Looking up at seesaw and GUT scales from TeV

Hitoshi Murayama

Institute for the Physics and Mathematics of the Universe, University of Tokyo, Chiba 277-8568, Japan
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA
Theoretical Physics Group, Lawrence Berkeley National Laboratory, MS 50A-5104, Berkeley, CA 94720, USA

Abstract. In this talk, I discuss how we may approach physics at the seesaw- and GUT-scales using data from the TeV scale. Even though we cannot hope to directly reach these energy scales using particle accelerators, we may get convinced of grand unification and seesaw mechanism based on experimental data if Nature is kind to us. In addition, we may find compelling reason to believe in leptogenesis based on experimental data. This cannot be achieved by a single experiment, but rather a collection of them, based on LHC, ILC, neutrino oscillation, neutrinoless double beta decay, direct dark matter detection, CMB power spectrum and its tensor mode.

Keywords: neutrino, unification, double beta decay, dark matter, inflation, gravitational wave, accelerator, supersymmetry

PACS: 14.60.Pq,12.60.Jv,12.10.-g,12.10.Kt,23.40.-s,95.35.+d,98.80.Cq

INTRODUCTION

Neutrino physics has been full of surprises, and we have learned a lot in the last ten years. We would like to learn more. But what exactly can we learn from neutrinos? Will we ever know the origin of neutrino mass? Is it connected to the origin of baryon asymmetry of the universe? Possibly the origin of universe itself?

Much of our discussions on this subject have been framed by the famous seesaw mechanism [1], the dominant paradigm for the origin of finite but tiny neutrino mass. It relies on physics close (but below) the GUT scale, which is well beyond the reach of any conceivable accelerator experiments. Without accessing that energy scale directly using particle accelerators, how do we ever know if the seesaw mechanism is true? Is there a way to test it experimentally?

Unfortunately, the short answer is no. However, what I would like to discuss in this talk is that there is a way for us to get convinced that the seesaw mechanism is right, if Nature is kind to us [2].

What we can hope to do is to do a very good job at the accessible energy scales, namely precision measurements from meV to TeV energies to fix physics at the low-energy end. On the other hand, if there is a way of knowing boundary conditions at high energies, such as the GUT-scale, we can say something non-trivial about physics between the two energy scales.

For this program to succeed, we have to be very lucky, like all the planets lining up. But let me remind you that this has gotten a little easier, now that there are only eight planets to worry about, not nine.

WHY NEUTRINOS?

Why have people been interested in neutrinos, especially their mass? There are good reasons, both from the particle-physics and cosmology points of view.

Special Role of Neutrino Mass

It is useful to recall why theorists had always been interested in the small neutrino masses and their consequences on neutrino oscillation. It is because we are always interested in probing physics at as high energies as possible. One way to probe it is of course to go to the high-energy collider experiments and study physics at the energy scale directly. Another way is to look for rare and/or tiny effects coming from the high-energy physics. The neutrino mass belongs to the second category.
To study rare and/or tiny effects from physics at high energies, we can always parameterize them in terms of the power series expansion,

\[ \mathcal{L} = \mathcal{L}_4 + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots. \] (1)

The zeroth order piece \( \mathcal{L}_4 \) is renormalizable and describes the Standard Model. On the other hand, the higher order terms are suppressed by the energy scale of new physics \( \Lambda \). Possible operators can be classified systematically, which I believe was done first by Weinberg (but I couldn’t find the appropriate reference). With two powers of suppression, there are many terms one can study:

\[ \mathcal{L}_6 \supset QQLL, L\sigma^{\mu\nu}W_{\mu
u}He, \text{tr}(W_\mu^\nu W_\lambda^\nu W_\mu^\lambda), \bar{s}d\bar{s}d, (H^\dagger D_\mu H)(H^\dagger D^{\mu\dagger} H), \cdots \] (2)

The examples here contribute to proton decay, \( g \sim 2 \), anomalous triple gauge boson vertex, \( K^0 - \overline{K}^0 \) mixing, and the \( \rho \)-parameter, respectively. It is interesting that there is only one operator suppressed by a single power:

\[ \mathcal{L}_5 = (LH)(LH). \] (3)

After substituting the expectation value of the Higgs, the Lagrangian becomes

\[ \mathcal{L} = \frac{1}{\Lambda} (LH)(LH) \rightarrow \frac{1}{\Lambda} (L(H))(L(H)) = m_\nu \nu \nu, \] (4)

nothing but the neutrino mass.

Therefore the neutrino mass plays a very unique role. It is the lowest-order effect of physics at short distances. This is a very tiny effect. Any kinematical effects of the neutrino mass are suppressed by \( (m_\nu/E_\nu)^2 \), and for \( m_\nu \sim 0.1 \text{ eV} \) as suggested by the current data and \( E_\nu \sim 1 \text{ GeV} \) for typical accelerator-based neutrino experiments, it is as small as \( (m_\nu/E_\nu)^2 \sim 10^{-20} \). At the first sight, there is no hope to probe such a small number. However, any physicist knows that interferometry is a sensitive method to probe extremely tiny effects. For interferometry to work, we need a coherent source. Fortunately there are many coherent sources of neutrinos in Nature, the Sun, cosmic rays, nuclear reactors (now part of the Nature), etc. We also need interference for an interferometer to work. Because we can’t build half-mirrors for neutrinos, this could have been a show stopper. Fortunately, there are large mixing angles that make the interference possible. We also need long baselines to enhance the tiny effects. Again fortunately there are many long baselines available, such as the size of the Sun, the size of the Earth, etc. Nature was very kind to provide all necessary conditions for interferometry to us! Neutrino interferometry, a.k.a. neutrino oscillation, is therefore a unique tool to study physics at very high energy scales.

At the currently accessible energy scale of about a hundred GeV in accelerators, the electromagnetic, weak, and strong forces have very different strengths. But their strengths become the same at \( 2 \times 10^{16} \text{ GeV} \) if there the Standard Model is extended to become supersymmetric. Given this, a natural candidate energy scale for new physics is \( \Lambda \sim 10^{16} \text{ GeV} \), which suggests \( m_\nu \sim (H)^2/\Lambda \sim 0.003 \text{ eV} \). Curiously, the data suggest numbers quite close to this expectation. Therefore neutrino mass under our current studies may be probing physics at the energy scale of grand unification.

**Ubiquitous Neutrinos**

Another reason to be interested in neutrinos is its sheer number in the universe. In fact, neutrinos are the most ubiquitous matter particles in the universe. They were produced in the Big Bang, when universe was so dense that neutrinos, despite their only weak interactions, were in thermal equilibrium with all other particle species. Similarly to the cosmic microwave background photons, their number density had been diluted by the expansion of the universe. In comparison, constituents of ordinary matter, electrons, protons, and neutrons, are far rarer than photons and neutrinos, by about a factor of ten billions. It is clear that we need to understand neutrinos in order to understand our universe.

In terms of energy densities, yet unknown dark matter and dark energy dominate the universe. If neutrinos were massless, their energy density could have been completely negligible in our current universe. However, in the last several years, finite mass of neutrinos had been discovered. It implies that the neutrinos are as important as all stars combined. Unfortunately, we do not know the mass of neutrinos precisely at this moment, and they may in fact be a sizable fraction of dark matter. The precise amount of neutrino component is relevant to the way galaxies and stars had been formed in the evolution of the universe.
FIGURE 1. Apparent unification of gauge coupling unification in the MSSM at $2 \times 10^{16}$ GeV, compared to the suggested scale of new physics from the neutrino oscillation data.

FIGURE 2. The number density (left) and energy density (right) of various components in our universe.

Neutrinos are important part of the stellar dynamics; without them, stars would not shine. There are about $7 \times 10^9 \text{cm}^{-2} \text{sec}^{-1}$ neutrinos from the Sun reaching (and streaming through) the Earth. They also govern dynamics of supernovae.

WHAT WE’VE LEARNED

Data

Given the theoretical motivation discussed above, neutrino oscillation has been searched for over many decades. Fig. 3 summarizes the best information we have on neutrino oscillation. There are two main parameter regions that are now established by experimental data. The oscillation of atmospheric neutrinos is the first established
FIGURE 3. The compilation of the best neutrino oscillation data.

evidence, which was later confirmed by long-baseline accelerator neutrino oscillation experiments. It corresponds to $\Delta m_{23}^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$ and $\sin^2 \theta_{23} \approx 1$. The flavor transformation of solar neutrinos was discovered using water Cherenkov detectors (light and heavy water), which was established as a consequence of neutrino oscillation using reactor anti-neutrinos. It corresponds to $\Delta m_{12}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2$ and $\tan^2 \theta_{12} \approx 0.5$.

In both cases, the mixing angle came out large, which allowed us to observe neutrino oscillation. This is the generosity of Nature we discussed. At the same time, the neutrino mass scale is tiny. According to the previous discussion, it is a good indication that we are probing physics at very high energy scales.

**Surprises**

It is useful to recall what a typical theorist used to say back around 1990.

- The solution to the solar neutrino problem must be the small mixing angle MSW solution because it is so beautiful.
- The natural scale for $\nu_\mu \rightarrow \nu_\tau$ oscillation is $\Delta m^2 \sim \text{eV}^2$ because it is the cosmologically interesting range.
- The angle $\theta_{23}$ must be of the same order of magnitude as $V_{cb}$ because of the grand unification.
- The atmospheric neutrino anomaly must go away because it would require a large mixing angle to explain.

Needless to say, theorists have a very good track record in neutrino physics.

Indeed, the recent results from neutrino oscillation physics had surprised almost everybody. The prejudice has been that the mixing angles must be small because quark mixing angles are small, and the masses must be hierarchical because both quarks and charged lepton masses are hierarchical. Given that the LMA is now chosen, all mixing angles are large except for $U_{e3}$ that must be small-ish (but the current limit is not very strong, $|U_{e3}| \lesssim 0.2$).

Another surprise is their mass spectrum. The quarks and charged leptons have so-called hierarchical mass spectra, namely that the masses of similar types are drastically different among three generations of elementary particles. For
instance, the masses of the up- and top-quarks are different by five orders of magnitude. On the other hand, two heavier neutrino masses differ at most by a factor of about five, possibly even degenerate.

However, the measurements of neutrino masses and mixings are still incomplete. Future measurements are likely to bring more surprises.

**The Big Questions**

The discussions above lead to the following set of big questions concerning neutrinos:

- What is the origin of neutrino mass?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in the birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?

These are big questions, and by definition are very difficult questions to answer.

What we try to see is if future data will address any of these big questions. Clearly no guarantee. But I’d like to argue that there is a chance. That is basically the whole point of my talk here.

**SEESAW AND SUSY-GUT**

The famous seesaw mechanism is meant to be an explanation why neutrino mass is finite but yet tiny. You introduce right-handed neutrinos, fermion species completely neutral under the gauge groups of the standard model.

The Lagrangian (for the case of single flavor) is extremely simple. The right-handed neutrino $N$ has the Yukawa coupling to Higgs boson the same way as any other fermion species we know (charged leptons and quarks), while it is neutral under the standard model gauge groups and is allowed to have a Majorana mass term

$$\mathcal{L} = -y_N H N + \frac{1}{2} M N N + \text{c.c.}$$  \hspace{1cm} (5)

Upon the condensation of the Higgs boson in the universe $\langle H \rangle = v$, we find a mass matrix of neutrinos,

$$\frac{1}{2} (v, N) \begin{pmatrix} 0 & y_N \\ y_N & M \end{pmatrix} \begin{pmatrix} v \\ N \end{pmatrix}. \hspace{1cm} (6)$$

Because the Majorana mass $M$ does not rely on the electroweak symmetry breaking it may well be much higher, $M \gg v$. Then one of the eigenvalues of this mass matrix would be simply $M$. On the other hand, due to the vanishing $(1,1)$ entry, the product of two eigenvalues, namely the determinant, is $-(y_N)^2$. Therefore the other smaller eigenvalue must be $-(y_N)^2/M$, which is much smaller than the electroweak scale if $M \gg v$. This way, we can understand why the
neutrino mass is much lighter than other quark and charged lepton masses of $O(y\nu)$ because of the heavy right-handed neutrino mass scale $M$. The heavier $M$ is, the lighter the neutrino mass becomes, hence the seesaw.

If we naively assume $y \approx 1$ (as suggested by the top Yukawa coupling) and take $m_\nu \approx (\Delta m_{23}^2)^{1/2} \approx 0.05$ eV, we find $M \approx \text{a few } \times 10^{14}$ GeV.

Indeed, there is a reason to think that the seesaw scale is related to the grand unified theory. For instance, there is a special interest in the unified group $SO(10)$. It is the smallest gauge group which has complex representations yet is automatically anomaly-free. Its smallest representation (16) accommodates all of the observed fermions and right-handed neutrinos. If this is the case, the Majorana mass of right-handed neutrinos is not allowed above the GUT-scale because of its complex nature, while can be induced by the breaking of the GUT group down to the standard model. This way, the seesaw scale $M$ is tied to the GUT-scale as $M \approx M_{\text{GUT}}$, if $SO(10)$ is broken by 126-Higgs, while $M \approx M_{\text{GUT}}^2 / M_{\text{Planck}}$ if broken by 16-Higgs. The latter appears to be a good numerical match to the neutrino mass seen in experiments.

In addition to inducing finite but tiny neutrino mass, right-handed neutrinos may have played a critical role for our existence in the universe. Given that the neutrinos come in three families (actually two is enough for the purpose below), they may violate CP. The right-handed neutrinos are expected to be heavy, but the early universe may have produced them at temperatures above their masses. At the tree-level, they decay 50:50 into leptons and anti-leptons. However the interference between the absorptive part of the one-loop diagram and the tree-level amplitude can violate CP and makes the branching fractions a little different. Namely that the right-handed neutrinos may decay preferentially into anti-leptons over leptons, creating a (negative) lepton asymmetry of the universe.

It turns out that this created lepton asymmetry gets partially converted to the baryon asymmetry by the standard model gauge interaction. This is because both the lepton and baryon number currents are not conserved in the $SU(2)$ gauge theory because of its chiral nature,

$$\partial \mu j_\mu^L = \partial \mu j_\mu^e \propto \epsilon^{\mu \nu \rho \sigma} \text{tr} W_{\mu \nu} W_{\rho \sigma} \neq 0.$$  \hfill (7)

It allows for the baryon number and lepton number to change by an equal amount due to the thermal fluctuations of the $W$-fields. In other words, the (negative) lepton asymmetry can be converted to the (positive) baryon asymmetry. The question then is if this conversion actually occurs. Simply by thermodynamic considerations, keeping the asymmetry only in leptons costs more free energy than distributing the asymmetry both among leptons and quarks. Therefore, the lepton asymmetry does get partially converted to the baryon asymmetry. This is what is called leptogenesis [3].

Right-handed neutrinos might have played an even bigger role; they may be the origin of the universe [4]. The idea of grand unification has the hierarchy problem, and the standard model particle content is actually not consistent with the observed values of the gauge coupling constants. Supersymmetry solves both problems. Once we have supersymmetry, the right-handed neutrinos come with their scalar partners. Because of their large mass, the potential for the right-handed sneutrinos is dominated by their mass term, $M^2 |N|^2$. Interestingly, this simple potential is what may make the cosmological inflation possible. The universe starts out microscopically small with an amplitude of right-handed sneutrino larger than the Planck scale. Then the right-handed sneutrino rolls down the potential slowly, thereby expanding the universe to a macroscopic size. Eventually the amplitude becomes less than the Planck scale and the exponential expansion stops. The right-handed sneutrino oscillates around the minimum of the potential (zero) and behaves as matter, which is nothing but a Bose–Einstein condensate of the right-handed sneutrino. It then decays, just like the decay of right-handed neutrinos discussed above, which can create a negative lepton asymmetry. Namely that the right-handed sneutrinos may play the role of the origin of the universe as well as our existence.

This is all interesting, and a large amount of ink has been devoted to further elaboration of these subjects. Now we come to the central question in my talk.

**EXPERIMENTAL TEST**

As we have seen above, the seesaw mechanism is quite attractive, especially in conjunction with the GUT, leptogenesis, or inflation. Is there a way of proving this mechanism?

Obviously the short answer is no. Here is an irony: the reason why the seesaw mechanism is so attractive is because it refers to physics well beyond the reach of any conceivable particle accelerators, while this very point makes it impossible to prove. Is it hopeless?

I’d like to argue that the future experiments may provide us information which will make us believe that the seesaw mechanism is right after all [2]. It is not a direct proof as we became accustomed to in particle physics, such as the
precision electroweak measurements that completely convince us of the validity of the gauge theory. It will rather be a collection of circumstantial evidences which so strongly argue for it that we will buy into it.

This is not to be ashamed of. Observational cosmology has made an enormous progress in recent years, but it is and will be a form of archaeology. We never redo the Big Bang. Nonetheless that power spectrum in the cosmic microwave anisotropy is so precisely measured and theoretically clean that we are (most of the time) happy to accept its implications, such as the energy budget, age of the universe, non-baryonic dark matter, etc. This is the best we can hope for in the case of the seesaw mechanism.

Proving Seesaw

One such example was worked out by my student Matt Buckley and myself [2]. If we will see the following outcomes from the future experiments, we will all (except for some die-hard skeptics) believe in the seesaw mechanism:

- Discovery of Supersymmetry at LHC and ILC, whose precision measurements confirm its mass spectrum as predicted by GUT.
- Discovery of neutrinoless double beta decay.

In addition, other supporting measurements will boost the credibility of the conclusion:

- Consistency of the SUSY parameters measured at colliders and the cosmological abundance of the Lightest Supersymmetric Particle.
- Improved limits or discovery of Lepton Flavor Violation.

I will explain why this is so in the remainder of this talk.

If supersymmetry is discovered, the precision measurement of its mass spectrum is extremely important [3]. The case of our interest here is if the masses unify.

As we discussed earlier, the observed gauge coupling constants are consistent with the GUT assuming the particle content of the minimal supersymmetric standard model. We know that the unification scale is approximately $2 \times 10^{16} \text{ GeV}$. But it is basically three straight lines meeting at a point. One may say that two lines always meet, with 50:50 chance meeting at an energy scale above (not below) TeV. Then it may be just a numerical coincidence that the third line appears to go through the same point.

Once we measure the gaugino masses, the situation will be quite different. There are three gaugino masses, $M_1$ (bino), $M_2$ (wino), $M_3$ (gluino). If two of them meet at the same energy scale where the gauge coupling constants appear to meet, this is the second coincidence. If the third gaugino mass meets at the same energy and mass, it is the third. The case for unification becomes far stronger.

Then come the masses of sfermions, namely the superpartners of quarks and leptons. For each generation in a GUT, left-handed quark doublet (in three colors=six degrees of freedom), right-handed up quark (in three colors), and right-handed charged lepton are unified in a decouplet ($3 \times 2 + 3 + 1 = 10$), while left-handed lepton doublet (charged lepton and neutrino) and right-handed down quark (in three colors) in a quintet $(2 + 3 = 5)$. The masses of their superpartners therefore unify at the same energy scale where both gauge coupling constants and gaugino masses unify. This gives three more coincidences per generation.

Once the data show the gaugino mass and sfermion mass unification, it could still be just an accident, but the coincidences comes in such a multitude that we will be led to believe there is indeed unification. Probably some die-hard skeptics will remain, but the GUT becomes extremely compelling and undeniable.

Such an experimental observation would tell us several things. First of all, there is unification at $2 \times 10^{16} \text{ GeV}$. Second, given its successful description in terms of a simple gauge theory, the renormalizable quantum field theory must be applicable up to this energy scale. Third, we can then use the GUT as the boundary condition for physics at high energies, so that we can start constraining physics below the GUT scale.

1 In other words, we may not convict “O.J. Simpson” in a criminal court, but possibly in a civil case.
2 Boris Kayser once remarked that a severe funding problem prevents us from attempting it.
FIGURE 5. Three possible sets of new particles below the GUT-scale that would preserve the unification of gauge coupling constants and gaugino masses, and can generate Majorana neutrino mass.

FIGURE 6. From the low-energy point of view, the new sets of particles cannot be discerned based on the unification of gauge coupling constants and gaugino masses.

On the other hand, an observation of neutrinoless double beta decay would tell us that there is indeed the Majorana neutrino mass operator

\[ \mathcal{L}_3 = \frac{1}{\Lambda} (LH)(LH), \]  

where the scale \( \Lambda \) is significantly below the GUT scale. Since this operator is non-renormalizable, it needs to be generated by integrating out some heavy particles below the GUT scale. In other words, there is “new physics” below the GUT scale responsible for generating this operator, and therefore we need to add new particles beyond the minimal supersymmetric standard model.

What could such new particles be? Given the non-trivial success of unification, new particles should not spoil it. It is well-known that the addition of complete \( SU(5) \) multiplets would maintain the unification of gauge coupling constants. It turns out that complete multiplets would maintain the unification of gaugino masses as well [6]. There are three possible \( SU(5) \) multiplets that can generate the Majorana neutrino mass operator for all three generations.\(^3\) We add either three adjoints (24), three singlets (1), or one symmetric tensor (15 + \( \overline{15} \)). The last possibility is often called Type-II seesaw, while the standard (Type-I) seesaw we discussed earlier is the second possibility.

However, the scalar mass unification is affected [6]. Depending on the three options, the observed spectrum may or may not unify at the GUT scale. This is because the gauge-non-singlet particles affect the running of gauge coupling constants and gaugino masses, which in turn feed into the scalar masses-squared. Having seen the data consistent with simple unification, the gauge non-singlet options will be excluded; indirectly establishing the gauge singlet options for the origin of the neutrino mass, namely the seesaw mechanism.

This way, we may well be convinced that the seesaw mechanism is the origin of the neutrino mass.

There are a few loose ends, which can be tied up by additional data. For instance, once both supersymmetry and neutrinoless double beta decay are discovered, one may suspect that the neutrinoless double beta decay may be due to the \( R \)-parity violation, not Majorana neutrino mass. This ambiguity can be resolved if the following happens. Once

\(^3\) It is possible that only two out of three neutrinos have mass as far as the current data are concerned. We assume here that all three have mass, but the rest of the discussions can be trivially modified if that is not the case.
the supersymmetry parameters are measured accurately, we will be able to compute the abundance of the Lightest Supersymmetric Particle (LSP) [7]. If it agrees with the cosmological abundance of dark matter, it can be taken as a very strong evidence that the dark matter of the universe is indeed the LSP. Then the LSP must live much longer than the age of the universe, and hence the $R$-parity must be a very good symmetry. In addition, the scattering cross section of LSP on nucleus can also be compared to data if direct detection experiments succeed to detect dark matter. Overall, we may well know that the neutrino mass is Majorana.

Another possible loose end is the mass scale $M$ of the additional particles needed to generate the Majorana neutrino mass operator. If their masses are very close to the GUT scale, their impact on the running of fermion masses will be small. One way this can be avoided is if the neutrinoless double beta decay suggests rather high mass of neutrinos $\sim 0.1$ eV. Another way is to know that Lepton Flavor Violation (LFV) is suppressed. The higher their masses, the larger the Yukawa couplings $y$ must be to reproduce the same neutrino mass $\propto y^2/M$. Then their loops introduce flavor-dependent effects in the slepton masses-squared $\propto y^2$, inducing LFV at low energies. Therefore small LFV suggests low $M$, and hence a certain minimum size in the running of fermion masses-squared.

Leptogenesis

OK, it may be possible to prove the seesaw mechanism if the SUSY-GUT turns out to be correct as we’ve discussed. What about leptogenesis?

That is obviously much harder. Certainly, we may find additional circumstantial evidence. We may find $\theta_{13}$ is not too small which leptogenesis models tend to prefer. We may find CP violation in neutrino oscillation, establishing that CP is violated in the lepton sector. But both of them are plausibility tests, not really an experimental evidence.
We can certainly do better. Given the gravitino problem [8], we know that the reheating temperature after inflation must be low, which in turn requires whatever particles responsible for baryogenesis must be much lighter than the GUT-scale. On the other hand, once the superparticle spectrum is consistent with simple SUSY-GUTs, we know there are no extra particles charged under the standard model gauge groups well below the GUT-scale, as we discussed above. Then it leaves only two options: baryogenesis with gauge singlets, or use particles in the Minimal Supersymmetric Standard Model.

The latter possibility implies the electroweak baryogenesis. We know it is already tightly constrained by the search for electric dipole moments (electron, neutron, Mercury) and the Higgs search. (The latter constraint may be relaxed if the Higgs sector is more complicated, such as the Next-to-Minimal Supersymmetric Standard Model.) Nonetheless we need light bosons to make the electroweak phase transition first order, such as stop, which may be excluded by collider searches. Overall, we may well exclude the electroweak baryogenesis using a combination of collider and EDM searches. Then it only leaves the option of baryogenesis via gauge singlets. It awfully looks like leptogenesis. It is certainly not a proof, but very compelling [4].

If we are lucky, we may do even better. The improved cosmological data may find the spectral index and the tensor component consistent with the $\phi^2$ chaotic inflation, $n_s \approx 0.96, r \approx 0.16$, with $M \approx 10^{13}$ GeV. Since this mass is well below the GUT-scale, it has to be a gauge singlet. Here, the search for the $B$-mode fluctuation in the cosmic microwave background anisotropy (Planck, Polarbear, Quiet, etc) is crucial. But having established that the seesaw mechanism is correct, it is tempting to identify the inflaton $\phi$ with the right-handed neutrino which we know should exist [4]. Then the reheating process itself is leptogenesis.

---

4 I do not know at this moment if Affleck–Dine baryogenesis is a way out of this argument.
CONCLUSIONS

We are going through a revolution in neutrino physics, and are excited that the discovered neutrino mass may tell us something about physics at very high-energy scales. Unfortunately this very nature of neutrino mass makes it impossible to directly access its origin. However, by a collection of experiments, the seesaw mechanism may be revealed as the only consistent explanation for the origin of neutrino mass. We may further find circumstantial evidence that no other mechanism of baryogenesis, other than leptogenesis, works. If we are lucky, we may even find a compelling reason that the seesaw mechanism is the origin of the universe, namely that the right-handed neutrino is an inflaton.

Planets do not often line up, but they sometimes do. We just hope that Nature is as kind as she has been to us.

ACKNOWLEDGMENTS

This talk is primarily based on a work with my student Matt Buckley, but also on a collection of works with many collaborators including Keisuke Fujii, Toshifumi Tsukamoto, Masahiro Yamaguchi, Yasuhiro Okada, Yoshiharu Kawamura. Ippp thank them for fruitful discussions and collaborations. This work was supported in part by World Premier International Research Center Initiative (WPI Program), MEXT, Japan, in part by the U.S. DOE under Contract DE-AC03-76SF00098, and in part by the NSF under grant PHY-04-57315.

REFERENCES

1. P. Minkowski, Phys. Lett. B 67, 421 (1977); T. Yanagida, In Proceedings of the Workshop on the Baryon Number of the Universe and Unified Theories, Tsukuba, Japan, 13-14 Feb 1979; M. Gell-Mann, P. Ramond, and R. Slansky, In Supergravity, North Holland, Amsterdam, 1979; S. Glashow, NATO Adv. Study Inst. Ser. B Phys. 59, 687 (1979).

2. M. R. Buckley and H. Murayama, Phys. Rev. Lett. 97, 231801 (2006) [arXiv:hep-ph/0606088]; 
   ibid, in preparation.

3. M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986).

4. H. Murayama, H. Suzuki, T. Yanagida and J. Yokoyama, Phys. Rev. Lett. 70, 1912 (1993).

5. T. Tsukamoto, K. Fujii, H. Murayama, M. Yamaguchi and Y. Okada, Phys. Rev. D 51, 3153 (1995).

6. Y. Kawamura, H. Murayama and M. Yamaguchi, Phys. Lett. B 324, 52 (1994) [arXiv:hep-ph/9402254].

7. E. A. Baltz, M. Battaglia, M. E. Peskin and T. Wizansky, Phys. Rev. D 74, 103521 (2006) [arXiv:hep-ph/0602187].

8. M. Kawasaki, K. Kohri and T. Moroi, Phys. Rev. D 71, 083502 (2005) [arXiv:astro-ph/0408426].

9. J. Hisano and D. Nomura, Phys. Rev. D 59, 116005 (1999) [arXiv:hep-ph/9810479].

10. E. Komatsu et al. [WMAP Collaboration], [arXiv:0803.0547] [astro-ph].