The Next Twenty Years in Particle Physics

Hitoshi Murayama (IAS/Berkeley)
MSU Colloquium
March 25, 2004
We are interested in things we don’t see
Energy budget of Universe

- Stars and galaxies are only \(~0.5\%\)
- Neutrinos are \(~0.1–1.5\%\)
- Rest of ordinary matter (electrons, protons & neutrons) are 4.4\%
- Dark Matter 23\%
- Dark Energy 73\%
- Anti-Matter 0\%
- Higgs Bose-Einstein condensate \(~10^{62}\%??\)

![Pie chart showing the distribution of energy budget of the Universe.](image)
The Cosmic Questions

- What is Dark Matter?
- What is Dark Energy?
- How much is Neutrino component?
- Are we really swimming in a BEC?
- Where did Anti-Matter go?
Einstein’s Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)
History of Unification

- planets → apple
- gravity → mechanics
- GR

- electromagnetism
- electric
- magnetic

- Quantum Electrodynamics

- Quantum mechanics

- Special relativity

- Weak force
- Strong Force
- Grand Unification?

- α-decay
- β-decay
- γ-decay

- String theory?
- GR

- Atoms
We are just about to achieve another layer of unification

Unification of electromagnetic and weak forces

⇒ electroweak theory

Long-term goal since ‘60s

We are getting there!

The main missing link: Higgs boson
Outline

- Introduction
- Recent Surprises
- Dark Side of Universe
- Condensate in Universe
- Beyond Higgs Condensate
- Anti-Matter
- Conclusions
Recent Surprises
Neutrinos Have Mass

SuperKamiokande

KamLAND

Sudbury Neutrino Observatory

SNO
From the Back Stage to the Center Stage

- Pauli postulated neutrinos in order to save the energy conservation in nuclear $\beta$-decay in 1930
- Finally discovered by Cowan and Reines using a nuclear reactor in 1958
- Massless Neutrinos in the Standard Model (‘60s)

- First evidence that the minimal Standard Model of particle physics is incomplete!
- 2002 Nobel to pioneers: Davis and Koshiba
Progress in 2002 in the Solar Neutrino Problem

March 2002

April 2002 with SNO

Dec 2002 with KamLAND
Raised More Questions

- Why do neutrinos have mass at all?
- Why so small?
- We have seen mass differences. What are the masses? \( \Omega_\nu \approx m_\nu/15\text{eV} \)
- Do we need a fourth neutrino?
- Are neutrinos and anti-neutrinos the same?

\[ \begin{array}{ll}
& m_0^2 \\
\text{solar} & \approx 7 \times 10^{-5} \text{eV}^2 \\
\text{atmospheric} & \approx 2 \times 10^{-3} \text{eV}^2 \\
\end{array} \]

How do we extend the Standard Model to incorporate massive neutrinos?
Evidence for Dark Matter

- Observe galaxy rotation curve using Doppler shifts in 21 cm line from hyperfine splitting
- Galaxy is held together by mass far bigger than all stars

- Galaxies form clusters bound in a gravitational well
- Hydrogen gas in the well get heated, emit X-ray
- ~20 times more mass than seen
WMAP satellite result

\[ h = 0.71 \pm 0.04 \]
\[ \Omega_M h^2 = 0.135 \pm 0.009 \]
\[ \Omega_b h^2 = 0.0224 \pm 0.0009 \]
\[ \Omega_{tot} = 1.02 \pm 0.02 \]

- >12\sigma signal for exotic dark matter
**Particle Dark Matter**

*It is not dim small stars (e.g., MACHOs)*

- **WIMP** (Weakly Interacting Massive Particle) *strongly favored*
- Stable heavy particle produced in early Universe, *left-over from near-complete annihilation*

\[
\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2} \sigma_{\text{ann}} M_{\text{Pl}}^3} \frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2}{(\text{TeV})^2} \frac{\sigma_{\text{ann}}}{\sigma_{\text{ann}}}
\]

- **TeV=10^{12}eV the correct energy scale**
Type-IA Supernovae

- Type-IA Supernovae “standard candles”
- Brightness not quite standard, but correlated with the duration of the brightness curve
- Apparent brightness $\Rightarrow$ how far (time)
- Know redshift $\Rightarrow$ expansion since then
- Expansion of Universe is accelerating
Accelerating Universe

- Einstein’s equation
  \[ \left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi}{3} G_N \rho \]

- If the energy dilutes as Universe expands, it must slow down

- Need something that gains in energy as Universe stretches
  \( \text{i.e., negative pressure} \)

- The cosmological constant \( \Lambda \) has the equation of state \( w = p/\rho = -1 \)

- Generically called “Dark Energy”
Embarrassment with Dark Energy

- A naïve estimate of the cosmological constant in Quantum Field Theory:
  \[ \rho_\Lambda \sim M_{Pl}^4 = G_N^{-2} \sim 10^{120} \text{ times observation} \]

  The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero

- But now it seems finite???
Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- “Why Now” problem
- Actually a *triple coincidence problem* including the radiation
- If there is a deep reason for $\rho_\Lambda \sim ((\text{TeV})^2/M_{Pl})^4$, coincidence natural
Cosmology and Particle Physics meet at TeV scale

- **Dark Matter**
  \[ \Omega_M = \frac{0.756(n + 1)x_f^{n+1}}{g^{1/2} \sigma_{\text{ann}} M_{\text{Pl}}^3} \frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2}{(\text{TeV})^2} \]

- **Fermi (Higgs) scale**
  \[ \nu = 0.25\text{TeV} \]

- **Dark Energy**
  \[ \rho_\Lambda \sim (2\text{meV})^4 \text{ vs } (\text{TeV})^2/M_{\text{Pl}} \sim 0.5\text{meV} \]

- **Neutrino**
  \[ (\Delta m^2_{\text{LMA}})^{1/2} \sim 7\text{meV} \text{ vs } (\text{TeV})^2/M_{\text{Pl}} \sim 0.5\text{meV} \]
  
  **TeV-scale physics likely to be rich**
Fermi’s dream era

- Fermi formulated the first theory of the weak force (1933)

- The required energy scale to study the problem known since then: ~TeV

- We are finally getting there!
Where we are

- **Decades-long problems are being resolved**
  - CP violation, T violation, Dark Matter

- **New surprises**
  - Neutrino mass, Dark Energy

- There are many reasons to believe that this decade will be particularly exciting

- **We plan for a program that brings us to the next level**
Dark Side of Universe
Detection of Dark Matter

- **Direct detection**
  - CDMS-II, Edelweiss, DAMA, GENIUS, etc

- **Indirect detection**
  - SuperK, AMANDA, Icecube, Antares, etc

Complementary techniques are getting into the interesting region of parameter space.
Particle Dark Matter

- **Stable, TeV-scale particle**, electrically neutral, very weakly interacting
- **No such candidate in the Standard Model**
- **Lightest Supersymmetric Particle (LSP)**: superpartner of a gauge boson in most models
- **LSP a perfect candidate for WIMP**

- **Detect Dark Matter to see it is there.**
- **Produce Dark Matter in accelerator experiments to see what it is.**
What is the Dark Energy?

- We have to measure \( w \)
- For example with a dedicated satellite experiment

\[ w = \frac{p_u}{\rho_u} \]

SNAP

\[ \Omega_M = 1 - \Omega_{D.E.} \]

Supernova Cosmology Project
Perlmutter et al. (1999)

Domain wall

\( w = -1/3 \)

network of cosmic strings

\( w = -1 \)

Friedland, HM, Perelstein
Condensate in Universe
Mystery of the “weak force”

- **Gravity** pulls two massive bodies (*long-ranged*)
- **Electric force** repels two like charges (*long-ranged*)
- **“Weak force”** pulls protons and electrons (*short-ranged*) acts only over $10^{-16}$ cm [need it for the Sun to burn!]

[Diagram showing gravitational and electric forces]
Something is in the Universe

- There is *something filling our Universe*
- It doesn’t disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- In fact, it is the “mother of mass” for all elementary particles
- *What is it??*
Like a superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the “penetration length”
  \[ \Rightarrow \text{Magnetic field is short-ranged!} \]
- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her “Universe”
  - But doesn’t know what the condensate is, nor why it condenses
  - Doesn’t have enough energy (gap) to break up Cooper pairs

  That’s the stage where we are!
Higgs Boson is Most Likely “Just Around the Corner”

- Higgs boson = gap excitation
- Current data combined with the Standard Model theory predict \( m_H < 196 \text{GeV} \) (95%CL)
- Tevatron at Fermilab has a chance to discover or exclude the SM Higgs boson by 2008
Large Hadron Collider (LHC): Exploring the TeV-scale

- proton-proton collider
- 14TeV energy
  (cf. 2TeV @ Fermilab)
- Under construction at CERN, Geneva
- Mostly European
- Contributions from US, Japan, Canada
- Turn on in ~2007
Higgs Boson at LHC

- LHC would discover Standard Model Higgs boson of any mass within 3 years!
- Measure mass, some ratio of couplings
Questions to be answered

- Is the particle discovered really the Higgs boson?
  - Is it really responsible for particle masses?
  - Does this have the right quantum number $J^P=0^+$?
  - Is it condensed in the Universe?
- Prove it is the “Mother of Mass”
  - Spin/Parity
  - Couplings
  - Branching Ratios
  - Size of the condensate
Linear Collider

- **Electron-positron collider**
- $e^-$, $e^+$ point-like with no structure
- Well-understood environment
- Linear instead of ring to avoid synchrotron loss
- Super-high-tech machine
- Accelerate the beam over $>10$ km
- Focus beam down to a few **nanometers** and make them collide
Prove its coupling $\propto$ mass

- Branching Fractions test the relation
  
  coupling $\propto$ mass

$\Rightarrow$ proves that Higgs Boson is the Mother of Mass
Prove it is condensed

- ZH final state
- Prove the ZZH vertex
Prove it is condensed

- ZH final state
- Prove the ZZH vertex
- We know Z: gauge boson, H: scalar boson
  \[ \Rightarrow \text{only two types of vertices} \]
Prove it is condensed

- ZH final state
- Prove the ZZH vertex
- We know Z: gauge boson, H: scalar boson
  \[ \Rightarrow \text{only two types of vertices} \]
- Need a condensate to get ZZH vertex
  \[ \Rightarrow \text{proves it is condensed in Universe} \]

HM, hep-ex/9606001
Prove it is condensed

- ZH final state
- Prove the ZZH vertex
- We know Z: gauge boson, H: scalar boson
  ⇒ only two types of vertices
- Need a condensate to get ZZH vertex
  ⇒ proves it is condensed in Universe

HM, hep-ex/9606001
Beyond Higgs Condensate
Post-Higgs Problem

- We see “what” is condensed
- *But we still don’t know “why”*
- *Two problems:*
  - Why anything is condensed at all
  - Why is the scale of condensation
    \[ \sim \text{TeV} < \text{M}_{pl} = 10^{15}\text{TeV} \]
- *Explanation most likely to be at \(~\text{TeV}\) scale because this is the relevant energy scale*
Three Directions

- *History repeats itself*
  - Crisis with electron solved by anti-matter
  - Double #particles again $\Rightarrow$ supersymmetry

- *Learn from Cooper pairs*
  - Cooper pairs composite made of two electrons
  - Higgs boson may be fermion-pair composite
    $\Rightarrow$ technicolor

- *Physics as we know it ends at TeV*
  - Ultimate scale of physics: quantum gravity
  - May have quantum gravity at TeV
    $\Rightarrow$ hidden dimensions (0.01 cm to $10^{-17}$ cm)
Task

○ Find *physics responsible for condensation*
○ *We can eliminate many possibilities at LHC*
○ *But new interpretations necessarily emerge*
○ *Race will be on:*
  ○ *theorists coming up with new interpretations*
  ○ *experimentalists excluding new interpretations*
    ⇒ *A loooong process of elimination*
○ *Crucial information is in details*
○ *Elucidate what that physics is*
    ⇒ *Reconstruct the Lagrangian from measurements*
Absolute confidence is crucial for a major discovery

- As an example, supersymmetry
- “New York Times” level confidence
  “The other half of the world discovered”
  still a long way to
- “Halliday-Resnick” level confidence
  “We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances.”
Hidden Dimensions

- Hidden dimensions
- Can emit graviton into the bulk
- Events with apparent energy imbalance

⇒ How many extra dimensions are there?
Supersymmetry

Tevatron/LHC will discover supersymmetry

Can do many measurements at LHC

\[ A_0 = 0, \tan \beta = 35, \mu > 0 \]

\[ E_T^{\text{miss}} (300 \text{ fb}^{-1}) \text{miss} \]

\[ E_T^{\text{miss}} (100 \text{ fb}^{-1}) \text{miss} \]

\[ E_T^{\text{miss}} (10 \text{ fb}^{-1}) \text{miss} \]

Fermilab reach: < 500 GeV

one week @10^{33}

one month @10^{33}

one year @10^{34}

cosmologically plausible region

Fermilab reach: < 500 GeV

\[ M_{\tilde{\chi}_1^0} (\text{GeV}) \]

\[ M_{\tilde{\chi}_1^0} (\text{GeV}) \]

0 50 100 150 200 250 300 350 400

0 50 100 150 200 250 300 350 400

S5

O1
Prove Superpartners have different spin

- Discovery at Tevatron Run II and/or LHC
- Test they are really superpartners
  - Spins differ by 1/2
  - Same $SU(3) \times SU(2) \times U(1)$ quantum numbers
- Supersymmetric couplings

Spin 0?

$$e^+e^- \rightarrow \mu^+\mu^-$$

$\sqrt{s} = 350 \text{ GeV}$

Tsukamoto, Fujii, HM, Yamaguchi, Okada
Superpartners as probe

- Most exciting thing about superpartners beyond existence:

  They carry information of small-distance physics to something we can measure

  “Are forces unified?”

$\begin{array}{|c|c|}
\hline
\text{Energy (GeV)} & \text{Gaugino mass (GeV)} \\
\hline
10^2 & M_1 \\
10^5 & M_2 \\
10^8 & M_3 \\
10^{11} & \\
10^{14} & \\
10^{16} & \\
\hline
\end{array}$
Dark Matter: The Missing Link?

- Dark Matter likely to be TeV-scale electrically neutral weakly interacting particle (e.g., LSP, Lightest KK)
- Accessible at accelerators (LHC & LC)
- Precision measurement at LC of its mass, couplings in order to calculate its cosmic abundance
- If it agrees with cosmological observations, we understand Universe back to $10^{-10}$ sec after the Big Bang
Anti-Matter
Baryon Asymmetry
Early Universe

\[ \frac{q}{\bar{q}} = \frac{10,000,000,001}{10,000,000,000} \]
Baryon Asymmetry
Current Universe

\[ q \quad \bar{q} \]

The Great Annihilation
Baryogenesis

- **What created this tiny excess matter?**
- **Necessary conditions for baryogenesis (Sakharov):**
  - Baryon number non-conservation
  - CP violation
    (subtle difference between matter and anti-matter)
  - Non-equilibrium
    \[ \Gamma(\Delta B > 0) > \Gamma(\Delta B < 0) \]
- **Possible new consequences in**
  - Proton decay
  - CP violation
- Is anti-matter the exact mirror of matter?
- 1964 discovery of CP violation in neutral kaon system
- But only one system, hard to tell what is going on.
- 2001 Found kaon and anti-kaon decay differently at $10^{-6}$ level
- 2002 Found CP violation also in B-meson system
- But no CP violation observed so far is large enough to explain the absence of anti-matter
Electroweak Baryogenesis

- Supersymmetric Standard Model
- First order phase transition when Higgs condenses
- Dynamics of bubbles and particles reflected by bubble walls may create the excess matter
- Consequences on properties of B-mesons
- Testable at Tevatron and future improvements in B physics (HM, Pierce)
Leptogenesis

- Neutrinos may be their own anti-particles
- They can transform matter to anti-matter and vice versa
- Maybe they are responsible for our existence!

- CP-violation may be observed in neutrino oscillation

\[
P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13} s_{23} c_{23} \\
\sin \delta \sin \left( \frac{\Delta m_{12}^2}{4E} L \right) \sin \left( \frac{\Delta m_{13}^2}{4E} L \right) \sin \left( \frac{\Delta m_{23}^2}{4E} L \right)
\]

- Plans to shoot neutrino beams over thousands of kilometers to see this
Very Long Baseline Experiment

It’s of course completely safe!
But aren’t these all expensive?
US Budget in Basic Research

- US budget in physical sciences effectively declined over many years
- Need boost to the entire physical sciences

obligations in billions of constant FY 2003 dollars

Time for True Internationalism

- The goal in particle physics common throughout the globe
- We have been sharing facilities all along
- Putting together world-wide resources will move us ahead
- Possible thanks to world-wide agreement: ECFA, ACFA, HEPAP, all put a LC as the next major step beyond the LHC
- We can realize this ambitious program including LC in the US with ~30% boost in particle physics budget if foreign contribution of ~1/3
Many Interesting Proposals…

Choices need to be made.
Setting Priorities

- **HEPAP subpanel**
  
  Largest projects, decision every ~5 years

- **P5 (Particle Physics Projects Prioritization Panel)**
  
  Medium-size projects, on-going

- **Laboratory PAC (Physics Advisory Committee)**
  
  Projects at a given laboratory

- Sometimes tough decision is necessary to keep projects in line with funding with sound scientific priorities
Conclusion

- Many cosmic questions accessible
  - Dark Matter, Dark Energy, Higgs Condensate, Anti-Matter
- The current program well positioned
  - Tevatron, B-factory, neutrino experiments, etc
- Physics at TeV scale likely to be rich
- LHC the next major breakthrough at TeV-scale
- To fully understand it, we will likely need a lot of detailed information
- LC will study new particles one by one
  ⇒ reconstruct the underlying Lagrangian
- Then we can move on further with an absolute confidence
I feel lucky to be in this age.