Trends, Needs and Dreams in Astro-Physics

Katsushi Arisaka

University of California, Los Angeles
Department of Physics and Astronomy

arisaka@physics.ucla.edu
Talk Outline

- **Astro-Physics**
  - Cosmology
  - High-energy Particle Astro-physics

- **Experiments**
  - Ongoing
  - Future

- **Photo-detectors**
  - Demands
  - New Detectors on Horizon
  - Dream Detectors
Talk Outline

- **Astro-Physics**
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  - Demands
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  - Dream Detectors
Hubble Deep Field

~100 Billion Galaxies

Red shift up to 10
Evolution of the Early Universe

Time (sec) | Temp. (°K) | Energy (GeV) | Radius of Universe (cm) | Now
---|---|---|---|---
$10^{-45}$ | $10^{30}$ | $10^{18}$ | $10^{-33}$ | Golf Ball
$10^{-40}$ | $10^{25}$ | $10^{15}$ | $10^{-20}$ | People
$10^{-35}$ | $10^{20}$ | $10^{12}$ | $10^{-15}$ | Mountain
$10^{-30}$ | $10^{15}$ | $10^{9}$ | $10^{-10}$ | Earth
$10^{-25}$ | $10^{10}$ | $1PeV$ | $10^{-5}$ | 1 A.U.
$10^{-20}$ | $10^{5}$ | $1TeV$ | $10^{5}$ | 1 Light Year
$10^{-15}$ | | $1GeV$ | $10^{10}$ | Galaxy
$10^{-10}$ | | $1MeV$ | | |
$10^{-5}$ | | $1KeV$ | | |
1 | $10^{10}$ | $1eV$ | | |
$10^{5}$ sec | $10^{5}$ | $10^{-3}eV$ | | |
1 year | | | | |
$10^{3}$ | | | | |
$10^{6}$ | | | | |
$10^{9}$ year | | | | |

June 17, 2002
Beaune 2002, Katsushi Arisaka
# Tools to explore the Early Universe

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Temp. (°K)</th>
<th>Energy (GeV)</th>
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<tbody>
<tr>
<td>$10^{-45}$</td>
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<td>$10^{-15}$</td>
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<td>$1$</td>
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<td>$10^3$</td>
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<td>$10^{-3}$ eV</td>
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<td>$10^6$</td>
<td></td>
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<tr>
<td>$10^9$ year</td>
<td></td>
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</tr>
</tbody>
</table>

Accelarator

Telescope
Unification of Fundamental Forces

Time (sec) | Temp. (°K) | Energy (GeV)
--- | --- | ---
$10^{-45}$ | $10^{30}$ | $10^{18}$
$10^{-40}$ | $10^{25}$ | $10^{15}$
$10^{-35}$ | $10^{20}$ | $10^{12}$
$10^{-30}$ | $10^{15}$ | $10^9$
$10^{-25}$ | $10^{10}$ | $10^4$
$10^{-20}$ | $10^6$ | $10^1$
$10^{-15}$ | $10^3$ | $1$
$10^{-10}$ | $1$ | $10^{-5}$
$10^{-5}$ | $10^{-3}$ | $10^{-6}$
$1$ | $10^{-9}$ | $10^{-9}$
$10^5$ sec | $10^5$ | $10^{-3}$
$1$ year | $10^5$ | $10^{-3}$
$10^3$ | $10^5$ | $10^{-6}$
$10^6$ | $10^6$ | $10^{-9}$
$10^9$ year | $10^9$ | $10^{-12}$

Planck
GUT
EW
Gravitation
Strong
Weak
Electromagnetic

Fundamental Interaction

Energy (GeV)
1 PeV
1 TeV
1 GeV
1 MeV
1 KeV
1 eV
$10^{-3}$ eV

Now
Physicists’ View of Early Universe
Symmetry Breaking

Time (sec)  Temp. (°K)  Energy (GeV)

10^{-45} sec  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}  10^6
10^{-20}  10^5  10^3
10^{-15}  10^{2}  1
10^{-10}  10^{-5}  10^{-10}
10^{-5}  10^{-15}  10^{-20}
1  10^{-25}  10^{-30}
10^5 sec  1 year  10^{-30}
10^{3}  10^{-4}  10^{-3}
10^{6}  10^{-7}  10^{-6}
10^{9} year  10^{-8}  10^{-5}

Simple

Symmetry Break Down

Complex
Relics from the Earliest Universe

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

Big Bang

Gravitational Wave
GUT Particle

Neutralino
(Cold Dark Matter)

Relic Neutrino
(Hot Dark Matter)

CMB
CMB Anisotropy by COBE DMR

North Galactic Hemisphere

South Galactic Hemisphere

$-100 \mu K$  $100 \mu K$
CMB Anisotropy by Boomerang
Recent Results of CMB Anisotropy

Angular Scale [Degrees]

$\ell$ vs. $\left(\ell+1\right)C_{\ell}/2\pi^{1/2}$ [$\mu$K]

- COBE
- MAXIMA
- BOOM2001
- DASI

N=1 H=50 CDM+10% B

Ned Wright - 6 May 2001
The Accelerating Universe

[Graph showing Type Ia Supernovae data with different cosmological models: Open, Flat, and Closed. The graph compares magnitude against redshift, illustrating the accelerating universe concept.]
Density of Our Universe

- Universe is Flat. $\Rightarrow$ Inflation
- 70% is Dark Energy. $\Rightarrow$ Accelerating
Talk Outline

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  - Cosmology
  - High-energy Particle Astro-physics

- Experiments
  - Ongoing
  - Future

- Photo-detectors
  - Demands
  - New Detectors on Horizon
  - Dream Detectors
Relics from the Earliest Universe

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

Temperature ($^\circ$K)

- $10^{30}$
- $10^{25}$
- $10^{20}$
- $10^{15}$
- $10^{10}$
- $10^5$
- $10^3$
- $10^6$
- $10^9$

Energy (GeV)

- $10^{18}$
- $10^{15}$
- $10^{12}$
- $10^9$
- $10^7$
- $10^5$
- $10^3$
- $10^{-3}$

Energy (eV)

- $10^{30}$
- $10^{25}$
- $10^{20}$
- $10^{15}$
- $10^{10}$
- $10^5$
- $10^3$
- $10^1$

Gravitational Wave

GUT Particle

Neutralino
(Cold Dark Matter)

Relic Neutrino
(Hot Dark Matter)

CMB

Dark Energy

Big Bang
Messengers from the Universe

- **Photons**
  - Visible, Infrared, UV
  - X-rays, Gamma-rays
  - Microwave, Radio

- **Charged Particles**
  - Ultra High Energy Cosmic Rays
  - Anti-particles

- **Neutrinos**
  - Solar-neutrino, Supernova
  - Relic Neutrino

- **Dark Matter**

- **Gravitons**
  
  *not covered in this talk*
Messengers from the Universe

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- **Gravitons**
SDSS (Sloan Digital Sky Survey)

- 2.5m Diameter
- $3^\circ \times 3^\circ$ FOV
- f/2.25
- 30 x 4Mega-pixel CCD
SDSS Early Data Release

Goal:

500 sq. degree of the sky.

14 million objects.

Spectra for 50,000 galaxies 5,000 quasars.
LSST (Large-aperture Synoptic Survey Telescope)

- 8m Diameter
- $3^\circ \times 3^\circ$ FOV
- f/1.2, 50cm Focal plane
- 1.4Giga-pixel CCD
NGST (Next Generation Space Telescope)

- Mirror Diameter: ~6.5 m
- FOV: 4’ x 4’
- Wavelength: 0.6-28 μm
- Orbit: L2 point
- Payload mass: ~3000 kg
- Mission duration: 5-10 years

GSFC Design
SNAP (SuperNova Acceleration Probe)

- Mirror Diameter: 2 m
- FOV: 1° x 1°
- Wavelength: 0.35-1 µm
- IR Photometry: 10’ x 10’, HgCdTd
- IR Spectroscopy: 2” x 2”
SNAP – Dark Energy Sensitivity

Current ground-based data compared with binned simulated SNAP data and a sample of Dark Energy models. Each SNAP point represents ~50-supernova bin.
Deep Sky Survey by Telescopes

Field of View (Degree)

Mirror Diameter (Meter)

- Space
  - HST
  - SNAP
  - NGST

- Ground
  - LSST
  - Keck

Larger Mirror
Larger FOV
The Extreme Universe

AGN

SNR

Radio Galaxy

EGRET All-Sky Map Above 100 MeV

Pulsar

GRB
GLAST - Gamma Ray Sky Survey

Si Strip

CsI + Photo Diode

Exploded View: One of Forty-nine Towers

Gamma-ray Large Area Space Telescope

10 Layers of 0.5 rad Length Converter (pb)
12 Layers of XY Silicon Strips

Gamma Rays
Positrons/Electrons
Gamma ray Telescopes

VERITAS

- 8.5 km
- 0.8°
- Cerenkov Light Cone
- 80 m
- ~0.05 - 50 TeV

HESS

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

June 17, 2002
Beaune 2002, Katsushi Arisaka
MAGIC under Construction

- 17m mirror
- 3.6° FOV
- 600 PMTs
- Upgrade to GaAsP HAPD
γ-ray Wide-FOV Telescope

- >3m diameter
- >30° FOV
- Mega pixel
Messengers from the Universe

- **Photons**
  - Visible, Infrared, UV
  - X-rays, Gamma-rays
  - Micro-wave, Radio

- **Charged Particles**
  - Ultra High Energy Cosmic Rays
  - Anti-particles

- **Neutrinos**
  - Solar-neutrino, Supernova
  - Relic Neutrino

- **Dark Matter**

- **Gravitons**
Energy Spectrum of Cosmic Rays

- Energy Spectrum $\sim E^{-3}$
- The spectrum extends beyond $10^{20}$ eV
- Beyond $10^{20}$ eV, Flux is only one particle per km$^2$-century

1 TeV
Tools to explore the Early Universe

Time (sec) | Temp. (°K) | Energy (GeV)
---|---|---
$10^{-45}$ | $10^3$ | $10^{18}$
$10^{-40}$ | $10^9$ | $10^{15}$
$10^{-35}$ | $10^{15}$ | $10^{12}$
$10^{-30}$ | $10^{20}$ | $10^9$
$10^{-25}$ | $10^{25}$ | $10^6$
$10^{-20}$ | $10^{30}$ | $10^3$
$10^{-15}$ | $10^{35}$ | $1$
$10^{-10}$ | $10^{40}$ | $10^1$
$10^{-5}$ | $10^{45}$ | $10^{-3}$
$1$ | $10^{50}$ | $10^{-6}$
$10^5$ sec | $10^5$ | $10^{-9}$
$1$ year | $10^6$ | $10^{-12}$
$10^3$ | $10^9$ | $10^{-15}$
$10^6$ | $10^{12}$ | $10^{-18}$
$10^9$ year | $10^{15}$ | $10^{-21}$

UHE Cosmic Rays

Accelerator

Telescope
Why is $10^{20}$eV so special?

- Nearly impossible to accelerate beyond $10^{20}$eV by nature.  
  → Top-down Mechanism?

- Protons can travel straight at $E > 10^{20}$eV.  
  → Charged-Particle Astronomy

- Protons can \underline{not} travel beyond $\sim 50$Mpc at $E > 5 \times 10^{19}$eV due to interaction with CMB.  
  → ZGK Cut-off
Pierre-Auger Observatory

Northern Auger in Utah

Southern Auger in Argentina

50 km
Surface Detector and the Andes

1,600 Water Tanks x 3 PMTs = 4,800 of 9” PMTs
EUSO on International Space Station
Night Sky
EUSO Detector

- 2.5m Diameter
- 60° FOV
- f/1.25

Support structure

Electronic system

Focal surface detector

Hamamatsu R7600-M16/64 250k Pixel

Optics system
OWL Stereo View from Space

~1,000km
AMS - Anti-Matter Search

- RICH uses Multi-anode PMT
- Hamamatsu R7600-M16
- 14k Pixel

Measuring $V(V < C)$ to the accuracy of 0.1%, to identify $\text{He}^3$, $\text{He}^4$, ...
Messengers from the Universe

- **Photons**
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- **Charged Particles**
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- **Neutrinos**
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  - Relic Neutrino

- **Dark Matter**

- **Gravitons**
Super-Kamiokande

- 11,200 of 20” PMTs
- Expected to resume end of this year with 50% PMTs
Future: Hyper-K/UNO

~200k of 20” PMTs

1 Mton fiducial volume: Total Length 800m (16 Compartments)
NESTOR and ANTARES

NESTOR

ANTARES

June 17, 2002
AMANDA

Depth

surf at 80 m

snow layer

AMANDA-A

AMANDA-B10

Optical Module

main cable

pressure housing

silicon gel

light diffuser ball

Eiffel Tower as comparison (true scaling)

AMANDA as of 2000

zoomed in on AMANDA A (top)

AMANDA B10 (bottom)

zoomed in on one optical module (Ohl)
ICECUBE

10 TeV Muon Event

60 PMTs/string x 80 strings = 4,800 PMTs

1 km
Detection of Cosmic Radiation

Larger Volume
Lower Threshold

 detectors:
- CDMS
- Super-K
- AMANDA
- Pierre-Auger
- Hyper-K
- ICECUBE
- EUSO
- OWL

applications:
- Neutrino
- Cosmic Ray
- Dark Matter
- Zeplin

log-log plot:
- Detector Volume (Ton) vs. Energy Threshold (eV)
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Photon Detector

- LSST
- SDSS
- CCD
- PMT
- EUSO
- OWL
- γ Wide FOV
- Hyper-K
- Auger-FD
- Super-K
- Auger-SD
- AMS
- VERITAS

More Pixels
Better Sensitivity
Demands on Photon Detectors

- **Giga-Pixel CCD**
  - Sky Survey

- **Mega-Pixel (1-5mm), Photon Counting**
  - EUSO/OWL, Wide-FOV $\gamma$-ray Telescope

- **Large Area (>50cm), Photon Counting**
  - Neutrino, Proton decay

- **Time-resolving Imaging**
  - Transient Phenomena

- **Low Costs!**
Demands on Photon Detectors

- Giga-Pixel CCD
  - Sky Survey

- Mega-Pixel (1-5mm), Photon Counting
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- Low Costs!
New Detectors on Horizon

- **Vacuum**
  - Multi-Pixel HPD: DEP
  - Flat Panel PMT: Hamamatsu, Burle
  - Silicon MCP: Nano-science
  - New Photo Cathode

- **Solid State**
  - Silicon PMT: Russia
  - STJ: ESTEC
  - TES: Stanford
DEP Hybrid Photodiode (HPD)

- Baseline design for LHC-b RICH
- 8cm diameter
- 61 Pixel, (5mm view)
Energy Resolution

\[ \frac{\sigma}{E} = \sqrt{\frac{\text{ENF} \cdot \text{QE} \cdot C_{ol}(N_\gamma + N_{BG}) + (\text{ENC}/G)^2}{\text{QE} \cdot C_{ol} \cdot N_\gamma}} \]

\[ \approx \sqrt{\frac{\text{ENF}}{\text{QE} \cdot C_{ol} \cdot N_\gamma}} \]

- \(\text{QE}\) as high as possible. \((> 30\% )\)
- \(C_{ol}\) as close as 100\% \((> 0.9 )\)
- \(\text{ENF}\) as close as 1.0 \((< 1.2 )\)
- \(G\) \(\gg\) \(\text{ENC}\) (~1000e\(^{-}\)) \((\gg > 10^4 )\)
- \(N_{BG}\) \(<<\) \(N_\gamma\) \((<< 1 )\)
Energy Resolution

![Energy Resolution Graph]

- **Energy Resolution** vs. **No. of Photons**
- Lines represent different detectors:
  - **APD**
  - **HPD**
  - **PMT**

**Poisson Limit** and **Photo Diode** are also indicated on the graph.
Hamamatsu Flat Panel PMT

64 Pixels

Location of Anode (Pixel Number)

<table>
<thead>
<tr>
<th>No.</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
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<tr>
<td>20</td>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>28</td>
<td>2.5</td>
<td>100</td>
<td>3.4</td>
</tr>
<tr>
<td>36</td>
<td>0.0</td>
<td>0.7</td>
<td>0.1</td>
</tr>
</tbody>
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(unit: %)

Light Source: W Lamp
Wavelength: 400nm
(5x5 mm Mask is used.)
Applied Voltage: 1000V
Burle Flat PMT

- 2 inch Square
- Ceramic Case
- Dual MCP-PMT
- 4 anodes, uniformity < 2:1
- Maximum Gain ~ $1 \times 10^6$

85001 Single Electron Spectrum

The BURLE 85001 Low Profile PMT is significantly shorter than a conventional glass envelope PMT

by Paul Hink
Silicon MCP

• ~7µm pores
• >75% open area
• Diamond coated

Gain > 1,000

By O. Siegmund, U.C. Berkeley
Semiconductor Photo-cathode

by Hamamatsu

Aiming at even longer wavelength!
Silicon Photomultiplier

by P. Buzhan, B. Dolgoshein et. al.

Gain~$10^6$

ENF=1.0

DQE~10%
Superconducting Tunneling Junctions (STJ)

- Developed by ESTEC, ESA
- Detect Photon by Photon:
  - Energy < 0.1 eV
  - Time < 1 nsec
  - Position < 10 μm
Transition Edge Sensor (TES)

The Astrophysical Journal, 563: 221È228, 2001 December 10
R. Romani ,et al.

20 x 20 µm²

TES Array
Tc ~ 70 mK

Dilution refrigerator

2.7m Harlan Smith

400µm–200µm Taper
GRIN & spherical lens

3 m length cold loop

200 µm UV fiber optic
Crab Pulsar observed by TES
Detect Photon by Photon:

- Energy $< 0.1$ eV
- Time $< 1$ nsec
- Position $< 10$ $\mu$m

Ultimate Photon Detector!
Dream Team for Astro-Physics

- **CCD:** $\sim 10\,\mu m$ 1G pixels
- **STJ:** $\sim 20\,\mu m$ 1M pixels
- **HAPD:** $\sim 1\,mm$ 1K pixels
Multi-pixel Hybrid APD

- Glass Window (1mm\text{t})
- InGaN Photo Cathode
- Ceramic Case
- APD Array (32 x 32 = 1024 Pixel)
- Readout Electronics

- 1.4mm Pixel Size, 1.5mm Pitch
- 32 x 32 = 1,024 Pixels
- QE ~ 50\% at 350 ~ 400nm
- Gain ~10^5
Katsushi’s Dream Telescope

Ground & Space-based $2\pi$ observatory:

- 20m diameter mirror
- 30° FOV, f/0.8
- 0.1arcsec pixel size
- 1Tera pixels
- Photon counting
- 1nsec time resolution
- 0.01eV energy resolution
Concluding Remarks

- Where did we come from?  Where are we going?
- The answer is still hidden in the dark side of the Universe which only more advanced photo-detectors can see.
- Time is now to develop dream detectors!
Can “your photo-detector” see the dark side of this picture?