Roadmap to the Future

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This summary talk for the 2004 SLAC Summer Institute starts with the questions that define particle physics. These questions are tied into a roadmap relating the questions to projects carried out over time. The future of particle physics, with particular attention to the U.S. program, is discussed in terms of the major regions covered by the roadmap of particle physics.

1. PARTICLE PHYSICS AT THE BEGINNING OF THE 21ST CENTURY

1.1 Questions

Particle physics can be defined in terms of the questions that the field is trying to answer: What is the nature of the universe and what is it made of? What are matter, energy, space, and time? How did we get here and where are we going?

Questions related to these have intrigued humans from the earliest times. Of course, the specific formulation of the questions has changed as a consequence of the dramatic increase in our understanding of nature, along with the development of tools to get at the answers. The three questions about the universe written above have been phrased in an attempt to capture particle physics in a way that reflects the evolving nature of the field over the second half of the 20th century.

During the last several decades, it has becoming increasingly apparent that the answers to these questions are deeply and inextricably connected. For example, understanding the fundamental particles and their interactions, which is embedded in the first question, has proven to be essential to understanding the cosmological third question, and *vice versa*. Following the timeline[1] of important events in the early universe shown in Figure 1 back toward the big bang, this connection becomes more explicit. Consider Big Bang Nucleosynthesis and the quark-hadron transition.

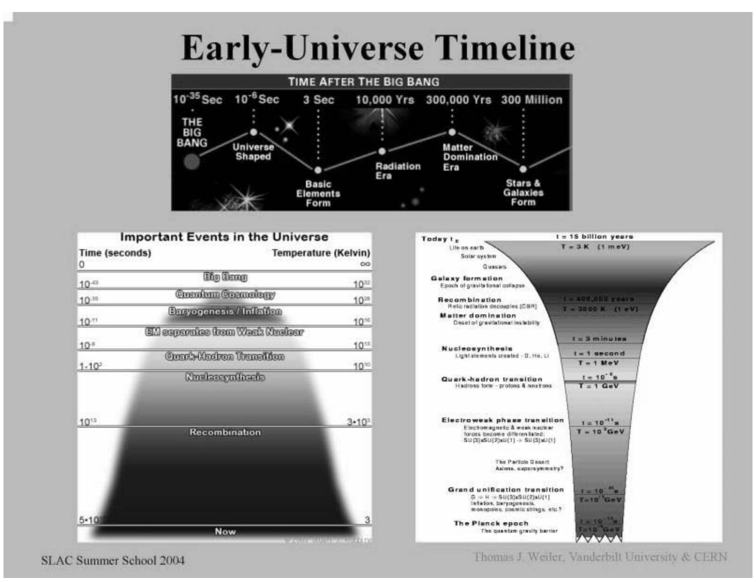

Figure 1 – Timeline of important events in the early universe.[1]

Big Bang Nucleosythesis takes place when temperatures correspond to energies of roughly a MeV. Particle physics measurements that show there are three, and only three, light neutrinos yield the right mix of light elements. Cosmologists might state it the other way around: measurement of the primordial element abundances shows that there are three light neutrinos. Going farther back in time toward the big bang, the next major cosmic event is the quark-hadron transition at energies of about a GeV. The particle physics discovery of a just a few quarks as the constituents of the zoo of hadrons gave cosmologists the ability to break through the "hadron wall" and project back far closer to the beginning of time. The next major cosmological event, the electroweak transition, awaits us at times corresponding to energies around a TeV. We will have much more to say about this later.

1.2 Old questions, New Questions

One may break up the big questions of particle physics into a longer list of more specific sub-questions. These characterize the frontier of particle physics in more detail at a given time. Such are the ten questions that form the framework of this 2004 SLAC Summer Institute,[2] or the nine questions of the recent report, Quantum Universe.[3]

As our exploration of nature has continued, old questions get answered. Answers to old questions often lead to new, deeper questions. We sometimes even learn to pose profound and dramatic new questions that we didn't even know were within reach as experimentally answerable questions. Their very formulation is a revolution in our thinking. Less dramatic but important progress has been repeatedly made by simply understanding at what energy scale a given question may be answered.

Progress also comes from knowing that a given domain of science is understood precisely. Then, if there are discrepancies with experiment, they must come from something new. Such was the case at the end of the twentieth century for the part of the universe made of quarks and leptons that we find immediately around us. Four decades of extraordinary experimental and theoretical ferment led to a great synthesis in our understanding of these particles and their interactions – the Standard Model. It is simple, elegant, and predictive through the level of quantum loops.
Thus, as we began the 21^{st} century, we thought that we knew the fundamental fields and interactions that make up the universe around us. This was not true. Instead, our commanding knowledge of "normal" matter has provided the framework against which the new surprises can be measured.

1.3 Dark Matter and Dark Energy

Astrophysical observations have shattered the view that we understood the fundamental fields: the bulk of the universe is dark matter and dark energy. The matter of which we and our immediate surroundings are composed accounts for only a few percent of the energy budget of the universe.

The evidence for dark matter has been piling up since the 1930s.[4],[5] Its effects were first seen in the motion of clusters of galaxies and in galactic rotation curves. The evidence from gravitational lensing, both strong and weak, is much more recent. A spectacular example[6] of strong lensing is shown in Figure 2. In the primary image from the Hubble Space Telescope, a relatively nearby cluster of galaxies is causing multiple images of a more distant galaxy. In the second part of the figure, the mass distribution extracted from the image is shown. The spikes in the mass distribution occur at the visible galaxies in the primary image, but it is instantly clear that the great bulk of the mass of the cluster is to be found in a great, dark lump. One would like to have been able to show this picture to Einstein, who was evidently pestered to publish his paper on the lensing of two stars, something whose probability of observation was infinitesimally small. Instead of a single astronomer, little could he have imagined billions of pixel "eyes" scanning regions of the sky night after night, nor guessed at immense amounts of dark matter in a galaxy cluster being the lens.

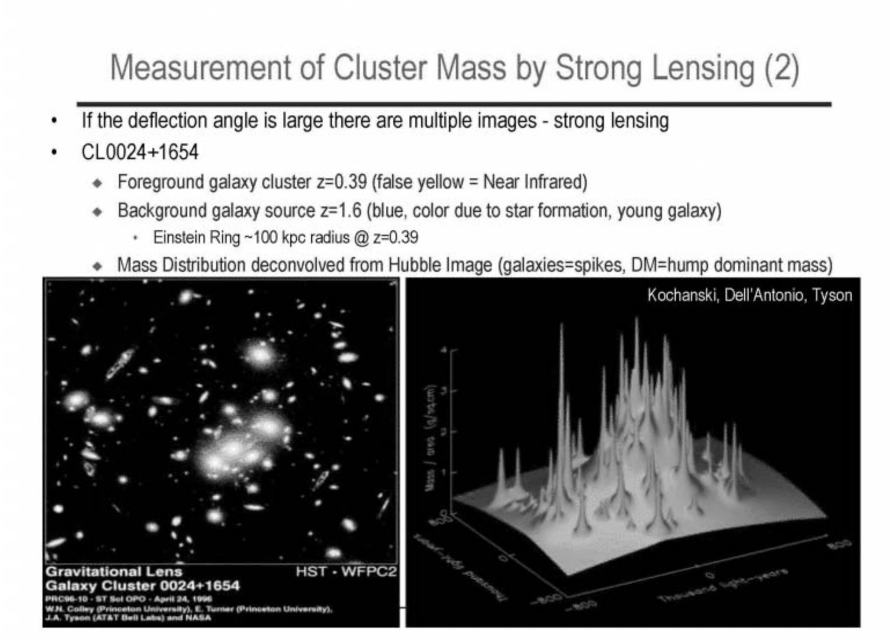

Figure 2 – Strong gravitational lensing with multiple images of a background galaxy by a foreground cluster.[6]

Not only are there multiple pieces of direct evidence for dark matter,[4] but computer simulations of the early universe have dark matter playing an essential role in understanding, for example, the evolution of large scale structure in the universe, the formation and properties of clusters of galaxies, and the formation of massive black holes within galaxies.

The even more astounding presence of dark energy, while only recently discovered and based on a more limited range of measurements than dark matter, seems established as well. It was originally deduced from measuring the accelerating expansion of the universe using supernovae as standard candles. A compilation[7] of this data is shown in Figure 3. Instead of the matter in the universe, whether luminous or dark, simply decelerating the universe's expansion, something else is in play and causing the opposite effect: accelerating the universe's expansion. The cause or causes of this expansion, whatever it is or they are, has been named dark energy.

There are two other pieces of information that point toward the same conclusion. These come from the Cosmic Microwave Background (CMB) radiation left over from the big bang and measurements of the matter density in the universe from measurements of the motion within galaxy clusters. These latter constraints are shown, together with the result from supernovae, in Figure 4.[8] The region where the CMB and matter density constraints overlap lies smack in the middle of the region allowed by the supernovae data. This triple-overlap region also lies right on the line corresponding to an inflationary, flat universe, $\Omega_\Lambda + \Omega_m = 1$, where the dark energy and matter densities, Ω_Λ and Ω_m, respectively, are normalized to the critical density. This agreement is referred to as the Concordance ΛCDM Model of cosmology.

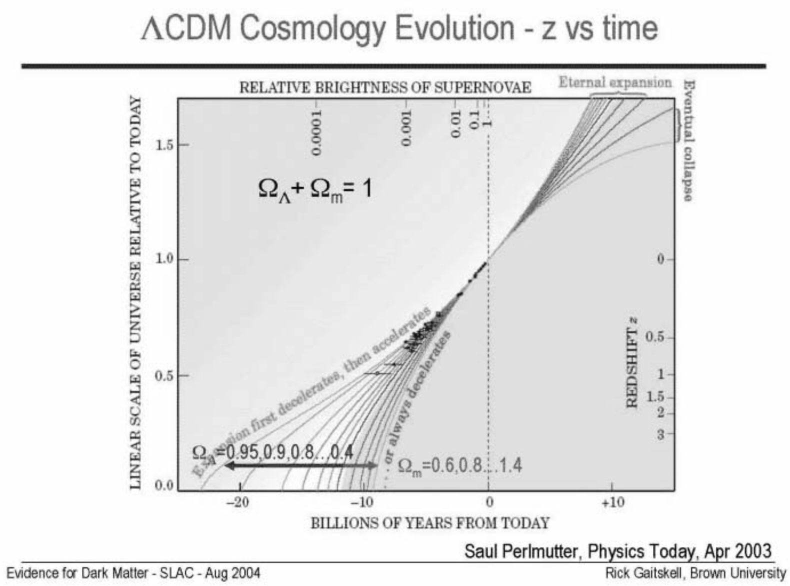

Figure 3 – Evidence using supernovae as standard candles for the accelerating expansion of the universe.[7]

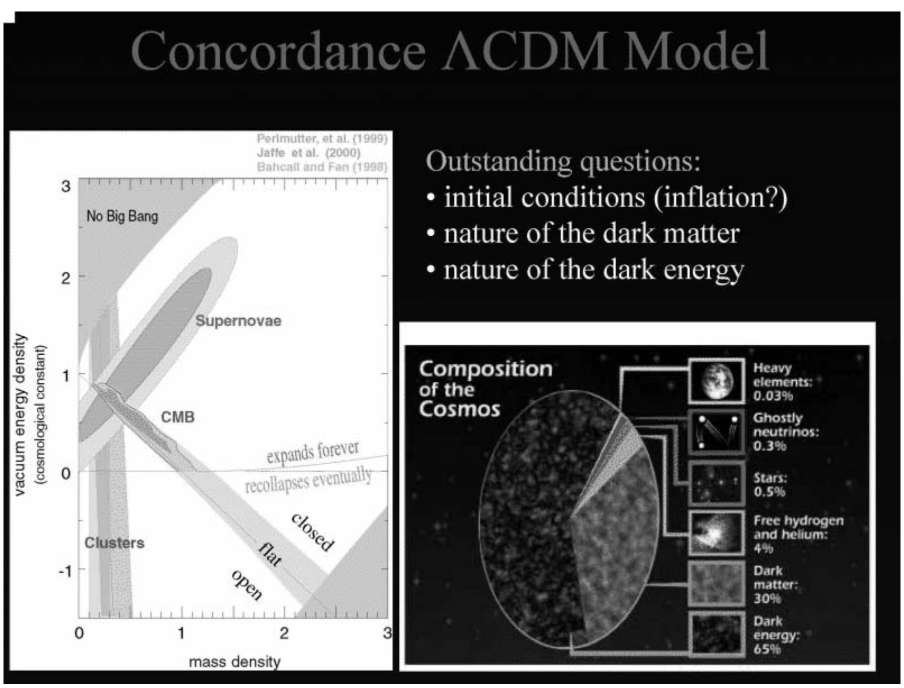

Figure 4 – The components of the Concordance ΛCDM Model of cosmology.[8]

1.4 Accelerators and the Cosmos

All around us in the universe are the relics of the Big Bang, the ultimate particle physics experiment. These relics provide us with essential information about the composition of the universe. Indeed, it is the cosmological discoveries of recent years that tell us that our present model of the universe is incomplete; it must be incorporated into a deeper, more inclusive theory that can incorporate the new phenomena. That necessarily means new physics.

We can also produce at accelerators, under controlled conditions, time/energy-slices of the universe right after the Big Bang. This "melting of the vacuum" not only reveals the fundamental constituents in a given epoch, but allows their detailed study together with their unstable relatives that have long since decayed and no longer appear in today's universe. The knowledge and understanding gained from accelerator experiments will allow us to work forward from the Big Bang and to provide the essential check: Does the physics from the big bang onward match up with what we see today? It is the combination of the data from particle accelerators, cosmological observations, and underground experiments that are needed to exploit the revolutionary discoveries and open a new era of particle physics.

We know the tools that will provide us with the information that we need to begin to take the next steps. The assembly of those tools, viewed systematically in the form of facilities and experiments, are the subject of the next part of this talk: the particle physics roadmap.

2. PARTICLE PHYSICS ROADMAPS

The set of current and future experiments directed at answering the set of basic questions of particle physics can be viewed in terms of a roadmap. For U.S. particle physics, such a roadmap of proposed projects and their timeline was set forth by the Long-Range Planning Subpanel of HEPAP in 2002 and shown in Figure 5.[9] While the planning reflected in the roadmap was made for the U.S. program, these projects will be done in the context of particle physics across the globe. Some will be done on-shore and some off-shore. Almost all will involve international collaborations.

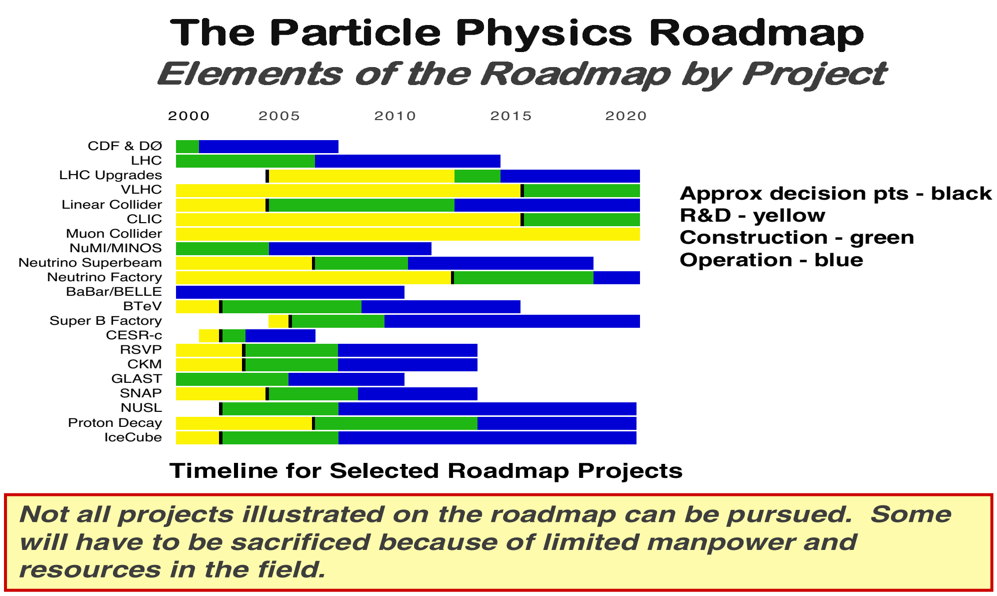

Figure 5 – The U.S. Particle Physics Roadmap.[9]

A slightly different, but closely related, type of roadmap was developed in the last few years by the Consultative Group on High Energy Physics of the OECD Global Science Forum.[10] The part of the roadmap focused on high-energy accelerators is shown in Figure 6. In this case, the roadmap combines not only the projects and their timeline, as in the U.S. roadmap above, but through the use of spotlights introduces a third connection that relates the projects to some of their principal physics exploration goals.

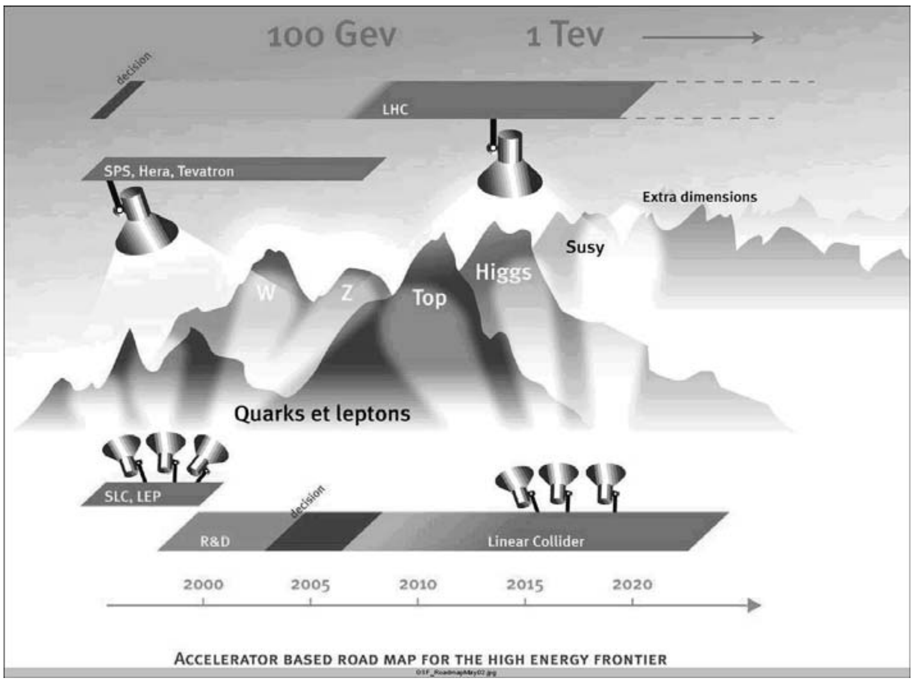

Figure 6 – High-Energy Accelerator Roadmap of the OECD Global Science Forum.[10]

Any such roadmap needs to be updated as science changes, new experiments are proposed, and decisions are made on whether one proceeds with a given project or not. In the U.S., a special advisory body, the Particle Physics Project Prioritization Panel (P5), was formed to update the roadmap and to make recommendations on mid-sized particle physics projects. P5 made its first report[11] to HEPAP in September 2003, assigning priorities to three projects and updating the U. S. roadmap. Encompassing and in parallel with the planning for U.S. particle physics, the DOE Office of Science has developed a Twenty-Year Facilities Plan.[12] Unveiled by the Secretary of Energy in September 2003, it included five of the HEP facilities recommended by HEPAP: the Joint Dark Energy Mission (JDEM), BTeV, a Linear Collider, a Double-Beta Decay Detector, and a Neutrino Super Beam.

3. THE ROADMAP TO THE FUTURE

In the following, we examine the U.S. roadmap, classifying the specific projects into broad themes. We take special note of recent developments.

3.1 The Assault on the TeV Scale

We know that the weak and electromagnetic interactions unify at the TeV scale of energies. Since assuming just the presently known particles and interactions yields predictions in this regime that contradict unitarity, there must be new physics. In fact, there must be something profoundly and fundamentally new, such as Higgs bosons, supersymmetry (SUSY), and/or extra dimensions.[13], [14], [15],[16],[17],[18],[19]

It is difficult for me to avoid the feeling that we have been quite unlucky in uncovering this new physics. After all, we have some indications that we don't have to reach a full TeV in energy; rather, at 100 to 200 GeV something might well turn up.[14] It seems that new physics might well have been found at the SLC or LEP, at the Tevatron Collider, or at the intensity frontier. But we have found neither flavor-changing-neutral-current amplitudes nor CP-violating effects that go beyond the Standard Model, let alone a Higgs boson or an indication of SUSY. A reflection of that is that we seem to be doing more than a little tuning of our models, thereby pushing physics that might have been found over the energy horizon.[17] Is this just bad luck, or are we missing something about the deeper theory that awaits us?

Working from the observed matter density of the universe, we expect non-relativistic dark matter particles to have a mass on the TeV scale as well. Particle physics and cosmology appear to be pointing in the same place. An oft-quoted candidate is the lowest mass SUSY particle, and in particular the neutralino. As argued above, it will be imperative to create dark matter particles in the laboratory, understand their physics in depth, and then see if we can match their creation in the big bang to their relic abundance in the universe today. In short, we could paraphrase this as seeing if colliders meet cosmology. I believe that we would want to explore the TeV scale at colliders for reasons related to dark matter alone.

Returning to the bigger connection between particle physics and cosmology, we want to understand the electroweak phase transition – the precise mechanism by which the electromagnetic and weak forces become one -- as the next giant step back towards the big bang. And once we master the electroweak transition, will we be able to see all the way to energies where there is a grand unification of all the forces? Or is there something in between?

We will need both blunt instruments and fine tools to discover and examine what we find at the TeV scale and understand how it all fits together. On the U.S. roadmap in Figure 5, that involves operating the Tevatron; finishing the U.S. accelerator and detector LHC construction projects, followed by commissioning and operations; doing R&D for possible future hadron and muon colliders; and moving toward construction of a Linear Collider as an international project.

Let us focus on the Linear Collider, which is the top priority for the future U.S. particle physics program.[9] It also has first priority in the second trimester of the DOE SC 20-Year Facilities Plan.[12] The 2003 Report of the GSF

Consultative Group on High Energy Physics[10] was endorsed by the OECD science ministers in 2004, who noted the worldwide consensus of the scientific community on an electron-positron linear collider as the next accelerator-based facility and called for it to be built as an international project.

Within the particle physics community, following the worldwide consensus in 2001-2002 on the Linear Collider being the next large machine, steering committees were formed in each the three regions of the world. These committees continue to coordinate research and development and physics activities for their regional communities, plus work through the International Linear Collider Steering Committee towards forming an international project.

In the meantime, the strong regional R&D efforts have continued to pass high level milestones. Linear Collider technology has reached the stage where it is being used to start x-ray laser projects at both DESY and at SLAC. An International Technology Recommendation Panel (ITRP) has been established by ICFA to choose between warm (room temperature RF) and cold (superconducting RF) technologies shortly. Once the technology choice is made, ICFA aims to establish an international design effort soon thereafter. To keep on a track that will see the Linear Collider operating in the middle of the next decade, it will be crucial to have a ramp-up in the international R&D and design effort in the next few years.

3.2 Quark Flavor Physics

We can bring the top level questions of particle physics down one level to quark flavor physics and ask for example: Why are there six quarks? Why do they occur in three generations? What happened to the antimatter? Where and how will new physics affect quarks? These are the kinds of questions that we would like quark flavor experiments to address.[20],[21][22]

In particular, we have made great progress in understanding precisely how the quarks and antiquarks respond to the weak interaction. The last few years have seen experiments at accelerators conjoined with theoretical work that has led to a precise understanding of CP violation, the way that the weak force affects matter and antimatter differently. Although this establishment of the Cabbibo-Kobayashi-Maskawa paradigm is somewhat unheralded, as it has occurred through a series of landmark measurements over time, this is a triumph of a combination of theory, experiment, and accelerators all working at their best.

There is still much to do, even in the area of CP violation. There are hints of new physics effects that should get sorted out over the next few years.[23] For the longer-term, we will want to know the footprint of whatever physics is discovered at the TeV-scale on quarks and antiquarks, both for its own sake and as a diagnostic of that new physics. Ultimately, we want to measure CP violation in the laboratory and match it to the CP violation needed to explain why our present universe is made out of matter and not antimatter. Our present understanding leads to a woeful mismatch.

To do this, we need experiments at both electron-positron colliders and hadron machines. On the U.S. roadmap, that involves operating BaBar, CESR-c, and CDF/D0; building K0PI0 and BTeV (recommended by P5). Discussion continues as well on the possibilities and physics program of a Super B-Factory.

3.3 Lepton Flavor Physics

The discovery that neutrinos have mass and can change over time from one neutrino flavor to another has made for a worldwide burst of activity in lepton flavor physics.[1],[24],[25],[26] We would like to know: Are there more than three neutrinos? At what level does charged-lepton flavor violation show up? Is the neutrino its own antiparticle with a mass connected to physics at the GUT scale? Is there CP violation in the neutrino sector? Could the neutrino sector be the key to explaining a universe made of matter? The present and future neutrino programs are designed to give us answers.

The situation in the case of a 'normal' spectrum for the three known neutrino flavors is laid out in Figure 7.[24] It is possible that instead we have an 'inverted' spectrum with the doublet of states lying above the singlet. A significant part of the near- and medium-term world program aims to pin down the parameters describing neutrino oscillations, especially the mixing angle θ_{13}, and to determine if there are CP-violating effects due to a non-trivial phase, δ.

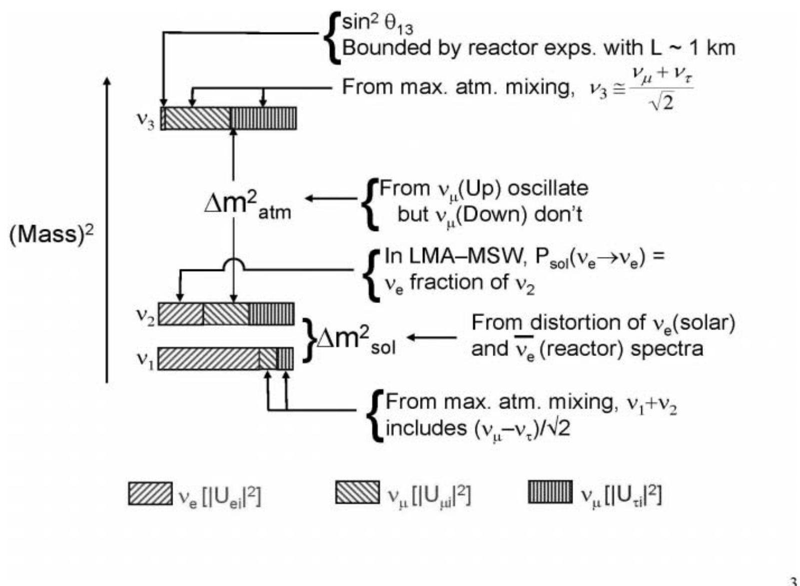

Figure 7 – Experimental inputs toward determining neutrino mixing.[24]

On the U.S. roadmap, MiniBooNE is running and NuMI/MINOS is being built at Fermilab; the charged-lepton flavor-violation experiment MECO is on course to begin construction. Looking out over the medium-term, the Off-Axis neutrino detector and reactor experiments are being discussed in order to pin down the remaining neutrino mixing parameters. Observation of neutrinoless double-beta decay would allow us to immediately conclude that the neutrino is its own antiparticle. Looking farther out in time brings into view the possibilities of a Neutrino Super Beam, a National Underground Scientific Laboratory with neutrino and proton decay experiments, and a Neutrino Factory.

In planning the medium- and long-term U.S. roadmap, the Neutrino Physics Study being conducted under the auspices of several divisions of the American Physical Society will have an important role to play in laying out the physics opportunities and in developing the key experiments. The report is expected later this year,[27] at which point we hope to begin filling in further the neutrino-physics portion of the US roadmap.

3.4 Cosmic Connections

As a final portion of the roadmap, we return to where particle physics and astrophysics overlap and where the greatest surprises have come in the last few years.[4],[5] We want to know: What is dark matter and dark energy? What is the precise connection of dark matter to physics at the TeV scale? Could the understanding of dark energy be related somehow to what happens in the scalar sector that we expect to explore at the TeV scale? Does the dark energy density vary with time? What does the high-energy universe tell us about astrophysics and about particle physics?[28],[29]

With some of the major discoveries coming so recently, it does not come as a surprise that this portion of the particle physics roadmap is somewhat less developed. We know so little that first and foremost we need much better data to help guide us both experimentally and theoretically. On the US roadmap, we are searching for cosmological relic dark matter particles with CDMS; we are using and planning accelerators at the TeV scale to create dark matter particles in the laboratory. For dark energy, in addition to ground-based measurements, the Joint Dark Energy Mission (JDEM), planned as a joint DOE/NASA effort, will be a giant step forward. As for the high-energy universe, Auger is measuring the highest energy cosmic rays from the ground; GLAST, measuring gamma rays in space, and Ice Cube, measuring neutrinos in the Antarctic ice, are under construction.

4. CONCLUSIONS

The particle physics roadmap is proving to be useful. It not only is helping us get an overall view of the interrelationships between different pieces of the field, but to plan a program that has depth, breadth and balance in addressing the questions that confront us at the beginning of the 21st century. Several decisions for the U.S. program have already been taken with the input of P5; other important decision points will be coming up in the next few years.

All this, however, should not divert our attention from the main point of this talk: the excitement of recent discoveries and where they put us: Particle physics has entered an era that should see major discoveries from experiments in space, underground, and at accelerators. Colliders will push into a region of energies that holds the answers to some of the most basic questions of particle physics, answers that connect the universe that existed very soon after the Big Bang to the universe we live in today.

Acknowledgments

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