The Neutrino Highway in the Particle Physics Road Map

André de Gouvêa

Northwestern University

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- Make the physics case for new, neutrino experiments.

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The Charge to the Theory Group is, Perhaps, a Simple One:

- Make the physics case for new, neutrino experiments.
- Make a **compelling** physics case for new, **expensive** neutrino experiments.
- Make a **very compelling** physics case for new, **very expensive** neutrino experiments.

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The Charge to the Theory Group is the Following:

- Make the physics case for new, neutrino experiments.
- Make a **compelling** physics case for new, **expensive** neutrino experiments.
- Make a **very compelling** physics case for new, **very expensive** neutrino experiments.
- Make a **very compelling** physics case for new, **very expensive** neutrino **facilities**.

Outline

1. Key Issues in Fundamental Physics;
2. Neutrino Surprises;
3. Neutrinos and the New Physics;
4. Neutrinos and Cosmology;
5. Neutrinos as Probes;
6. Outline.

Over the years, we have built a very successful theoretical framework, capable of describing, in relatively simple terms, how nature seems to operate at the smallest distance scales.

Furthermore, this Standard Model allows us to recreate the time evolution of the Universe perhaps as far back as temperatures of order 1000 GeV. Our "recreation" is accurate and even predictive.

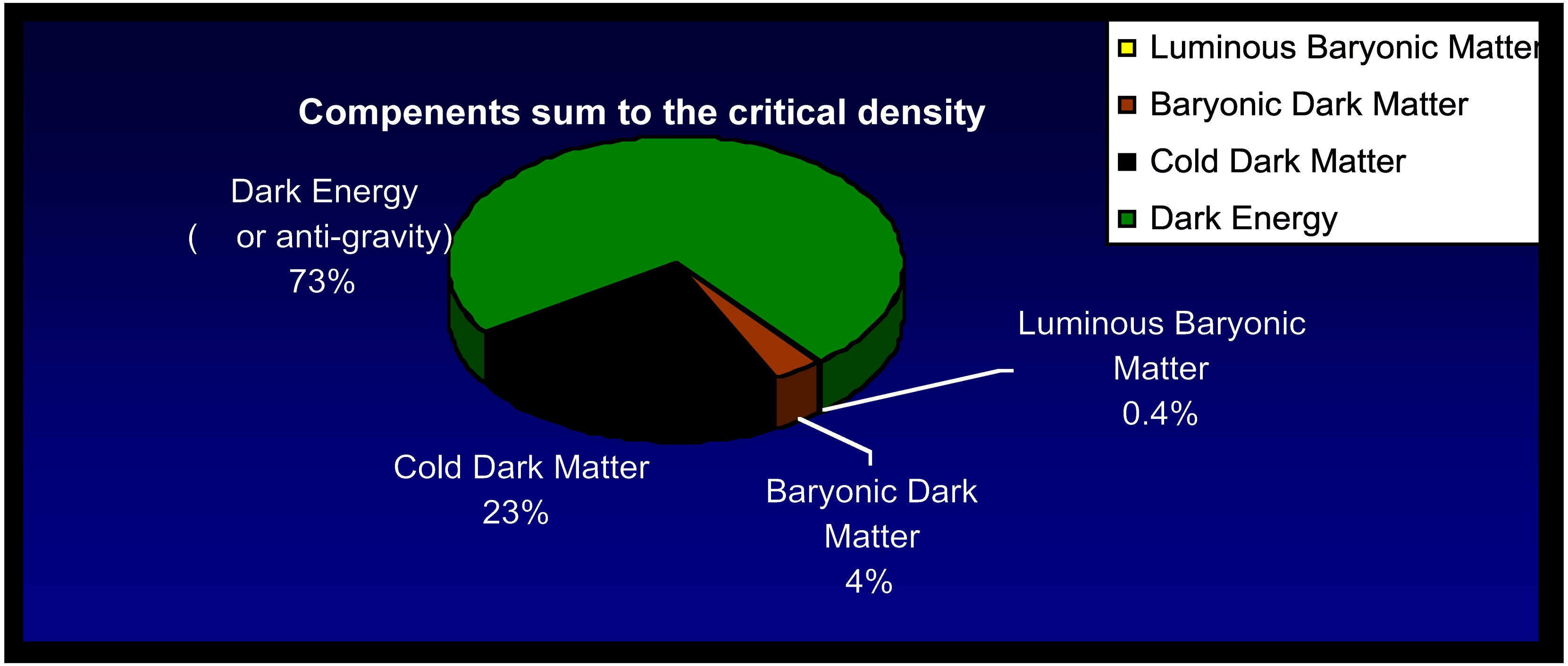
In order to make further progress, we need to follow the **clues** that indicate that something is afoot. Here, I am going to concentrate on three of them:

First: We don't know the physics responsible for electroweak symmetry breaking

- Is there a Higgs boson?
- Why is $v = 246$ GeV? Is that a question?
- Are there other degrees of freedom at the TeV scale? Will they serve as evidence for another organizational principle? [Supersymmetry? New Strong Dynamics? New Space-Time Dimensions? etc]

We don't know the answer to any of these questions. This is why the **LHC** is coming on line. It will address some of these issues, and hopefully bring about **new clues** regarding how we should attempt to describe nature at the most fundamental regime we can concoct.

Second: We "see" 0.4% of the energy in the Universe, and (think we) understand what 4% of it is made. Another 23% may be within grasp – both theoretically and experimentally.



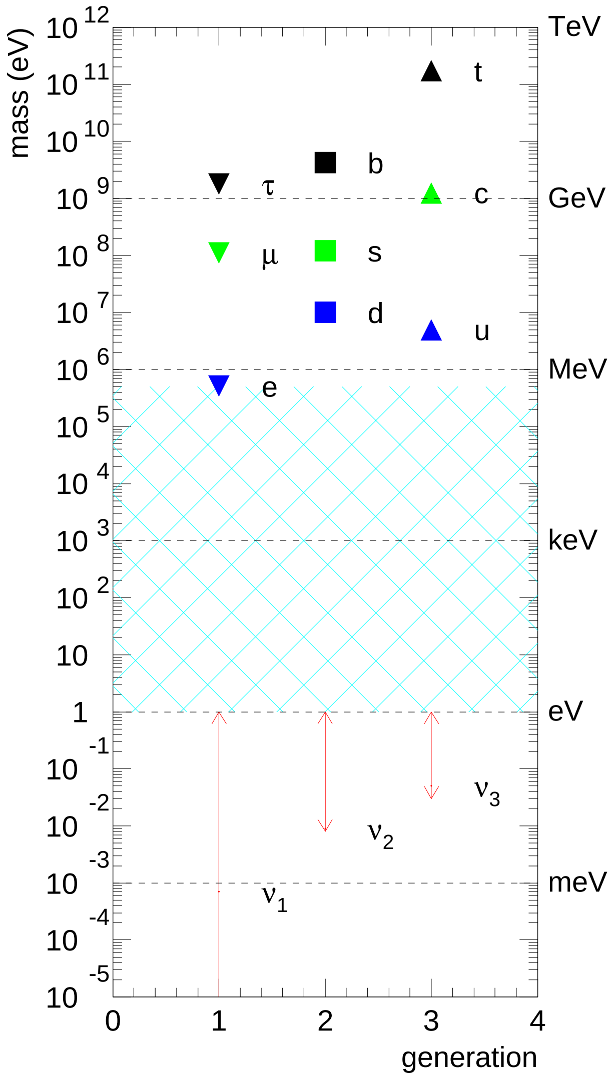
- Is there really "dark matter" and "dark energy" out there?
- Are these "particle physics" questions? Or are these "GR" question?
- What is the dark matter?
- Does it have anything to do with the physics of electroweak symmetry breaking?
- What is dark energy? Is it really the energy of the vacuum, or does it have anything to do with new degrees of freedom?

We don't know the answers to any of these questions. By exploring the different possibilities, we hope to get somewhere as far as properly explaining the **mass-energy budget of the Universe**, and obtain more **clues** regarding how to describe nature in the most fundamental way possible.

Third: We have direct, experimental evidence that there are natural phenomena that the Standard Model is unable to explain.

The properties of one of the "bread-and-butter" particles of the SM – **neutrinos** – were incorrectly predicted by the SM. The data obtained by the neutrino oscillation experiments provide the **only direct, experimental clue** that something is afoot.

First Evidence of Physics Beyond the Standard Model:



NEUTRINOS HAVE MASS

albeit very tiny ones...

We don't know why that is, but we have a "gut feeling" it means something important.

Are neutrinos fundamentally different?

Are neutrino masses generated by a distinct dynamical mechanism?

Understanding Fermion Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

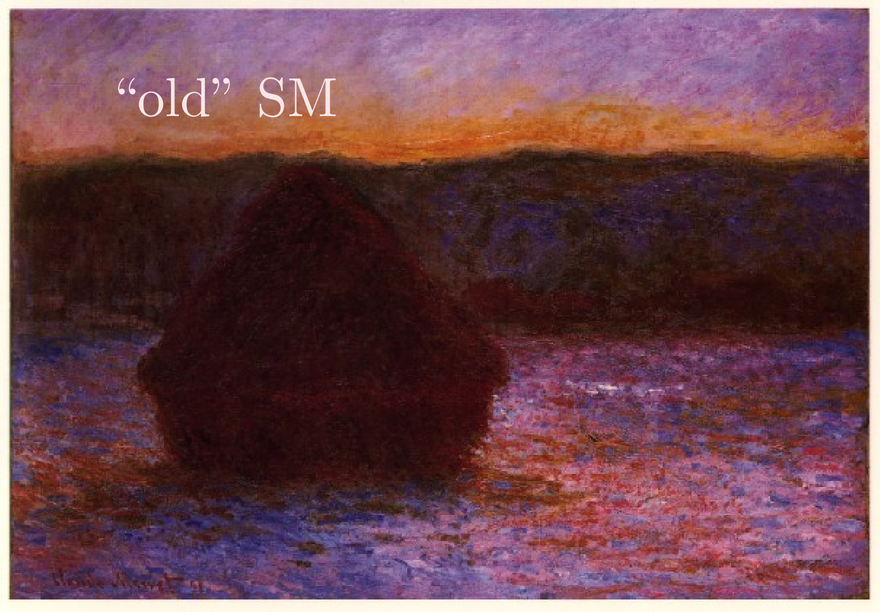
It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$[|(V_{MNS})_{e3}| < 0.2]$

WHY?

They certainly look VERY different, but which one would you label as "strange"?



Massless Neutrinos:

- gauged $SU(3)_c \times SU(2)_L \times U(1)_Y$
- global $U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$
- No "leptonic" CP-invariance violation

Massive Neutrinos:

- gauged $SU(3)_c \times SU(2)_L \times U(1)_Y$
- global $U(1)_B$ $(\times U(1)_L)$
- Leptonic CP-invariance violated (?)

$(\star) \Rightarrow$ to be determined experimentally!

(with apologies to C. Monet)

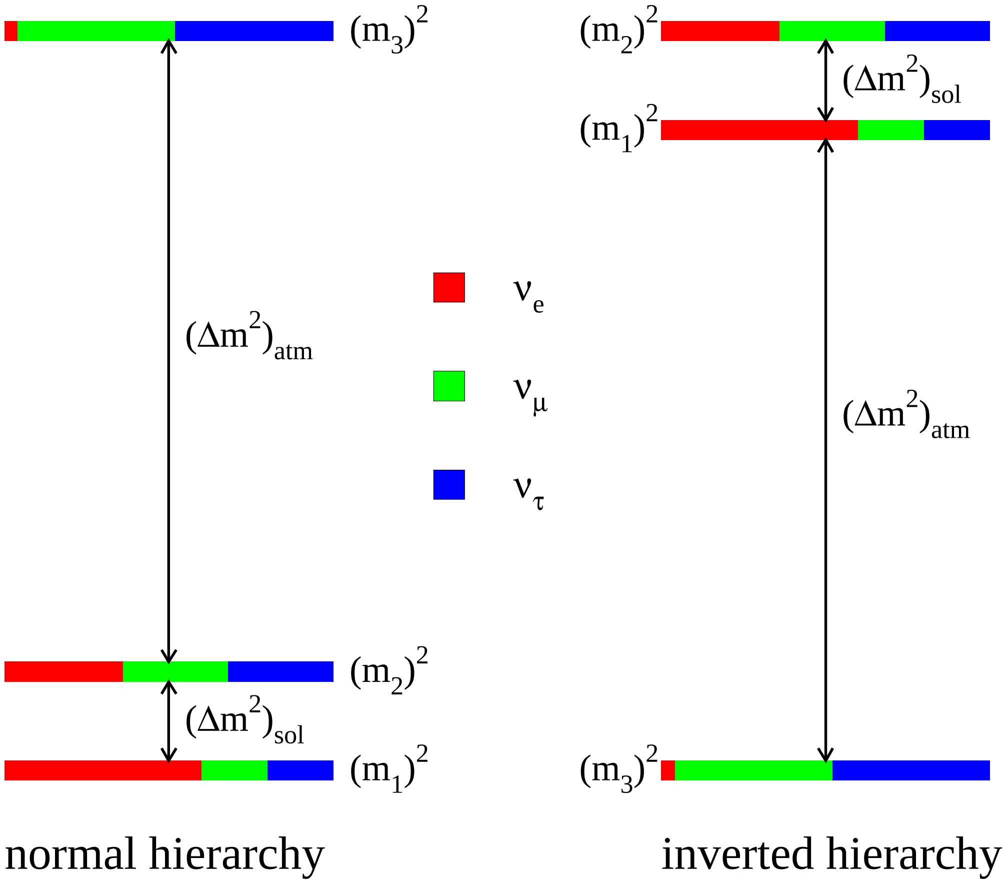
It is our "duty" to pursue these clues in order to improve our knowledge of fundamental physics! This is why we are here (This is of course, my opinion. Feel free to disagree, complain, contradict me, etc!).

At a more theoretical (or speculative) level, we strongly believe that the dividends we will obtain from further studying neutrinos and the newly uncovered phenomenon of neutrino oscillations will more than compensate for our initial investments.

I'll discuss some of these in the remainder of this talk. Many of our speculations tie neutrino physics to physics at the TeV scale, the nature of dark matter (and even dark energy), and beyond.

Needless to say, we don't know if any of this is true. We need experiments to tell us that. **The strategy we choose to follow is to pursue the answers to the questions we can already ask:**

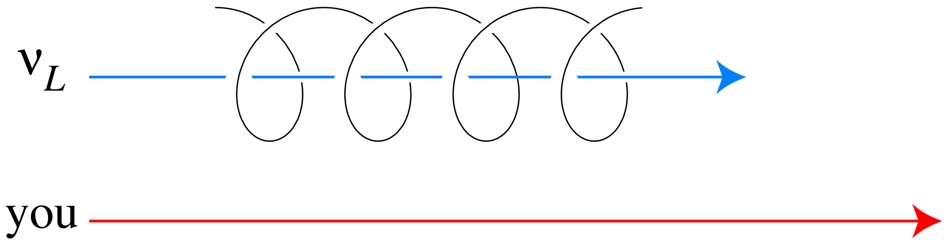
What We Know We Don't Know (1)

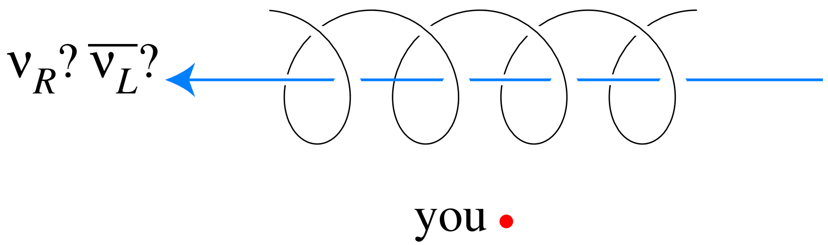


- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of these can be addressed in neutrino oscillation experiments **if** θ_{13} is large enough.

What We Know We Don't Know (2) – Are Neutrinos Majorana Fermions?





The neutrino is the only neutral elementary fermion. There is a left-handed one and a right-handed one.

as far as we can tell (experiments) . . . the left-handed has lepton number $L = +1$, while the right-handed one has $L = -1$:

$(\nu_\ell)_L + X \to \ell^- + X'$, while
$(\nu_\ell)_R + X \to \ell^+ + X'$, so we call $(\nu_\ell)_R \equiv \bar{\nu}_\ell$

However:

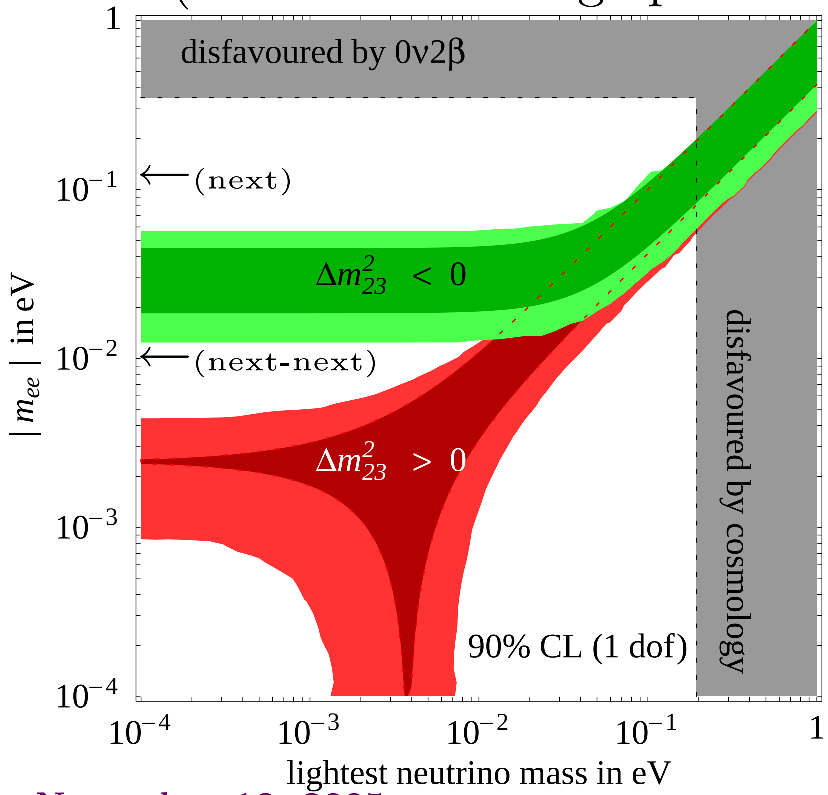
If the neutrino is its own antiparticle (Majorana fermion), then the lepton number conservation law must not be exact $\to$ look for L-violation.

Search for the Violation of Lepton Number (or $B-L$)

In order to make significant theoretical progress, we need to decide whether the neutrinos are Dirac of Majorana fermions

Best Bet: search for Neutrinoless Double-Beta decay: $Z \to (Z+2)e^-e^-$

(neutrino exchange picture: $2n \to 2p + 2e^- + \bar{\nu}_e + \bar{\nu}_e \to 2p + 2e^-$)



Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

Some Speculative Questions/Possibilities:

- Are there other light neutral fermions (sterile neutrinos)? Are there other "light" degrees of freedom that "talk" only to the neutrinos?

  Sterile neutrinos may be required to address the LSND anomaly, explain the observed abundance of heavy elements, and account for the anomalous peculiar velocities of pulsars.

  Could they be the Dark Matter?!

- Do neutrino masses teach us anything about electroweak symmetry breaking? Or, perhaps, neutrinos provide the only handle on physics happening at REALLY high energy scales.

  Are massive neutrinos a window to the GUT scale? Can we learn that from the small masses and the large mixing angles?

NEUTRINOS AND THE COSMOS

- What is the role of neutrinos in shaping our universe?

  The currently best bound on the absolute neutrino mass scale comes from a combination of neutrino oscillations, WMAP, and LSS data. Perhaps a more interesting way to paint this picture is to argue that, once we know the overall neutrino mass scale, we can compare the laboratory measurement to the cosmological estimate. This comparison will teach us a lot about our understanding of the history of the universe!

- Are neutrinos the key to understanding the matter–antimatter asymmetry of the universe?

  Leptogenesis. See other talks that took place today.

NEUTRINOS AS PROBES

- What can neutrinos tell us about known and unknown astrophysical sources?

  Neutrinos are deeply penetrating. They bring otherwise inaccessible information about the Sun and Supernova explosions.

  Neutrinos are unstoppable. High energy neutrinos produced at the yet to be understood sources of high energy cosmic rays will follow "a straight line" between the production point and the Earth, unaffected by magnetic fields and the CMB. Neutrino astronomy is bound to change the way we view the sky.

In order to be successful in these types of endeavors, we need to pin down neutrino properties (masses, mixing) with good precision.

Experiments to Further Our Understanding of the νSM:

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation ($\mu \to e\gamma$, etc);
- searches for lepton number violation (neutrinoless double beta decay, etc);
- **precision measurements of the neutrino oscillation parameters;**
- searches for fermion electric/magnetic dipole moments (electron edm, muon $g-2$, etc);
- searches for new physics at the TeV scale – we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

Outline

- The particle physics road map.
  - The energy frontier
  - Dark matter dark energy
  - Massive neutrinos
- Neutrino masses and the νSM
- What we know we don't know: the "driving force" behind future experimental endeavors
- Examples
  - Massive neutrinos and New Physics at the Energy Frontier
  - Massive neutrinos as probes of GUTs
  - Massive neutrinos and the Universe (dark matter, leptogenesis)
  - Massive neutrinos as probes of astrophysical objects