Particle Physics and Nuclear Physics are not really different fields.
Rather a continuum
Continuum Evidence I

- We use the same units
- $c=1$
- $\hbar=1$
- Mass measured in MeV
- *cf.* atomic physicists: $e=m_e=\hbar=1$
- *cf.* biologists: calories!
We share many experimental techniques. For example, we like to smash things together.
Continuum Evidence III

- Line is drawn for convenience of funding agencies in a ridiculous way
- e.g., underground expts supported by US DOE

<table>
<thead>
<tr>
<th>Energy</th>
<th>Nuclear</th>
<th>HEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sim 1-100) GeV</td>
<td></td>
<td>accelerator V</td>
</tr>
<tr>
<td>(\sim 5-12) MeV</td>
<td>solar V</td>
<td></td>
</tr>
<tr>
<td>(\sim 2-8) MeV</td>
<td>reactor V</td>
<td>reactor V</td>
</tr>
<tr>
<td>(\sim 10-100) keV</td>
<td></td>
<td>dark matter</td>
</tr>
</tbody>
</table>
• Other guests can easily point at a physicist apart from the bank meeting in the next room

• but they can’t tell nuclear and particle physicists apart
Continuum Evidence V

Common scientific questions

- Heart of the matter
  - constituents
  - dynamics
  - fundamental symmetry
- the origin
  - chemical elements
  - matter
  - Universe
Rocky Kolb: Allocate funding proportionately!
Outline

- Intersection (rather a continuum)
- Vision (or the lack of)
- Hallucination
- Outlook
Vision
(or the lack of)
Distance Visual Acuity Test (E Game)
(Read in good light at 10 feet.)

Line 1
20/200

Line 2
20/100

Line 3
20/40

Line 4
20/20

100 Millimeter Calibration Bar
(If not 100 mm, see text of visual acuity page.)
Apocalypse of St. John (San Juan) by Albrecht Dürer
our scientific goal

obstruction
misty TeV

- We don’t cross a new threshold very often
- **atomic scale**: eV ~ 1900
  - discovered quantum mechanics
- **nuclear scale**: GeV ~ 1950
  - many many new “particles”
  - new layer in nature, new QFT dynamics
- **electroweak: scale**: TeV ~ 2010
  - ???????????????????????????????????????????????????
  - new dimensions? new symmetries?
- new threshold only every ~50 years
- until we know the answer to TeV, we are in the misty rainforest
we need to work together

• How do we see through the rainforest?
• We need experts in many types of trees, shrubs, snails, flowers, snakes, water, climate, ecosystem, ....
The Big Questions

- Einstein’s Dream of Unified Forces
  - Are there undiscovered principles of nature: new symmetries, new physical laws?
  - How can we solve the mystery of dark energy?
  - Are there extra dimensions of space
  - Do all the forces become one?
- The Particle World
  - Why are there so many kinds of particles?
  - What is dark matter? How can we make it in the laboratory?
  - What are neutrinos telling us?
- The Birth of the Universe
  - How did the universe come to be?
  - What happened to the antimatter?

e.g. HEPAP Quantum Universe Report
Vision

• We do not have right to expect that any of the big questions can be answered
• Nonetheless there is a good potential for us to answer some or many of them
• How exactly do we do it?
• It would require the whole field maintaining the diversity yet getting together
Hallucination
Our continuum

Nuclear Physics

CIPANP

Particle Physics

ν

cosmic rays

reactor

Sun

Δm^2 [eV^2]

10^{-3}

10^{-6}

10^{-9}

10^{-12}

10^{-1}

10^{0}

10^{2}

tan^2θ

http://hitoshi.berkeley.edu/neutrino
What we learned

- Lepton Flavor is not conserved
- Neutrinos have tiny mass, not very hierarchical
- Neutrinos mix a lot

the first evidence for

incompleteness of Minimal Standard Model
Immediate Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is $\theta_{13}$?
- CP Violation?
- Mass hierarchy?
- Is $\theta_{23}$ maximal?
- LSND? Sterile neutrino(s)? CPT violation?

![Diagram showing mass spectrum with $m_1^2$, $m_2^2$, $m_3^2$, and mass differences for solar and atmospheric neutrinos]
The Big Questions

• 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 **birth of the universe**?

Big questions ≡ tough questions to answer
Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but $\nu_R$ SM neutral

\[
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\begin{pmatrix}
m_D \\
M
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\]

\[
m_\nu = \frac{m_D^2}{M} \ll m_D
\]

To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14} - 10^{15}$GeV
Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become the same at $\sim 2 \times 10^{16}$ GeV if supersymmetry
- To obtain

$$m_3 \sim (\Delta m_{\text{atm}}^2)^{1/2}, \ m_D \sim m_t$$

$$\Rightarrow M_3 \sim 10^{14} - 10^{15} \text{ GeV!}$$
Can we prove it experimentally?

- Short answer: no. We can’t access physics at $>10^{10}$ GeV with accelerators directly.
- But: we will probably believe it if the following scenario happens.

Archeological evidences
A scenario to “establish” seesaw

- Next generation experiments discover neutrinoless double beta decay
- Say, $\langle m_{\nu} \rangle_{ee} \sim 0.1 \text{eV}$
- There must be new physics below $\Lambda \sim 10^{14} \text{GeV}$ that generates the Majorana neutrino mass
  \[
  \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_{\nu\nu}
  \]
- But it can also happen with R-parity violating SUSY
The Other Half of the World Discovered
Geneva, Switzerland

No QCD, no party
unification
Gaugino and scalars

Can’t be an accident!
The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

**SQUARK MASS**

<table>
<thead>
<tr>
<th>VALUE (GeV)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>538±10</td>
<td>OUR FIT</td>
<td></td>
<td>mSUGRA assumptions</td>
</tr>
<tr>
<td>532±11</td>
<td>ABBIENDI 11D</td>
<td>CMS</td>
<td>Missing ET with mSUGRA assumptions</td>
</tr>
<tr>
<td>541±14</td>
<td>ADLER 11O</td>
<td>ATLAS</td>
<td>Missing ET with mSUGRA assumptions</td>
</tr>
<tr>
<td>652±105</td>
<td>ABBIENDI 11K</td>
<td>CMS</td>
<td>extended mSUGRA with 5 more parameters</td>
</tr>
</tbody>
</table>

1ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set \( A_\eta = 0 \) and \( \tan \beta = 3 \). See Fig. 5 of the paper for other choices of \( A_\eta \) and \( \tan \beta \). The result is correlated with the gluino mass \( M_\tilde{g} \). See listing for gluino.

2ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with \( \tan \beta = 5 \).

3ABBiendi 11K extends minimal supergravity by allowing for different scalar mass-squared for \( H_u, H_d, 5^* \) and 10 scalars at the GUT scale.

**SQUARK DECAY MODES**

<table>
<thead>
<tr>
<th>MODE</th>
<th>BR(%)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>j+miss</td>
<td>32±5</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td>lepton universality</td>
</tr>
<tr>
<td>j±miss</td>
<td>73±10</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td></td>
</tr>
<tr>
<td>j e+miss</td>
<td>22±8</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td></td>
</tr>
<tr>
<td>j μ+miss</td>
<td>25±7</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td></td>
</tr>
<tr>
<td>q ±χ±</td>
<td>seen</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td></td>
</tr>
</tbody>
</table>
$0\nu\beta\beta$: Majorana neutrino or R-parity violation?

- Consistency between cosmology, dark matter detection, gamma-ray telescopes, and LHC/ILC say LSP is stable
- R-parity is not broken!
Need to understand the latent heat from the QCD PT
Need to know precision nuclear matrix element e.g. $\Delta s$
Need “New Physics” \( \Lambda < 10^{14} \text{GeV} \)

- Now that there must be Majorana operator at \( \Lambda \approx \text{a few} \times 10^{14} \text{GeV} < M_{\text{GUT}} \), we need new particles below \( M_{\text{GUT}} \)

\[
\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu \nu
\]
scalar masses
tell them apart
No new gauge non-singlets below $M_{\text{GUT}}$

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_{\nu}\nu$$

- If data come out this way, only possibility is gauge singlets if $M<10^{14}\text{GeV}$
- Nothing but the right-handed neutrinos

\[ L_i \quad \text{singlets} \quad L_j \]

\[ H \quad H \]
Can we do this?

- CMS: in some cases, squark masses can be measured as $\Delta m \sim 3$ GeV, if LSP mass provided by ILC, with jet energy scale suspect. No distinction between $u_R$ and $d_R$ (Chiorboli)
- ILC measures gaugino mass and slepton mass at permille levels: negligible errors (HM)
- Squark mass from kinematic endpoints in jet energies: $\Delta m \sim$ a few GeV (Feng-Finnell)
- Can also measure squark mass from the threshold: $\Delta m \sim 2-4$ GeV (Blair)
- 0.5-1% measurement of $m^2$ Not inconceivable
How light are \( M \)?

- \( \nu_R \) loops induce lepton flavor violation
- Large mixings make the effect big
- The current limit on \( \mu \rightarrow e\gamma \) prefer \( M < 10^{13} \text{GeV} \)
- Uncertainties in SUSY parameters will be removed

\[
\Gamma(\mu \rightarrow e\gamma) \propto \frac{m_\mu^5}{m_{\text{SUSY}}^4} (G_F m_\nu M)^2
\]

Experimental

Allowed

\[ M_\nu = 130 \text{GeV}, \ m_{\text{SUSY}} = 170 \text{GeV}, \ m_\nu = 0.07 \text{eV}, \ m_\nu = 0.004 \text{eV} \]

Hisano&Nomura, hep-ph/9810479
The Big Questions

- 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 birth of the universe?

Big questions = tough questions to answer
Matter and Anti-Matter
Early Universe

$10,000,000,001$
$q$

$10,000,000,000$
$q'$
Matter and Anti-Matter Current Universe

The Great Annihilation
Limited choices

• B-factories: no other CP violation than Kobayashi-Maskawa at TeV scale
• Need new particles
• only particles below $M_{\text{GUT}}$ are singlets
• Either:
  • particles at TeV $\rightarrow$ EW baryogenesis
  • heavy singlets, i.e. $\nu_R$
Electroweak Baryogenesis

- Supersymmetric Standard Model
- First order phase transition when Higgs condenses
- Different reflection probability for matter and anti-matter
- Excess matter in the end

Testable at Tevatron and future improvements in $B$ physics, Electric Dipole Moments
Leptogenesis

- You generate *Lepton Asymmetry* first. (Fukugita, Yanagida)
- Generate $L$ from the direct CP violation in right-handed neutrino decay

\[ \Gamma(N_1 \rightarrow \nu_i H) - \Gamma(N_1 \rightarrow \bar{\nu}_i H) \propto \text{Im}(h_{1j}h_{1k}^*h_{lk}^*h_{lj}^*) \]

- $L$ gets converted to $B$ via EW anomaly
  \Rightarrow More matter than anti-matter
  \Rightarrow *We have survived “The Great Annihilation”*
- Despite detailed information on neutrino masses, it still works (e.g., Bari, Buchmüller, Plümacher)
Origin of Universe

• Maybe an even bigger role: inflation
• Need a spinless field that
  • slowly rolls down the potential
  • oscillates around its minimum
  • decays to produce a thermal bath
• The superpartner of right-handed neutrino fits the bill
• When it decays and reheats the Universe, it produces the lepton asymmetry at the same time

Neutrino is mother of the Universe?
Origin of the Universe

- Right-handed scalar neutrino: $V = m^2 \phi^2$
- $n_s \sim 0.96$
- $r \sim 0.16$
- Need $m \sim 10^{13}\text{GeV}$
- Completely consistent with latest WMAP
- Detection possible in the near future
The Big Questions

• 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 **birth of the universe?** ✓

fossils all lined up
Hallucination

• Big questions in neutrino physics
• But how do we know?
• By collection of experiments and theories
  • $0\nu\beta\beta$, LHC/ILC, spectroscopy, dark matter detection, gamma-ray/neutrino telescope, QGP, nucleon structure, GPD, B-factory, EDM, CMB, LSS, Lepton Flavor Violation, nuclear matrix elements, NNLO QCD, etc
• We could well find convincing enough answers to the big questions
Outlook

- We don’t know what we will see through the misty TeV rainforest
- What we got is a Substandard Model (Tipton)
- no guarantee that we can solve any of the big questions to get New Abovestandard Model
- We need to pull ALL THE STOPS
- requires many many elements of our fields
- used neutrino physics as an example, but I assume many other questions go similarly
Thank you!

And all the other organizers
conveners
secretariat