KAGRA and the Global Network of Gravitational Wave Detectors

- Construction Status and Prospects for GW Astronomy with Data Sharing Era -

Nobuyuki Kanda (Osaka City U.)
KAGRA collaboration
at CHPE2015, Okinawa, April 14th 2015.
Gravitational Wave as the frontier of fundamental physics

Gravity
  • is the interaction that we know from the most older.
  • However, we know less about it.

100 years ago, Einstein predicted the wave solution in his equation of General Relativity,
  • which is called as “gravitational wave (GW)”.
  • This is important prediction of the general relativity.
  • However, we humankind did not measure the gravitational wave directly.

\[ f = -G \frac{m_1 m_2}{r^2} \]  

“action at a distance” by Newton

\[ R_{\mu \nu} - \frac{1}{2} g_{\mu \nu} R = -\kappa T_{\mu \nu} \]  

“distortion of space-time” by Einstein

\[ R_{\mu \nu} : \text{Riemann curvature tensor} \]
\[ R : \text{Scalar curvature} \]
\[ g_{\mu \nu} : \text{metric tensor} \]
\[ T_{\mu \nu} : \text{Energy-Momentum tensor} \]

There is ‘in-direct’ proof of GW. Also, many experimental tests support the general relativity.

However, we never detect GW directly yet (in early 2015), and these GR tests are in weak gravity field.
### Laser Interferometric GW detector vs. Collider Experiments

<table>
<thead>
<tr>
<th><strong>Target Sources</strong></th>
<th><strong>GW from Super-novae, Blackholes, Neutron stars, etc. (&quot;High-energy&quot; phenomena in the universe.)</strong></th>
<th><strong>High-energy particles</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resemblance</strong></td>
<td>Long base-line apparatus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Controls are distributed, but have to be integrated.</td>
<td></td>
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<tr>
<td></td>
<td>World highest class techniques: highest energy/highest sensitivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stableness of the system is important.</td>
<td></td>
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<tr>
<td></td>
<td>We often choose the sites out of the way (underground, desert, etc.).</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Large amount of data</strong>: Many channels including environmental monitors.</td>
<td></td>
</tr>
<tr>
<td><strong>Difference</strong></td>
<td>Main signal is in single channel.</td>
<td><strong>Huge # of multi-channels</strong> for event reconstruction</td>
</tr>
<tr>
<td></td>
<td>Signals are embedded in the time series</td>
<td>Triggered events</td>
</tr>
<tr>
<td></td>
<td>Various waveform (variations in raw signal extraction)</td>
<td>Each channel calibration is more simple.</td>
</tr>
</tbody>
</table>
Plan of Talk

Gravitational Wave: prediction, detection and science

How to detect

Global Network of GW Detectors
  • and Status of KAGRA

Computing in GW detectors (in KAGRA)
  • Digital control of the laser interferometer
  • Data transfer and storage
  • Data Analysis (GW Event Search)

Follow-up / Coincidence observations
Plan of Talk

Gravitational Wave: prediction, detection and science

How to detect

Global Network of GW Detectors
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Computing in GW detectors (in KAGRA)
  • Digital control of the laster interferometer
  • Data transfer and storage
  • Data Analysis (GW Event Search)

Follow-up / Coincidence observations

• Full data have to be recorded without trigger or front-end level selection
• Dead time less!
• Data processing must be faster than real data.
What is Gravitational Wave?

Gravity distorts the space-time!

**Einstein Eq.**

\[ R_{\mu \nu} - \frac{1}{2} g_{\mu \nu} R = -\kappa T_{\mu \nu} \]

**Metric tensor**

- "flat" space-time (Minkowski)
  \[ g_{\mu \nu} = \eta_{\mu \nu} = \begin{pmatrix} ct & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \]

- "curved (distorted)" space-time
  \[ g_{\mu \nu} \neq \eta_{\mu \nu} \]

**Small perturbation ‘h’ \rightarrow Waves**

\[ g_{\mu \nu} = \eta_{\mu \nu} + h_{\mu \nu} \]

\[ \left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu \nu} = 0 \]

flat space-time

distorted space-time = gravity

Gravitational Wave

propagation of distortion
What is Gravitational Wave?

Gravity distorts the space-time!

*Einstein Eq.*

$$\frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$

**metric tensor**

- "flat" space-time (Minkowski)
  $$g_{\mu\nu} = \eta_{\mu\nu} = \begin{pmatrix} ct & x & y & z \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- "curved (distorted)" space-time
  $$g_{\mu\nu} \neq \eta_{\mu\nu}$$

*small perturbation ‘h’ --> Waves*

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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Gravitational Wave

propagation of distortion
GW Sources

Occasional events:
- **Compact Binary Coalescence** (NS-NS, NS-BH, BH-BH)
  - NS: neutron star, BH: black-hole
- Supernovae
- BH ringdown
- Pulsar glitch

Continuous waves:
- Pulsar rotation
- Binaries

Stochastic Background
- Early universe (i.e. Inflation)
- Cosmic string
- Astronomical origin
  - (e.g. many NS in galaxy cluster)
  
  (& Unknown sources...)

Typical target: \( h \lesssim 10^{-22} - 10^{-24} \)

\( h \) is strain, non-dimensional.

\[ h = \frac{\delta \ell}{\ell} \]
Typical Source: Compact Binary Coalescence

Binary radiates GW, shrink the orbit, going to coalescence...

...Merge, and finally becomes a blackhole.

$h \sim 10^{-24}$ for NS-NS at 200Mpc away!
Typical Source: Compact Binary Coalescence

Binary radiates GW, shrink the orbit, going to coalescence...

...Merge, and finally becomes a blackhole.

\[ h \sim 10^{-24} \text{ for NS-NS at 200Mpc away!} \]
Propagating and action of GW

Characteristics:

- light speed
- transverse
- quadrupole
- (tidal force)

\[ h_+ \cos(\vec{k} \cdot \vec{x} - 2\pi f_{GW} t) \]

Tidal force on masses will be induced by GW incident.

\[
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & h_+ & h_\times & 0 \\
0 & h_\times & -h_+ & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]
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Tidal force on masses will be induced by GW incident.

$$h_{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$h_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\hat{h}_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$
Laser Interferometric GW detector (=free mass type)

Free Test Masses & Laser interferometer

Free mass = mirror

light

distorted space-time

flat space-time
Free Test Masses & Laser interferometer

Free mass = mirror

light

flat space-time

x

 Free mass = mirror

t

distorted space-time

x

t
Free Test Masses & Laser interferometer

- **Flat space-time**
  - Free mass = mirror
  - Light travel

- **Distorted space-time**
  - Light travel

**Interference**

\[ \cos(2 \pi \frac{2dL}{\lambda}) \]

**Michelson Interferometer**

---

"KAGRA and the Global Network of Gravitational Wave Detectors" at CHEP2015
Free mass
  • --> suspended mirror

To integrate strain ‘h’
  • --> long baseline arms.

Limited size
  • --> Folding arms / Storage cavity

Against noises -->
  • high power laser
  • Cooling
  • etc..
observed signal = instrumental noise + GW

The simulation is TAMA detectors real data + theoretical waveform embedded. This is the event near near by our earth as like a few pc...
observed signal = instrumental noise + GW

The simulation is TAMA detectors real data + theoretical waveform embedded. This is the event near near by our earth as like a few pc…
observed signal = instrumental noise + GW

The simulation is TAMA detectors real data + theoretical waveform embedded. This is the event near near by our earth as like a few pc…
World Wide Projects

- GEO 600m
- LIGO (Livingston) 4km
- advanced LIGO
- Virgo 3km
- advanced Virgo
- LIGO (Hanford) 4km
- LIGO-India
- TAMA 300m
- CLIO 100m
- KAGRA 3km
Advanced LIGO will start in 2015, and will continuously upgrade its sensitivity. Virgo has similar schedule.
bKAGRA operation (cryogenic) will be start in late 2017 or early 2018.
Sensitivity target of GW detectors

Note: Sensitivity = Noise level

In simple understanding, GW which larger than the noise level can be detected.
In case of particular waveform, noise can reduce with long time integration, with wiener-optimal filter etc.

Advanced LIGO will start in 2015, and will continuously upgrade its sensitivity.
Virgo has similar schedule.
bKAGRA operation (cryogenic) will be start in late 2017 or early 2018.
KAGRA’s **NS-NS** detection range is **280 Mpc** for optimal direction, **173 Mpc** for all sky average
- -> 10 event/yr

For **supernovae**, the range may be **typically ~100kpc** ~**1Mpc** or as like, depending on the SNe model.
KAGRA and the Global Network of Gravitational Wave Detectors

Underground
- in Kamioka, Japan
- Silent & Stable environment

Cryogenic Mirror
- 20K
- sapphire substrate

3km baseline

Plan
- 2010 : construction started
- 2015 : first run in normal temperature at December
- 2017- : observation with cryogenic mirror

KAGRA collaboration : 227 persons (78 affiliations )
Tunnel excavation completed at March 2014
Location of Center (BS)
- latitude: 36.41°N, longitude: 137.31°
- Y arm direction: 28.31 deg. from the North.
- Height from the sea level: about 372m.

- 2 entrances for the experiment room.
- Center, Xend, Yend are inside more than 200m from the surface of the mountain.
- Tunnel floor is tilted by 1/300 for natural water drainage.
- Height of the Xend: 382.095m.
- Height of the Yend: 362.928m.

Mozumi entrance
- 980m (620m + 360m)

New Atotsu entrance
- 470m

Tilt: 1/300

Water drain point

by T. Uchiyama
Cryostat
MC chambers and cryostats installation

Transportation of cryostat in Y arm

Installation of MC chambers (center area)
construction of the clean booths

X-end
Hardware of iKAGRA data system

@Kamioka surface bilding

200 TiB lustre storage system
(FEFS), separate MDT and OSS
1 data server
4 calculation nodes (8cores x
2CPUs) = 64cores
2 job management servers

VPN switch

@Kashiwa (ICRR building 6th floor)

100 TiB lustre storage system
(FEFS), single storage for MDT
+OSS
2 login server
VPN switch

placed at computer area
beside the control room, 1st floor of analysis build.

200 TiB ‘lustre’ file system
Schedule to the observation era

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<thead>
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<td>Tunnel excavation</td>
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<td>baseline-KAGRA</td>
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</tbody>
</table>

- Project start
- Tunnel excavation
- initial-KAGRA
- baseline-KAGRA
- Observation

Drawn by T. Kajita
Various layers computations are necessary for KAGRA operation.

- Digital control for the interferometer
- Data transfer and storage
- Data analysis
Digital control and acquisition

Important role as interface to subsystems

Like a brain for KAGRA

Digital system

Control room
- Control
- Diagnostic
- Tuning
- Automatic operation
- Observation

Online monitor system
- Sensitivity monitor
- Seismic monitor
- IFO status monitor
- IFO diagnostic monitor

Data analysis
- Detector characterization
- Online analysis
- Offline analysis

Data storage

Sequencer controller

Digital system
- MC
- FSS
- LSC
- ASC
- IP
- OSEM
- Oplev

Input/Output Optics
- Main interferometer
- Vibration Isolation

Mirror temp.
- Seismic motion
- Temperature
- Humidity
- Sound

Cryostat
- Environment monitor

Facility
- Entrance/exit
- Air control

Vacuum
- Gate valve
- Vacuum mon.

Laser

Power Temp.

by O. Miyakawa

"KAGRA and the Global Network of Gravitational Wave Detectors" at CHEP2015
Data flow overview

Kamioka
- pre-process server(s) (calibration, DetChar)
- spool

Kashiwa
- Main storage server
- mass storage
- ICRR’s computers (for analysis queues)

Primary Archive = Tier 0

Tier 0.5 Low latency distribution

Osaka City U., Osaka U. for GW searches

Tier 0.5: main signal and proc. data for low latency searches
Tier 1: full data mirror
Tier 2: proc. data
Tier 3: partial cache of proc. data

Tier 1 mirroring
- for redundancy and safe of the full archive, offline processing with more computing power, multi-messenger astro.

Oversea KAGRA collaborator sites

Tier 2 partial distribution

Tier 2? or 3?
Main Stream of KAGRA Data

KAGRA's raw data rate: ~ 20MB/s (~630 TB/yr)

surface building at Kamioka

final storage (Tier-0) at Kashiwa

iKAGRA data system overview

"KAGRA and the Global Network of Gravitational Wave Detectors" at CHEP2015
Main Stream of KAGRA Data

KAGRA and the Global Network of Gravitational Wave Detectors at CHEP2015

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iKAGRA data system overview

"KAGRA and the Global Network of Gravitational Wave Detectors" at CHEP2015
### Amount of Data

<table>
<thead>
<tr>
<th>phase</th>
<th>duration</th>
<th>data rate / duty</th>
<th>total expected amount</th>
<th>from -&gt; to</th>
</tr>
</thead>
<tbody>
<tr>
<td>iKAGRA</td>
<td>about 1 month at December 2015</td>
<td>20MB/s / 100%</td>
<td>100 TiB</td>
<td>Kamioka -&gt; Kashiwa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1MB/s / 100%</td>
<td>5TiB</td>
<td>Kamioka -&gt; Osaka City U./Osaka U.</td>
</tr>
<tr>
<td>commissioning</td>
<td>2016-2017</td>
<td>20MB/s / ?(5~10%)</td>
<td>?</td>
<td>Kamioka -&gt; Kashiwa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1MB/s / ?(5~10%)</td>
<td>?</td>
<td>Kamioka -&gt; Osaka City U./Osaka U.</td>
</tr>
<tr>
<td>bKAGRA</td>
<td>2017 -</td>
<td>20MB/s / 100%</td>
<td>3PB / 5yrs</td>
<td>Kamioka -&gt; Kashiwa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1MB/s / 100%</td>
<td>150 TiB / 5yrs</td>
<td>Kamioka -&gt; Osaka City U./Osaka U.</td>
</tr>
</tbody>
</table>

### Diagram

- **Detector (tunnel)**
  - Raw data ~20MB/s
- **Kamioka**
  - Raw data ~20MB/s + Proc. data ~1MB/s
- **Kashiwa Tier-0**
  - Raw + Proc. data
- **Mirror archive Tier-1**
  - Partial data set
- **Tier-2**
  - Osaka U./ Osaka City U.
  - for low latency search
Data analysis (GW event searches)

Search for various GW waveforms in data stream

- Fast processing pipeline (calculation > observation)
- Low latency for end-to-end of the system: Tier-0 data transfer, storage, calibrated data generation, distribution, search and event alert.

GW event search pipeline

- Compact Binary Coalescence
- Burst
- BH QNM
- Event candidate
- Coincidence, waveform coherence
- Coincidence, more knowledge of sources using multiple obs.
- Detection of GW event
- Mutual Follow-ups (more convincing detection)
- Optical, X-ray, Gamma-ray, Neutrino, etc.

Alert Exchange
Follow-up obs.
Challenge in GW data analysis

We don’t know where, when GW events will arrive.
  • → search with a fine tooth comb for all data of long observation period.

Waveform and amplitudes depend on various parameters of progenitors (e.g. distance, mass of star, spins, EOS(equation of state), direction, alignment, initial condition of the orbit, etc.)
  
  (We will get different waves event by event. Therefore, the identification of signals is quite different from the case of photo-multiplier tube.)
  • → search for all possible parameter spaces.

We don’t know ‘real’ signal yet.
  Also, some kind of GW may be always present. (Continuous, Stochastic GW.)
  • → It is difficult to adopt triggers or to reduce in DAQ level.
Computing cost for CBC

- For CBC search, it requires \( \sim 1 \) TFlops for minimal requirement. (Several \( \sim \) ten times more for complete search)
- Continuous and Burst searches also require \( \sim 1 \) TFlops respectively.
- Stochastic require less than above.

At least, a few~several Tflops is necessary for GW data analysis.

### Estimation of calculation costs for CBC (by Tagoshi)

<table>
<thead>
<tr>
<th>KAGRA sensitivity</th>
<th>mass search region</th>
<th>necessary numbers of templates</th>
<th>calculation costs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>noise model</td>
<td>( m_{\text{min}}^{}[M_\odot^{}] )</td>
<td>( m_{\text{max}}^{}[M_\odot^{}] )</td>
<td>( N_{\text{temp}} )</td>
</tr>
<tr>
<td>VRSE-B</td>
<td>1</td>
<td>3</td>
<td>( 1.4 \times 10^5 )</td>
</tr>
<tr>
<td>VRSE-B</td>
<td>1</td>
<td>100</td>
<td>( 7.0 \times 10^5 )</td>
</tr>
<tr>
<td>VRSE-B</td>
<td>0.2</td>
<td>3</td>
<td>( 1.8 \times 10^7 )</td>
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<tr>
<td>VRSE-B</td>
<td>0.2</td>
<td>100</td>
<td>( 3.1 \times 10^7 )</td>
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<tr>
<td>VRSE-D</td>
<td>1</td>
<td>3</td>
<td>( 1.2 \times 10^5 )</td>
</tr>
<tr>
<td>VRSE-D</td>
<td>1</td>
<td>100</td>
<td>( 5.9 \times 10^5 )</td>
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<tr>
<td>VRSE-D</td>
<td>0.2</td>
<td>3</td>
<td>( 1.6 \times 10^7 )</td>
</tr>
<tr>
<td>VRSE-D</td>
<td>0.2</td>
<td>100</td>
<td>( 2.7 \times 10^7 )</td>
</tr>
</tbody>
</table>
Effective performance of FFT

Dominant calculation cost is FFT (Fast Fourier Transform).
  • One of the problem is the length of the data($>2^{20}$)

FFT performance will be drastically reduced with data exceeds cache size.

Key technique:
→ parallel computing
→ GPGPU
etc.
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- etc.

Comparison with 8 jobs, 100 templates

- Intel(R) Xeon(R) CPU E5-2660 0 @ 2.20GHz
- Intel(R) Xeon(R) CPU E5-2670 0 @ 2.60GHz
KAGALI

- We are using LIGO, Virgo software. However to add more KAGRA original functions, we are developing own library (KAGALI).

### KAGRA coding rule

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
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<tbody>
<tr>
<td>7.2.1</td>
<td>General [required]</td>
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<td>7.2.2</td>
<td>Programming language [required]</td>
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<td>Environments [required]</td>
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<td>System-dependence [required]</td>
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<td>7.2.7</td>
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<td>7.2.8</td>
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<td>7.2.9</td>
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<td>Namespace [required]</td>
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<tr>
<td>7.2.11</td>
<td>Naming guideline [required/recommended]</td>
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<tr>
<td>7.2.12</td>
<td>Declaration and definition</td>
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<tr>
<td>7.2.13</td>
<td>Function arguments [recommended]</td>
</tr>
<tr>
<td>7.2.14</td>
<td>Static in a function [recommended]</td>
</tr>
</tbody>
</table>

We can use KAGALI to discover something which no one has never seen before.
Global network with data sharing

To determine the direction of GW sources,
- Triangulation with arrival time difference
- +constraints: amplitude ratio, polarization etc.

*cf: diffraction limit $\lambda/D$

Since $\lambda$ is order of 100km or longer, we have to use detectors of global distributed network.
Data Transfer

- Detector (tunnel)
  - raw data ~20MB/s

- Kamioka
  - raw data ~20MB/s
  - Proc. data ~1MB/s

- Kashiwa Tier-0
  - raw + Proc. data
  - partial data set

- Mirror archive Tier-1
  - Oversea GW experiment (1)
  - Oversea GW experiment (2)

- Osaka U./ Osaka City U.
  - for low latency search

- GRID or alternative socket or alternative

- GW channel data (+ alpha)
1. Fast processing of KAGRA data
   • Search GW, especially in “low latency analysis”.

2. Mutually follow-ups with EM and neutrino
   • Generate, validate and distribute GW event alert from KAGRA
   • Search GW with external trigger

3. Further more science on GW data analysis
   • Try new physics possibility or new methodological improvement with the theory researches
Summary

We are targeting first gravitational wave detection.
  • International competition and cooperation are important.

To convince the GW detection, we need coincidence and follow-up observations.
  • The low latency event searches are necessary to realize it.
    A computing is one of a key of the project success.
  • Multi-messenger observation of GW objects will open new era.

KAGRA will have its first operation in this year!
  • We also expect the operation of advanced LIGO, advanced Virgo.

We hope that GW detection and astronomy will be realized with enough computing power.
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http://www.gw.hep.osaka-cu.ac.jp/GWPAW2015/
Reserved Viewgraphs
Aim of direct detection / measurement of GW!

- **We have to test in ‘strong’ gravity field!**
  
  Past experimental GR (General Relativity) tests had been done in weak gravity field (in Solar system)

  Direct measurement of wave property is important as the test of a fundamental interaction.

- **GW waveform carry information of its sources**
  New probe for astrophysics and cosmology

- **Tagging GW events = seeing sources**
  Gravitational Wave Astronomy

- There will be many interesting sources of GW, which can be observed with counterparts: e.g. EM emission, particles.

With what can we be convinced of detection of GW?

Need Counterparts!
Mass quadrupole moment is lowest order of GW radiation.

\[ I_{\mu\nu} = \int dV (x_\mu x_\nu - \frac{1}{3} \delta_{\mu\nu} r^2) \rho(\vec{r}) \]

Amplitude
\[ h_{\mu\nu} = \frac{2G}{Rc^4} \ddot{I}_{\mu\nu} \]

Energy (Luminosity)
\[ E_{GW} \sim \frac{G}{5c^5} < \dddot{I}_{\mu\nu} \check{}^{\mu\nu} > \]
Indirect proof of GW

Binary Pulsar PSR1913+16

*by Hulse & Taylor*

- Kepler orbital period of binary will change due to the GW emission, that carry away the energy and angular momentum of binary system.
- Measurement agree very precisely with a GR theoretical prediction.

*Duncan R. Lorimer, “Binary and Millisecond Pulsars”, Living Reviews in Relativity*

*Figure 26: Orbital decay in the binary pulsar B1913+16 system demonstrated as an increasing orbital phase shift for periastron passages with time. The GR prediction due entirely to the emission of gravitational radiation is shown by the parabola. Figure provided by Joel Weisberg.*
Interferometer’s antenna pattern is widely spread as almost ‘omni-directional’.
Interferometer’s antenna pattern is widely spread as almost ‘omni-directional’.
\( h \sim \text{factor} \times 10^{-24} \left[ \sqrt{\text{Hz}} \right] \) for observation band

![Graph showing strain equivalent noise spectrum (1/\sqrt{\text{Hz}}) vs. frequency (\text{Hz}) for KAGRA sensitivity limit and noise budget components including mirror substrate Brownian thermal noise, mirror substrate thermoelastic noise, seismic noise, suspension thermal noise, and standard quantum limit.](image-url)
KAGRA Collaboration in the world

- Research organizations of laboratories and faculties of universities are 41 in Japan and 37 in overseas
- 158 researchers in Japan and 69 in abroad, 227 members in total
Not including experiment rooms.

2013/9/1-30
Xarm: 359.4m
Yarm(down slope): 301.2m
Total: 660.6m

Xarm
3000m/14month=210m/month

by T.Uchiyama
Vibration isolation and cryostat

14 m

Payload

Vibration Isolation

Cryogenic mirror

Cryostat

PTC units

S.Koike

R.Takahashi

"KAGRA and the Global Network of Gravitational Wave Detectors” at CHEP2015

viewgraph by K.Yamamoto, S.Koike & R.Takahashi
New building (“Analysis build.”)
New building (“Analysis build.”) at Jan. 2014
(1) NS-NS連星合体１分前に検出（アラート発信）できるか？

チャープ波の周波数発展

- NS-NS (1.4-1.4 Msolar)
- BH-BH (10-10 Msolar)
- (0.5-0.5 Msolar)
(1) NS-NS連星合体1分前に検出（アラート発信）できるか？

チャープ波の周波数発展

LCGTの観測帯域

$h > 10^{-22}$
合体前XX秒までの積分で得られるS/N（最終的にえられるS/Nで規格化）

・NS-NSの場合、
1分前だと1割くらい
10秒前でも4割
検出するのにS/N>8とする
と、予報が可能な連星までの距離は
1分前：25Mpc
10秒前：80Mpc
（＊ただし最適方向。平均の目安はx0.59）
The online analysis process which produced GW candidate triggers is shown in Fig. 2. After event candidates were placed in a central archive, additional software used the locations of nearby galaxies and Milky Way globular clusters to select likely source positions (Sect. 5).

The process of downselecting this large collection of triggers to the few event candidates that received EM follow-up is described in this section.

The few event candidates that received EM follow-up are validated manually. If no obvious problem was found, the trigger's estimated coordinates were sent to telescopes for potential follow-up.

These candidate triggers were imaged for each trigger that was validated by telescopes. The online analysis process which produced GW candidate triggers was written into the GraCEDb archive. The LUMIN and GEM algorithms identified triggers and determined probability skymaps.

Selected statistically significant triggers from the archive and these were pointed to telescopes.
Control computers (installation)

Inside of Front room

Server room/Power supply room

W7.2m × D5.4m × H3m
P(DC power) rack height: 210cm
N, D, G(computers) rack height: 200cm
VPN and GRID

Tentative Plan

Kamioka detector site

Kashiwa main storage Tier-0

Kashiwa ICRR common computer

Osaka C.U./Osaka low latency search proc.data

by wire (FC or IB)

GRID

KAGRA Tier-1 (Mirror)

oversea GW observatories

KAGRA Tiers
“Chirp” of mass

0.5-0.5 \( M_{\text{solar}} \)

1.4-1.4 \( M_{\text{solar}} \)

10-10 \( M_{\text{solar}} \)

frequency development --> mass of stars
"Chirp" of mass

0.5-0.5 $M_{\text{solar}}$

1.4-1.4 $M_{\text{solar}}$

10-10 $M_{\text{solar}}$

frequency development --> mass of stars
“Chirp” of mass

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