THE HIDDEN UNIVERSE

Dark Matter, Dark Energy, and Gravitational Waves
Ultra Deep Field Image
Hubble Space Telescope
The End of Physics?

"The more important fundamental laws and facts of physical science have all been discovered,

and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote."
The End of Physics?

Nobel Laureate
Albert A. Michelson,
at the dedication of
Ryerson Physics Lab,
U. of Chicago, 1894
What is the universe made of?

• Atomic ("ordinary") matter
  - mostly protons, neutrons and electrons
  explains **visible universe**

• But the **visible universe** is only a fraction of
  the entire universe that we have discovered

  Dark Matter
  Dark Energy
  Gravitational Waves
1929 - Hubble Discovered Universe is Expanding

First evidence that Universe began with a Big Bang

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

predicted following Hubble’s discovery

confirmed early universe of Big Bang

Detailed measurements of this “Cosmic Microwave Background” yields the total mass/energy density of the universe today:

5 hydrogen atoms/m³ equivalent
Nuclear Physics in the Early Universe

• Early universe produced atomic abundances

• Nicely explained in Big Bang Theory

• Establishes density of nuclear/atomic matter
  – today (after expansion) $1 \text{ hydrogen atom/ } 4 \text{ m}^3$
  – 1/20 of total mass/energy of universe
The Matter Crisis

- not enough matter
to “make-up” known matter & energy of the Universe

5 hydrogen atoms/m$^3$

4.9 % Atoms (1 hydrogen atom / 4 m$^3$)

This pie represents all the matter & energy in the universe

Planck 2013
Halo of Dark Matter

M31 - Andromeda
How we know dark halos surround galaxies?

**Expected** based on visible 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
Bullet Cluster
X-Ray emissions (red) - Hot gas produced during pass through.
Imaging Dark Matter

Lensing
Bullet Cluster

Lensing of more distant galaxies reveals dark matter (shown in blue)
Animation of Bullet Cluster collision
The Matter Crisis

- better
- still not enough matter to “make-up” known matter & energy of the Universe

This pie represents all the matter & energy in the universe

5 hydrogen atoms/m³ equivalent

4.9 % Atoms

Planck 2013
What is the Dark Matter that Dominates Atomic Matter by 5/1?

• We have motivated ideas, but only direct evidence will be definitive
  ✓ Neutrinos?  ✗ WIMPs?  ✗ Neutralinos?
  ✗ Axions?  ✗ MACHOs?  ✗ Exotics?

• Accelerator, satellite, or underground experiments may discover Dark Matter particles
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 x bigger
  Dimension of String = 10^{-25} atomic size = 10^{-35} meters

- Requires another set of matching particles
  • the super-partners of ordinary particles
Supersymmetry, Strings, and Dark Matter

• The supersymmetric particles have just the properties expected of Dark Matter

But the dark matter particles may arise from even more fascinating New Physics. We just don’t know - the search goes on!
Searching for Dark Matter Particles
many approaches

Particle Collider
Large Hadron Collider (LHC)
ATLAS Collaboration w/ U. Oregon

Signals from Space
Fermi/GLAST Satellite

Underground Detectors
CDMS Underground
• What could account for the missing matter/energy of the Universe?

This pie represents all the matter & energy in the universe.
Mass & Energy

It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind. Furthermore, the equation $E = mc^2$, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned above.
Measuring Expansion of Universe

Distant Supernovae

Hubble Space Telescope - ACS

After Supernova

After Supernova

After Supernova
Type Ia Supernovae are “Standard Candles”

Standard Candle = known luminosity

Chandrasekhar Limit
- $1.4 \times M_{\text{SUN}}$ (density = 1000 kg/cm$^3$)
- over this mass white dwarf collapses and explodes
- luminosity determined by mass = $1.4 \times M_{\text{SUN}}$
Looking Back in Time

Recession velocity

Decelerating universe

Accelerating universe

$H_0 = 70 \text{ km/s/Mpc}$
Measuring Expansion of Universe

Expansion of the Universe is Accelerating
Driven by Dark Energy

How much of the Universe’s matter and energy is needed to cause this large acceleration?
Acceleration Component called “Dark Energy”

- The dominant “stuff” of the universe is dark matter and dark energy.
The Dark Side Controls the Universe

Dark Matter HOLDS IT TOGETHER

Dark Energy DETERMINES ITS DESTINY

Dark Matter is strange!

Dark Energy stranger

- the greatest mystery in physics!
What is Dark Energy?

- Cosmological constant?
  - Einstein’s addition (1917) to General Theory of Relativity.
  - Designed to overcome natural pull of gravity, producing a “static universe”.
  - 1929 - Edwin Hubble’s discovered universe was expanding
  - Einstein called cosmological constant his “greatest blunder.” He retracted the constant.
What is Dark Energy?

Cosmological Constant could result from quantum vacuum fluctuations

- Quantum physics -> no truly empty space
- "Empty space" filled with "virtual" particles
Vacuum Fluctuations

- The effect of these virtual particles can be calculated using Quantum Field Theory
  - But this theoretical result is far too big
    - By a factor of
      \[
      1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 = 10^{120}
      \]
    - This is a BIG-time mystery
      - we know how the universe might make Dark Energy, but we don’t know how to make so little
  - There is no fundamental understanding of Dark Energy
Substance of the Universe

- 68.3% Dark Energy
- 26.8% Dark Matter
- 4.9% Atoms

Planck 2013

Jim Brau  UO Quarknet  June 26, 2014
Future Studies of Dark Energy

Four Techniques
- distant supernovae
- frozen sound waves in early universe
- gravitational lensing
- galaxy clusters

Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory high in the Chilean Andes.
Search for Gravitational Waves

LIGO Scientific Collaboration
w/ U. Oregon

Laser Interferometer Gravitational-wave Observatory (LIGO)
Hanford, WA
Mass-free “flat” Space-time
Mass “warps” Space-time

The curvature of Space-Time
Kurdistan Panetarium
Gravity & Gravitational Waves

• The curvature of Space-time changes as masses within the spatial fabric move

• Large masses (black holes, neutron stars,…) will produce observable changes:

  producing ripples in space gravitational waves
Detecting Gravitational Waves

• Disturbances in space very small - space is STIFF!
  – small fraction of atomic nucleus over a kilometer
• Small disturbance can be measured by large laser interferometer (LIGO)
Global Network of Gravitational Wave Interferometers

LIGO 4 km
GEO 600m
Virgo 3 km

LSC: LIGO+GEO
The next astronomy - Gravitational waves

• Many discoveries resulted from expanding astronomy for electromagnetic radiation radio waves, infrared, ultraviolet, X-rays, gamma-rays

• Revolutionary discoveries such as
  – neutron stars, black holes, gamma ray bursts, dark matter, dark energy, etc.

• We anticipate unexpected discoveries from gravitational wave astronomy
**BICEP2**

- Have gravitational waves from the **VERY EARLY** Universe been observed?

---

**Inflation**

- \( \sim 10^{-37} \) s
- \( \sim 10^{15} \) GeV
The End of Physics?

What is Dark Matter?
What is Dark Energy?
What can gravitational waves tell us about the universe?

What is the Higgs boson?
How are electrons related to quarks?
How can gravity and quantum mechanics be reconciled?
Why are neutrinos so light?

---

Jim Brau          UO Quarknet          June 26, 2014
The Hidden Universe: Dark Matter, Dark Energy, & Gravitational Waves

• The Universe is dominated by mysterious components:
  – 5% “ordinary”, atomic matter
  – 27% dark matter - what is it?
  – 68% dark energy - what is it?

• Many upcoming scientific projects will advance our knowledge of these mysterious components of the HIDDEN UNIVERSE

• Advanced LIGO may soon open the gravitational wave window on the Universe
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

Acknowledgement: images from http://www.AstroPics.com