institutes for Standards and Technology (NIST). Both are single-mode waveguide coupled devices, using feedhorns to control the response of the detector. The ANL devices are fabricated as individual dual-polarization pixels, mounted behind profiled smoothwall aluminum horns and operated in the 90 GHz atmospheric window. The NIST devices are fabricated as arrays of 84 dual-polarization pixels, mounted behind hexagonal arrays of gold-plated silicon feed horns.

Figure 14 shows the arrangement of SPTpol's focal plane, with 588 pixels (1176 detectors) at 150 GHz in the central portion surrounded by 192 pixels (384 detectors) at 90 GHz. The feed/detector assembly is cooled below 300 mK in operation. The increase in total detector count over the current SPT receiver—as well as the increased bandwidth of each detector—will require a greater daily data volume transmitted to the U.S. to keep the analysis up to date with the data taking.

By averaging the response of the two detectors in each pixel, the new receiver will remain sensitive to total intensity (unpolarized) signals. The SPTpol survey will be concentrated on a much smaller ($\sim$ 600 sq. deg.) area of sky than the SPT-SZ survey, integrating significantly deeper over that region. The survey will therefore probe the cluster population to lower mass threshold, significantly increasing the total number of clusters detected by SPT and very useful for the characterization of dark energy.

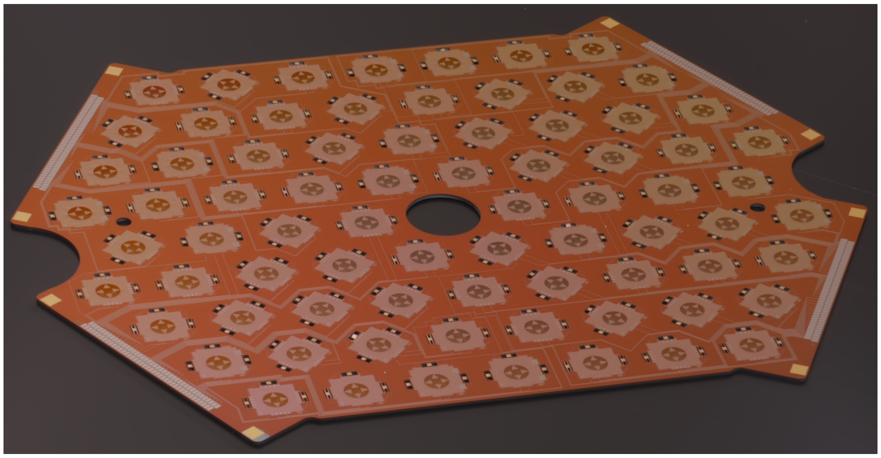

Figure 13: A prototype test-device array of 150 GHz detectors fabricated at NIST for SPTpol. Each light-colored patch is an independent dual-polarization pixel, coupled to the sky via matching feedhorn array (not shown). The subsequent generation detector arrays, slated for deployment in SPTpol, is currently in the fabrication process.

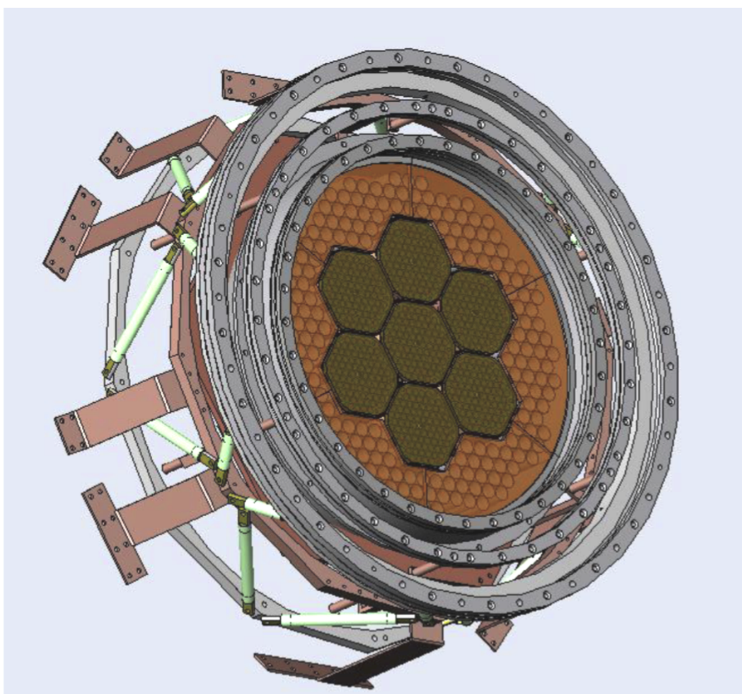

Figure 14: The SPTpol focal plane consists of seven 150GHz hexagonal subarrays fed by corrugated feedhorn platelet arrays (green). Each subarray has 84 dual-polarization pixels, and twice that number of detectors. Surrounding the 150 GHz array is a collection of 192 dual-polarization 90 GHz pixels, again using twice that number of bolometers. The 150 GHz detectors are concentrated at the center of the array to take advantage of the optically superior central portion of the focal plane. The entire array is cooled to below 300 mK using a copy of the current SPT-SZ cryogenics system.

2.5 The POLAR-1 Experiment

The POLAR-1 telescope represents a large increase in sensitivity beyond SPTpol and SPUD. Construction of the instrument is already funded by an MRI grant and is well underway. The telescope is a novel 1.6 m off-axis design to maximize focal plane throughput (see Figure 15). With 2000 pairs of antenna-coupled TES detectors, the POLAR-1 focal plane camera is much larger than that of BICEP2/SPUD (see Figure 16). This increase relies on developing tapered antennas for optimal focal plane density with acceptable sidelobe control. The focal plane is constructed from separate modules that can be individually tested and replaced if necessary.

POLAR-1 is proposed to operate for 3 seasons, with the goal of mapping 400 square degrees of sky to a sensitivity of 2.5 μK-arcmin. With its 5.2 arc-minute angular resolution at 150 GHz, POLAR-1 will measure the B-mode CMB polarization signal produced by gravitational lensing of the background E-mode CMB even better than SPTpol. This map will allow POLAR-1 to determine the sum of neutrino masses to an accuracy of 0.12 eV, and to constrain early dark energy, both being parameters that affect the growth of structure at $z \approx 3$. The lensing signal traces the redshift-integrated gravitational potential, which can then be compared with galaxy formation and other tracers of structure such as weak lensing and baryon acoustic oscillation measurements. The POLAR-1 map will also serve as a working data set for using numerical techniques for removing the lensing polarization, enabling potentially deeper searches for inflationary polarization.

POLAR-1 will be testing many of the mm-wave technologies and observing strategies, as well as the assumptions on foregrounds and systematics, that will be needed for the future polarization measurements described in the next section. As an example, a scheme to scatter the spillover toward the cold sky with random metal diffusers will be put to test in POLAR-1. If this novel idea works, it would greatly simplify the optical design and significantly reduce the cost of future telescopes.

2.6 A Future CMB Polarization Facility

The CMB community is driving towards a future ground-based CMB polarization facility that will make extremely high-sensitivity measurements of CMB lensing and inflationary polarization. The scale of this project, which we generically term the "CMB Polarization Facility" (CPF), closely matches the example of a CMB polarization facility for the NSF Mid-Scale Innovations Program that was recommended by the Astro2010 report[3]. The CPF project is envisaged as an inclusive project involving a substantial fraction of the US CMB community. The facility would operate later this decade, prior to a possible space mission which has been placed beyond 2020 by the Decadal committee.

The motivations for a CPF include the fact that, while SPUD, SPTpol and POLAR-1 have amazing capabilities, it is possible that the inflationary B-mode signal lies below their sensitivity threshold. On the other hand if and when an inflationary signal is detected it will become enormously exciting to measure that signal in fine detail. In addition, although SPTpol and POLAR-1 will make ground breaking polarization measurements of CMB lensing and neutrino mass, considerable information will remain to be extracted.

[3] `http://sites.nationalacademies.org/bpa/BPA_049810`

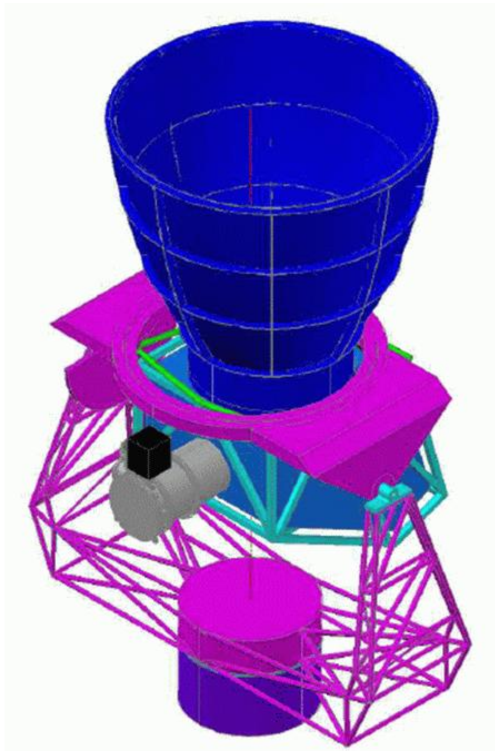

Figure 15: Rendering of a preliminary design for the POLAR-1 telescope.

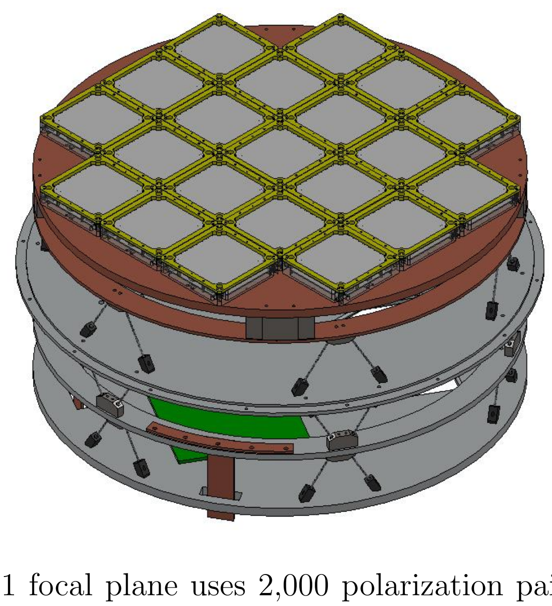

Figure 16: The POLAR-1 focal plane uses 2,000 polarization pairs operating at 150 GHz. The focal plane is built from individual detector modules, with multiplexed SQUID readouts housed behind each detector sub-array in a magnetically shielded enclosure.

The size of the possible inflationary B-mode signal is characterized by the tensor-to-scalar ratio r. SPUD and SPTpol will have sufficient raw sensitivity to detect a signal down to $r \sim 0.01$. However, at a few times this level the search will become complicated by foreground signals from our galaxy and from the lensing B-modes. By using multiple frequencies, moderate angular resolution and overwhelming sensitivity, the CPF will overcome these foregrounds and reach a sensitivity approaching $r \sim 0.001$.

In order to undo the lensing process it is necessary to invert the observed polarization pattern to obtain the projected mass distribution of the Universe between us and the last scattering surface of the CMB. However, this mass map is very far from a by-product—it is actually incredibly interesting in its own right. The CPF will produce a legacy high-z large scale structure map over a significant part of the southern sky that can be used for a wide variety of correlation studies by the wider astrophysics community. The full implications of this map are not yet understood—but it is a fundamental observable of our Universe and will undoubtedly have a profound impact.

The lensing B-mode measurements will provide constraints on the combination of three cosmological parameters, the dark energy equation of state, the spatial curvature, and the sum of the neutrino masses ($\sum m_\nu$). Assuming flat geometry and Λ dark energy (cosmological constant), the CPF will provide a measurement of $\sum m_\nu$ to 0.05 eV, which will either set the absolute mass scale or distinguish between the normal and inverted hierarchies.

Since the CPF is intended to be a comprehensive and possibly "ultimate" ground based CMB polarization experiment it must be carefully optimized. To enable both science themes, the facility would observe in two modes: (i) a wide survey for gravitational deflection field measurements through lensing B-modes, and (ii) a deep survey to obtain the best possible sensitivity to the inflationary B-mode from the ground. The current concept is an array of five mid-size (2 m) crossed-Dragone reflectors surveying through the atmospheric windows at 95, 150, and 220 GHz (shown in Figure 1 attached to a replacement for the MAPO building). Future increases in infrastructure capability at the South Pole station, including buildings, data volume, and power management should be carefully planned to enable the CPF.

The tentative choice of the aperture sizes was based on comparisons between different array scenarios with larger/smaller primary apertures with fewer/more elements, and their abilities in constraining cosmological parameters such as neutrino mass, spatial curvature, scalar spectral index, dark energy parameters (with the wide survey), and the tensor-to-scalar ratio (with the deep survey), assuming a fixed physical size of the receivers. For a given budget, the smaller aperture/more elements option is moderately favored over larger aperture/fewer elements in terms of the constraints from the lensing survey. However, the former option is overwhelmingly favored when considering sensitivity to the inflationary B-mode, both in terms of the best possible limit on r, and constraints on inflationary parameters if r is detected to be nonzero, even after delensing is taken into account.

Each CPF telescope requires approximately 12 kW of electrical power for the pulse tube cryocooler, the glycol/water cooling system, and the readout electronics. With the current specifications, the array will produce up to 1 TBytes of data per day, a necessary consequence of its large focal plane detector arrays. The analysis would benefit greatly if the data can be transferred in real time to the U.S. However, it is also possible to transfer only samples of the raw time stream data for quality checks, in addition to the binned processed data, physically transporting the full data set during the summer season.

Before such a proposal can be fully developed, it is important to continue to study the optimal experimental parameters such as survey depth, sky coverage, angular resolution versus sensitivity, frequency range, availability of multi-wavelength data, and other issues. The atmospheric conditions and loading at the South Pole in these frequency bands is already very well known and will be further characterized from large to fine angular scales by SPUD and SPTpol. The massive scale and parallelized nature of this facility call for robust, cost-effective, and scalable focal plane and millimeter-wave technologies that are being pioneered by SPUD, SPTpol and POLAR-1. The deployment of SPTpol in fall 2011, and POLAR-1, proposed to replace BICEP2 in the Dark Sector Lab in fall 2012, will inform the design of the CPF in these important respects.

3 Astroparticle Physics and Neutrino Astronomy

One of the most tantalizing questions in astronomy and astrophysics is the origin and the evolution of the cosmic accelerators that produce the highest energy cosmic rays (UHECR). Single cosmic rays, thought to be protons, have been observed striking the Earth's atmosphere with energies of up to 10^{21} eV, an energy that exceeds the kinetic energy of a professional baseball pitch. Because protons are charged particles, their directions are scrambled by the magnetic field of our galaxy. Therefore, they reach us isotropically, yielding no clue to their origins. The mystery of what forces could accelerate particles to these energies has confounded scientists since cosmic rays were first discovered nearly 100 years ago. One of the 11 Science Questions for the New Century put forward by the NRC Turner Committee on Connecting Quarks with the Cosmos [16] is: "How do cosmic accelerators work and what are they accelerating?" The answer to this question requires a multi-pronged approach including cosmic ray observatories, space and ground based gamma ray observatories, and more recently, neutrino observatories.

Particle physics and astrophysics are inextricably linked by the fact that our knowledge of the universe is derived from fundamental particles that act as messengers, providing a window into their origin. However, all particles, like the cosmic ray protons, suffer interactions along their route which will limit their horizon or scramble the information they carry. Unlike protons, gamma rays, having no charge, will travel in straight lines. However, at energies above 30×10^{12} eV, gamma rays pair-produce on the pervasive cosmic microwave background (CMB), limiting their horizon.

Neutrinos are nearly massless particles which carry no charge, and since they only interact via the weak interaction, they will travel from their source undeflected by magnetic fields and unimpeded by interactions with the cosmic microwave background. Neutrinos will therefore have a mean free path that exceeds the radius of the observable Universe. It should also be noted that particles that propagate a long distance (in some cases billions of light years) carry with them information from an earlier time in the history of the Universe, since the image they create will be a snapshot of the time at which they were emitted. Neutrinos are a necessary byproduct of proton interactions in their source, making any source of protons also a source of neutrinos, thus the long-standing mystery of the origin of UHECRs may be best addressed by imaging the sky in neutrinos [17].

Since neutrinos have no electric charge, and only interact through the weak force, they may only be detected indirectly through their interactions in dense, transparent media. These media act as both a target for the interaction, and a Cherenkov radiator. The direction of the neutrino may be inferred by tracking the charged lepton (electron, muon, or tau) that is emitted when the neutrino is captured on a nucleus. The lepton can be detected through the electromagnetic radiation it emits as it travels faster than the speed of light through the medium.

The South Polar ice cap provides a large natural reservoir of pristine ice measuring nearly 3 km thick. Its optical clarity, which was demonstrated by the pioneering AMANDA (Antarctic Muon and Neutrino Detector Array) [19, 20], is largely free of dust and bubbles at depths greater than 1.35 km, making it an ideal medium for detecting the faint Cherenkov light. AMANDA was the proof of principle that large neutrino telescope could be built and and used for the detection of energetic neutrinos of energies from 10^8 GeV to 10^{16} GeV [18, 20].

AMANDA and later IceCube, have exploited this in the search for astrophysical neutrinos, and the recently commissioned IceCube is now poised to make the first discoveries of extragalactic neutrinos in this band.

At energies above 1 PeV, the radio frequency emission of the secondary lepton dominates. The cold polar ice (at a nearly constant -50 degrees C near the surface) has been demonstrated to be exceptionally RF transparent, making the South Pole the ideal environment to search for ultra high energy neutrinos through RF radiation. It has been host to several pioneering efforts to develop this approach, including RICE and ANITA. A discovery class instrument based on this technique, the Askaryan Radio Array, is currently under development.

3.1 IceCube: construction and operation

IceCube consists of a cubic kilometer of South Polar ice embedded with 5160 photomultiplier tubes capable of sensing the faint light emission from Cherenkov radiation. Because precise timing and accurate amplitude information are required to reconstruct the characteristics of the incoming neutrino, each tube was bundled inside of a glass pressure sphere with onboard electronics with clocks, digitizers, and calibration LEDs, forming a DOM (Digital Optical Module). The optical modules are connected to the surface via cables which provide power and communication. Eighty of the strings are deployed on a 125m triangular grid with 60 evenly spaced modules. To avoid the bubbles in the shallow ice which act as scattering sites, the modules were deployed at depths between 1450m and 2450m. An additional six strings with high sensitivity DOMs concentrated at depth below 2000m infill the center of the array to form a low energy core (the Deep Core). Each of the strings has an associated pair of Auger style tanks near the surface (IceTop) which acts as a veto and allows cosmic ray studies. Figure 17 shows a schematic of the IceCube system.

Major construction of IceCube was completed in December 2010 when the last string was deployed. After 7 years of South Pole drilling operations 86 strings and 162 IceTop tanks were installed and connected to the central data acquisition system in the IceCube Laboratory. A total of 5484 (including the deep core and IceTop arrays) optical sensors were deployed and commissioned — figure 18 shows the last module being deployed. More than 250 scientists in 36 institutions worldwide are mining the data for a wide range of science goals, such as the search for highest energy cosmic neutrinos, dark matter or neutrinos from supernova explosions. More than 50,000 atmospheric neutrinos at energies up to 1000 TeV energy are being measured with unprecedented statistics and cosmic rays are being measured with new techniques. IceCube's dense Deep Core central detector measures atmospheric neutrinos at energies down to 10 GeV while the outer IceCube detector provides an effective shield from backgrounds.

The biggest technological challenge for the construction of IceCube was the drilling of 86 holes to a depth 2500m and a diameter of 55cm. A highly trained crew of 30 drillers were able to drill up to 20 holes in a single South Pole construction season using IceCube's Enhanced Hot Water Drill. The drill provides 5 MW of thermal power in form of a high-pressure (1000psi) and high flow (200 gallons/minute) hot water jet to melt ice to a depth of 2500m in 24 hours. The drill consists of about 20 modular structures, some of which (hose reel, drill towers) have been assembled at the South Pole. The total weight is about 1 million

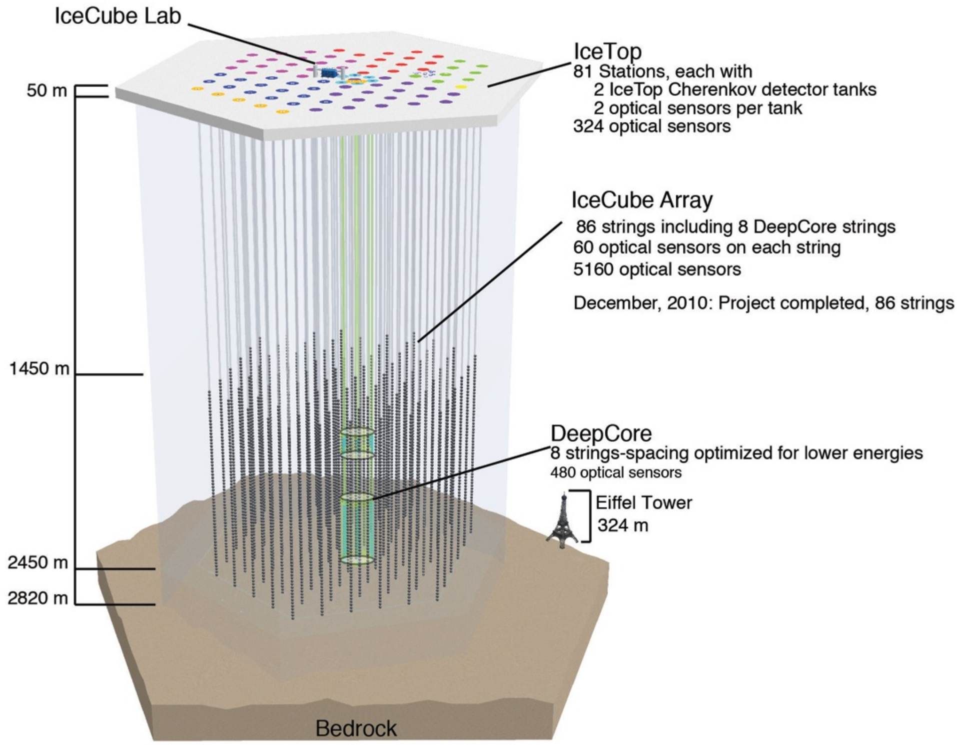

Figure 17: Schematic view of the IceCube neutrino detector at the South Pole

Figure 18: Deployment of the last optical sensor of IceCube on December 18, 2010

pounds. This machine which dwarfs any other hot water drill built to date on Earth (see Figure 19), is now stored in a winterized condition at the South Pole. The drill will drift in with snow and can be stored for several years without damage to equipment. When needed it can be excavated easily from the snowdrift.

Figure 19: IceCube drill with the main heating plant in the front (seasonal equipment site), the two drill towers and the IceCube laboratory.

3.1.1 IceCube Operations

About 1000GB of data are being produced every day. The data are processed in the IceCube Laboratory (see Figure 20) and reduced to an amount of 90GB/day, small enough to be transmitted by satellite to the North. The optical sensors were optimized for low power consumption and designed for high reliability. Together with the 20 racks of electronics and computers at the surface IceCube requires about 60kW of power. The sensors are highly reliable based on the first several years of the partial detector in operation. The gain of the sensors is highly stable with measured deviations in gain of only a fraction of a percent over one year. In more than 14,000 years of combined sensor lifetime, only 18 failures were recorded after commissioning. The expectation is that after 15 years still well above 95% of the sensors will be in full operation.

Important performance parameters such as angular and energy resolution already exceed the design goals stated in a 2004 journal paper [21]. The angular resolution for muon neutrinos is better than 0.5° at 100 TeV and the energy loss measurement for high energy muons is better than 10%.

3.2 IceCube Science

Since May 2011, IceCube has been successfully collecting data with 86 strings over the full sky. IceCube records about 100 billion cosmic ray muons per year with 50,000 upward going

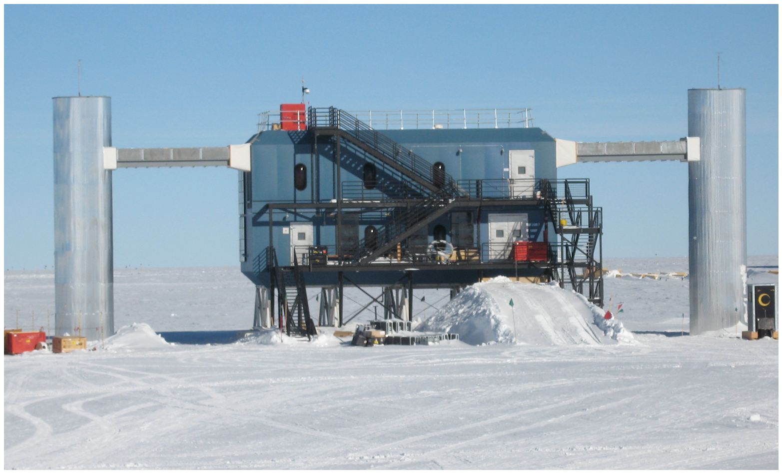

Figure 20: Data are collected and processed in the IceCube Laboratory at the South Pole.

neutrino induced events providing the primary data set for IceCube as a neutrino detector. Figure (Figure 21) shows a typical muon neutrino event recorded in IceCube. An example of a "cascade" signature of the type expected from the interaction of an electron (or a less than 1 PeV tau neutrino) is shown in Figure 22.

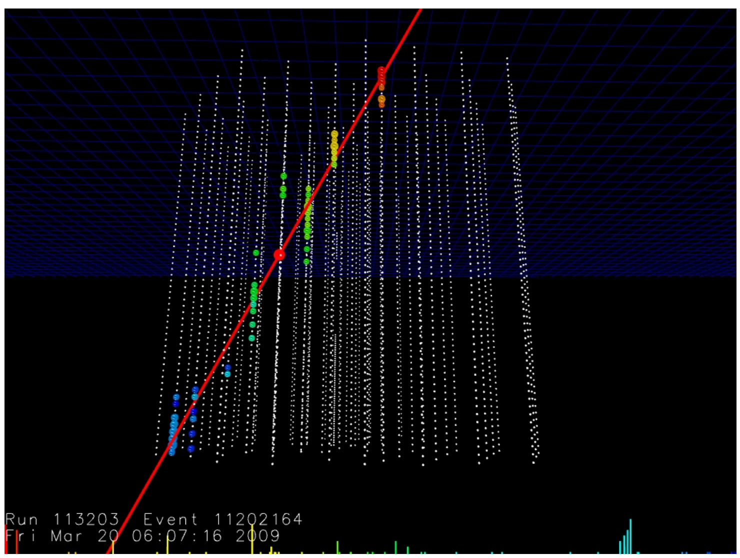

Figure 21: Display of a typical muon neutrino event in IceCube.

An extragalactic source of neutrinos would be manifested as a statistically significant clustering of high energy neutrinos on the sky. This search is complicated by the fact that muons and neutrinos are continually produced as a result of cosmic ray interactions with the Earth's atmosphere. The Earth itself can be used to screen atmospheric muons from the Northern Hemisphere, however, the atmospheric neutrinos comprise an irreducible background for neutrinos from astrophysical sources. The brightness of events may be used to estimate the energy, thereby extending the search to the Southern Hemisphere. A map of the sky in neutrinos made with 1 year of data from the first 40 strings of IceCube [22] are

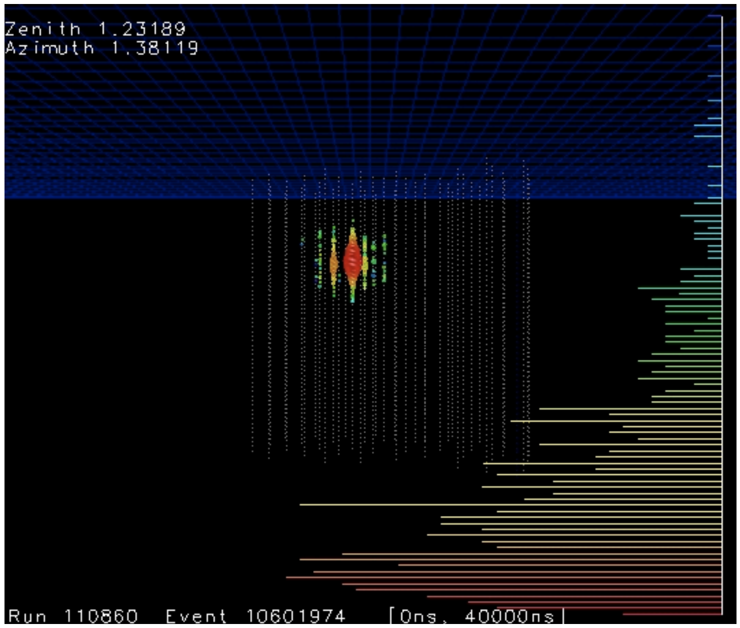

Figure 22: Cascade like event recorded in IceCube. According to preliminary analysis, this event was produced by an atmospheric electron neutrino of about 40 TeV energy.

shown in Figure 23.

Time dependent searches are performed to search for transient emission of neutrinos [23]. These searches are correlated offline and in real time with other observatories such as ground and space based gamma ray and optical telescopes and even the gravitational wave interferometer LIGO. Gamma ray bursts, which for a fleeting period of perhaps 10's of seconds will outshine the entire gamma ray sky, were first observed in the 1960's. They remain enigmatic, but the observation of neutrinos coming in time with a gamma ray burst, and from the same direction in the sky, would provide evidence of proton acceleration in the progenitors, thus providing a window into the processes which fuel them. Coordinated observations between IceCube and a network of gamma ray telescopes makes the search virtually background free [24]. Current observations of IceCube already exclude robust theoretical model predictions for neutrino emission from sources of gamma ray bursts. The substantial increase of IceCube sensitivity with the full array promises a high discovery potential.

IceCube will be for many years to come the leading experiment in neutrino astronomy, but IceCube is the world's largest particle detector as well. The atmospheric neutrinos that are a background in the search for astrophysical neutrinos may be viewed a steady beam of high energy neutrinos for study. This opens a new energy regime in the study of neutrino oscillation properties, and may provide a sensitive probe of quantum gravity [27]. The large fiducial volume for contained cascade events will provide a sure measurement of the atmospheric electron neutrino flux to energies well above 100 TeV. It will allow a search for extraterrestrial electron and tau neutrino fluxes [32]. Even before IceCube was complete, the collaboration published an atmospheric spectrum (Figure 24) measured to much higher energies than had been achieved before [25, 26]. At higher energies, from 10^{14} eV to 10^{18}eV, IceCube is by far the most sensitive detector for point, extended and diffuse sources of

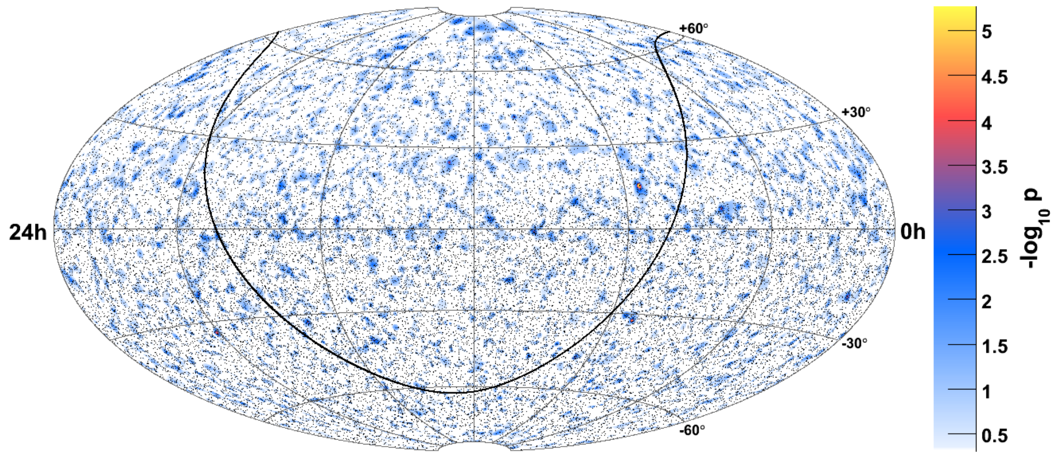

Figure 23: Skymap of neutrino events (Northern hemisphere) and downgoing muon events (Southern hemisphere).

neutrinos. The best limits have been published based on only 40 strings [33, 34], the full detector in continuous operation will enter discovery region for important predictions for the origin of cosmic rays. IceCube is also a powerful detector for the search for the elusive dark matter. With the densely instrumented Deep Core infill array, IceCube is by far the most sensitive dark matter detector for a large parameter space of models of the most promising candidates, so called Weakly Interacting Massive Particles, such as the neutralino (spin-dependent interaction). Searches for dark matter in the sun and in the galactic center are underway [31, 28, 29, 30]. Below further upgrades will be discussed for enhanced dark matter searches and other neutrino physics.

IceCube is highly sensitive to the emission of neutrinos in the core collapse of galactic supernova events. For a galactic supernova IceCube would record the time profile of the 10 second neutrino bursts with millisecond accuracy allowing a unique probe to understand the core collapse as well as associated fundamental neutrino oscillation physics and the mass hierarchy of neutrinos [31]. Other searches such as for magnetic monopoles, and other exotic forms of matter are under way already [35].

3.3 Cosmic Ray Science

In addition to its primary function as a neutrino telescope, IceCube is a unique cosmic-ray detector that covers a range of energies from TeV to EeV. The full detector reconstructs per year:

- 50,000 atmospheric neutrinos
- 100 billion atmospheric muons
- 1 billion air showers with IceTop (10% in coincidence with the deep IceCube).

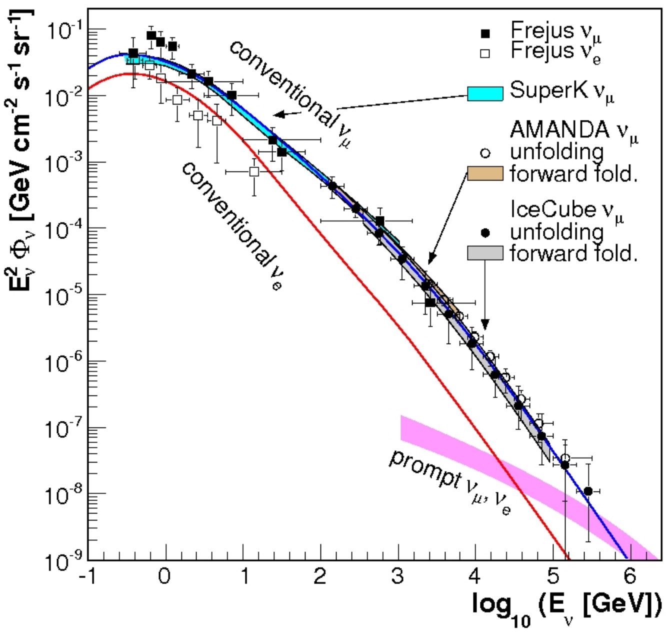

Figure 24: Observed energy spectrum of upward going atmospheric neutrinos.

The high event rate allows measurement of cosmic-ray anisotropy with high sensitivity (at level of parts per ten thousand) over a range of energy. Figure 25 shows the preliminary Southern hemisphere map of IceCube running in 2009-10 with 59 strings in comparison with results from the Tibet array in the North. Anisotropies are observed at small and large scales. While the lower energy (20 TeV) observations may be due to propagation effects, the situation is even more intriguing at high energies (1 PeV) where the anisotropy is still very significant but completely changed [36, 37, 38].

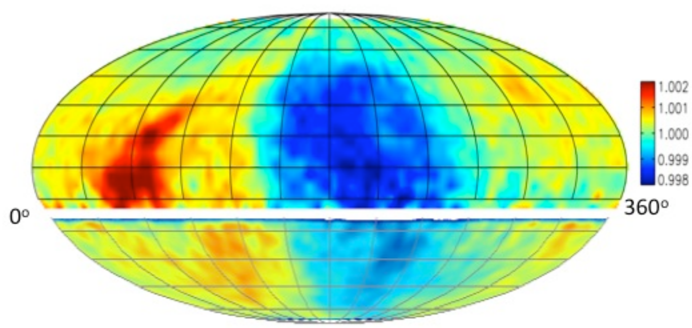

Figure 25: Preliminary Southern hemisphere map of IceCube running in 2009–10 with 59 strings in comparison with results from the Tibet array in the North.

IceCube is a three dimensional air shower array, which consists of the deep array of 5160 digital optical modules between 1450 and 2450 meters and the IceTop air shower array on the surface. IceTop is an array of ice Cherenkov tanks, two tanks per station at 81 stations. Tanks are instrumented with the same optical modules used in deep ice. All modules are integrated in a single DAQ system so that coincident events are readily reconstructed. Figure 26 shows the display of a large air shower event in June, 2010.

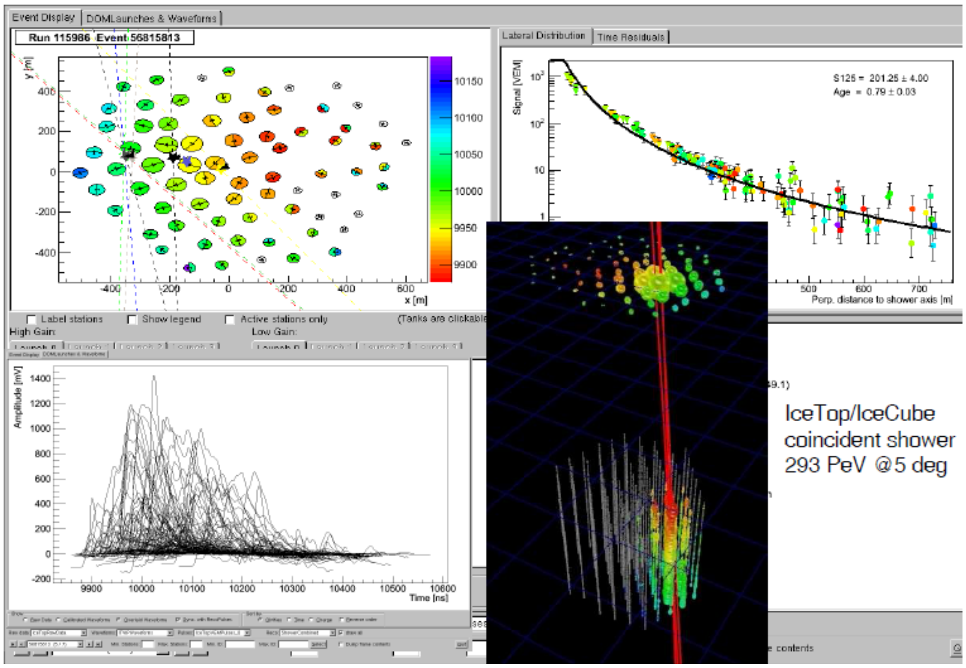

Figure 26: Display of a large air shower event seen by IceCube and IceTop in June, 2010.

The energy range accessible with IceCube as an air shower detector is 300 TeV to 1 EeV. The lower end of this range includes the knee of the cosmic-ray spectrum. A transition from cosmic rays of galactic origin to a population of particles accelerated at extragalactic sources is expected in the upper range of energy accessible to IceCube. A signature for such a transition would be a change in the relative composition of the primary cosmic ray nuclei. Detectors like Auger and Telescope Array are lowering their thresholds to study this important transition region. The transition is likely to be at the upper end of the energy range of IceCube, which motivates efforts to extend the reach of IceCube by using events with trajectories outside of the IceTop array. The possibility of constructing a larger array on the surface using the radio technique is also being considered.

3.4 IceCube Upgrades and Beyond

3.4.1 Megaton particle physics detector

The success of DeepCore, the 30 megaton, 10 GeV threshold extension of the IceCube Neutrino Observatory, lies in the exceptional clarity of the ice at depths below 2100 m, and in the use of the surrounding IceCube detector as a robust active veto against cosmic ray muons. These muons would otherwise mask the neutrino signals of interest from the atmospheric flux, dark matter annihilations and decays, and galactic point sources. The feasibility of a phased infill of the DeepCore detector, with the ultimate goal of a precision multi-megaton particle physics detector, is currently under investigation by an international group of physicists.

Phase 1 might comprise about 20 additional strings of high quantum efficiency digital optical modules at the center of the IceCube and DeepCore arrays, and would aim for a fiducial volume of 10 MT with an energy threshold near 1 GeV. Such a detector opens a window to indirect searches for very low mass dark matter, precision measurements of atmospheric neutrino oscillations, improved sensitivity to supernova neutrinos, and first exploration of proton decay searches with a distributed volume detector. While the scientific program of such a detector is clearly rich in its own right, phase 1 would also serve a valuable function as the proving ground for constructing a much larger scale, high precision neutrino detector in the Antarctic ice. Such a detector has the unique advantage that the fiducial medium is also the support mechanism for the instrument, avoiding the need for costly and difficult cavity excavations, and permitting considerable flexibility in detector geometry and construction.

To achieve the science goals of phase 1 and establish the foundation for a longer-term future detector, phase 1 would include a refined calibration program and extensive ice modeling to a level that would permit understanding of systematics at the level of a few percent, a significant advance over current IceCube analyses. This first phase of the infill would also include rejuvenation of the hot water drill system and demonstrate the possibility of smaller (5 m) inter-string spacing, to achieve the desired low energy threshold, as well as deployment and commissioning of prototype photodetectors that would be used for the phase 2.

Phase 2 would be a much more ambitious, longer term effort to achieve a detector with a fiducial mass of up to 5 MT with a target energy threshold as low as a few 10's of MeV. The obvious science goals for such a detector would be searches for proton decay, supernova neutrino physics with sensitivity out to 10 Mpc (ensuring detection of supernovae every year or two), as well as potential long baseline measurements from a northern hemisphere accelerator. This detector would require the collaboration to build on successes in phase 1 activities related to calibration, development of more advanced instrumentation, and extraction of precision physics measurements from the data.

The Antarctic ice cap offers an extremely large, high clarity, low noise Cherenkov medium. The reduced overburden relative to deep underground facilities can be largely neutralized by leveraging the existing IceCube and DeepCore arrays as active cosmic-ray muon vetos. There is significant scientific potential in the use of the ice as a relatively low cost, megaton-scale sub-GeV physics detector with the development of high photocathode area photon detection units coupled with high precision calibrations of the ice detection medium. Together these developments will allow measurements competitive with those from purpose-built underground facilities.

3.4.2 IceCube 3 dimensional air shower array

The surface array of IceCube has a dual role. It makes IceCube a 3-dimensional air shower detector for the study of cosmic rays and it serves as a partial veto of cosmic-ray background for IceCubes primary objective of neutrino astronomy. The veto function is particularly important in the EeV range where the search for cosmogenic neutrinos is limited to events near the horizontal because the Earth is opaque to neutrinos of such high energy from below. At present, the footprint of IceTop is limited to the area immediately above the deep IceCube array.

An attractive possibility for extending the coverage of the surface component of IceCube is with an array of radio antennas. The technique for radio detection of the geo-synchrotron radiation of extensive air showers is developing rapidly to the point that it is becoming a well understood technique. The technique has been demonstrated at the LOPES array triggered by the KASCADE air shower array at Karlsruhe. A radio array with a 20 sq km footprint is under construction at the Pierre Auger Observatory in Argentina. We expect the ability of radio arrays to self-trigger on air showers will be demonstrated soon, if not already. Figure 27 illustrates the concept as it could be realized at IceCube.

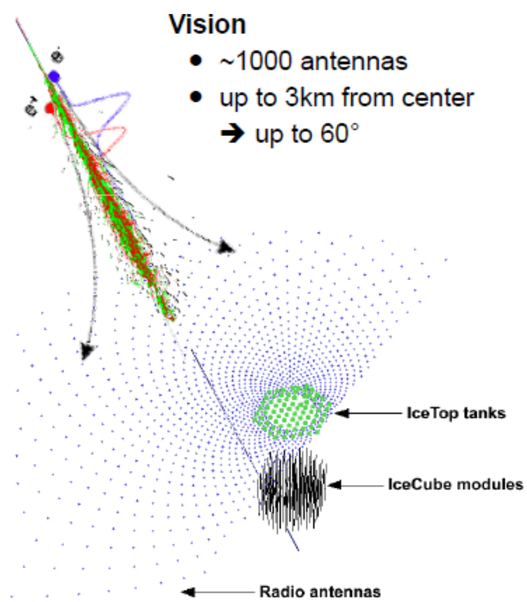

Figure 27: Vision of a large scale radio surface detector component.

A radio array with an area of order 30 sq km as indicated in the figure would extend the maximum cosmic-ray energy accessible to 5 EeV and would provide a considerable increase in the power of the surface array for vetoing EeV neutrinos. Before such an ambitious project can be contemplated, a smaller test demonstration project is needed.

Radio Air Shower Test Array (RASTA) is a proposal for 36 pairs of radio antennas on the edge of IceTop. The radio hubs would use existing cables left over from tank freezing to carry signals back to the IceCube Lab. The purpose would be to demonstrate the ability to self trigger on air showers with energies above 10 EeV by offline coincidences with IceTop. The plan would be to accomplish this in three seasons to determine the feasibility of proposing for a significantly larger array.

3.4.3 DM-Ice Dark Matter Search at the South Pole

Over the past decade the DAMA/Libra experiment at the Gran Sasso Laboratory (LNGS) in Italy has reported a statistically significant annual modulation in their event rate. The collaboration has interpreted the modulation as evidence for dark matter. With over 1.17 ton-years of data, DAMA observes a modulation with a significance of 8.9σ. More recently, the CoGeNT experiment has reported that they observe more low energy events than expected. CRESST has also observed an excess of low energy events, whereas other experiments such as XENON10, XENON100, and CDMS-II report null results. It is possible that all the experiments are consistent with the existence of light dark matter particles of 5–10 GeV — the current picture on the existence of dark matter is far from being clear.

It is fair to state that the DAMA collaboration has not succeeded in convincing the community that the modulation cannot be explained by a systematic effect associated with seasonal variations in the environmental radioactive background, the seasonal variations in the cosmic ray flux or any unidentified systematic associated with season, environment, or temperature. Despite the extensive efforts of the DAMA collaboration to mitigate all systematics, and given the importance of the science, it is essential to repeat the experiment in an entirely different environment.

We propose to build a similar experiment at the South Pole [46]. While most efforts in direct detection focus on better background rejection, we want to do an experiment with better sensitivity to the variation of the signal. The annual modulation of the dark matter particle flux is the same between the northern and southern hemispheres while many of the environmental effects are either reversed or absent. The ice provides the necessary overburden to shield the detectors from cosmic ray. Ice-core and optical measurements indicate that the ice is very clean and radio-pure. While simulations show that background due to direct muon events at this depth is negligible at the current sensitivity levels, IceCube offers an excellent muon veto giving an additional handle on the possible sources of backgrounds. The South Pole Station offers technical and logistical support equal to or exceeding those available at underground laboratories.

During the South Pole summer of 2010/2011, two NaI detectors were deployed at the end of two of the IceCube strings to assess whether it is possible to deploy and operate ultra-low background experiments in the Antarctic Ice using the drilling technology developed for IceCube. The robustness of the mechanical design of the NaI crystal mounting and the pressure housing has been demonstrated and radioactivity levels of the drill water immediately surrounding the detectors, and the ability to use electronics and data acquisition similar to those used in IceCube are currently being assessed.

The full-scale experiment will consist of 250–300 kg of NaI crystal detectors equipped with low-background photomultiplier tubes (PMTs). The DAMA experiment consists of 25 crystals of size 10x10x25 cm^3 arranged in a 5x5 array to allow for anti-coincidence veto. This arrangement allows them to tag events that occur on the surfaces of the crystals to keep only those events that occur in the bulk of the crystals.

The geometry of the full-scale DM-Ice will be optimized taking into account the unique requirements of this experiment, balancing the linear nature of the geometry of the holes while minimizing the number of pressure vessels to allow for close-packing of several crystals. We envision a detector consisting of several crystal arrays housed in separate pressure vessels of roughly 50 cm in diameter. To take full advantage of the shielding capabilities of the Antarctic ice from cosmic rays, the ice overburden should be as much as possible, between 2000–2500 m. Figure 28 shows preliminary sensitivity projections.

This is an exciting time for dark matter, with tantalizing results from numerous experiments. An independent verification of the results from DAMA is timely and is a necessary ingredient in the dark matter puzzle that we face today.

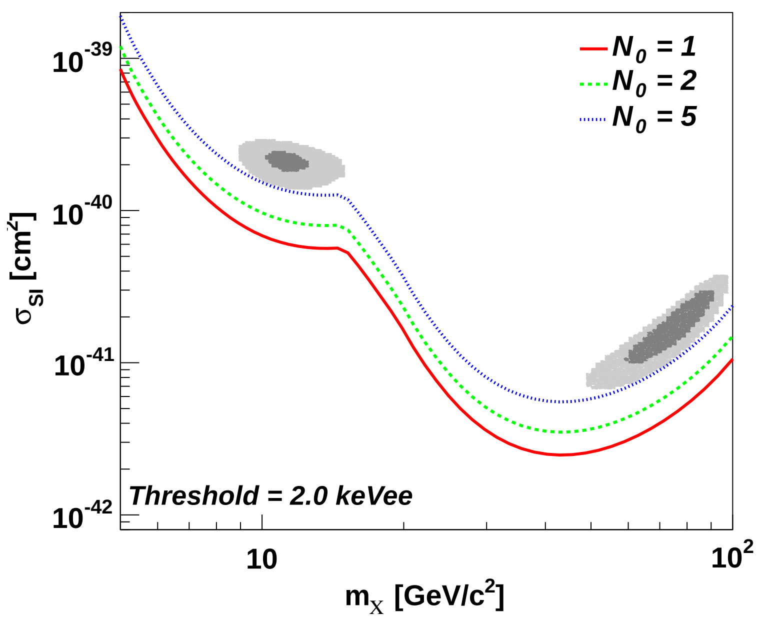

Figure 28: The curves show the sensitivity of hypothetical 500 kg-year exposures with varying total event rates (in cpd/kg/keVee) with a 2 keVee experimental threshold. The gray regions show the 90% (dark) and 99.7% (light) DAMA/LIBRA allowed regions for interactions with sodium (masses of $\sim$ 10 GeV) and iodine (masses of $\sim$ 100 GeV). DAMA/LIBRA allowed regions are calculated without channeling.

3.5 Neutron Monitor

CosRay at Pole had its origins in 1964 as a neutron monitor installed by Martin Pomerantz. Although it often referred to simply as "the neutron monitor," CosRay has been reinvented and reinvigorated several times over the years. In contrast to investigations that extend the range of IceCube to higher energy CosRay now works with IceTop to extend the range to lower energy (1–10 GeV) primarily to study the acceleration and transport of solar energetic particles. Most of the processes invoked in acceleration models for high energy astrophysical particles also occur on the sun but at different scales. CosRay is funded separately by NSF as event A-118-S. The key, new capability of the partnership with IceTop is resolving the element composition of solar energetic particles in the GeV regime.

Neutron monitors are air shower detectors like IceTop but with one key difference — the "air showers" are originated by low energy (typically 1–10 GeV) particles that produce only one secondary at the detector. There are two types of neutron monitor operating at Pole. Both use 3He filled proportional counters to count neutrons via the fission reaction $n + 3\text{He} \rightarrow p + 3\text{H}$. Three standard NM-64 are installed on the platform between the station and the clean air facility. NM-64 have proportional counters are embedded in layers of lead and polyethylene. Their peak response is to 100 MeV hadrons (mostly neutrons but also protons) that interact with 208Pb to produce multiple low energy "evaporation" neutrons. These "thermalize" in the polyethylene and are ultimately detected by the proportional counters. The mezzanine in B2-Science houses an array of twelve unleaded (or bare, hence Polar Bares) detectors. Unknown composition has traditionally been an important source of error when measuring the spectral index using neutron monitors alone. Figure 29 shows a simulation based on the spectral index and intensity of the large solar flare of 20 January 2005, under the assumption that the particles have the same composition as "galactic" cosmic rays. Statistical errors (one sigma) are represented by the line thickness. Considering the neutron monitor to bare ratio alone, any point on the red curve is equally allowed in other words the deduced spectral index can range from 4.0 to 4.5 depending on the actual composition.

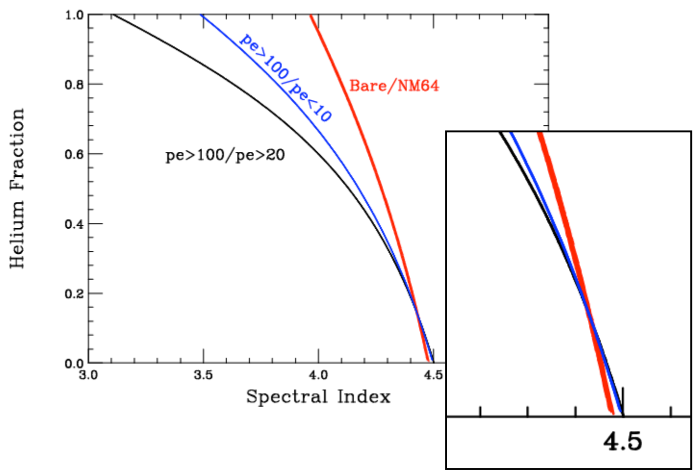

Figure 29: A simulation based on the spectral index and intensity of the large solar flare of 20 January 2005 — see text for details.

With IceTop multiple ratios can be formed from the analog output of the tanks. The black line and blue line in Figure 29 are examples of such ratios. Over some of the parameter space, requiring agreement of the spectral index and composition measured by all of the separate thresholds concurrently could resolve the ambiguity. However the various curves all tend to converge in what is probably the most likely region of parameter space a helium abundance of 10% or less. When the two types of detector are considered together the ambiguity is resolved. The lines have a well defined intersection at the correct (i.e. simulation input) values of spectrum and helium fraction.

3.6 The Askaryan Radio Array

IceCube will provide a new window on the universe at TeV (10^{12} eV) – PeV (10^{15} eV) energies, where protons provide no directional information. IceCube may be poised to answer such disparate questions as the source of intermediate energy cosmic rays, the mechanism behind gamma ray bursts, and the nature of the dark matter. However, because the flux of cosmic rays decreases with energy, IceCube is too small to address the origin of the highest energy cosmic rays. To do that, an observatory that is larger by 2–3 orders of magnitude is required.

In 1966, Greisen, Zatsepin, and Kuzmin pointed out that cosmic rays will interact with the cosmic microwave background at an energy of (6×10^{19} eV) to produce a delta resonance. This effectively limits the propagation distance of protons above this energy to less than 50 Mpc (160 million light years, a short distance is cosmological terms). They therefore predicted that there should be a sharp steepening of the cosmic ray spectrum at this energy, known as the "GZK" energy. A feature consistent with this effect, known as the "GZK cutoff", has recently been observed by both the HiRes and Auger cosmic ray observatories [39].

The observation of the GZK cutoff suggests that UHECR are being accelerated in extragalactic sources, such as active galactic nuclei, and reach us over a long baseline. One byproduct of the GZK interaction is the production of ultra high energy neutrinos, because the delta resonance produced will decay into neutrinos. The magnitude of the flux of GZK neutrinos is determined by our knowledge of particle physics and the measured cosmic ray spectrum, making this a guaranteed signal. Furthermore, on cosmological distance scales, the GZK induced neutrinos would point back to the source of the parent cosmic ray with sub-degree precision.

An EHE neutrino observatory large enough to amass a sample on the order of hundreds of events would provide two unique discovery opportunities based on the detection of GZK neutrinos. First, the GZK neutrino spectrum and directions would be indispensable in a multi-particle astronomical analysis to determine the sources of the highest energy particles in the Universe. Once the sources for UHECRs are identified, it may be possible to further investigate the evolution in time of the cosmic accelerators through the redshift dependence of their host galaxies. Complementing the astrophysical implications, mere detection of neutrino-induced events would extend our knowledge of neutrino properties. By measuring the event rate as a function of nadir angle, the opacity of the Earth can be used to determine neutrino-nucleon cross sections at center of mass energies unavailable to any current or planned laboratory facility. It should be noted that even the initial phase of the array, proposed here, will be large enough to observe 2-5 neutrinos per year, enough to make a statement about UHECR cosmic accelerators. Furthermore, it would already have the largest volume and exposure time of any UHE neutrino detector in the world.

3.6.1 ARA 37 and Beyond

While IceCube images the sky in neutrinos by detecting cones of (Cherenkov) light produced after neutrinos are captured in the clear ice covering the Pole, a new technology must be developed in order to build a larger array at a feasible cost. The Askaryan Radio Array (ARA 37) [45], shown in Figure 30, will employ an array of shallow embedded antennas to monitor approximately 100 square kilometers of the South Polar icecap for radio frequency emissions produced by ultra high energy cosmogenic neutrinos impinging on the ice. The technique, which is based Askaryan's premise [40] that high energy electromagnetic showers in dense media give rise to a detectable RF impulse, has been demonstrated in a series of experiments at the Stanford Linear Accelerator Center by directing pulses of electrons into sand, salt and ice [41]. The feasibility of this approach in searching for UHE neutrinos was first demonstrated by RICE [42], a small grid of submerged antennas embedded in the South Polar Icecap at depths of 100-300 m, and ANITA [43], a balloon borne antenna array that briefly surveyed the entire continent for RF emissions emanating from horizontal neutrino-induced showers that are refracted at the surface of the Antarctic ice. While these projects established the feasibility of RF detection, and demonstrated the exceptional RF clarity of the cold ice covering the geographic South Pole, both have thus far lacked the exposure in km^2-years to make the first neutrino detection [44].

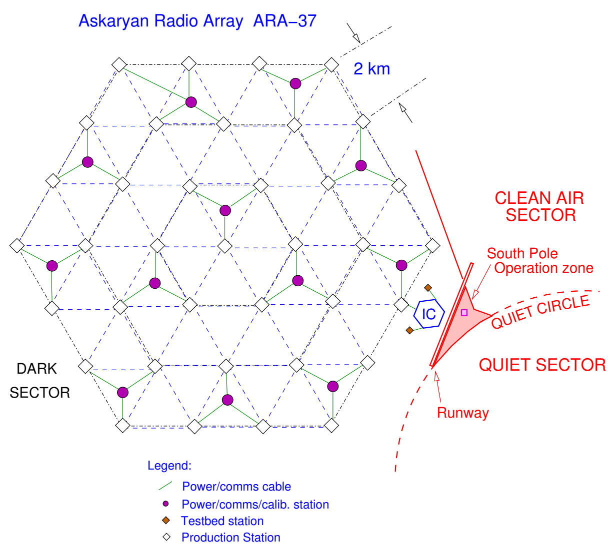

Figure 30: A schematic of the Askaryan Radio Array [45]. The white squares indicate the location of clusters of receiver antennas, and the red circles indicate the hubs that provide power and communications to three neighboring strings. The size of the footprint of the IceCube array is shown in blue for comparison.

ARA 37, will consist of 37 clusters of radio frequency receivers arranged on a triangular grid. The sparse spacing of 1.33 kilometers is feasible due to the long attenuation length in the cold South Polar ice. A power and communications hub consisting of a wind turbine, RF transmitter and calibration pulser will service three adjacent clusters. While trenching cables for power and communications would be feasible for this initial phase, ARA 37 will serve as a development platform for a future, larger array, and the demonstration of autonomous power and wireless communications will allow for such a future expansion. The initial phase of the array, already under construction (of $\sim$ 100km^2 will be large enough to make the first neutrino detections and deliver publishable physics results including lower limits on the GZK flux.

The ARA array will be large enough to make the first observation of cosmogenic neutrinos via RF emissions. The experience gained in building and operating this array would frame the performance requirements needed to propose an expanded array ($\sim 1000\text{km}^2$) in the future to collect a statistically significant number of cosmogenic neutrinos for study. In the meantime, ARA would occupy the energy frontier, having greater sensitivity to UHE cosmogenic neutrinos than any other observatory, and is expected to produce significant science results including the discovery of the UHE cosmogenic neutrino flux.

4 Science Opportunities at Other Wavelengths

4.1 Overview

The Antarctic plateau provides a superb platform from which to conduct a wide range of astronomical observations, due to an exceptionally thin, cold, dry and stable surrounding atmosphere. It provides superior conditions to even the best temperate latitude sites; indeed, *it is now recognized that some important observations cannot be routinely performed from anywhere else on Earth.*

Recent advances in detectors, telescope opto-mechanics, cryogenics, power generation and distribution systems, and remote satellite communications have opened up numerous opportunities for Antarctic astronomy to make significant scientific advances in the next 10+ years. Three exciting directions are outlined below, which underscore the importance of the Amundsen-Scott South Pole Station for astronomical studies on the high plateau.

All three opportunities underscore the need for continued development and support of smaller-scale astronomical projects at South Pole Station. Focused, relatively short-lived projects require power, communications, deployment and laboratory space during final integration and testing. Thus, multi-purpose laboratories such as the current Martin A. Pomeranz Observatory (MAPO) are important facilities that should be maintained, improved and expanded. Even for scientific experiments that deploy to higher sites on the plateau, such facilities at South Pole provide the necessary logistical support, staging space and testing capabilities that are critical to the successful operation of remote observatories.

- **Terahertz Astronomy**: Loosely defined as the wavelength between 600 and 60 μm (0.5 to 5 THz frequency) and often synonymous with the *far-infrared* and *submillimeter* wavebands, terahertz astronomy is the last frontier of the electromagnetic spectrum which has the possibility of being explored from the ground. It harbors the dominant spectral signatures of carbon, nitrogen, oxygen and their ions and molecules, which collectively serve as signposts of star and planet formation, the evolution of star-forming matter in galaxies, the rich astrochemistry of Galactic interstellar clouds, even the prebiotic building blocks of life. Yet, this waveband is relatively unexplored, in part due to the high opacity of water vapor in the Earth's atmosphere. While the South Pole site offers an excellent site for the lower frequencies of the terahertz window, recent site testing demonstrates that the summits of the Antarctic plateau are higher, colder, drier and more stable still. These exceptional conditions enable exciting new science capabilities which can be supported via land and air operations from South Pole. One example of an international collaboration pursuing science on the high plateau via South Pole are the recently funded High Elevation Antarctic Terahertz (HEAT) telescopes that will perform a Galactic Plane spectroscopic survey from the summit of the east Antarctic plateau starting in 2012. This opportunity is summarized in Section 4.2.

- **Ultraviolet Observations of the Cosmic Web**: Direct observations of the high-redshift intergalactic medium (IGM), long studied toward narrow, "pencil beam" lines of sight through the study of quasar absorption lines at visible and ultraviolet (UV) wavelengths, is expected to be possible over large fields of view through observation of weak redshifted emission of resonant UV lines, in particular, the 121.6 nanometer Lyman-α recombination line of atomic hydrogen. Such observations would provide direct probes of large scale structure and the dark matter distribution of the early Universe. South Pole provides the very best conditions which may make these observations possible from the ground! In particular, continuous access to a stable, dark sky with low extinction and scattering allows for optimal, spectral cancellation of the sky background, and hence higher sensitivity to the weak optical background. A pathfinding instrument, Gattini-SP, is currently in operation at South Pole to measure directly the properties of the ultraviolet sky, in particular the effect of aurora, to determine the suitability of the Antarctic plateau to a unique and powerful scientific application. Pending the results from Gattini-SP, a design study for the 2-meter aperture Antarctic Cosmic Web Imager (ACWI) (Section 4.3) has been performed.

- **Infrared Imaging and Interferometry**: While the South Pole is a good site for IR astronomy, to gain the full benefit requires mitigation of the debilitating effects of the turbulent surface boundary layer, about 300m thick. On the summits of the plateau the depth of this layer is only a few tens of meters at most, making it possible to build a tower that rises above the layer. However advances in ground layer adaptive optics capabilities now make it possible to readily build systems that will yield near-diffraction limited IR images for telescopes sited at the Pole. Combined with the stable, low sky background, a modest aperture IR telescope at the South Pole can be superior to large aperture mid-latitude telescopes for many applications. Combining several such apertures *interferometrically* is especially suitable to the Polar environment because of the slow, low-altitude turbulence, low water vapor content, and low temperature. Infrared interferometry from Antarctica would *have the potential to deliver space-like performance*, e.g. for the unique discovery and characterization of extra-solar planets. Sections 4.4 and 4.5 provide descriptions of these opportunities.

4.2 Tracing the Life Cycle of Galactic Matter via Terahertz Observations from Ridge A

Craig Kulesa, Chris Walker; University of Arizona

Based on the results of an NSF-funded design study in 2006 and the successful deployment of an early prototype (`Pre-HEAT`) to Dome A in 2008, two automated, 0.6-meter THz observatories are being readied for remote operation at the summit of the Antarctic plateau with the dual purpose of site testing and performing leading-edge terahertz astronomy. These *High Elevation Antarctic Terahertz (*`HEAT`*) telescopes* will operate from 150 to 400 μm, the range in which the most crucial astrophysical spectral diagnostics of the formation of galaxies, stars, planets, and life are found. `HEAT` will answer timely and fundamental questions about the evolution of the interstellar medium and star formation through large scale spectroscopic surveys of the Galaxy. The first prototype telescope has been deployed for a winter of testing at South Pole Station (Figure 31), and the first deployment onto the high plateau, to a site called "Ridge A", will follow in January 2012.

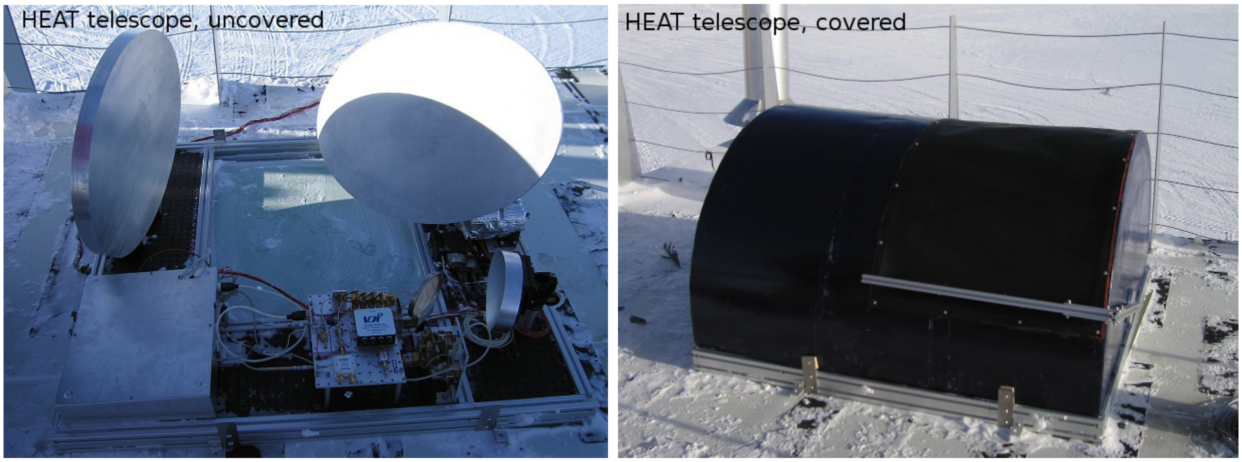

Figure 31: *The prototype HEAT telescope is shown installed on the roof of the MAPO building for testing at the South Pole station in February 2011. The experiment consists of a 60 cm off-axis Gregorian telescope, 0.44 and 0.81 THz heterodyne receivers, and a digital FFT spectrometer. HEAT's dimensional footprint allows it to be directly loaded onto a Twin Otter aircraft for remote deployment.*

Ridge A: The best site for terahertz astronomy on Earth?

Successfully fielded by a Chinese traverse in January 2008 and installed with the Australian-built Plateau Observatory (PLATO), the 20 cm aperture `Pre-HEAT` telescope performed site-testing measurements of the terahertz transmission above Dome A during 2008. It revealed exceptional terahertz observing conditions above the plateau's broad summit, with median atmospheric transmission in the terahertz windows of 40% (versus a few percent at best from other sites, including South Pole). Comparison of the `Pre-HEAT` data to passive sounding measurements from weather satellites showed however, that even better transparency lay 150-200 km further inland: a site labeled "Ridge A" by Yang et al [47]. ¿From there, the 1.9 THz window containing the pivotal ionized carbon line is projected to open during particularly dry winter periods. Testing this extraordinary projection, while simultaneously producing unique science, is the reason behind fielding the `HEAT` telescopes to Ridge A.

HEAT Science Opportunities

The HEAT telescope aims to achieve the following major science goals (also see Figure 32). The minimum mission is expected to be achievable in two seasons of survey operation from Ridge A, with *cryogenic and interferometric* missions to be proposed later.

1. *Mapping the Life Cycle of Matter in the Galaxy*: The formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been identified observationally! `HEAT` is designed with the unique combination of mapping speed, sensitivity

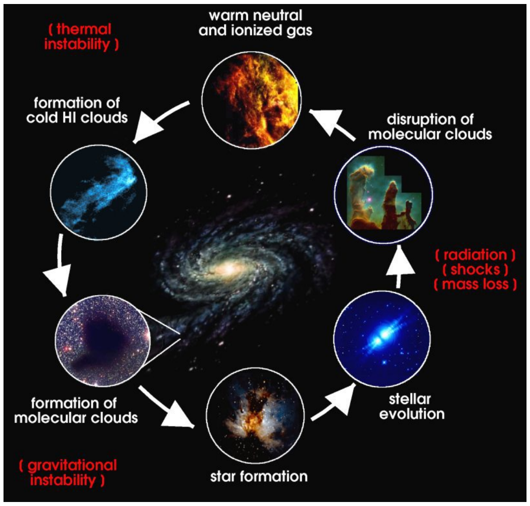

Figure 32: *By spectrally and spatially resolving the line emission of ionized, neutral, and molecular forms of carbon, nitrogen and oxygen from 0.8 to 2.0 THz, HEAT uniquely probes the pivotal formative and disruptive stages in the life cycles of interstellar clouds and sheds crucial light on the formation of stars by providing new insight into the relationship between interstellar clouds and the stars that form in them; a central component of galactic evolution.*

and resolution needed to observe atomic clouds in the process of becoming giant molecular clouds (GMCs) and their subsequent dissolution into diffuse gas via stellar winds, remnants, and radiation.

2. *Construction of a Milky Way template for star formation*: `HEAT` will probe the relation between the gas surface density on kpc scales and the spectroscopically-derived star formation rate, so that we might be able to better understand the empirical Schmidt Law used to estimate the star forming properties of external galaxies. HEAT's observations of the bright terahertz lines of carbon, nitrogen and oxygen will serve as a "Rosetta Stone" for interpreting the unresolved line emission from distant star-forming galaxies.

`HEAT` will provide the first velocity-resolved large-scale mapping survey of carbon, nitrogen, and oxygen. In particular, it measures all three principal forms of carbon in the gas phase: ionized, neutral, and molecular. In combination with existing infrared, HI and CO surveys, the potential to identify the formation and destruction of molecular clouds and GMCs observationally may finally be realized! This survey will provide the first barometric maps of the Galaxy, and illuminate the properties of clouds and their life cycles in relation to their location in the Galaxy. They highlight the delicate interplay between (massive) stars and the clouds which form them, a critical component of galactic evolution.

The importance of South Pole in supporting field science on the high plateau

The successful deployment of PLATO and `Pre-HEAT` to Dome A is a clear demonstration of a working international collaboration between China, the USA, and Australia. It shows that Antarctic science has reached a level of maturity where several options exist for fielding relatively simple instruments to remote sites. However, deployment through South Pole provides an intermediate opportunity for *complex systems integration and testing* that is not possible anywhere else. As scientific instrumentation for the plateau becomes ever more complex, this staging area for instrument assembly and testing will become essential to the successful deployment and operation of remote scientific experiments. Testing fully-integrated instruments while at South Pole reduces the duration, risk, and cost of remote field deployments.

4.3 Direct Imaging of the Intergalactic Medium at redshift 2-3 with the Antarctic Cosmic Web Imager

Anna Moore, Chris Martin; California Institute of Technology

The Antarctic Cosmic Web Imager (ACWI) is a proposed 2m-class telescope specifically designed to discover and map resonance UV line emission from the Intergalactic Medium (IGM) and to explore the low surface brightness universe. IGM mapping, as shown simulated in Figure 33, will provide a new measurement of large-scale structure and the distribution of dark matter over a large and unique range in overdensity. The South Pole provides a location with (1) a target elevation that is constant during observation hence sees constant airmass (2) the lowest measured extinction of any ground based site (3) a low and constant ecliptic elevation and hence zodiacal emission away from the target location and (4) long duration nights yielding stable sky and instrument properties enabling the required accurate sky subtraction. These factors combined imply a sky background that is the most stable of any ground-based site, a requirement for this particular science case where the subtraction of sky background, rather than the image quality, must be exquisite. The experiment is targeted to perform this science case only and is not a general purpose instrument, increasing robustness and reliability.

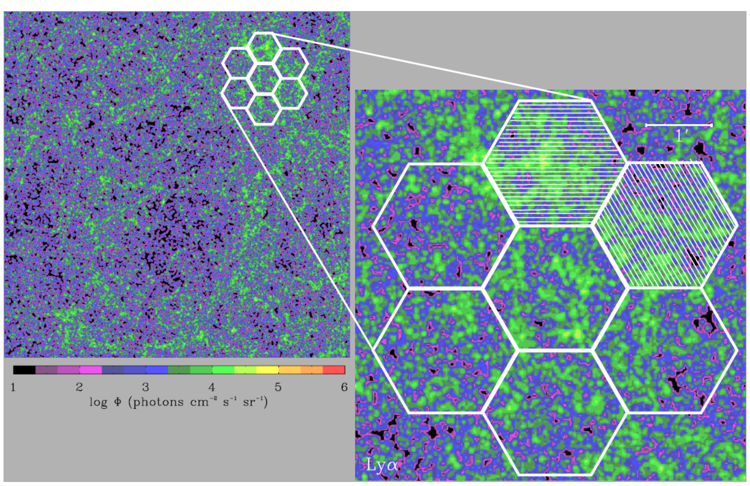

Figure 33: *Predicted Lyman-α emission line distribution for a matter simulation done with a smoothed particle hydrodynamics (SPH) code. The left panel shows a small portion of the ACWI wide survey; the right panel shows an enlargement of the selected box comparable to the deep survey area. The six IFU/spectrograph fields are shown, two with slits. Blue and green regions are detectable by ACWI in a wide survey, purple regions are detectable in the deep survey.*

The unique feature of ACWI is that the sky subtraction is performed in the spectral domain at a high resolution (R$\sim$5000). This permits a sky subtraction accuracy of at least 10^{-4} or better, essential for direct detection of the faint IGM signature. Combined with the ultra-stable instrument design and low sky backgrounds obtainable in the bluest wavelengths, we predict an extended source sensitivity performance better than any ground based location.

Site Verification: The Gattini South Pole UV Experiment

The sensitivity targeted by ACWI requires excellent sky background subtraction. To determine the properties of the South Pole winter sky at the bluest wavelengths, we have deployed a dedicated South Pole UV sky brightness experiment, called Gattini-SP. The instrument is shown in Figure 34 installed on the roof of the MAPO building at the South Pole station in January 2011. The experiment will, for the first time, produce (i) continuous sky brightness measurements in the Astronomical U, and B bands; (ii) continuous monitoring of a 2 degree patch of sky at zenith at a spectral resolution of R 1000; (iii) as a by product a catalogue of the U and B light curves of all stars within 2 degrees of the South Pole to a V magnitude of ∼16.

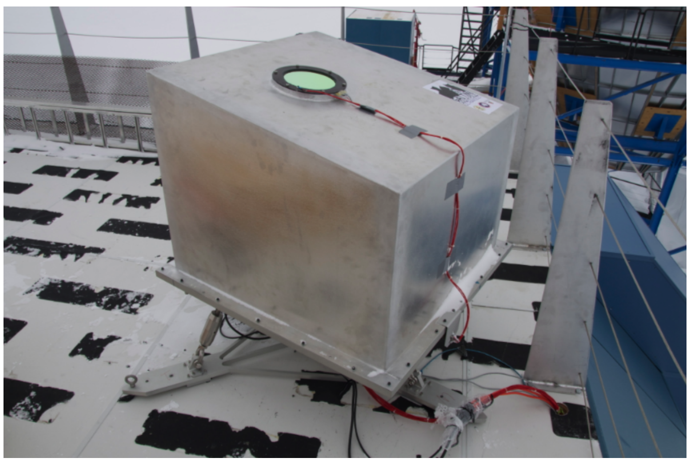

Figure 34: *The Gattini South Pole UV Experiment shown installed on the roof of the MAPO building at the South Pole station in January 2011. The experiment consists of a 4 degree imager and long slit spectrograph that will determine the sky brightness properties of the winter sky above the station in the astronomical blue bands for the first time. The results will determine the viability of the ACWI experiment.*

Summary

ACWI (see Figure 35 represents a 2m-class telescope with a targeted science case of direct detection and mapping of the faint Intergalactic Medium (IGM) at redshifts 2-3 at an unprecedented sensitivity. The experiment requires exquisite sky subtraction at the bluest wavelengths. To assess the viability of ACWI at the aurora-active South Pole site, the winter UV sky properties will be determined, for the first time, by the Gattini South Pole UV experiment, deployed in January 2011. The superior logistics of the Amundsen-Scott South Pole station and MAPO building provide an exceptional opportunity for location of the 2m-class ACWI optical experiment.

4.4 Infrared Astronomy with Robotic Adaptive Optics

Tony Travouillon, California Institute of Technology

The South Pole offers 3 key advantages over temperate sites when observing in the near infrared (NIR): (1) A low background, 20 to 40 times darker than Mauna Kea, which is advantageous for observing faint sources, (2) superb seeing conditions above the boundary layer which can push a 2-meter class telescope to its diffraction limit, and (3) long stretches of continuous observing which is ideal for fast transient events. This combination of factors is ideal for the discovery and study of exoplanets via microlensing events and transit signatures.

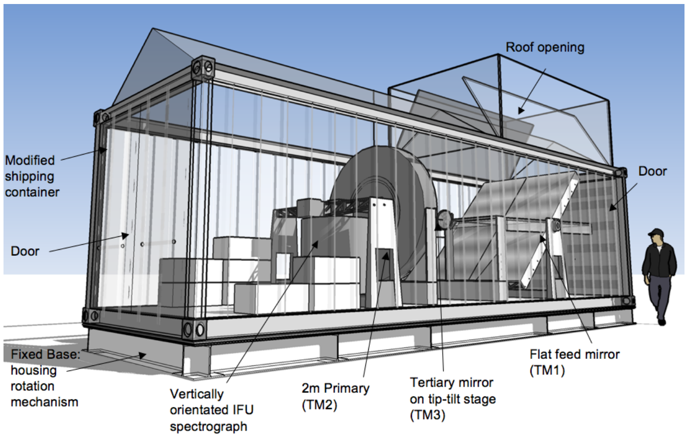

Figure 35: *Based on a standard sized shipping container, ACWI provides a 2-meter aperture RC telescope with zero flexure variation. The light from the secondary mirror is directed through a hole in the primary onwards to the bank of identical imager slicer spectrographs. The siderostat mirror is adjusted in tilt for target acquisition. The target is tracked during an observation by rotating the entire ACWI enclosure. Small tip-tilt adjustments of the small secondary mirror correct for any slight misalignments in the main bearing. A guide camera is located behind the primary mirror and fed by the main telescope beam.*

The microlensing collaborations of OGLE and MOA alert over 1000 new microlensing events each year, primarily during the Galactic bulge season which corresponds to the Antarctic Winter (May-September). These are monitored closely by follow-up teams in an attempt to detect anomalies, particularly those due to extra-solar planets. Twelve exoplanets have been discovered using this technique, but the major hindrances are achieving the needed time coverage and blending due to background sources. A diffraction limited, 2m class NIR telescope at the South Pole would mitigate both of these effects by providing almost continuous coverage of microlensing events during the bulge season and reducing the effects of blending due to the excellent seeing conditions.

The Kepler mission is breaking new ground in the discovery of many new transiting planets. However, this is restricted to relatively faint stars (V>12) in a restricted section of the northern sky. Ground-based surveys such as SuperWASP and HATNet are quite successful but are restricted in parameter space to periods less than 10 days due to the window function that results from both weather and longitude coverage. Additionally, background eclipsing binaries are the major source of transit false-alarms. An NIR South Pole telescope would be able to continuously monitor large sections of the southern sky and would also be able to resolve many of the expected contaminants due to eclipsing binaries over a reasonable field of view, providing an insight into early planet formation and frequencies of planets in cluster environment.

To carry out such studies, one needs to achieve the diffraction limit of a 2 to 3m class telescope over a field of several arc-minutes. This requires negating the effects of the boundary layer responsible for 90% of the South Pole seeing. Advances in the field of adaptive optics (AO) such as MEMs deformable mirrors and Ground Layer Conjugated Adaptive Optics (GLAO) open a new way to tap into the potential of high resolution observations at the South Pole (Figure 36). This combination allows for a practical and more affordable system that corrects the turbulence near the ground and with very high tolerance to the boundary layer height. This solution is more practical and adaptable than building a telescope physically above the boundary layer which is doable in higher parts of the plateau such as Dome

A and Dome C but out of reach at the South Pole. Such a GLAO system is currently being developed at Caltech with first light on the P60 telescope at Mt Palomar. A winterized copy of this system coupled with a 2-3m telescope would perform unique science and demonstrate the concept of such systems on the Antarctic plateau.

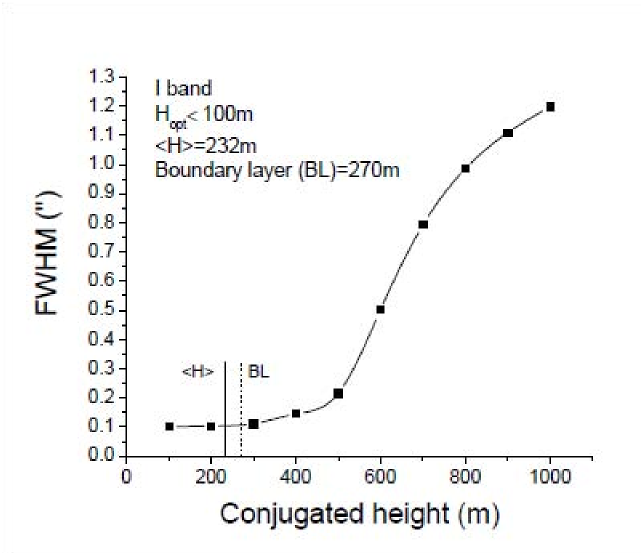

Figure 36: *I-band seeing at the South Pole after GLAO correction as a function of conjugation height of the deformable mirror. GLAO can effectively remove the contribution of the South Pole turbulent boundary layer despite its thickness and variability. This technique is therefore equally suited to the South Pole and other locations on the plateau where the turbulent layer is thinner.*

4.5 Long Term Vision: Exploring Exo-planets with Infrared Interferometry

For many of the challenging observational problems in astronomy, interferometry can often be a more cost-effective way to achieve high spatial resolution than a large filled-aperture telescope. Interferometry also naturally provides spatial filtering; the interferometer layout can be optimized for providing extremely high contrast imaging, ideal for the direct detection and characterization of planets around other stars.

Optimally, such an infrared interferometer would be placed in space (e.g. the former Terrestrial Planet Finder), however the cost is extremely high. A ground-based prototype would test the technologies needed to eventually realize space interferometry – but placed on the high plateau in Antarctica, it would also be able to perform a significant subset of the science as well, owing to the exceptional coherence times, stable conditions, low turbulence, and high sensitivity due to the prevailing cold dry atmosphere.

The most developed proposal for infrared interferometry is the Antarctic Planet Interferometer (API, Figure 37), developed by Swain et al. [48]. The interferometer is comprised of several 2-meter class telescopes with baselines up to 400 meters. The 1.4-5.4 μm wavebands would be targeted to yield maximum resolution and sensitivity. Spectroscopy would be possible at resolving powers ($\lambda/\Delta\lambda$) as high as 10^4. The API instrument would be able to tackle ambitious science programs such as the measurement of binary star orbits in the LMC, protoplanetary disk formation, active galactic nuclei, star formation and the interstellar medium, and high resolution observations to complement the James Webb Space Telescope (JWST).

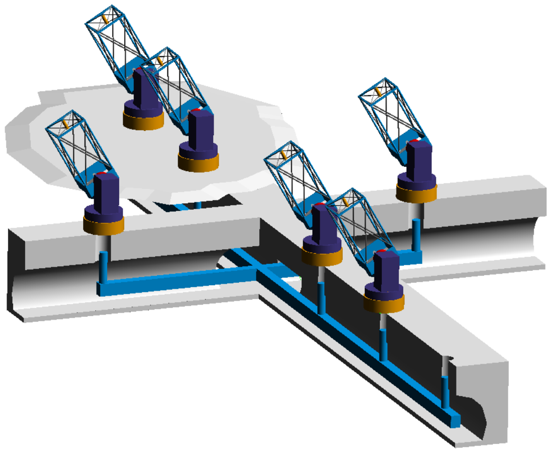

Figure 37: *Concept drawing of the Antarctic Planet Interferometer (API). 2-meter apertures in Antarctica yield sensitivities comparable to 8-meter class facilities at midlatitude sites, and the atmospheric properties of the Plateau are the closest analog to space that can be achieved from the ground. API would be able to discover and explore spectroscopically the atmospheres of extra-solar planets, with the goal of searching for biomarkers of life.*

Infrared interferometry remains at a natal stage but is being actively developed on several large 8-meter class telescopes at temperate sites (VLTI, Keck, LBTI). In particular, the Large Binocular Telescope Interferometer is designed at the outset with this capability and can operate in multiple interferometer modes. An Antarctic infrared interferometer should be best viewed as an opportunity for follow-on to these mid-latitude efforts and therefore should build upon the experiences gained from these programs. While it offers significant science capabilities in its own right, it also serves as a stepping stone to space interferometry.

5 Research Capabilities at Other Sites in Antarctica

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Results from Astronomical Site Testing

The South Pole is a superb site for a wide range of astronomical observations. Nevertheless, there are significantly better ice-based sites in Antarctica for some types of observations, located at summits of the Antarctic plateau. Here the air is thinner, colder, drier and even more stable. The last two attributes, in particular, can lead to substantive gains over even the South Pole for some observations. Here we briefly review Antarctic plateau site characteristics, comparing the South Pole to recent results obtained from the site testing programs underway at high plateau sites. A more in-depth coverage of this can be found in the review of Burton [49].

Infrared Sky Brightness

In the thermal infrared, from $2.2 - 30\mu$m, emission from both telescope and atmosphere is greatly reduced, by between 1–2 orders of magnitude depending on wavelength, at the South Pole compared to temperate sites [50, 51]. The SPIREX 60-cm prototype IR telescope, operated at the Pole 1994-99, demonstrated that these gains are attainable [52], though it also illustrated the limitations caused by the surface seeing (see below). The colder, drier conditions at high plateau sites should provide better conditions, though to date only day time measurements have been made — at Dome C [53] — yielding similar sky fluxes as the South Pole winter time measurements. The further gains projected for high plateau sites for IR astronomy arise primarily from the drier and more stable conditions and the much narrower boundary layer, compared to Pole (e.g. as discussed by Lawrence [54] for the proposed PILOT telescope at Dome C).

Water Vapor

Precipitable water vapor (ppt H_2O) levels of $\sim$300 μm are typical at the South Pole for much of the year, levels only occasionally reached at the Atacama plateau site of ALMA [55]. Moreover the stability of the resulting sky emission (both spatially and temporally) is typically 3 times better than at the ALMA site [56]. It is this combination that has facilitated the remarkable development of CMBR facilities at Pole, as the exceptional stability in measurement conditions is essential to make precise measurement of the CMBR flux and its variation across the sky. It also facilitated the success of the 1.7 m AST/RO sub-mm telescope at Pole, despite its modest aperture.

Atmospheric water vapor content is sensitive to altitude, as well as to cold temperature. At the very highest sites on the Antarctic plateau the ppt H_2O levels were projected to drop significantly from those measured at Pole. With the opening of Dome A this supposition has been confirmed through the measurements made using the preHEAT instrument on the PLATO observatory [47]. A median winter value of 140μm ppt H_2O was found, a 1st quartile value of 100μm and a lowest recorded value of just 25μm, from the first season of measurements – the best value being comparable to that obtainable from an airborne observatory. Such low ppt H_2O levels open up new windows in the atmosphere for surface-based observation, particularly in the THz and IR regimes.

Combining these data with downward radiometry from the NOAA-18 satellite (which covers all of Antarctica), Yang et al. also hypothesize that at Ridge A, 150 km SW of Dome A, water vapor levels are even lower, having determined the 25% and 50% quartile levels for the ppt H_2O to be 80 and 120μm respectively.

Seeing and Boundary Layer

A strong temperature inversion exists over the plateau during the most stable conditions in winter. Within this surface boundary layer turbulence is high, greatly impairing observations made in the optical and IR when image quality is important for a science objective. Above the boundary layer, however, the free air seeing is exceptionally good, as high altitude turbulence is low due to the absence of jet streams. For instance, at the Pole the boundary layer height is typically ∼300 m. Within the boundary layer the visual seeing can be 2-3″. However, above it the seeing can be a factor two better than the ∼0.7″ seeing above the best temperate sites [57].

On the summits of the high plateau, where the wind speed is minimal, the depth of the boundary layer was predicted to be much less than Pole, offering the prospects of raising a telescope above it and so directly experiencing the superb free atmospheric seeing. These projections have now been demonstrated.

At Dome C Lawrence et al. [54] found the boundary layer to be ∼ 30 m high, and the free air seeing to have a median value of just 0.27″ in the visual if the telescope could be raised above it. Measurements of the boundary layer height have now been made at Dome A [58] using an acoustic radar capable of sampling this layer with 1 m resolution. They find 25% and 50% quartile levels of just 10 m and 14 m for the height of the boundary level, sufficiently low that a telescope may readily be raised above it for most of the time.

Current and Projected Activities at other Sites on the Plateau

Four sites on the summits of the Antarctic plateau are now the focus for astrophysical experiments: Domes A, C & F and Ridge A. These efforts place the astronomical efforts at South Pole Station in context. We review the activity underway at each of them briefly, below.

- **Dome A** (4,083 m): The highest location on the plateau, first visited by humans in just 2005. In 2009 China began the construction of Kunlun station, including installing the Australian-built PLATO autonomous laboratory [59]. This controls several astronomical, as well site testing, experiments, including the CSTAR optical telescope, the Snodar acoustic radar and the Pre-HEAT sub-mm tipper. PLATO is in its third season of operation, and currently has been running for over 800 days continuously, controlled remotely via Iridium satellites. One traverse per season is conducted to Dome A from Zhongshan station, and can transport ∼ 570 tons of equipment. A three-telescope array of 0.5 m optical Schmidt telescopes (AST3) is under construction, designed to search for time-varying events over large fields of view (e.g. exo-planet transits, supernovae light curves). Under the 12^{th} Chinese 5-year plan, $150 million is being sought for developing the station. Astronomy provides the primary scientific driver, with a 2.5m IR telescope (KDUST) and a 5 m THz telescope (DATE5) as the first major facilities planned.

- **Dome C** (3,268 m): Concordia station at Dome C, built by France and Italy, was opened in 2005 for winter operation following a decade-long construction phase. Winter time site qualification began in 2003 using the Australian-built AASTINO laboratory (a development from the South Pole AASTO laboratory). The main building for the station consists of two 12 m high towers, one for living and one for working and science. Currently a range of site testing experiments are operated, led by the University of Nice. Three overland traverses per year from Dumont Durville supply equipment, and personnel are transported by Twin Otter from either Maria Zuchelli or Dumont Durville stations. The European Union-funded ARENA program considered the scientific rationale for the station, and prioritized the development of a 2 m class IR telescope as the first major astronomical infrastructure. A preliminary design study was conducted by Australia for a 2.4 m optical/IR telescope (PILOT [60]), and the European Union have recently selected the 2.4 m IR PLT (with a subset of PILOT's capabilities) for consideration for funding for a full design study, under the 7^{th} Framework Programme (FP7).

- **Dome F** (3,810 m): The Japanese Fuji station at Dome F was first used for wintering in 1995. The primary scientific purpose of the station was ice core drilling. This was a limited operation, and the station has only been used for summer activities in recent years. However astrophysics is now a part of the scientific plans for Dome F. In January 2011 an overland traverse from Syowa installed an Australian PLATO laboratory (PLATO-F), as well as operating a 40 cm IR telescope during the 2-week period the site was occupied. Several site testing instruments are currently being operated, including an acoustic radar to measure the height of the boundary layer. The next traverse to the station will be in 2013. Two astronomical telescopes have been proposed for Dome F, an ultra-light weight 2 m IR telescope and a 10 m-class THz telescope.

- **Ridge A** (4,050 m): This site has not yet been visited, and lies 150-200 km inland from Dome A. It is slightly lower in elevation. However satellite observations indicate that the atmospheric water content is even lower than at Dome A, with the 1.9 THz window, containing the important [CII] line, becoming accessible at times. This could be the only surface-based site where this line may be regularly measured. A 0.6 m single-axis THz telescope (HEAT) is scheduled for deployment to Ridge A in 2012 by the USA, via Twin Otter deployment from the South Pole. It will make use of a cut-down version of the PLATO laboratory (PLATO-R) for power and control. HEAT will map the Galaxy in the [CI], CO, [CII] and [NII] lines. A prototype for HEAT is currently operational at the South Pole.

6 Infrastructural Implications of Future Projects

6.1 Data Transmission Bandwidth

Data communication from South Pole is via satellite with bulk data transmission currently occurring through a special high speed link on NASA TDRS geostationary spacecraft. Over the last few years the capacity of this link has been massively expanded to match the ever growing requirements of the science experiments. Figure 38 shows the data transmission over time with proposed future experiments shown dashed. AMANDA and its successor IceCube send only a portion of their data back daily over the satellite link, whereas up to now the CMB experiments have been able to send 100% out in “real time”.

As is clear from the figure, the future CMB Polarization Facility seeks to increase again by a factor of ten the data bandwidth. It must be emphasized that it is by far the most efficient in terms of accelerating scientific discovery to send the data in real time—subtle problems with the experiments often arise and if found they can be fixed resulting in better quality data. However if it proves impossible to send all of the data out in real time, sending as large a fraction as possible, while bringing the remainder out on tape/disk during the summer remains a fall-back position.

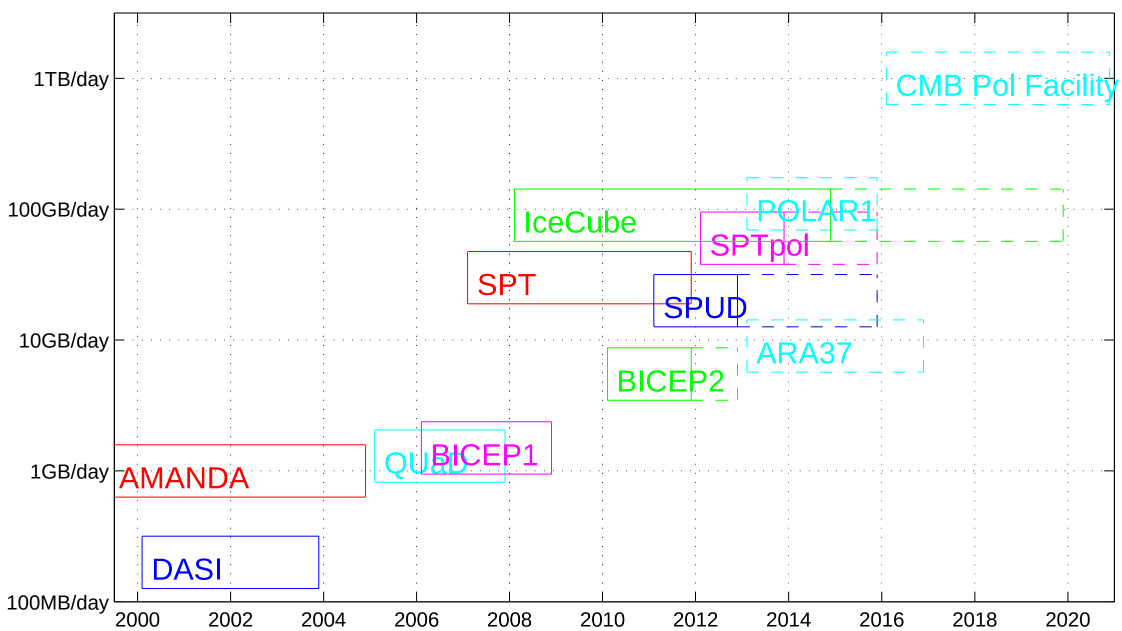

Figure 38: Daily satellite data transmission of South Pole experiments over time. Past and approved future usage is show as solid box and proposed is shown as broken line.

6.2 Observatory Buildings

Possibly the most pressing science need identified in this study is for a new general purpose observatory. The existing MAPO building is now approaching 20 years old and showing its age—snow grooming to keep it from being submerged is a constant requirement. Also the building has heat leaks and is no longer code compliant which complicates modifications. A full "gut" refit is one option but would require suspending the science programs currently operating in MAPO for at least one summer plus winter season.

A possible replacement building is shown in Figure 1 which shows it equipped with multiple modular towers with individual off-axis telescopes that are suitable for the future CMB Polarization Facility concept. However such towers, and/or the main building itself, would also be suitable for the exciting new projects described in Section 4, and also potentially for aeronomy research. We suggest to build this new observatory adjacent to the existing MAPO building, and transition over to it as rapidly and cleanly as possible once it is ready. Minimizing overlap of the two building will of course minimize the use of scarce resources such as power and heat.

MAPO has shown the value of a multi purpose observatory building, and has hosted a wide range of successful experiments over the years. It is time for a replacement to serve for the next twenty years.

6.3 Cargo Requirements

Figure 39 shows the total per season weight over the last nine seasons for various cargo categories arriving at South Pole. The direct cargo requirements of many of the experiments described above fall into the small bottom band marked "Science/Cryo". The "big two" experiments IceCube and SPT experiments are called out separately. In the case of IceCube a considerable amount of extra fuel was required for drilling as can be seen from the bulge in fuel consumption. The New Station was a massive construction project which was completed during this period.

Of the possible future projects described above only a few would be noticeable on such a plot. The future CMB Polarization Facility would require cargo on a similar scale to SPT, although probably spread out over a somewhat longer timescale. The MAPO replacement building would also require significant cargo, although clearly a small amount compared to the New Station project. Although the technology is intrinsically lighter in weight, cargo for a full blown Askaryan Radio Array might reach the scale which was required for IceCube.

6.4 Electrical Power Demands

The New Station Power Plant is equipped with three identical main generators. At South Pole altitude and conditions the maximum sustained power output of these units is around 660-680 kW. Normally one of these units is running, one is on standby in case of failure of the running unit, and the third is undergoing maintenance. A smaller peaking generator copes with short term spikes in the load. While renewables and efficiency gains are being actively pursued increasing electrical power generation significantly beyond that provided by the existing power plant would involve an extremely large and costly project and is not anticipated. Note from Figure 39 the large fraction of cargo weight capacity which is already dedicated to fuel.

At the present time a significant fraction of the direct science power consumption is used to run pulse-tube-cryocoolers. These devices generate temperatures as low as 4 Kelvin using electrical power alone and are in the process of massively simplifying operations at Pole by

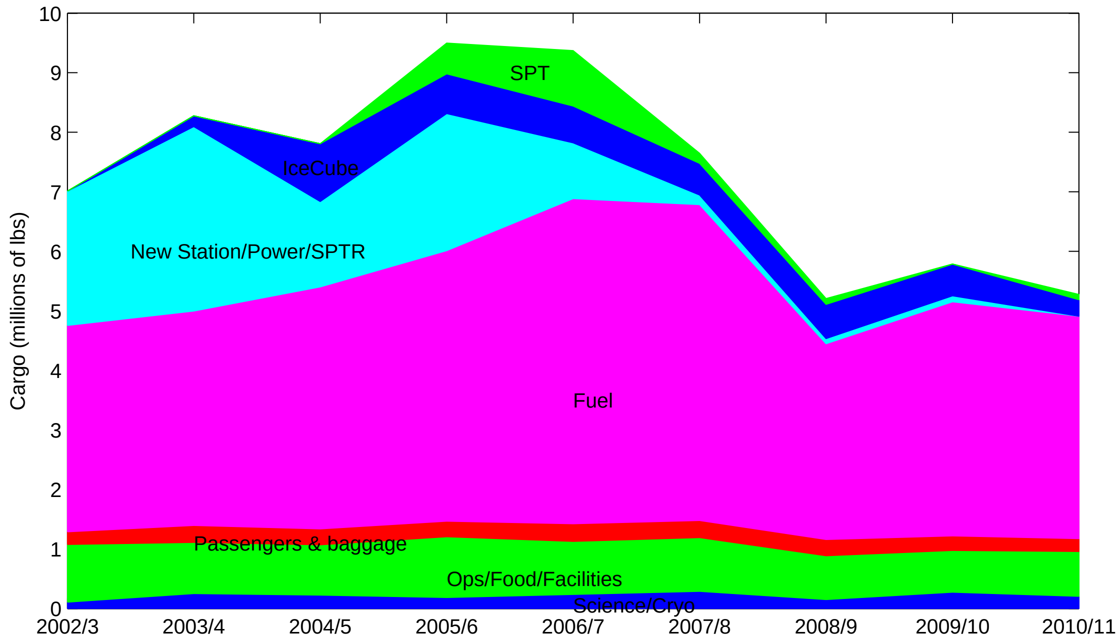

Figure 39: South Pole cargo weight over the last nine seasons. (Based on season end totals of on-site tracking data.)

dispensing with the need to fly in large amount of liquid helium. The power consumption of each cooler is around 10 kW. In the 2011 winter season a total of 8 are running (2 for SPT, 3 for SPUD and 3 for BICEP2 as reliquifiers in the Cryo-Facility). This number is expected to increase to 10 for the 2012 season, but then drop to 7 in 2013 as the Cryo-Facility is shut down. Another substantial current science power draw is the IceCube electronics and computer room using approximately 60 kW.

Of the possible future projects discussed above, the future CMB Polarization Facility would involve the ongoing use of at least one pulse-tube per telescope. i.e. a power consumption similar, or somewhat greater than the full SPUD-Array. Askaryan radio array is intended to be mostly powered by remote wind turbines.

7 Conclusions

From humble beginnings astrophysical research at the Amundsen-Scott South Pole Station has developed over the past decades to become highly sophisticated and very successful. Past and current experiments have achieved ground-breaking and transformative scientific discoveries. With the completion of the modern and well equipped New Station and power plant etc. the infrastructure at South Pole is mostly in good shape to support even greater scientific successes in the future.

The large SPT and IceCube experiments are now complete. Over the next years IceCube will enter routine operation phase collecting data on millions of neutrino events—it is by far the biggest and best neutrino telescope ever built. At the same time, as described above, a vigorous program of upgrades to the overall detector systems is underway enabling many sorts of additional science. To reach to still higher neutrino energies the the Askaryan Radio Array is under development—a true next generation neutrino detection array.

The 10 meter SPT has had an incredibly successful first few years of observation detecting some of the most distant and massive galaxy clusters ever discovered—the scientific papers are coming thick and fast. In fall of 2011 SPT will be upgraded with a state-of-the-art polarization sensitive receiver to join the global quest for CMB polarization measurements.

Meanwhile the focused CMB polarization program of the DASI/QUAD/BICEP1/BICEP2/SPUD experiments has been proceeding full tilt. Since the first detection of polarization in the microwave background by DASI in 2002 sensitivity has been increasing exponentially with South Pole experiments repeatedly delivering best-in-the-world results. The quest for evidence of hyper-inflation in the first moments after the Big-Bang is widely agreed to be amongst the most exciting and important in contemporary science. There are many experiments globally pursuing this goal but BICEP1 currently leads the field in terms of published results—soon to be eclipsed by BICEP2 and SPUD.

The future vision is for South Pole to play host to a large, comprehensive, and possibly ultimate, ground-based CMB experiment. This would be an inclusive collaboration uniting a significant fraction of the CMB community to build an array of telescopes with unprecedented sensitivity and exquisite fidelity.

While neutrino science and CMB observations have dominated South Pole astrophysics to date fresh ideas are leading to path-finding experiments at other wavelengths. One plan is to use South Pole as a staging post to deploy robotic experiments even higher on the Antarctic plateau—necessary at terahertz frequencies—and probably the only place on Earth from which these observations can be made. Ultraviolet and observations at detecting the Cosmic Web are also underway and there are ideas for new technology infrared astronomy.

The infrastructure at South Pole is mostly now in good shape. Going forward there are two pressing science driven needs: Firstly are higher bandwidth, and more continuous, satellite communication is needed. Modern science is extremely fast paced and the loss of productivity which comes from time lag communications is a real problem. Having made the investment of deploying science experiments to Pole, and the winter-overs to operate them, it is critical to also provide the communications which allow these resources to be efficiently exploited. Secondly a replacement for the aging MAPO observatory building is urgently needed. At this point MAPO should be consider a "legacy" facility out of step with the otherwise fully modernized South Pole Station. On the other hand it is critically important to the science program housing the science machine shop, the cutting edge SPUD polarization experiment and two of the small pathfinder astrophysics experiments. The best plan would be to construct a new building alongside, move operations over when complete, and then decommission MAPO.

In conclusion South Pole has a storied past, a vibrant present, and a bright future in astrophysical research. Further investment in infrastructure will reap rich scientific rewards.

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