Today, we discuss "What is the mysterious Dark Matter that dominates the mass in the Universe?"

Teruki Kamon

"Fought well you have, my Padawan. May the Force be with you."

The Dark Matter Awakens

Dark Particle Hunters

Prologue

--- The Dark Matter Awakens ---

Dark Particle Hunters
Simplified Cycle of Science Curiosity

Particle Physics

String Theory?

Nuclear Physics

Biology /

Chemistry

Astronomy

Cosmology

Particle Physics

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Biology /

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Nuclear Physics

String Theory?

Simplified Cycle of Science Curiosity

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**Quiz #1: Einstein and Hawking**

He is the author of a book "A Brief History of Time". Who is he?

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On Feb. 11, 2016, scientists announced the detection of gravitational waves (Sep. 14, 2015) that are ripples in space-time created by violent collision of two massive black holes in the universe. This was predicted by his theory in 1916. Who is he?

---

He predicted black-body radiation by black holes. Who is he?

---

He is famous for this simple equation E = mc^2. Who is he?

---

He failed his University Entrance Exam and had to reapply a year later, but received a Nobel Prize for photoelectric effect. Who is he?

---

He is the first person to point out there is unseen matter in the universe. Who is he?
Episode 1: Dark Matter in the Universe

Episode 2: Where and how the DM can be probed?

Episode 3: Fun examples of Particle Physics

Who Wanted “Dark Matter”?

Darth Vader: No. I am your father.
What? He was the first to infer the existence of unseen matter, what is now called Dark Matter by using the Virial Theorem.

Where? Coma Galaxy Cluster (large cluster of galaxies – over 1,000 identified galaxies; mean distance from Earth is 99 Mpc or 321 million ly).

What? M_{galaxy cluster} \approx 160 \times M_{luminous matter}

Today? The same calculation today shows a smaller factor, based on greater values for the mass of luminous material. What? [http://en.wikipedia.org/wiki/Fritz_Zwicky]

Fritz Zwicky (1933)
Rotation curve of a typical spiral galaxy: predicted (A) and observed (B). The discrepancy between the curves is attributed to dark matter.

Vera Rubin (1970) "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions"
Dark Matter in the Universe

Another Clear Evidence of Dark Matter – Splitting Normal Matter and Dark Matter Apart

Ordinary Matter (NASA’s Chandra X-Ray Observatory) (gravitational lensing)

Dark Matter

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Can it be one of the known particles?

Let's check out!

It Doesn't Matter.

Right, it doesn't shake hands easily. Two dark matter clusters (in blue) are just passing each other. It is a long-lived (stable) object.

It's a Cold Matter.

Yes, it is a "relativistically slowly moving" ("cold") object.

It's an Invisible Matter.

Right, it doesn't respond to your flash light. This means it is a neutral object.

So, it's Cold Dark Matter (CDM).

Properties of Cold Dark Matter

- Ordinary Matter: Atoms, quarks, protons, neutrons, electrons.
- Dark Matter: Long-lived (stable) object, not seen directly.
- Cold Dark Matter: Relativistically slowly moving object, neutral.
12 elementary particles are known fundamental building blocks of matter. 4 fundamental forces govern the transitions between particles. The Standard Model, a mathematical rule, includes 12 particles and 3 forces plus Higgs boson. The Standard Model, a mathematical rule, includes 12 particles and 3 forces. A fundamental forces govern the transitions between particles.

The table lists the following particles:

- quarks: up (u), down (d), strange (s), charm (c), top (t), bottom (b)
- leptons: electron (e), electron neutrino (νₑ), muon (μ), muon neutrino (νμ), tau (τ), tau neutrino (ντ)

All masses are in MeV.

Contact: Teruki Kamon, Mitchell Institute for Fundamental Physics and Astronomy

Solution will be posted at URL: http://faculty.physics.tamu.edu/kamon/research/talk/
[Q2a] Can be the dark matter a Standard Model particle?

**Recap: Dark matter particles**

1. Weakly interacting
2. Neutral
3. Heavy
4. Relativistically slowly moving

**Answer:**

Quarks, electron, muon, and tau cannot be the dark matter, because they are interacting via strong and/or electromagnetic forces. Neutrinos are too light.

[Q2b] What should we do?

**Answer:**

Expand the Standard Model framework based on a new symmetry, e.g., Supersymmetry (SUSY) or SUSY (next page). A set of new particles, including a dark matter candidate.
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Feynman Diagram

Particle-Physics "Circuit" Diagrams
### Interconnection in Researches

**Today's Focus**

<table>
<thead>
<tr>
<th>Mirror</th>
<th>24.5-meter Primary</th>
<th>Dark Matter</th>
<th>Dark Matter: 8 trillion electron-volts</th>
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<tbody>
<tr>
<td>GMT</td>
<td></td>
<td>DM Amplitude</td>
<td>Dark Matter in pp collisions at CERN's LHC</td>
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<tr>
<td>Chile</td>
<td>Galaxy Formation</td>
<td>DM Annihilation</td>
<td>Dark Matter in pp collisions in Ge or Lar detector</td>
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<tr>
<td>2013</td>
<td>On near-Earth orbit</td>
<td>North America</td>
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<tr>
<td>Fermi-LAT</td>
<td></td>
<td>GCMS/LUX</td>
<td>CMS</td>
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<td>2008</td>
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</tbody>
</table>

**Interconnection between Particles and Dark Matter**

- **Hunt for Dark Matter**
  - **Interconnection** physics circuit diagrams tell us...
  - Lightest
  - Neutal
  - SUSY

**Current Experiments**

- Large Hadron Collider
- Fermi Large Area Telescope
- Giant Magellan Telescope
- Geant Hadron Tracker

**Possible Dark Matter Interactions**
Twenty-six years ago, an event at CERN changed the world forever. Tim Berners-Lee handed a document to his supervisor Mike Sendall entitled "Information Management: a Proposal." "Vague, but exciting" is how Mike described it, and he approved it to go forward. The following year, the World Wide Web was born.

"We've learned Earth's languages through the WWW."

"We've learned Earth's languages through the WWW."

CERN in 1989

Large Hadron Collider

LHC

LHC

Large Hadron Collider

LHC

European Organization for Nuclear Research

Recherche Nucléaire

Conseil Européen pour la Physique Nucléaire
LHC: Proton-Proton Collider

27 km ring

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27 km-long ultra-high vacuum tubes with about one thousand 14.3m-long dipole magnets and 8000 other types of magnets, accelerating protons to 99.999999% of speed of light.

Geneva Airport

You would have to connect 0.6 trillion (600,000,000,000) 12V batteries to accelerate protons to 99.999999% of speed of light.

Applicaton: Proton Therapy

Super-fast detector takes a snapshot of particles just like the first fraction of seconds after the Big Bang.

Energy in each collision is transformed to particles just like the first fraction of seconds after the Big Bang.

Study of particles allows us to answer some of big questions closer to understanding of the universe.

Scientific Program

Energy in each collision is transformed to particles just like the first fraction of seconds after the Big Bang.

Study of particles allows us to answer some of big questions closer to understanding of the universe.
Yes! Possible to create heavier new particles in the “elementary particle” world.

Mission Possible?

New Particles

Proton and (anti)proton collision can produce the Standard Model particles like heavy top quarks (~180 times heavier than a proton) as well as dark matter particles.

A Little Bit of Einstein

E = mc²

Physics Magic in Collisions

Fast Ping-pong balls → Slow Steel Balls

Proton (anti)proton collision can produce the Standard Model particles like heavy top quarks (~180 times heavier than a proton) as well as dark matter particles.

My Wife's Dream

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Dark Matter!
Pretty Big & Heavy Detector

21 m x 15 m x 15 m, 12,500 tons

The CMS is one of two super-fast & super-sensitive detectors, consisting of 15 heavy elements, collecting debris from the collision and converting a visual image for us.
Experimental Method

Take pictures

We take many pictures using a "particle telescope". After each proton-proton collision, we record "debris" debris and use a super-fast/super-sensitive detector to extract evidence ("peaking signal") of new and rare phenomena. The evidence is then analyzed extensively to confirm the presence of new particles.

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"Particle Telescope" at CERN vs. Hubble Space Telescope in outer space.
We expect an evidence of dark matter to appear as "Peaking Signal" in complex final states. LHC is powerful enough to re-discover those particles in 4 months.
Dark Particle Hunters

1400 × 10^{12} Collisions

Peaking Signal of Higgs Bosons (1)

ATLAS Preliminary

H → γγ channel

Data + background-only

\int L = 0.02 fb \text{, Apr 18, 2011}
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The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles."

Nobel Prize in 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles."

1400 x 1012 Collisions

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Sheldon Cooper

July 4, 2012

Peaking Signal of Higgs Bosons (II)
Why $1400 \times 10^{12}$?

Supposed that you have a black box of a “die” system (you don’t know the number of dices and its shape), but you know the total number.

How do you know the probability of seeing “1”?  
What do you do to report it accurately?

If the nature were a complex die system, how can we probe?

We need many trials !!!

Quiz: How Many Giraffes?

One !
We need more than one snap-shot!!!

No!  It is two!!

Yes, definitely!!!

Still, one!

Shot #2

Shot #3

Shot #4

Teruki Kamon, Dark Matter Hunters

13 TeV pp Collisions 2015 - 2018

13,000-GeV pp Collisions x 10^12 Collisions

(200+ /g198 12,000) x 10^12 Collisions
How about the dark matter particles?

Where will more new particles be discovered?

Neutrino Mass

Quark, c, b, top,

Bosons
Spin-0, 1

Fermions
Spin-1/2

Gluon

Graaviton
Spin-2

Spin-0, 1

Quark, c, b, top,

W, Z, h

Neutrino Mass

Which particle is which?

My Answer: (Excitement) = (Motivation) x (Curiosity)²

(PROGRESS) = (SPEED x LEARNING) / (COST) or P = SL / C

Your Answer:

(PROGRESS) = (SPEED x LEARNING) / (COST) or P = SL / C

Contents

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(well, those $\Omega_{DM}$ and the Milky Way background by E.M. inclinations with cosmic images of Emission Acoustic?

Premiere Props

©

Dark Matter "Cube Menu"

Still huge puzzle

Dark Matter (27%)

Ordinary Matter (5%)

New Particles?

An elementary particles?

What is the dark matter?

Explained by known Particles.
Particle-Physics in Movie [2]