Gravity and Gravitational-Wave Physics

Masaki Ando
(National Astronomical Observatory of Japan)
Self Introduction

• Was a Special Associate Professor of this GCOE program for 3.5 years (2009.1 – 2012.5)
  → Special Research Unit for ‘Gravity and Gravitational-Wave Physics’ (Belonging to ‘Tentaikaku’ astrophysics theory group)

• From June 2012, an Associate Professor of NAOJ (National Astronomical Observatory of Japan)

Gravitational-Wave Project office
- Host for TAMA300 GW detector
- Co-host for KAGRA GW antenna

~20 members (1 Prof. to come, 1 Assoc. Prof., 5 Research Associates, 3PDs, 3 Engineers, 2 Secretaries, and 4 Grad. Students)
Gravity and Gravitational waves

General Relativity

Gravity
Nature of space-time

Einstein equation

\[ G_{\mu \nu} = \frac{8\pi G}{c^4} T_{\mu \nu} \]

Curvature of space-time
Mass (Energy Momentum)

Gravitational wave
GW astronomy
New probe for the Universe
Violent phenomena, Early universe, ...
Test of general relativity

Precise Measurement
Displacements of
Macroscopic objects
Laser interferometer
Quantum optics, ...
Fundamental noises
Thermal fluctuation, ...

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
KAGRA (かぐら)
2nd generation GW detector in Japan
Obs. Start ~2017 \rightarrow Direct detection of GW

Large-scale Detector
Baseline length: 3km
High-power Interferometer

Cryogenic interferometer
Mirror temperature: 20K

Underground site
Kamioka mine,
1000m underground
Outline

- Gravitational-Wave Astronomy
- Overview KAGRA GW Antenna
- Current Status of KAGRA
- Summary
Gravitational Wave Astronomy
"Mass tells space-time how to curve, and space-time tells mass how to move."
John Archibald Wheeler

Gravitational Wave

General Relativity
Gravity: Curvature of space-time

Acceleration of Mass
→ Fluctuations in space-time
→ Propagates as
‘Ripples in space-time’

Gravitational Waves
Gravitational-Wave Astronomy

Reveal the universe by Gravitational Waves.

Nature of GWs
Radiated by accelerated masses
Strong transmissivity

New probe to the universe
Complementary with EMWs.
Unique sciences
Early universe before CMB era
High-energy phenomena

CMB
Radio
IR
x-ray
GW ?

GRBs
γ-ray

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Laser Interferometric Detector

Laser Interferometer
(Michelson interferometer)

When GW comes...

Differential length (strain) changes in two arms
Detected at photo detector
International observation network for GW astronomy will be on-line in ~5 years. >200Mpc range → Event rate ~10 events/year.
Target of Ground-based Detectors

Terrestrial Detectors – Obs. Band ~10Hz – 1kHz

- Compact and high-energy astronomical phenomena

- EoS of high-density Matter → Nuclear Phys.
- Test of Relativity Physics in Strong Gravity
- Understandings on High-E phenomena
- EM Waves
- Neutrino
- High-energy CR

Follow-up observation
Numerical Relativity

Neutron Star
Pulsar
Supernova
Soft Gamma-Ray Repeater
Star Oscillation
Long GRB
Binary merger
Short GRB
Black Hole
EMRI
Stochastic Background
Early Universe
Quasi-normal Oscillation

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
GW targets and data analysis

Signal duration

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Short (bursts)</th>
<th>Long (stationary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known</td>
<td>Binary merger → Chirp wave, Ringdown wave</td>
<td>Pulsar, LMXB → Continuous</td>
</tr>
<tr>
<td>Unknown</td>
<td>Stellar core collapse → burst wave</td>
<td>Stochastic background → Random wave</td>
</tr>
</tbody>
</table>

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Primary target: Inspiral and merger of NS binary

- Quantitative estimation of event rate from pulsar observations.
- Precise waveform is predicted.
  → Sophisticated analysis method using an optimal filter.

Promising for first detection
EoS of Neutron Stars

Neutron-star EoS
(Density $2 \sim 15 \rho_0$)

Density-Pressure

Radius-Mass of NS

Lattimer+ (2010)

High-energy Phenomena
→ Astrophysics, Frontier Physics

Radio Pulsar

Supernova

Binary Merger

Short GRB

Soft GRR

LMXB

Magnetar

Black-hole formation

Nuclear Physics
Natural Laboratory for high-density nuclear physics

Relativity and Cosmology

Compact Binary
→ Standard Siren

Physics in Strong Gravity
Cosmological Parameters

Messenger and Read, arXiv:1107.5725

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Numerical Simulation

Hotokezaka+, PRD (2011)

Type I

Equal-mass NS merger

Type II
Lifetime < 5ms

HMNS

Type III
Lifetime > 5ms

M > M_{max}
Supported by centrifugal force

= \text{Type I}

Collapse to BH

\text{Type II}

Short lived

Collapse to BH

\text{Type III}

Long lived

Collapse to BH

\(\text{Hotokezaka+}, \text{PRD (2011)}\)

(5a) type I

APR4-29
\text{T4}

Time (msec)

5 10 15 20

(2a) type II

H3-27
\text{T4}

Time (msec)

5 10 15 20

(3a) type III

H4-27
\text{T4}

Time (msec)

5 10 15 20 25 30 35
KAGRA Project
KAGRA (かぐら)
Large-scale Cryogenic Gravitational-wave Telescope
2\textsuperscript{nd} generation GW detector in Japan

- Large-scale Detector
  - Baseline length: 3km
  - High-power Interferometer

- Cryogenic interferometer
  - Mirror temperature: 20K

- Underground site
  - Kamioka mine,
  - 1000m underground
Organization of KAGRA

~150 Collaborators (Host : ICRR, Co-hosts: NAOJ, KEK)

Subsystems
- Tunnel (TUN)
- Facility (FCL)
- Vacuum (VAC)
- Cryogenics (CRY)
- Vibration Isolation (VIS)
- Mirror (MIR)
- Laser (LAS)
- Main Interferometer (MIF)
- Input-output Optics (IOO)
- Auxiliary Optics (AOS)
- Analog Electronics (AEL)
- Digital System (DGS)
- Data Management (DMG)
- Data Analysis (DAS)
- Geophysics Interferometer (GIF)
**KAGRA Schedule**

- **iKAGRA** (2010.10 – 2015.12)
  - 3-km FPM interferometer
  - Baseline 3km room temp.
  - Operation of total system with simplified IFO and VIS.

- **bKAGRA** (2016.1 – 2018.3)
  - Operation with full config.
  - Final IFO+VIS configuration
  - Cryogenic operation.

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Underground site at Kamioka, Gifu prefecture

Facility of the Institute of Cosmic-Ray Research (ICRR), Univ. of Tokyo.

- 220km away from Tokyo
- 1000m underground from the top of the mountain. (Near Super Kamiokande)
- 360m altitude
- Hard rock of Hida gneiss (5 [km/sec] sound speed)

Neutrino
Super Kamiokande, Kamland
Dark matter
XMASS
Gravitational wave
CLIO, KAGRA
Geophysics
Strain meter
Tunnel Design

- Excavation methods
- New Australian Tunneling Method (NATM).

Mozumi entrance

End rooms

New Atotsu entrance

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Mozumi:
Y-arm tunnel
(~1000m)

New Atotsu: Center room
Surface Facility at Kamioka

Rent and remodel a public building (140m²) for free. → On-site office and laboratory for GW group.

Aug. 29, 2012
Announcement for local people → Open as office in Nov.
KAGRA Vacuum duct

- 12m, Φ800mm ducts for 3km x 2 arms.
  → ~90% of 478 ducts have been delivered.

Press to form a duct
Bellows for each duct

Baking at MIRAPRO Co. Noda/MESCO, Kamioka
Test at MIRAPRO Co. Noda
Transportation to Kamioka
Installation Test Facility

KAGRA tunnel simulator for installation test
(MIRAPRO, Noda factory)

June 28, 2012, Photo by Kamiizumi and Iwasaki (ICRR)

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Cryostat Construction

Cryostat #1 in preparation for installation of radiation shield.

Cryostat #2 in leak test.

3rd and 4th cryostats under construction

Radiation shield

Toshiba Keihin Factory (Oct 31, 2012)

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Cryo-cooler Construction

Cryo-cooler units at ICRR (Kashiwa)  
Vibration measurement

Storage at ICRR (Akeno)

T.Suzuki at External Review (April 2012)

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Sapphire Mirror Isolator

Pre Isolator prototype at Lucca (Pisa)

GAS filter prototype

‘Type-A’ system

Cryogenic payload ½-scale prototype

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
Isolator Prototypes

Pre-Isolator Prototype test (Kashiwa)

Global COE Symposium 'Development of Emergent New Fields' (Feb. 13, 2013, Kyoto University, Kyoto)
2 Sapphire substrates were delivered
(Φ220mm, t 150mm, c-axis)
Summary
Summary

KAGRA : Under Construction

• Sufficient sensitivity for direct GW detection
• Form global network as one of the 2nd-gen. detectors
  ➤ Aim to detect GW, and to open new astronomy
• KAGRA will demonstrate 3rd generation detector techniques: cryogenics and underground

Status

• Technology based on TAMA and CLIO experiences
• Tunnel and facilities are becoming real.
• Prototype developments : SAS, Cryostat, Control Sys.
Experiences in GCOE

For me...

• Enjoyed life in Kyoto.
• Research experiences in Kyoto was vary fruitful.
  - ‘Tentaikaku’ astrophysics theory group:
    → Interactions with theorists
  - Quantum Optics group.
    → Precise atomic spectroscopy for fundamental phys.

Opportunities to tackle on new fields

Thank You Very Much!!!
End