Cosmology and Particle Astrophysics

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Talk Outline

Part I 8:10-9:30am
- Introduction to Cosmology
  - From Quarks to Cosmos
  - Origin of Universe
  - Remaining Questions

Part II 10:00-11:00am
- Particle Astrophysics
  - Messengers from the Earliest and the Extreme Universe

Discussion 11:00-11:30am
Part I

Introduction to Cosmology
Central Theme

➢ Why are we here?
  - Origin of Ourselves
  - Origin of Life
  - Origin of the Solar System
  - ...
  - Origin of the Universe

➢ What is the most fundamental law in nature?
History of Life and the Human beings

Time
- 10B years
- 1 Billion
- 100 Million
- 10 Million
- 1 Million
- 100,000
- 10,000
- 1,000
- 100
- 10
- 1 year
- 100 days
- 10 days
- 1 day
- 10 hours
- 1 hour
- 10 minutes
- 1 minute

Big Bang!
Solar System formed
First life on the Earth
Plants, Fish...
Mammals
Homo sapiens

Fossils

Written Documents

Videos, Pictures

Jesus Christ was born.
Einstein was born.
You were born.

You woke up this morning.
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.**
- **Telescopes**
- **Fossils**
~100 Billions Stars in a Galaxy

ANDROMEDA GALAXY
Hubble Deep Field

Red shift up to ~10

~100 Billion Galaxies
Hubble’s Law: Expansion of the Universe

Sun/Earth

Horizon of Universe

1.4 Billion Light Years

Moving Away at Speed of Light
Expansion of Universe

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

Horizon $\propto cT$
Temperature of Universe

Temperature = 1/Size

Temperature = 2.7°K
Evolution of the Early Universe

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Temp. (°K)</th>
<th>Energy (GeV)</th>
<th>Radius of Universe (cm)</th>
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<td>10^{-20}</td>
<td>10^5</td>
<td>1 TeV</td>
<td>1 Light Year</td>
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<td>Galaxy</td>
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<td>10^9 year</td>
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Big Bang!

Now
Tools to explore the Early Universe

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Fermi Lab near Chicago

6km Circumference
1+1=2 TeV
Elementary Particles (~1970)
Elementary Particles and Forces

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

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

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

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

**Force Carriers**
- Matter (fermions)
- Force carriers (bosons)

**Examples**
- \( p = uud \); \( \Lambda^0 = uds \); \( \Lambda^0_b = udb \)
- \( \pi^+ = ud \); \( \psi = cc \); \( Y = bb \)
Unification of Fundamental Forces
(~1975)

Time (sec)

10^{-45} \text{sec}
10^{-40}
10^{-35}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^5 \text{sec}
1 \text{ year}
10^3
10^6
10^9 \text{ year}

Temp. (°K)

Energy (GeV)

10^{18}
10^{15}
10^{12}
10^9
1 \text{ PeV}
1 \text{ TeV}
1 \text{ GeV}
1 \text{ MeV}
1 \text{ eV}
10^{-3} \text{ eV}

Fundamental Interaction

GUT
Electro-Weak
Strong
Gravitation

Energy (GeV)

10^{18}
10^{15}
10^{12}
10^9
1 \text{ PeV}
1 \text{ TeV}
1 \text{ GeV}
1 \text{ MeV}
1 \text{ eV}
10^{-3} \text{ eV}

6/25/2004 at QuarkNet, Katsushi Arisaka
Physicists’ View of Early Universe

Lorentz Invariance

Local Gauge Invariance
### Symmetry Breaking

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<tr>
<td>$10^9$ year</td>
<td>$10^5$</td>
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**Simple**

**Symmetry Break Down**

**Complex**
Spontaneous Symmetry Breaking
- Higgs Mechanism -
Spontaneous Symmetry Breaking
- Higgs Mechanism -
Spontaneous Symmetry Breakdown at a Dinner Table

by Nambu Yoichiro

6/25/2004 at QuarkNet, Katsushi Arisaka
CERN and LHC in Geneva

27km Circumference
7+7=14 TeV
Higgs Decay into 4 muons (2008?)

(+30 minimum bias events)

All charged tracks with pt > 2 GeV

Reconstructed tracks with pt > 25 GeV
Unification of Fundamental Forces

Time (sec)

10^{-45} sec
10^{-40}
10^{-35}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^5 sec
1 year
10^3
10^6
10^9 year
1

Temp. (°K)

10^{18}
10^{15}
10^{12}
10^9
1 PeV
1 TeV
1 GeV
1 MeV
1 KeV
1 eV
10^{-3} eV

Energy (GeV)

Planck
GUT

10^{18}
10^{15}
10^{12}
10^9
1 PeV
1 TeV
1 GeV
1 MeV
1 KeV
1 eV
10^{-3} eV

Fundamental Interaction

GUT

Proton Decay
(1980)

Electro-Weak

Higgs Mechanism
(1970)

Gravitation

Strong

Weak

Electromagnetic

6/25/2004

at QuarkNet, Katsushi Arisaka

27
“Fossils” from the Earliest Universe

Time (sec) | Temp. (°K) | Energy (GeV)
---|---|---
10^{-45} | 10^{30} | 10^{18}
10^{-40} | 10^{25} | 10^{15}
10^{-35} | 10^{20} | 10^{12}
10^{-30} | 10^{15} | 10^{9}
10^{-25} | 10^{10} | 1 PeV
10^{-20} | 10^{5} | 1 TeV
10^{-15} | 1 | 1 GeV
10^{-10} | 10^{-5} | 1 MeV
10^{-5} | 10^{-10} | 1 KeV
1 | 10^{-15} | 1 eV
10^{5} | 10^{-20} | 10^{-3} eV
1 year | 10^{5} |
10^{3} | 10^{10} | Now
10^{6} | 10^{15} | Relic Neutrino (Hot Dark Matter)
10^{9} year | 10^{20} | CMB

Gravitational Wave
GUT Particle

Decoupling of “Fossils”

Neutralino (Cold Dark Matter)

The Big Bang!

6/25/2004 at QuarkNet, Katsushi Arisaka
Cosmic Microwave Background (CMB) Matter-Radiation Decoupling

Time (sec)

10^{-45} sec
10^{-40}
10^{-35}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^5 sec
1 year
10^3
10^6
10^9 year

Temp. (°K)

10^{25}
10^{15}
10^9
10^6
10^5

Energy (GeV)

10^{18}
10^{15}
10^{12}
10^9
1 PeV
1 TeV
1 GeV
1 MeV
1 KeV
1 eV
10^{-3} eV

Planck
GUT
EW

Time = 300,000 years
Temperature = 3,000 °K
Energy = 0.3 eV
Z = 1,100

Matter-Radiation Decoupling ⇒ CMB
Cosmic Microwave Background (Discovered in 1964)

T = 300,000 years after the Big Bang

Temperature = 3,000°K

z = 1,100

Today: 3000°K/1,100 = 2.7°K
Expansion of Universe

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

Horizon $\propto cT$

Same Temperature within $1^\circ$

Beginning $300k$ Years

Today
Universe is Flat.  \Rightarrow \text{Inflation}
Geometry of the Universe

- **Open** $\Omega < 1$
- **Flat** $\Omega = 1$ (predicted by Inflation)
- **Closed** $\Omega > 1$
**Two Fundamental Problem of Big Bang Cosmology**

**Horizon Problem**
- At early Universe, Size $>>$ Horizon.
- Why is CMB so uniform in every direction?

**Flatness Problem**
- $|\Omega-1|$ grows promotional to the size of the Universe.
- Why is $\Omega$ of today close to 1?
Inflation in Early Universe

Size

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

Horizon $\propto cT$

Beginning

Today

Time

Inflation
Origin of Inflation
Origin of Large Scale Structure

Dark Matter is required!
CDMS Dark Matter Detector
Zeplin Dark Matter Detector

Zeplin II

Zeplin IV

Liquid Xenon Scintillator
SDSS (Sloan Digital Sky Survey)

- 2.5m Diameter
- 3° x 3° FOV
- f/2.25
- 30 x 4Mega-pixel CCD

Focal Plane
Density Fluctuations

\[ \Omega_{\text{Matter}} = 0.3 \]
Supernova as a Standard Candle

Supernova 1998ba
Supernova Cosmology Project

(as seen from Hubble Space Telescope)

3 Weeks Before
Supernova Discovery

(as seen from telescopes on Earth)

Difference
The Accelerating Universe (1998)

\[ \Omega_\Lambda = 0.7 \]

After inflation, the expansion either...
- first decelerates, then accelerates
- or always decelerates
- expands forever
- collapses

Billions Years from Today

Origin of Dark Energy

Same as Inflation
Density of Our Universe

- \( \Omega_{\text{Total}} = \Omega_\Lambda + \Omega_{\text{Matter}} = 1.0 \)

- Universe is Flat. \( \Rightarrow \) Inflation

- 70% is Dark Energy. \( \Rightarrow \) Accelerating
Cosmic Pyramid (2003)

- Dark Energy: 70%
- Dark Matter: 25%
- Gas, Dust: 5%
- Star: 0.5%
- Metal: 0.01%

Baryonic Matter

6/25/2004
Cosmic Triple Coincidence

Why Now?

astro-ph/000511
Cosmic Coincidence

- Time (sec)
  - $10^{-45}$ sec
  - $10^{-40}$
  - $10^{-35}$
  - $10^{-30}$
  - $10^{-25}$
  - $10^{-20}$
  - $10^{-15}$
  - $10^{-10}$
  - $10^{-5}$
  - 1
  - $10^5$ sec
  - 1 year
  - $10^3$
  - $10^6$
  - $10^9$ year

- Temp. ($^\circ$K)
  - $10^{30}$
  - $10^{25}$
  - $10^{20}$
  - $10^{15}$
  - $10^9$
  - $10^6$
  - $10^3$
  - 1
  - $10^5$

- Energy (GeV)
  - $10^{18}$
  - $10^{15}$
  - $10^{12}$
  - $10^9$
  - $10^6$
  - $10^3$
  - 1
  - $10^{-3}$

- Energy (eV)
  - $10^{18}$
  - $10^{15}$
  - $10^{12}$
  - $10^9$
  - $10^6$
  - $10^3$
  - 1
  - $10^{-3}$

- $\alpha_{\text{Gravity}} \approx \alpha_{\text{Strong}} \approx \alpha_{\text{EM}} \approx \alpha_{\text{Weak}}$

- $\frac{E_{\text{EW}}}{E_{\text{Planck}}} \approx \frac{E_{\text{Now}}}{E_{\text{EW}}} \approx 10^{-15}$

- $\Omega_{\text{Rad}} \approx \Omega_{\nu} \approx \Omega_{\text{CDM}} \approx \Omega_{B} \approx \Omega_{\Lambda}$
Is there the Unification of Fundamental Forces?

Time (sec)

- $10^{-45}$ sec
- $10^{-40}$
- $10^{-35}$
- $10^{-30}$
- $10^{-25}$
- $10^{-20}$
- $10^{-15}$
- $10^{-10}$
- $10^{-5}$
- 1
- $10^5$ sec
- 1 year
- $10^3$
- $10^6$
- $10^9$ year

Temp. ($^\circ$K)

- $10^3$
- $10^{25}$
- $10^{20}$
- $10^9$
- $10^8$
- $10^7$
- $10^6$
- $10^5$
- $10^4$

Energy (GeV)

- $10^{18}$
- $10^{15}$
- $10^{12}$
- $10^9$
- $10^8$
- $10^7$
- $10^6$
- $10^5$
- $10^4$
- $10^3$
- $10^2$
- $10^1$
- $10^{-1}$

Energy (eV)

- $10^{18}$
- $10^{15}$
- $10^{12}$
- $10^9$
- $10^6$
- $10^3$
- $10^1$
- $10^{-1}$

Fundamental Interactions

- GUT
- Electro-Weak
- Electromagnetic
- Strong
- Gravitation

Planck

GUT

EW

Now

10^{-3} eV

6/25/2004 at QuarkNet, Katsushi Arisaka
Is there the Unification of Fundamental Forces?

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<td>10^{-3} eV</td>
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<tr>
<td>10^6 year</td>
<td>10^5</td>
<td>Now</td>
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Fundamental Interactions:
- EW (Electro-Weak)
- GUT (Grand Unified Theory)
- Gravitation
- Strong
- Weak
- Electromagnetic
Cyclic Model

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

M theory

Shadow Universe

Our Universe
Are there more than one Universe?
$10^{100}$ possible vacuum states

Bousso, Polchinski, 2000
Douglas, 2003

Prediction by String Theory
Linde’s Multiverse by Chaotic Inflation
There may be ~100 Billion Universes.
Part II

Particle Astrophysics
Cosmic Radiation

(by Halzen after Ressell & Turner ‘90)
Tools to Explore the Early Universe

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<tr>
<td>$10^{9}$ year</td>
<td>1</td>
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</table>

- **UHE Cosmic Rays**
- **Accelerator**
- **Telescope**
The Extreme Universe

Time (sec) | Temp. (°K) | Energy (GeV)
--- | --- | ---
$10^{-45}$ sec | $10^3$ | $10^{18}$
$10^{-40}$ | $10^9$ | $10^{15}$
$10^{-35}$ | $10^{12}$ | $10^{12}$
$10^{-30}$ | $10^{10}$ | $10^9$
$10^{-25}$ | $10^7$ | $1PeV$
$10^{-20}$ | $10^5$ | $1TeV$
$10^{-15}$ | $10^3$ | $1MeV$
$10^{-10}$ | $10$ | $1KeV$
$10^{-5}$ | $1$ | $1eV$
$1$ year | $10^5$ | $10^{-3}eV$
$10^3$ | $10^5$ | $10^{-3}eV$
$10^6$ | $10^5$ | $10^{-3}eV$
$10^9$ year | $1$ | $10^{-3}eV$

Big Bang

Gamma Ray Burst
Active Galactic Nuclei
Supernova
Neutron Star
Black Holes

Planck
GUT
EW

6/25/2004 at QuarkNet, Katsushi Arisaka
The Extreme Universe

EGRET All-Sky Map Above 100 MeV

AGN

SNR

Radio Galaxy

Pulsar

GRB
Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust Disk

380 Arc Seconds
88,000 LIGHTYEARS

17 Arc Seconds
400 LIGHTYEARS
AGN Central Engine
Absorption of photons by Atmosphere

[Graph showing the absorption of photons by the atmosphere across different wavelength ranges.]
Gamma ray Telescopes

VERITAS

- 10m Diameter
- ~500 PMT/Camera
- 4-7 Telescopes

Prof. Rene Ong

HESS

- 8.5 km
- 0.8° Cerenkov Light Cone
- 80 m

6/25/2004 at QuarkNet, Katsushi Arisaka
Super-Kamiokande

- 11,200 of 20” PMTs
Nuclear Burning in High Mass Stars
(times for a 20 $M_\odot$ star)

- Hydrogen: $10^7$ yr
- Helium: $10^6$ yr
- Carbon: $10^3$ yr
- Oxygen: 1 yr
- Neon
- Magnesium
- Silicon: 1 week
- Iron: $< 1$ day
Nobel Prize in 2002

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.  Masatoshi Koshiba  Riccardo Giacconi
10 TeV Muon Event

AMANDA-II

IceCUBE

Ice Top
Snow Layer

IceCube

1 km

6/25/2004 at QuarkNet, Katsushi Arisaka
High Energy Neutrino

Prof. David Saltzberg

SN1987A
LISA Detector Concept

[Diagram of LISA configuration with orbits of Earth, Venus, and Mercury around the Sun, illustrating relative orbits of spacecraft with 5 x 10^6 km distance.]
Sensitivity of LIGO and LISA

- Coalescence of Massive Black Holes
- Resolved Galactic Binaries
- Unresolved Galactic Binaries
- NS–NS and BH–BH Coalescence
- SN Core Collapse

Gravitational Wave Amplitude vs. Frequency [Hz]

6/25/2004 at QuarkNet, Katsushi Arisaka
Gravitational Waves Escape from the Earliest Moments of the Big Bang

- Big Bang
- Inflation (Big Bang plus $10^{-35}$ seconds)
- Big Bang plus 300,000 Years
- Gravitational Waves
- Big Bang plus 15 Billion Years
- Cosmic microwave background, distorted by seeds of structure and gravitational waves
- Light
- Now
Gravitational Wave
Ultimate Goals

- **Energy Frontier of Particle Physics, Cosmology and Astronomy**
  - Earliest Universe: Inflation, Planck Scale ...
  - Extreme Universe: AGN, GRB ...

- **Need for Multi-Messenger Approach**
  - Gamma ray: Veritas, GLAST ...
  - Charged Particle: Auger, EUSO ...
  - Neutrino: Icecube, Auger ...
  - Gravitational Wave: LIGO, LISA ...
Cosmic Radiation

(by Halzen after Ressell & Turner '90)

6/25/2004 at QuarkNet, Katsushi Arisaka
Energy Spectrum of Cosmic Rays

- Energy Spectrum \( \sim E^{-3} \)
- The spectrum extends beyond \( 10^{20} \text{eV} = 10^{11} \text{GeV} \).
- Beyond \( 10^{20} \text{eV} \), Flux is only one particle per \( \text{km}^2 \)-century.
Possible Acceleration Sites

- Several possible accelerators in nature up to $10^{20}$eV.

- Extremely difficult to accelerate above $10^{20}$eV.
Effect of GZK Cut-off

- Protons above $\sim 10^{20}\text{eV}$ cannot travel more than $\sim 50\text{Mpc}$ ($\sim 1\%$ of the Horizon of the Universe.)
Interaction Length of UHE Protons

Blasi, astro-ph/0307067
Trajectory of Cosmic Ray Protons in the Galaxy

\[ E=10^{20}\text{eV} \quad E=10^{19}\text{eV} \quad E=10^{18}\text{eV} \]
Trajectories of Protons in inter Galactic Space

3D trajectories projected on X–Y plane

- B = 10^-9 gauss
- Cell size 1Mpc
- B dir random

- Y (Mpc)
- X (Mpc)

- 10^{18} eV
- 3 \times 10^{18} eV
- 10^{19} eV
- 10^{20} eV

Jim Cronin, astro-ph/0402487
6/25/2004
at QuarkNet, Katsushi Arisaka
Why is \( \sim 10^{20} \text{ eV} \) so special?

- Protons can **not** travel beyond \( \sim 100 \text{Mpc} \) at \( E > 10^{20} \text{eV} \) due to interaction with CMB.
  - **GZK Cut-off**

- Protons can travel straight at \( E > \sim 4 \times 10^{19} \text{eV} \).
  - **Charged-Particle Astronomy**
  - **New Window of Extreme Universe**

- Difficult to accelerate beyond \( 10^{20} \text{eV} \).
  - **Top-down Mechanism?**
Rich Physics and Astronomy

\[ 10^{18} \text{ eV} \]
\[ 10^{19} \text{ eV} \]
\[ 10^{20} \text{ eV} \]
\[ 10^{21} \text{ eV} \]

Top-Down?

GZK?

Charge Particle Astronomy

Bottom-Up

Trapped by Inner-Galactic B (~μG)

Bent by Extra-Galactic B (~nG)

Straight Trajectories

Ankle

6/25/2004 at QuarkNet, Katsushi Arisaka
Galaxies (R < 45 Mpc)

Matter (7 < R < 93 Mpc)
Matter Distribution

(7 < R < 93 Mpc)

Projected matter distribution in a constrained realization (7 < R < 93 Mpc)

A. Kravtsov
Distribution of Matter
(7-21Mpc)

Matter distribution 7–21 Mpc. Exclusion zones; north array (black), south array (green)

Jim Cronin, astro-ph/0402487
6/25/2004 at QuarkNet, Katsushi Arisaka
Arrival Direction of UHECR (>4x10^{19}eV) by AGASA

Equatorial Coordinates

- 6 doublets and 1 triplet within 2.5° cone.

• 6 doublets and 1 triplet within 2.5° cone.
HiRes vs. AGASA
# Pierre-Augier Collaboration

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<td><strong>TOTAL</strong></td>
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Pierre-Auguer Observatory

Northern Auger in Utah

Southern Auger in Argentina

at QuarkNet, Katsushi Arisaka
Principle of Hybrid Detection

MC Simulation of $10^{19}$ eV Proton Shower

$10km$

$\sim 27X_0$

$\sim 11\lambda_i$

$e^\pm$

$\mu^\pm$

Ground Array

Air Fluorescence Detector
Southern-Augur in Argentina

Surface Array
1600 Detector Stations
1.5 km spacing
3000 km$^2$

Fluorescence Detectors
4 Telescope Enclosures
6 Telescopes per Enclosure
24 Telescopes Total
The First Fluorescence Detector
Pierre-Augier Shower Detector Tank
UCLA PMT Test Facility at STRB

Four-corner PMTs are kept as reference
PMT Potting Underway at UCLA
# UCLA Auger Group

- **Katsushi Arisaka**
  Professor

- **William Slater**
  Professor

- **Arun Tripathi**
  Research Scientist

- **Tohru Ohnuki**
  5th year grad.

- **David Barnhill**
  4th year grad.

- **Joong Lee**
  3rd year grad.

- **Matt Healy**
  2nd year grad.

- **...**
Annual Festival of Malargue City (Nov, 2003)
Observatorio de Rayos Cósmicos Pierre Auger
Malargüe, Provincia de Mendoza, Argentina
Visiting High School Exhibition
(Nov, 2003)
Receiving 10 tanks per week
Checking Electronics
Don’t get stuck!
Surface Detector inspection by residents of the Pampa
Southern-Augur in Argentina

Surface Array
1600 Detector Stations
1.5 km spacing
3000 km$^2$

Fluorescence Detectors
4 Telescope Enclosures
6 Telescopes per Enclosure
24 Telescopes Total
**Status of Construction**

**Los Leones**
- 350 surface detector stations deployed
- 270 surface detector stations have electronics and are operational – **World’s largest array!**
- 6 telescopes operational in Los Leones

**Coihueco**
- 2 telescopes operational in Coihueco

**Deployed Stations**

**Surface Array**
- 350 surface detector stations deployed
- 270 surface detector stations have electronics and are operational – **World’s largest array!**

**Fluorescence detectors**
- 6 telescopes operational in Los Leones
- 2 telescopes operational in Coihueco
Event Simulation based on Real Event
$\sim 7 \times 10^{19}$ eV Event

Mon Dec 29 09:23:45 2003
Easting= 470347 ± 7m
Northing= 6095443 ± 11m
dt= 114.0ns

Theta= 34.4 ± 0.3 deg
Phi= 140.2 ± 0.3/sin(theta) deg

R= 12.5 ± 0.8 km

Preliminary Xmax= 1040 ± 66 g/cm^2

S(1000)= 365.51 ± 20.78 VEM
E= 74.81 EeV ± 6%
Angular distribution of UHECR by Pierre-Auger (Preliminary, No energy cut)
Two Candidate Sites for Northern Site

- Utah
- Colorado
Colorado Site

View to west, Sept 23, 2003
Integrated Sensitivity (at $10^{20}$ eV)

 updated on 4/24/2004

![Graph showing integrated sensitivity over time for various experiments such as Flye Eye, AGASA, HiRes-Mono, Auger-S, Auger-N, Original Auger(S+N), and EUSO. The graph plots integrated aperture (km$^2$*str*year) against year (1985 to 2020).]
EUSO/OWL Detector Concept

Owl-AirWatch Detector

\[ H \approx 500 \text{ km} \]

\[ FOV \approx 60^\circ \]

Cosmic Ray Shower

Atmosphere (~10 km)

Ground

\[ \approx 600 \text{ km} \]
EUSO on International Space Station
OWL Stereo View from Space

~1,000km
# Multi-Messenger Exploration

<table>
<thead>
<tr>
<th>Messenger</th>
<th>Experiment</th>
<th>Energy (eV)</th>
<th>Stage</th>
<th>Year Starts</th>
<th>Total Budget (M$)</th>
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<td>Swift</td>
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<td>Y</td>
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<td>Icecube</td>
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<td>LISA</td>
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</tbody>
</table>
Summary

- Why are we here?
- What is the most fundamental law in nature?
- Observation of the extreme universe by cosmic radiations may tell us something totally unexpected.
Thank you!

- Feel free to stop by my office any time.
  - Katsushi Arisaka
  - Knudsen 4-145
  - (310) 825-4925
  - arisaka@physics.ucla.edu

- This talk available at:
  http://www.physics.ucla.edu/~arisaka/quarknet