Introduction to Physics Research
Origin of Universe and Ourselves

Katsushi Arisaka

University of California, Los Angeles
Department of Physics and Astronomy

arisaka@physics.ucla.edu
Why are we here?
Solar System

Sun

Earth
History of Life and the Human beings

Time

- 10B years
  - Big Bang!
  - Solar System formed

- 1 Billion
  - First life on the Earth
  - Plants, Fish...

- 100 M
  - Mammals

- 1 Million
  - Homo sapiens

- 100,000

- 10,000

- 1,000
  - Jesus Christ was born.

- 100
  - Einstein was born.

- 10
  - You were born.

- 1 year

- 100 days

- 10 days

- 1 day

- 10 hours

- 1 hour
  - You woke up this morning.

- 10 minutes

- 1 minute
  - You saw this viewgraph.
Brief History of Universe and Life

- **Big Bang!**
- **First Galaxy formed**
- **Solar System formed**
- **First life on the Earth**
- **Plants, Fish...**
- **Homo sapiens**
- **You were born.**

*You were born.*

**Telescopes**

**Fossils**
Andromeda

~100 Billions Stars in a Galaxy
Hubble Deep Field

~100 Billion Galaxies
Red shift up to ~10
Hubble’s Law: Expansion of the Universe

Big Bang!

Sun/Earth

14 Billion Light Years

Moving Away at Speed of Light

Horizon of Universe
Expansion of Universe

Size of Universe $\propto \sqrt{\text{Time}}$

Horizon $\propto cT$
Temperature of Universe

Temperature = 1/Size

Temperature = 2.7°K
Tevatron at Fermi Lab near Chicago (1980 – 2010)

6km Circumference
Elementary Particles

ATOM

NUCLEUS

PARTICLE

QUARK

ELECTRON
Elementary Particles

Fermions

<table>
<thead>
<tr>
<th>Charge</th>
<th>up (u)</th>
<th>charm (c)</th>
<th>top (t)</th>
<th>photon (γ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge</th>
<th>down (d)</th>
<th>strange (s)</th>
<th>bottom (b)</th>
<th>gluon (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge</th>
<th>electron neutrino (ν_e)</th>
<th>muon neutrino (ν_μ)</th>
<th>tau neutrino (ν_τ)</th>
<th>Z boson (Z)</th>
<th>W boson (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>±1</td>
<td></td>
</tr>
</tbody>
</table>

Bosons

Charge

<table>
<thead>
<tr>
<th>Charge</th>
<th>0</th>
<th>0</th>
<th>±1</th>
</tr>
</thead>
</table>

Three Families of Matter

+ Anti-particles
Elementary Particles and Forces

**Strong**
- Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

\[ 1 \]

**Weak**
- Bosons (W, Z)
- Neutron decay
- Beta radioactivity
- Neutrino interactions
- Burning of the sun

\[ 10^{-13} \]

**Electromagnetic**
- Photon
- Atoms
- Light
- Chemistry
- Electronics

\[ 10^{-2} \]

**Gravitational**
- Graviton?
- Solar system
- Galaxies
- Black holes

\[ 10^{-38} \]
Unification of Forces (1980)

- Strong force
- Electromagnetic force
- Weak force
- Electroweak
- Gravity

Grand Unification

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>10^{15}</th>
<th>10^{29}</th>
<th>10^{32}</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^{16} GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^{19} GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Copyright © Addison Wesley.
Unification of Forces (1980)

- Strong force
- Electromagnetic
- Weak force
- Electroweak
- GUT force

Plank Epoch

Relative strength of force

Gravity: 100 GeV

Temperature (K):
- 10^{15}
- 10^{29}
- 10^{32}

10^{16} GeV
10^{19} GeV

Copyright © Addison Wesley.
Physicists’ View of Early Universe

Fiat lux
Let there be light
Structure of DNA

3 billion base pairs
Symmetry Breaking

Simple

Symmetry Break Down

Complex
The Beginning

Everything was the same ↔ Perfect symmetry.
- All the particles are the same as photons.
- All four forces are the same.

The Universe was 10 dimension.
Spontaneous Symmetry Breakdown at a Dinner Table

Dinner Table

Dish

Glass of Water

by Nambu Yoichiro
Seven Phases of Cosmic Evolution

Spontaneous Symmetry Breaking

14 billion years ago

Origin of Particles
CERN and LHC in Geneva

27km Circumference

7+7=14 TeV
# CMS Collaboration (1993 ~

(144 Institutions with about 1700 scientists)

| ARMENIA | · Yerevan Physics Inst., Yerevan |
| AUSTRIA | · HEPHY, Wien |
| BELARUS | · Institute of Nuclear Problems, Minsk |
| · National Centre of Part. and HEP, Minsk |
| · Res. Inst. of Applied Physical Probl., Minsk |
| · Byelorussian State Univ., Minsk |
| BELGIUM | · Univ. Instelling Antwerpen, Wilrijk |
| · Univ. Libre de Bruxelles, Brussels |
| · Vrije Universiteit Brussel, Brussels |
| · Univ. Catholique de Louvain, Louvain-la-Neuve |
| · Univ. de Mons-Hainaut, Mons |
| BULGARIA | · Inst. for Nucl. Res. and Nucl. Energy, Sofia |
| · Univ. of Sofia, Sofia |
| CHINA, PR | · Inst. of High Energy Physics, Beijing |
| · Peking Univ., Beijing |
| · Univ. for Science & Tech. of China, Hefei, Anhui |
| CROATIA | · Tech. Univ. of Split, Split |
| CYPRUS | · Univ. of Cyprus, Nicosia |
| ESTONIA | · Inst. of Chemical Phys. and Biophys., Tallinn |
| FINLAND | · Helsinki Institute of Physics, Helsinki |
| · Optphys. Univ. of Helsinki, Helsinki |
| · Univ. of Jyväskylä, Jyväskylä |
| · Helsinki University of Technology, Helsinki |
| · Univ. of Oulu, Oulu |
| · Tampere Univ. of Tech., Tampere |
| FRANCE | · LAPP, IN2P3-CNRS, Annecy-le-Vieux |
| · IPN, IN2P3-CNRS, Univ. Lyon I, Villeurbanne |
| · LPCHE, Ecole Polytech., IN2P3-CNRS, Palaiseau |
| · DSM/DAPNIA, CEA/Saclay, Gif-sur-Yvette |
| · IRIM, IN2P3-CNRS - ULP, UHA, LEPSI, Strasbourg |
| GEORGIA | · High Energy Phys. Inst., Tbilisi State Univ., Tbilisi |
| · Inst. of Physics Academy of Science, Tbilisi |
| GERMANY | · RWTH, I. Physik. Inst., Aachen |
| · RWTH, III. Physik. Inst. A. Aachen |
| · RWTH, Physik. Inst. B. Aachen |
| · Humboldt-Univ. zu Berlin, Berlin |
| · Inst. für Exp. Kompphysik, Karlsruhe |
| · Univ. of Athens, Athens |
| · Inst. of Nucl. Phys. "Democritos", Attiki |
| · Univ. of Ioannina, Ioannina |
| HUNGARY | · KFKI Res. Inst. for Part. & Nucl. Phys., Budapest |
| · Kossuth Lajos Univ., Debrecen |
| · Institute of Nuclear Research ATOMKI, Debrecen |
| · Panjab Univ., Chandigarh |
| · Bhabha Atomic Res. Centre, Mumbai |
| · Univ. of Delhi South Campus, New Delhi |
| · IFIPT, IHEP, Mumbai |
| · TIFR - HECR, Mumbai |
| INDIA | · Univ. di Bari e Sez. dell INFN, Bari |
| · Univ. di Bologna e Sez. dell INFN, Bologna |
| · Univ. di Catania e Sez. dell INFN, Catania |
| · Univ. di Firenze e Sez. dell INFN, Firenze |
| · Univ. di Genova e Sez. dell INFN, Genova |
| · Univ. di Padova e Sez. dell INFN, Padova |
| · Univ. di Pavia e Sez. dell INFN, Pavia |
| · Univ. di Perugia e Sez. dell INFN, Perugia |
| · Univ. di Pisa e Sez. dell INFN, Pisa |
| · Univ. di Roma I e Sez. dell INFN, Roma |
| · Univ. di Torino e Sez. dell INFN, Torino |
| KOREA | · Cheju National University, Cheju |
| · Chonnam National University, Kwangju |
| · Chonbuk National University, Chongju |
| · Dongguk University, Suwon |
| · Kangnung National University, Gangnung |
| · Kangwon National University, Chuncheon |
| · Kon-Kuk University, Seoul |
| · Korea University, Seoul |
| · Kyungpook National University, Taegu |
| · Pohang University of Science and Technology, Pohang |
| · Yonsei University, Seoul |
| · Yonsei University, Seoul |
| · Seoul National Univ. of Education, Seoul |
| · Wonsung University, Iri |
| · Quaid-I-Azam Univ., Islamabad |
| · Ghulam Ishaq Khan Institute, Swabi |
| · Inst. of Exp. Phys., Warsaw |
| · Soltan Inst. for Nucl. Studies, Warsaw |
| · ULP, Lisbon |
| · JINR, Dubna |
| · Inst. for Nucl. Res., Moscow |
| · Inst. for Theoretical and Exp. Phys., Moscow |
| · P.N. Lebedev Phys. Inst. Moscow |
| · Moscow State Univ., Moscow |
| · Budker Inst. for Nucl. Phys., Novosibirsk |
| · Inst. for High Energy Phys., Protvino |
| · Petersburg Nucl. Phys. Inst., Gatchina (St Petersburg) |
| · Slovak University of Technology, Bratislava |
| · IREMA, Madrid |
| · Univ. Autonoma de Madrid, Madrid |
| · Univ. de Oviedo, Oviedo |
| · IFCA, CSIC-Univ. de Cantabria, Santander |
| · Univ. Basel, Basel |
| · CERN, Geneva |
| · Paul Scherrer Inst., Villigen |
| · Inst. for Teilchenphysik, ETH, Zurich |
| · Univ. Zürich, Zurich |
| · CERN, Geneva |
| · Paul Scherrer Inst., Villigen |
| · Inst. für Teilchenphysik, ETH, Zurich |
| · Univ. Zürich, Zurich |
| · Middle East Technical Univ., Ankara |
| · Inst. of Single Crystals of Nat. Acad. of Science, Kharkov |
| · Kharkov Inst. of Phys. and Tech., Kharkov |
| · Kharkov State Univ., Kharkov |
| · Univ. of Bristol, Bristol |
| · Brunel Univ., Uxbridge |
| · Imperial College, Univ. of London, London |
| · UCLA, Los Angeles |
| · Univ. of California San Diego, La Jolla |
| · Virginia Polytech. Inst. and State Univ., Blacksburg |
| · Univ. of Wisconsin, Madison |
| · Inst. of Nucl. Phys. of the Uzbekistan Acad. of Sciences, Tashkent |
Particle detectors constructed at Westwood, now at LHC, CERN
First Event at LHC – Recreation of the Big Bang!  (Nov 7, 2009)
Physicists find 'tantalizing hints' of Higgs boson 'God particle'

Two teams of scientists at the Large Hadron Collider in Geneva say they have detected "tantalizing hints," but not definitive proof, of the long-sought Higgs boson, the so-called God particle that is crucial to physicists' understanding of why mass exists in the universe.

Physicists announced Tuesday that they had detected "tantalizing hints," but not definitive proof, of the long-sought Higgs boson, the so-called God particle that is crucial to physicists' understanding of why mass exists in the universe.

Two large teams of scientists based at the Large Hadron Collider near Geneva separately saw what they believe are telltale tracks of the maddeningly elusive particle in the aftermath of about 400 trillion proton collisions carried out since January.
Seven Phases of Cosmic Evolution

Spontaneous Symmetry Breaking

14 billion years ago
Dark Matter is required!
Formation of Structure in the Universe

Dark Matter is required!
Cosmic Pie Chart

- Dark Energy: 70%
- Dark Matter: 25%
- Free Hydrogen and Helium: 4%
- Stars: 0.5%
- Neutrinos: 0.3%
- Heavy Elements: 0.03%
What is Dark Matter?

- Must be a heavy particle
  - Only weakly interacting.
  - Gravitationally attracted.

- Candidates
  - “MACHO” (Massive Compact Halo Objects)  X
    - → Baryonic Dark Matter
  - Heavy Neutrino  X
    - → Hot Dark Matter
  - “WIMP” (Weakly Interacting Massive Particle)”
    - → Cold Dark Matter
SUSY Particles and Neutralino

Spin: 1/2, 1, 0
SUSY Particles and Neutralino

Super Symmetry

Neutralino
XENON100 Detector

170 kg

(50 kg)
XENON100 Detector (2009)
Where backgrounds come from?

Ultimately photon detectors are the major source of backgrounds.
Structure and Electron Trajectories of 3” QUPID

Photo Cathode (-6 kV)

Quartz

Al coating

APD (0 V)

Quartz

Quartz
Mechanical Samples on Base plate
Comparison of Detector Size

<table>
<thead>
<tr>
<th>Year</th>
<th>Detector</th>
<th>Size (kg)</th>
<th>Weight (kg)</th>
<th>Diameter (cm)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>ZEPLIN-II</td>
<td>31 kg</td>
<td>14 kg</td>
<td>14 cm</td>
<td>1 m</td>
</tr>
<tr>
<td>2007</td>
<td>XENON10</td>
<td>14 kg (5.4 kg)</td>
<td>170 kg (50 kg)</td>
<td>15 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>2009</td>
<td>XENON100</td>
<td>14 kg (5.4 kg)</td>
<td>170 kg (50 kg)</td>
<td>30 cm</td>
<td>30 cm</td>
</tr>
<tr>
<td>2011</td>
<td>XENON100+</td>
<td>250 kg (100 kg)</td>
<td>170 kg (50 kg)</td>
<td>60 cm</td>
<td>2 m</td>
</tr>
<tr>
<td>2014</td>
<td>XENON1ton</td>
<td>2.7 ton (1 ton)</td>
<td></td>
<td>1 m</td>
<td>1 m</td>
</tr>
<tr>
<td>2017</td>
<td>XAX</td>
<td>19 ton (10 ton)</td>
<td></td>
<td>2 m</td>
<td>2 m</td>
</tr>
</tbody>
</table>

Katsushi Arisaka, UCLA
XENON1T

Alex’s Project
**MAX Detector (G3)**

- **Xe**
  - 20 ton (10 ton)

- **$^{40}$Ar**
  - 70 ton (50 ton)

- 3” QUPID x 595 (Top)
- 3” QUPID x 595 (Bottom)

- 3” QUPID x 2644 (Top)
- 3” QUPID x 2644 (Bottom)
Seven Phases of Cosmic Evolution

14 billion years ago

Origin of Particles

Origin of Structure

Origin of Life

Spontaneous Symmetry Breaking
Organic Polymers (4.5B → 4B years)

organic monomers from space

organic polymers

an amino acid

organic monomers

inorganic molecules from Earth

methane

water

carbon dioxide

hydrogen cyanide
RNA Word (4B → 3.5B years ago)


2. RNA molecules become self-replicating.

3. Membrane-enclosed pre-cells arise.

4. True cells with RNA genome appear.

5. Modern cells with DNA genome evolve.
Eukaryote (~2 Billion years ago)

Symmetry breaking

Cell made by proteins

Gene made by DNA

Up to ~2 m long

2 nm wide

10 – 50 μm
How to observe the “Origin of Life”

- Exactly the same way as we look for the “Origin of Universe”

  Telescope ↔ Microscope

- We must look for “Live Life”

- Take advantages of the state of art “Photon Detectors” in particle physics.
The H33D detector attaches to a standard fluorescence microscope. It will permit to track multicolor qdot-labeled proteins in live cells virtually background-free.

Single Molecule Imaging

Particle Physics Detector

Nano Technology

Prof. Shimon Weiss

Katsushi Arisaka, UCLA
Gold nano particle (40nm) attached to Transferrin Receptor (TfR) on Cancer Cell

Prof. Manuel Penichet (Oncology)

(10,000 frame/sec)

UCLA Fast Bio-Imaging Group
Arisaka’s Campus-wide Collaborations on High-Speed Bio-imaging

California Nano Systems Institute (CNSI, Laurent Bentolila)

Dept. of Physics & Astronomy (Dolores Bozovic, Mayank Mehta)

Dept. of Electrical Engineering (Bahram Jalali)

Dept. of Chemistry & Biochemistry (Shimon Weiss)

Dept. of Surgical Oncology (Manuel Penichet)

Dept. of Neurology & Neurobiology (Carlos Portera-Cailliau, Jack Feldman, Tom Otis, Joshua Trachtenberg)

Industrial Partners (Hamamatsu Photonics, Photron, Leica, Spectra Physics)

11/14/12 Katsushi Arisaka, UCLA
High-speed Confocal Microscope with ICMOS at CNSI
(1,000 frame/s)

ICMOS Camera
(Photron SV200i)

Leica Microscope

EMCCD Camera
(Ando iXon 897)

Confocal Spinner
(Yokogawa CSU-X1)

Laurent Bentolila (CNSI)
Seven Phases of Cosmic Evolution

Spontaneous Symmetry Breaking

Origin of Particles
Origin of Structure
Origin of Life
Origin of Consciousness

14 billion years ago
Ca^{2+} Signal in cultivated Rat’s Brain
Assembly of cortical circuits during development

Sensory (afferent) Neurons

Sensory input

INTEGRATION

Interneurons

Motor (efferent) Neurons

Motor output

Brain and spinal cord

Peripheral nervous system (PNS)

Central nervous system (CNS)
How can I recognize a woman so far away?

- Genetically encoded?
- Learning and memory?
The Cerebral Cortex

Conscious

Unconscious

1
2
3
4
5
6
7

Thalamus
Subcortical areas
Nature vs. Nurture

Nature → Nurture
Mutiphoton Microscope

Conventional Confocal

Two Photon Excitation

440 nm

500 – 600 nm

880 nm

500 – 600 nm
In vivo calcium imaging of neuronal activity
3D Structure of Barrel Cortex of Mouse

Fluo-4 AM labeled astrocytes are colabeled with sulforhodamine 101 to eliminate background (yellow)

Sulforhodamine 101 labeled astrocytes (orange)

Fluo-4 AM labeled neurons in layer 2/3 (green)

Layer 5 pyramidal neuron soma and apical dendrite from a transgenic animal demonstrates imaging depth (blue)

Glass microelectrode for dye injection and electrophysiology
- cell-attached voltage follower
- whole-cell voltage/current clamp
- $10^{15}$ Ohm input impedance, < 150 fA input current bias

150 µm deep

Adrian Cheng (Physics)
Tiago Goncalves, Peyman Golshani, Carlos Portera-Cailliau (Neurology)
In vivo calcium imaging of Barrel Cortex of Mouse

Barrel Cortex Layer 2/3
150 µm deep
240 fps Raw Data (x3 faster than real)

Beam 1 (0 ns)
Beam 2 (+3 ns)
Beam 3 (+6 ns)
Beam 4 (+9 ns)
In vivo calcium imaging of Barrel Cortex of Mouse

Barrel Cortex
Layer 2/3
150 µm deep

After averaging (x3 faster than real)

58 neurons
(~100 billions neurons in our brain)

300 µm
Activity of (excitatory) pyramidal neurons in CA depends on rat’s position: place cells

Hippocampus has a cognitive map of space
Learning and Memory by Hippocampus

Motion Direction

Firing Rate Hz

After learning

Before learning

Location cm

Mayank Mehta (UCLA)
Virtual Reality Experiment on Awake Rats

Two Photon Excitation Microscope

Ti:Sa Laser

Spherical Screen for Virtual Vision

Speakers

Olfactory Stimulator

Tetrodes

Floating Ball

Optical Mice

Pressurized air

Mayank Mehta
Daniel Aharoni
Bernard Willers
Seven Phases of Cosmic Evolution

Spontaneous Symmetry Breaking

14 billion years ago

Origin of Particles
Origin of Structure
Origin of Life
Origin of Consciousness
Why are we here?
Cyclic Model

- “bang”
- radiation
- matter
- dark energy
- “contraction”
- “crunch”

M theory

Shadow Universe

Our Universe
Are there more than one Universe?
Linde’s Multiverse by Chaotic Inflation
There may be ~100 Billion Universes.
Four Major Science

Origin of Particles
Particle Physics

Origin of Universe
Cosmology

Origin of Life
Molecular Biology

Origin of Consciousness
Neurophysics