Opportunities in Neutrino Theory – a Snowmass White Paper

André de Gouvêa*,[1] Alexander Friedland†,[2] Patrick Huber‡,[3] and Irina Mocioiu§[4]

[1] *Department of Physics & Astronomy, Northwestern University, IL 60208-3112, USA*
[2] *Theoretical Division T-2, MS B285, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[3] *Center for Neutrino Physics, Virginia Tech, Blacksburg, VA 24061, USA*
[4] *Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA*

Neutrino masses are clear evidence for physics beyond the standard model and much more remains to be understood about the neutrino sector. We highlight some of the outstanding questions and research opportunities in neutrino theory. We show that most of these questions are directly connected to the very rich experimental program currently being pursued (or at least under serious consideration) in the United States and worldwide. Finally, we also comment on the state of the theoretical neutrino physics community in the U.S.

I. INTRODUCTION

No area of fundamental particle physics research changed more dramatically or rapidly over the past two decades than neutrino physics.[1] It was demonstrated, in a spectacular and conclusive fashion, that the long-standing solar and atmospheric neutrino "problems" were in fact caused by neutrino flavor oscillations. Moreover, the mass splittings and the three-flavor mixing parameters have been since established with impressive accuracy and the subject has entered a high-precision era.

These discoveries, in turn, opened the door to a rich, exciting, and promising research program aimed at elucidating the origin of neutrino masses, exploring the flavor structure of the lepton sector, pursuing new sources of CP-invariance violation, looking for new particles and interactions, and testing fundamental physics principles. Nonzero neutrino masses also modify, sometimes dramatically, the role of neutrinos in cosmology and astrophysics.

Experimentally, the path forward is well defined: a diverse neutrino program is required in order to explore the new physics revealed in the neutrino sector. It includes, necessarily, very intense neutrino beams, very large (tens of kilotons and above), finely instrumented detectors with different detection media (water, argon, hydrocarbons, etc), very large, ultra clean detectors to search for neutrinoless double-beta decay, novel detectors for precision measurements of beta-decay, etc. In the next decades, a deluge of neutrino-related data is expected. Neutrino theorists and phenomenologists will be in the enviable position of exploiting these unique probes of fundamental physics, interpreting the data, building models to accommodate new phenomena and connecting the new discoveries in neutrino physics to other areas of particle physics, astrophysics, and cosmology.

In the next section, we briefly discuss a sample subset of the many outstanding opportunities in 'neutrino theory,' most of which are either directly or indirectly related to, or facilitated by, the discovery of nonzero neutrino masses and ongoing efforts to perform precision measurements of the neutrino sector. The breadth of topics is noteworthy, ranging from collider physics to cosmology and astrophysics, from nuclear physics to grand unification. Most of the activities are synergistic with the current and future neutrino experimental programs, and many require specialized technical and theoretical skills that are not encountered in abundance within the theoretical particle physics community in the United States. We comment on this last point more concretely in the last section.

II. NEUTRINO THEORY: SELECT OUTSTANDING QUESTIONS AND OPPORTUNITIES

In order to illustrate the richness and diversity of scientific endeavors in neutrino physics and to highlight the close connection to the planned experimental program, we briefly discuss a sample of select physics topics.

A. Understanding the Origin of Neutrino Masses – Model Building and Phenomenology

Neutrino masses represent one of the very few experimental clues regarding the physics that lies beyond the standard model. Given the standard model gauge symmetries and particle content, new degrees of freedom are necessarily required, and the symmetry structure of the Lagrangian must be modified qualitatively. The dynamics behind neutrino masses is currently unknown. The number of options is large and incredibly diverse, and so are the many distinct, potentially observable, signatures associated with the different options. As an example, neutrino masses may be a consequence of physics

*email: degouvea@northwestern.edu
†email: friedland@lanl.gov
‡email: pahuber@vt.edu
§email: irina@phys.psu.edu

[1] The nature of this document is such that no references to the literature will be included.

that violates lepton number, either explicitly or spontaneously. The current data allow virtually any value for the lepton-number breaking scale, from a few eV to 10^{15} GeV – twenty-four orders of magnitude.

Extensive theory effort is required in order to identify the different models that lead to non-zero neutrino masses and to work out the relevant phenomenology, both within and outside of neutrino physics. The mechanism behind neutrino masses, it is well-known, can manifest itself in a variety of different observables including lepton-number violating processes like neutrinoless double-beta decay, forbidden meson decays (e.g. $K^+ \to \pi^- \mu^+ \mu^+$), and high energy collisions (e.g., $pp \to$ jets $e^+\mu^+$ and no missing energy), lepton-flavor number violating processes like $\mu \to e$-conversion in nuclei, $\tau \to \mu\mu\mu$, and $K_L \to e\mu$. A sufficiently low scale of neutrino mass generation may result in measurable "non-standard" neutrino interactions, which may reveal themselves in a variety of experimental setups, from neutrino oscillations to LHC collisions, as described below. Additionally, the mechanism responsible for neutrino masses often predicts additional, "sterile" neutrino states, which could be revealed in precision oscillation experiments.

More broadly, the mechanism behind neutrino masses may also be related to other fundamental problems in particle physics, including the nature and origin of the dark matter, the dynamics responsible for the matter–antimatter asymmetry of the universe, electroweak symmetry breaking, and grand unification. Theory work is required in order to identify potential connections and explore all corroborating phenomenological consequences. Well-known examples include the possibility that nonzero Majorana neutrino masses are a consequence of a more complicated Higgs sector (e.g., the so-caled Type-II seesaw), the hypothesis that the dark matter is related to right-handed neutrinos (which can be probed, for example, by looking for cosmic X-rays from dark matter decays), and baryogenesis via leptogenesis, a natural consequence of the so-called Type-I seesaw mechanism, as long as the lepton-number breaking scale is high enough. Phenomenologically, leptogenesis in particular provides a most interesting challenge: under what conditions can it be falsified (or "confirmed")?

B. Flavor Models, CP Violation in the Lepton Sector

In the quark sector, the pattern of masses and mixing parameters seems to hint at the existence of some yet-to-be-uncovered organizing principle. Such an organizing principle remains unknown, in spite of half of century of theoretical work. The discovery of nonzero neutrino masses and lepton mixing added new pieces to the flavor puzzle. In particular, the leptonic mixing matrix appears to be providing qualitatively different information. Unlike the quark mixing matrix, it cannot be understood as an identity matrix perturbed by small, hierarchical, off-diagonal elements.

Precision neutrino oscillation experiments provide a unique opportunity to test different ideas in flavor physics. Next-generation data will rule out a large subset of the parameter space of flavor models, and will guide the next-generation of flavor physics. On the flip side, flavor models are necessary in order to provide guidance regarding precision milestones for neutrino oscillation experiments. A concrete recent example: the discovery of a "large" value for θ_{13} "ruled out" many flavor paradigms, and triggered interest in the precise value of θ_{23}, especially when it comes to its deviation from maximal. Identifying whether θ_{23} deviates from maximal "at the θ_{13} level" is also a very stringent test of several classes of flavor models. In addition, flavor physics allows one to relate, with the help of "more" new physics, different types of observables, including measurements of oscillation parameters, the rates of different charged-lepton flavor violating processes, and the masses and mixing patterns of new particles that may manifest themselves at the LHC or future high-energy collider enterprises.

Developments in neutrino physics provide another unique opportunity for theoretical physics: a new CP-violating sector. With nonzero neutrino masses, the ν Standard Model Lagrangian – whatever it is – accommodates, if the neutrinos are Dirac (Majorana) fermions, at least three (four) CP-violating parameters. They all appear to be unrelated, and only two are known. The CKM phase δ is around $\pi/2$ (hence quite large), while the strong CP "phase" is either zero or less than 10^{-9} (hence tiny). The study of CP-invariance violating phenomena in the lepton sector, which is possible in precise long-baseline neutrino oscillation experiments,[2] will open a new window on CP-violation and may shed light on its potential origin.

C. Non-standard Interactions, Neutrino Decays, Neutrino Electromagnetic Properties

As mentioned earlier, the existence of neutrino masses point towards new physics beyond the Standard Model, and perhaps one or more new mass scales. The values of such new scales are presently unknown. It is of great importance to understand whether there are other observable effects associated to these scales.

A general strategy is to search for other operators that could be generated at the new scale(s). Such operators are expected on very general grounds, but whether their effects are observable depends on how large is the new

[2] More CP-violating parameters can be studied via neutrino oscillations if there are more neutrino states (sterile neutrinos). If neutrinos are Majorana fermions, the so-called Majorana phases are also physical but very hard to study experimentally, as they usually manifest themselves only in observables that violate lepton number.

energy scale. Their effects range from unobservably tiny, if the corresponding new physics scale is very high, say, 10^{14} GeV, to within experimental reach, if the new scale is near a TeV or below. Given all presently available data, the latter possibility is perfectly allowed. The potentially revolutionary impact the discovery of new neutrino interactions renders the exploration of this possibility is mandatory.

Potentially observable effects include, in addition to some the processes mentioned in Sec. IIA, new "four-fermion" neutrino interactions with quarks and leptons (NSI), or electromagnetic interactions of the neutrino. NSI modify neutrino oscillation probabilities in matter via their contributions to the so-called matter potential, and potentially affect the production and detection processes. NSI may also manifest themselves in non-oscillation experiments, including the high energy colliders (in, for example, the monojet searches).

There are many issues associated with NSI still to be understood, and many possible approaches to doing so. One approach is to start from the model building side and try to understand all possible implications of a given model, as discussed above. Another possibility is to adopt the phenomenological approach where the effects of new interactions are parametrized by a general set of free parameters that can be constrained by data. In the model building context it is important to correlate predictions for neutrino oscillation parameters with the implications of the model in other directions like charged lepton measurements, and astrophysical or cosmological observations.

When adopting the phenomenological approach, one way to identify NSI is to look for inconsistencies of the three-flavor paradigm once one compares data from different experiments. This requires the ability to carefully and consistently combine different data sets, as will discussed more fully in the next section. Even if discrepancy are not observed, the presence of new interactions can affect the reconstruction of standard oscillation parameters. We understand, for example, that the NSI can introduce large degeneracies into the problem. A detailed quantitative analysis of such issues, however, is still missing.

Massive neutrinos couple to the electromagnetic field at the quantum level, and such couplings may lead to potentially observable effects in neutrino physics and astrophysics. Neutrino magnetic (transition) moments affect, for example, the flavor evolution of solar neutrinos in the solar magnetic field.literature. For many years, the interest in this possibility was driven by the hint of modulation of the Homestake event rate with the solar cycle. Nowadays, with precision solar neutrino data at hand, it is possible to ask whether such effects exist at the subdominant levels. It is also of great interest to understand what effect it may have on supernova neutrinos. The electromagnetic moments can also have an impact on the evolution of stars, as they can increase the rate of energy loss from stellar cores. In fact, the most stringent known bounds on the neutrino magnetic models come from the observations and modeling of red giant stars before helium flash.

Successful research efforts require a broad view of neutrino, particle physics, astrophysics and cosmology, making the connections between specific models trying to understand fermion mass origin and flavor physics, global fits to neutrino data and possible new implications of any new physics.

D. Neutrino Oscillation Phenomenology – Measuring Neutrino Properties and Looking for New Physics

Neutrino physics has been a data-driven field for most of its existence and phenomenology has always played a central role in advancing our understanding. Confronting the prevailing theoretical paradigm with data in the case of neutrinos has often led to dramatic revisions of the theoretical world view. What evolved into overwhelming evidence for neutrino oscillations started out as the "solar neutrino problem", which was, at first, attributed to everything but the underlying neutrino properties. The belief that neutrinos were massless or that their mixing angles were small were crushed by experimental data in a rather dramatic fashion. In all of these cases, combined analyses of prior data – "global fits" – guided the design of definitive experiments, such as SNO and KamLAND.

Presently, there are numerous experiments probing neutrino oscillations at very different energies and baselines, including the reactor experiments Daya Bay, RENO, and Double-CHOOZ and the beam neutrino experiments T2K, MINOS(+), and NOνA. To fully understand the implications of the measurements from these experiments, they need to be combined with one another, as well as with the solar neutrino data from SNO, SuperKamiokande, Borexino and GALLEX/SAGE, the atmospheric neutrino data from SuperKamiokande, the short-baseline data from LSND, Mini-BOONE, etc. The important point is that no single experiment dominates the determination of the entire oscillation matrix.

To further illustrate the value of global fits, consider the situation with the so-called "short-baseline" anomalies. Currently, we are confronted with a set of anomalies from a rather diverse set of experiments, including beams and reactors. Each single anomaly is at about the $3\,\sigma$ confidence level and, interpreted in isolation, does not amount to much. In combination, however, they may be pointing to the same region of the parameter space, if one interprets them as evidence for one or more sterile neutrinos. While more experimental and theoretical work is required in order to resolve these short-baseline anomalies, it is clear that combined analyses of data, performed outside of any experimental collaboration, have provided very valuable information.

Going forward, the need for global fits is likely to persist. They are expected to play a central role in deliv-

ering answers to the most central questions of the next decade and likely beyond. CP-violation searches, for example, will rely, in the foreseeable future, on interpreting he combination of data from T2K, NOνA, LBNE, and other experiments. Moreover, combined fit analyses will be essential to search for deviations from the basic three-flavor paradigm which may arise, for example, from non-standard interactions, as mentioned earlier. Global fits to all neutrino data will also play a fundamental role in addressing questions like the unitarity of the neutrino mixing matrix and testing predictions from a variety of flavor models.

Worldwide, there is a handful of groups dedicated to performing high-quality global fits. In the US there are no research groups performing this very technical (among the necessary skill are statistical analysis of very different data sets and a detailed understanding of neutrino flavor oscillations within and outside the standard three-flavor paradigm), but very impactful task. With the US poised to become the world-leader in long-baseline oscillation experimentation, it is highly desirable to build up this capability, to ensure we are able to extract as much information from the data as possible and to identify future directions for neutrino oscillation research.

E. Accurate Computation and Parameterization of Neutrino Nucleus Cross Sections

Despite the fact that the electroweak sector of the Standard Model is extremely well understood, it is very hard to perform precise computations of the neutrino-nucleus interactions. The nucleons are composite states with complex dynamics, which so far has eluded first principles calculations, despite QCD being a full description of the underlying physics. To make matters worse, neutrino detectors are not made of free nucleons but of materials consisting of nuclei covering a large atomic mass range from $A = 12$ carbon (scintillator) over $A = 40$ argon (TPCs) to $A = 56$ iron (calorimeters). Since nuclear structure is not well understood, especially in large nuclei, it is presently not possible to formulate a closed theory of neutrino-nucleus interactions. Moreover, multi-nucleon correlations as well as final state interactions have to be correctly included to provide reliable neutrino cross sections.

The situation is, however, not hopeless. It is possible, for example, to derive the correct initial state densities by exploiting the symmetries of the electroweak theory and using existing data from electron scattering – the results known as the spectral functions. However, to this date there is no complete and validated implementation of spectral functions in any publicly accessible event generator. More complicated issues, like meson exchange currents are even lacking a consensus theory formulation and are years away from being available in event generators.

At the same time, the next generation of neutrino oscillation experiments aim at percent level measurements of neutrino event rates and precise measurements of the energy distribution of events. Since existing neutrino beams are subject to large intrinsic uncertainties, neutrino–nucleus cross sections are only known at the the 10-30% level. Many nuclear effects have non-trivial energy dependencies and introduce large biases in neutrino energy reconstruction and therefore, most experiments really measure an effective cross section specific to the beam and energy response of the detector. This is also the reason that near detectors will not resolve all, or even the majority of the issues. At the time of this writing the largest contribution to the systematic error budget of T2K comes from neutrino interactions. The situation in the upcoming NOνA and LBNE experiments is expected to be at least as challenging.

Contributions to this effort require mastery of both precision nuclear and particle physics calculations, and in-depth understanding of detectors and event generator codes. The current theory effort, in the US, dedicated to attacking the challenges described above (and many others) is close to non-existent and starkly different from the large investment in experiments like NOνA and LBNE. In absence of an adequate theory effort dedicated to the understanding of neutrino scattering on nuclei, NOνA and LBNE will not be able to provide the world-class science they were designed for.

F. Supernova Neutrinos

The utility of core-collapse supernovae for particle physics is well recognized. For example, upon perusing the Particle Data Group summaries of various Beyond-the-Standard-Model (BSM) searches, one encounters numerous constraints on new physics scenarios derived from supernova cooling considerations. The cooling argument, in brief, is as follows. To account for the observed duration of the neutrino pulse from the 1987A supernova, the energy trapped in the collapsed core needs to get out on the time scale of a few seconds. It can be easily seen that "normal" astrophysical methods of transport, such as photon diffusion, are too slow for this: the photon gets stuck in the dense matter of the core because of its large scattering cross section. Neutrinos, particles with *much smaller* cross sections, take up the transport task. Indeed, a straightforward estimate for neutrinos of 10^7 eV energies suggests a diffusion time scale of a few seconds. It is instructive that neutrinos "win" over photons by having *smaller* cross sections, a situation that is highly counterintuitive by laboratory standards. Any putative new particle with a still smaller cross section would be even more efficient at carrying the energy out, so long as such a particle couples strongly enough to be produced in the core at all. Examples of such bounds include well-known constraints on axion-nucleon coupling, Majorons, Kaluza-Klein gravitons, unparticles, and extra-dimensional photons.

It should be stressed that the present constraints are based on the 1987 supernova observations, which gave us only two dozen neutrino events. Given this very limited statistics, rough order-of-magnitude statements about what new physics can be excluded are, for the most part, sufficient. For other scenarios, rough estimates are woefully inadequate. This is particularly true when the new physics "only" modifies neutrino transport by order one factors, rather than completely taking over. Furthermore, the next event should yield many more neutrinos. This is so, firstly, because the next supernova will, much more likely, take place in our Galaxy rather than in the Large Magellanic Could (and an r^2 enhancement factor of $\sim$ 10-100 is to be reasonably expected), and secondly, because we now have much bigger detectors than what was available in 1987 (Kamiokande and IMB).

With such abundant data, to properly interpret the neutrino signal, one will need to take into account neutrino flavor oscillations. Rather than being simply a nuisance, neutrino oscillations in a supernova environment represent an extremely rich source of physical information. The subject of supernova neutrino oscillations has undergone dramatic progress in the last ten years and more effects continue to be uncovered every year. For example, these oscillations can be impacted by the developing explosion: the expanding shock front and the turbulent region behind it change the density profile in which neutrinos change flavor. As the character of the transformation is changed (for example, from adiabatic to non-adiabatic by the front shock, or to an incoherent sum of states by the turbulent density fluctuations), an imprint should be left on the neutrino signal. Thus, properly reading the flavor-transformed signal can tell us how the explosion develops.

The uniqueness of the supernova environment is perfectly illustrated by the fact that it can host neutrino "self-induced" transformations, which are hopelessly inaccessible in the laboratory. Also known as "collective oscillations", these transformations happen when the density of streaming neutrinos is so high that their flavor evolutions become coupled. In the last decade, the available computing power made it possible to explore this novel many-body phenomenon and remarkable flavor-transformation patterns were uncovered. An observational confirmation of this dynamics would be a discovery of profound magnitude.

Taking a broader view, we must remember that supernova neutrinos are of great interest to many areas of physics. For example, in nuclear astrophysics, the fundamental question is the origin of heavy elements in the universe. Core-collapse supernovae are thought to be candidate sites for the r-process and other types of nucleosynthesis. The efficiency of the r-process depends on the physical conditions in the explosion, such as the entropy profile of the neutrino-driven wind and the energy spectra of the different neutrino components (which in turn depend on the oscillation physics). It is of great interest whether the future neutrino signals can shine light on the nucleosynthesis mechanism in core-collapse supernovae.

Supernovae are also of fundamental importance in astrophysics and cosmology, where they controll baryonic structure formation and evolution. They do so by creating and spreading heavy elements ("metals"), seeding star formation by shocks, blowing out gas from small gravitational potentials, etc. For all these reasons, the studies of the explosion mechanism have been occupying astrophysicists for over half a century.

The focal question for neutrino theorists here is to understand how different explosion mechanisms and new physics effects can manifest themselves in the neutrino signal and what detector characteristics are required to measure them. Specifically, one needs to identify what key, "smoking-gun" signatures to look for and what detector characteristics are necessary. For example, to test for the presence of new particles or new neutrino interactions, it is important to measure the neutrino energy spectra and to track their time evolution. To observe collective oscillations, one needs detailed flavor information, in both neutrino and antineutrino channels. Simply bigger detectors would thus not be enough. It is also important to have sensitivity to different neutrino flavors, as well as good energy resolution. While it is not known when the next galactic supernova will be observed, it would be a travesty to be caught unprepared for this "once-in-a-lifetime" opportunity.

To tackle these and several similar problems, a generation of theorists with broad education in particle physics, nuclear physics, nucleosynthesis, plasma physics, turbulence, transport, supercomputing, etc, is required. It is also imperative to develop a common language between the neutrino theorists and the experimentalists designing and simulating detectors. Clearly, as a community, we have our work cut out for us.

G. Neutrinos and Cosmology

Neutrinos are also well known to play a key role in cosmology, through their impact on the evolution of cosmic perturbations and growth of structure. Early on, during the radiation dominated epoch, the cosmic neutrino background was an important component of the gravitating matter in the universe. They, therefore, had a direct impact on the expansion rate before and during the cosmic microwave background (CMB) decoupling era. Additionally, neutrinos affected the evolution of density perturbations. In this role, neutrinos were quite different from photons: the latter stayed coupled to the plasma, while the former streamed out of the perturbations once allowed by causality.

All of this physics has recently become experimentally accessible, thanks to the data from the Planck satellite and terrestrial observatories such as ACT, SPT, etc. The Planck satellite, in particular, has presented constraints on $N_{\rm eff}$ – the number of neutrino-like relativistic species in the early universe. The constrains are extremely rel-

evant for models which extend the neutrino sectors to include new states (*e.g.*, "sterile neutrinos"). It should be noted, however, that there are a lot of open theoretical questions. For example, what if cosmology is less trivial (*i.e.*, goes beyond the "vanilla" 6-parameter study)? What if the extra neutrino-like species have non-thermal spectra? What if their abundance in the universe changes with time? As the measurements of $N_{\rm eff}$ enter a precision stage, these are the right questions to ask. For example, there are models of neutrino "recoupling", in which the number of new neutrino species appearing in CMB and big-bang nucleosynthesis calculations are different.

Neutrinos also show up in precision cosmological observations in another way: since they have a small mass, they should cluster on sufficiently large scales. This phenomenon should result in potentially observable CMB *lensing* signatures. It is expected that these signatures could allow us to probe very small neutrino masses, possibly bellow the 0.1 eV level suggested by the atmospheric oscillation data. Again, there are numerous theoretical questions to study in connection with this, for example, how these measurements would be sensitive to nonstandard physics in the neutrino sector.

Recently, a number of provocative ideas have been put forth on additional possible roles neutrinos could play in cosmology. As an illustration, if neutrinos couple to dark matter, they could alter the formation of structure, potentially alleviating the "missing satellite", or "too big to fail" problems. Neutrinos may also be messengers of dark matter annihilation, in our galactic halo, or in the core of the Sun.

With precision cosmological observations and oscillation experiments planned for the next 10-20 years, numerous potentially interesting developments may become possible. For example, suppose the next-generation oscillation experiments confirm the existence of sterile neutrinos, in a way that is seemingly incompatible with cosmologically inferred value for $N_{\rm eff}$. This conflict would be an indication of nonstandard cosmology and/or new physics in the neutrino sector and the task will be to understand how to best disentangle this situation. It is prudent to anticipate and prepare for such nonstandard scenarios now, as the experiments are being planned. Work in this field requires deep understanding of various aspects of cosmological physics (CMB, LSS, etc), laboratory neutrino data, as well as particle physics broadly defined.

H. Phenomenology of Astrophysical High-Energy and Ultra-High-Energy Neutrinos

Very high energy neutrinos are predicted to be produced by a variety of astrophysical sources and neutrino telescopes are actively looking for them. This year, the IceCube detector has brought the first observational indication of such astrophysical neutrinos. The collaboration has shown evidence for two events at PeV energies, as well as 28 events at slightly lower energy, a 4σ excess above atmospheric neutrino background. In the coming year, an additional data sample will be analyzed and the detector will continue accumulating new data. These exciting developments make theoretical study of the particle physics and astrophysics of the very high energy neutrinos quite urgent.

The physics and astrophysics that can be probed by high energy neutrinos is extremely rich. The relative effects of new physics on such signals can be large: thanks to very long propagation distances, even very small new physics effects can potentially add up to an observable signal. Moreover, the extremely high energies can provide access to the energy regimes that cannot be reached in colliders or other terrestrial experiments. On the astrophysics front, the weak interactions allow neutrinos to probe environments that are not otherwise accessible and may help answer many long-standing questions about the origin, composition and propagation of cosmic rays.

Observation of high energy neutrinos will likely have profound implications for both physics and astrophysics. Neutrino telescopes looking for such neutrinos already exist or are being planned to cover even higher energy ranges. The theoretical studies necessary to extract all the information from the observations and understand the signals and the various uncertainties have just begun. Much work is still to be done, including better modeling of sources, propagation and detection, considering all possible standard physics, astrophysics and new physics possibilities, as well as new detection techniques. Additional questions are likely to arise in the course of these analyses. All this work will require a good understanding of astrophysics, modeling of strong interactions (relevant for the production and detection of the neutrinos), neutrino physics and possible new physics, as well as a good understanding of what these telescopes can actually measure and correlations between different types of observables in neutrino, cosmic ray, astrophysical as well as other particle physics measurements.

III. NEUTRINO THEORY IN THE US: WHERE WE STAND AND PATHS FORWARD

While the opportunities in neutrino theory are many and the range of topics broad and interdisciplinary, the fraction of the US domestic theoretical physics effort dedicated to neutrinos is small. Currently, only very few university groups are active in neutrino phenomenology. Indeed, since 1998 – the year neutrino flavor change was unambiguously discovered by Super-Kamiokande – less than 10% of all particle theory university hires[3] were on

[3] This was extracted from the "Theoretical Particle Physics Jobs Rumor Mill," `http://particle.physics.ucdavis.edu/rumor/doku.php`, and private communications with members of the theory community.

neutrino theory or broadly defined related areas.

At the same time, with the start of the LHC in 2010 and the shutdown of the Tevatron in 2011, the focus of the US domestic experimental particle physics program has shifted to the so-called Intensity Frontier. Neutrino physics makes up a big fraction of the Intensity Frontier research currently being discussed. In order to ensure a vital program, the funding agencies and the community appear committed to making very significant investments into new experiments at the Intensity Frontier over the next decade. As we have illustrated in this white paper, this experimental program will require a commensurate level of activity on the theory side to ensure that this investment results in a corresponding return in science. This work ranges from identifying physics goals and desired detector characteristics to accurate theoretical calculations of expected signals and backgrounds, without which the experiments cannot succeed. This means that a much stronger US presence in neutrino theory in particular and Intensity Frontier phenomenology in general is not only scientifically well-motivated but also necessary to ensure the long-term success of the US domestic particle physics program.

The combination of a currently small neutrino theory community and the fact that neutrino theory research requires technical and theoretical skills – as exemplified above – outside the standard "tool-kit" of the US particle theory community implies that the neutrino theory community will not grow "organically" from within the current theory community on the short time scale required by the planned experimental program. A dedicated and coherent effort, with (a) significant investment from the funding agencies, (b) enthusiastic commitment and leadership from the present neutrino theory community, and (c) the support of the entire particle theory community is absolutely necessary. To meet the proposed experimental schedules, such a qualitative increase in the neutrino theory effort is needed now.

An informal 'Neutrino Theory' meeting took place on May 20, 2013 at Fermilab in order to foster discussion regarding the status of theoretical neutrino physics in the US and potential initiatives to strengthen and increase the domestic neutrino and Intensity Frontier theoretical communities. A little under twenty theorists attended the meeting while many other members of the theory community provided feedback and support via email. The issues presented in this White Paper are partially informed by these discussions and feedback collected during the last several months. It is anticipated that more discussions will follow during the next several months. Ultimately, the goal is to converge on a concrete "project" aimed at qualitatively strengthening the US "neutrino theory" community in order to take full advantage of the opportunities described here, along with many more that are sure to present themselves.

Acknowledgments

We are indebted to all of those that participated, directly or indirectly, in the several "neutrino theory" and related discussions that took place during the last several months, including the Neutrino Working Group Meeting at SLAC (March 2013), the Intensity Frontier Workshop at ANL (April 2013), the Neutrino Theory Meeting at FNAL (May 2013), and the Community Planning Meeting in Minneapolis (August 2013).