THE MYSTERIOUS UNIVERSE
Exploring Our World With Particle Accelerators

Jim Brau    Albuquerque    October 1, 2009
Large Hadron Collider

17 mile ring circumference
300 feet underground
1600 SuperC magnets @ 8.3 Tesla
Temp= 2 K
10,000 MegaJoules stored energy
600,000,000 collisions per second
at 14,000,000,000,000,000 eVolts
Large Hadron Collider

Proton beam stores 700 MegaJoules
equiv. to 747 energy on take-off
enough to melt 1/2 ton copper
• Exploring deep mysteries of the fundamental substance of the Universe
• Expect revolutionary discoveries to come soon
  - impact to human knowledge akin to quantum revolution of early 20th Century
  - Dark Matter, Dark Energy, Higgs Boson, Extra Dimensions, Other New Particles or Forces...
Aha!

$F = \frac{G M m}{r^2}$

Unification
What is the Sun’s source of energy
Solar Energy

• What is the Sun’s source of energy?
  – 19th Century - Chemical reactions? (burning)
    • Predicted solar lifetime too short - only 20,000 years
    • Evidence on Earth for much longer duration

- 20th Century
  • Einstein’s relativity \[ E=mc^2 \]
  • discovery of atomic nucleus and nuclear reactions
Solar Energy

• What is the Sun’s source of energy?

Enough energy for the Sun to shine for ten billion years
Relativity

• When a man sits with a pretty girl for an hour, it seems like a minute.

• But let him sit on a hot stove for a minute—and it’s longer than any hour.

• That’s relativity.

A. Einstein
Quasi-stellar Radio Sources (Quasars)
Quasars
Quasars

Brightest Objects in the Universe

- Distant, Active Young Galaxies

Speed of recession
44,000 km/sec
15% speed of light!

Distance
2.4 billion light yrs

Jim Brau
Albuquerque
October 1, 2009
1929 - Hubble Discovered Universe is Expanding

Edwin Powell Hubble (1889-1953)
1929 - Hubble Discovered Universe is Expanding

First evidence that Universe began with a Big Bang

Edwin Powell Hubble (1889-1953)

Hubble's Plot of Galaxy Velocity & Distance

Edwin Powell Hubble (1889-1953)
Universe’s Glow in Microwaves discovered in 1965

predicted following Hubble’s discovery

confirmed early universe of Big Bang
Big Bang
The Universe is Made of Particles

• Investigating the particles reveals the fundamental structure of the Universe and matter within it.
The Universe is Made of Particles

- Investigating the particles reveals the fundamental structure of the Universe and matter within it.
1897 - J.J. Thomson   Electron
J.J. Thomson, On 1897 Discovery
Speaking in 1934

Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? -- which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science.

From the soundtrack of the film, Atomic Physics

Credit: American Institute of Physics
20th Century
Particle Physics Laboratories

electron linear accelerator
at Stanford (SLAC)

proton synchrotron
at Fermilab (near Chicago)
1969 - Quarks discovered (inside atomic nucleus) Stanford
1969 - Quarks discovered (inside atomic nucleus) Stanford
1995 - Top Quark Discovered at Fermilab
1995 - Top Quark Discovered at Fermilab
1995 - Top Quark Discovered at Fermilab
1995 - Top Quark Discovered at Fermilab

Creation of massive matter \((E=mc^2)\)
Particles
Particles and Forces

“interactions”
Particles and Forces

“interactions”

- Gravity - weakest
Particles and Forces

“interactions”

- Gravity - weakest
- Electromagnetism
Particles and Forces

“interactions”

- Gravity - weakest
- Electromagnetism
- Weak Nuclear
Particles and Forces

“interactions”

- Gravity - weakest
- Electromagnetism
- Weak Nuclear
- Strong Nuclear
Are Forces Related?

1850

- Gravity
- Electricity
- Magnetism
Are Forces Related?

1864
Unified theory
- Electromagnetism
- Light (photons)

Forces
“interactions”

- Gravity
- Electricity
- Magnetism

1864
Are Forces Related?

2000
• Gravity
• Electromagnetism
• Weak Nuclear
• Strong Nuclear

Forces
“interactions”
Are Forces Related?

Next Advance Expected - discovery of the Higgs Boson at accelerators

Forces “interactions”

2000
• Gravity
• Electroweak
• Strong Nuclear

Jim Brau  Albuquerque  October 1, 2009
Are Forces Related?

Are all forces related? New particles would be involved in any unification.
What is Matter?

all Atomic
Halo of Dark Matter

M31 - Andromeda
Halo of Dark Matter
How we know dark halos surround galaxies?

Expected - based on stellar mass

Observed - reveals invisible ("dark") mass

Jim Brau  Albuquerque  October 1, 2009

Vera Rubin  1950s
How we know dark halos surround galaxies?

Expected—based on stellar mass

Observed—reveals invisible ("dark") mass

Vera Rubin 1950s
Early Dark Matter Evidence

- 1930s motions of clusters of galaxies cannot be understood – Fritz Zwicky

Coma Cluster
Imaging Dark Matter

Even more evidence
Imaging Dark Matter

We now know there is much more Dark Matter than Atomic Matter in the Universe

Hubble Data analyzed by Yale astrophysicists
What is Dark Matter?

- Perhaps a new form of elementary particle?
- Can we learn from history of physics?
1932 - Discovery of Anti-Matter

Jim Brau             Albuquerque          October 1, 2009
1932 - Discovery of Anti-Matter

Anti-particle for every known particle
Candidate Theory Explains Dark Matter

SuperString Theory

- Unifies all particles and all forces
  - gravity with quantum mechanics
- Fundamental particles are represented as vibrations on string

- Strings are miniscule
  - Atom is $10,000,000,000,000,000,000,000,000,000,000 \times$ bigger
    Dimension of String $= 10^{-25}$ atomic size $= 10^{-35}$ meters

- Requires another set of matching particles
  - the super-partners of ordinary particles
The Structure of Matter

........ hypothesis
Supersymmetry, Strings, and Dark Matter

- History repeats?
- Just as with anti-matter, New particles are predicted

- The supersymmetric particles have just the properties expected of Dark Matter
The Matter Crisis

• not enough matter (atomic or dark matter) to “make-up” known stuff of the Universe
Measuring Expansion of Universe

Distant Supernovae

Hubble Space Telescope - ACS

Before Supernovae

After Supernovae

Jim Brau  Albuquerque  October 1, 2009
Measuring Expansion of Universe

After Supernova

After Supernova

After Supernova
Measuring Expansion of Universe

Expansion of the Universe is Accelerating Driven by Dark Energy
Acceleration Component called “Dark Energy”

- Solves “Matter” Crisis
- The dominant “stuff” of the universe is dark matter and dark energy

![Pie chart showing 74% Dark Energy, 22% Dark Matter, and 4% Atoms]
The Dark Side Controls the Universe

- Dark Matter HOLDS IT TOGETHER
- Dark Energy DETERMINES ITS DESTINY

- Dark Matter is strange!
- Dark Energy stranger?
What is Dark Energy?

• No one knows yet
  – but we have some hints

• Cautioned by Einstein’s comment (1951) on the understanding of the photon:
  All these fifty years of conscious brooding have brought me no nearer to the answer to the question “what is the light quanta.” Nowadays every rascal thinks he knows, but he is mistaken.
Quantum Nature of Nothing is Something

Empty Space

“Vacuum”
Quantum Nature of Nothing is Something

Dark Energy

Dark Matter

Vacuum

Empty Space
Calculating Dark Energy

- Solid Quantum Mechanical Foundation
  - effect of particles in the vacuum

\[ E_0 = \frac{1}{4\pi} \hbar \omega \]

Vacuum energy is the sum of all the simple harmonic oscillators:

\[ E_0 = \sum_j \frac{1}{4\pi} \hbar \omega_j \]

\( \omega \) for the scalar field. This sum may be evaluated by going to infinity. The periodic boundary condition reduces this sum of integrals over all integer values of \( n \). There are then \( Ld\hbar/2\pi \) discrete states. Asymptotically, it becomes an integral:

\[ E_0 = \frac{1}{4\pi} \hbar L^3 \int_0^{\infty} \omega d^3 k \]

Suppose a cutoff at a maximum wavevector \( k_{\text{max}} \), where

\[ \rho_{\text{vac}} = \lim_{L \to \infty} \frac{E_0}{L^3} = \frac{\hbar k_{\text{max}}^4}{32 \pi^3} \]
Calculating Dark Energy

- Solid Quantum Mechanical Foundation
  - effect of particles in the vacuum

Does the calculation agree with measurement?

**NO!** 1,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000

\(= 10^{120}\) times too big.

\[E_0 = \frac{1}{4\pi} \hbar \omega\]

Vacuum energy is the sum of all the simple harmonic oscillators:

\[E_0 = \sum_j \frac{1}{4\pi} \hbar \omega_j\]

(\(\lambda\)) for the scalar field. This sum may be evaluated as an integral:

\[E_0 = \frac{1}{4\pi} \hbar L^3 \int \frac{\omega}{(2\pi)^3} d^3 k\]

Imposing a cutoff at a maximum wavevector \(k_{\text{max}}\)

\[\rho_{\text{vac}} = \lim_{L \to \infty} \frac{E_0}{L^3} = \frac{\hbar k_{\text{max}}^4}{32 \pi^2}\]
Large Hadron Collider (LHC)
Geneva, Switzerland
Large Hadron Collider (LHC)  
Geneva, Switzerland

Begins operation this year

Will search for Dark Matter, Higgs Bosons, other New Particles and Forces
Scientific Goals of the LHC and the ILC

- Dark Matter particles
- Higgs Boson
  - responsible for mass of fundamental particles
  - responsible for weak nuclear and electromagnetic force differences
- Hidden extra dimensions of space
- New forces
- New fundamental particles
Particle Accelerators and the Universe

• Big Bang occurred 13.7 billion years ago
  – expanding Universe, cosmic fireball, other observables
• Universe expanded and cooled; fundamental particles condensed into structures
• Accelerators have revealed fundamental particles and their interactions
• Dark Matter dominates mass of the Universe
  – controlled early evolution, continues impact today
• Dark Matter discovery could come from next accelerator experiments
  – Large Hadron Collider (LHC), International Linear Collider (ILC)
One thing I have learned in a long life: that all our science, measured against reality, is primitive and childlike—and yet it is the most precious thing we have.

The most beautiful experience we can have is the mysterious.

It is the fundamental emotion which stands at the cradle of true art and true science.
Acknowledgements

RESEARCH SUPPORTED BY

Department of Energy
OFFICE OF SCIENCE

NATIONAL SCIENCE FOUNDATION

Philip H. Knight