Report of A04
"Research on Data Analysis of Gravitational Wave Searches
Link up with Various Observations"

Nobuyuki Kanda (Osaka City U.)
on behalf of A04 group
2016/12/28
5th Annual Symposium on
"New development in astrophysics through multi-messenger
observations of gravitational wave sources"
Aim of A04 group

**Scientific targets**
- GW event search
- Search in low latency for transients: CBC (Compact Binary Coalescence), and Burst
  GW data analysis and alert for the observational era.

**To do**
- Construct computing environment
  Hardware and software
  Alert system
- **KAGRA** data analysis

**Organize Japanese GW data analysis group**
- including a cultivation of young researchers
A04 Members

Core staffs
- N.Kanda (Osaka City U.) : Leader, project, computer system construction
- H.Tagoshi (Osaka City U.) : Pipeline coordinate, compact binary coalescence search
- Y.Itoh (RESCEU, U. Tokyo) : Continuous wave search, grid

Cooperative researchers
- A.Araya (Earthquake R.I, U.Tokyo) : Time series analysis
- D.Tatsumi (NAOJ) : non-gauss noise

Post-docs
- K.Hayama (Osaka City U.) : Burst pipeline, GW detector characterization → moved to ICRR at 2016.3
- K.Ueno (Osaka U. → Osaka City U.) : Low latency pipeline for CBC → moved to UWM at 2016.4
- T.Narikawa (Osaka U. → Osaka City U.) : CBC analysis, Bi-gravity and testing GR with GW
- M.Kaneyama (Osaka City U.) : HHT, transient searches, determination of sky location
- N.Uchikata (Osaka City U.) : BH quasi-normal mode, ring down waveform study
- S.Tsuchida (Osaka City U.) : Dark matter on a laser interferometer, Burst waveform search

Post-docs (JSPS PD)
- T.Yokozawa (Osaka City U.) : Burst pipeline, GW-nu, KAGRA hardware injection

Students of KAGRA data group
A04 Public subscription researches

We had 6 related researches for A04.

(H.27-28)
- K.Somiya (Titech): “ブラックホール凍固有振動がもたらす重力波の観測”
- S.Hirobayashi (Toyama U.): “超解析精度技術を応用した重力波の解析システムの開発とその評価に関する研究”
- S.Mano (ISM): “重力波データ解析における統計的方法論の整備”

(→ See detail in their own talks)

(H25-26)
- J.Yokoyama (Tokyo U.): “非ガウスノイズを取り入れた重力波データ解析方法の研究”
- S.Hirobayashi (Toyama U.): “重力波に関する新知見を導き出す超高精度解析技術とその高速計算組み込み技術の開発”
- D.Tasumi (NAOJ): “低温干渉計性重力波検出器における突発性雑音低減”
Promotions of A04 members

**Staffs**
- H. Tagoshi: assistant prof. (Osaka U.) → associated prof. (Osaka City U.)
- Y. Itoh: specially appointed assistant prof. → assistant prof. (RESCEU, Tokyo U.)

**Post-docs**
- T. Yokozawa: post-doc → JSPS PD (Osaka City U.)
- K. Ueno: post-doc → JSPS PD oversea (UWM)
- K. Hayama: specially appointed assistant prof. (Osaka City U.) → specially appointed fellow (ICRR)

**Students going to academic path**
- M. Kaneyama: (Niigata U.) → post-doc (Osaka City U.)
- T. Yamamoto: (Osaka City U.) → project researcher (ICRR)
Topics of this year: iKAGRA run

**KAGRA had first test run at the early spring 2016!**

- **Period**
  - 2nd run: Apr.11 - Apr.25, 2016

- 3km Michelson interferometer

- In this test run, we did not insists on the sensitivity itself, but the ‘end-to-end’ of the system achieved its operation.

- We also had observational/expert ‘shifts’ during the operation.

**Sensitivity**

- limited by **seismic noise** below ~4 Hz, **acoustic/fan noise** at around 100 Hz, **ADC noise** above ~3 kHz

- ~3e-15 /rtHz @ 100 Hz

- ~ 4.2 pc for 1.4M-1.4M NS-NS (0.77 pc for 1st run)

**Plot** by T. Shimoda, M. Nakano, Y. Michimura
KAGRA data transfer has been working since February 2016, just before iKAGRA start.

KAGRA tunnel → surface building → Kashiwa/Osaka

Transfer latency for full data,

- Tunnel → surface : ~0.3 sec
- Tunnel → ICRR Kashiwa : ~2.5 sec
- Tunnel → Osaka City U. : ~3 sec
KAGRA data distribution (in 2016)

iKAGRA data that derived from the digital control system of KAGRA were transferred from the tunnel (interferometer site) to

- ICRR Kashiwa campus of U of Tokyo (in real time)
- Osaka City University (in real time)
- Academia Sinica at Taiwan (full/continuous mirroring)
- KISTI at Korea (iKAGRA data mirroring)
- RESCEU Tokyo U. (processed data set of calibrated signal)
- Niigata U. (proc data)
- Nagaoka U. of Technology (proc data)
Topics of this year: using LIGO's open data

Practical studies using LIGO open data
- using S6 open data
  Non-Gaussian noise treatment
- using GW waveform (GW150914, GW151226)
  Hilbert-Huang Transformation
  Non-Harmonic Analysis
  (->See following talks)
Progress in these 5 years

Construction of computing system for aims of:

- GW event search / Low latency process
  real time KAGRA data receiving
    -> enough storage for observation period
  first event search pipeline
    -> enough CPU performances

- Developing software
  -> We had to prepare the platform of the development

Advanced study of data analysis

Collaborative research with other group A01, A02, A03 and A05
Construction of computing environment of A04

We introduce VPN for A04 clusters
- unified environment between collaborator sites
- redundant system

The idea and test results of VPN were feedback to KAGRA data system.

A04 main cluster system CPU/Storage

- CPU [cores] (for calculation)
- Storage [TB] (/data, /home)

- 760 cores
- 304 TB

Fiscal Year: 2012-2016

iKAGRA run
Tagoshi-san leads the development.

GW sources

Short duration burst waves
  Compact Binary Coalescence (CBC)
  NS, BH
  Stellar core collapse
  Supernovae
  Pulsar glitch
  Cosmic string

Burst

Continuous waves
  Rotating NS

CW

Stochastic background
  Early universe
  Astrophysical origin

Stochastic

KAGALI (KAGRA Algorithmic Library) are also developed. We had 1st internal release.
Further studies of GW data analysis

**Testing GR**
- T. Narikawa

  Advanced ground-based gravitational-wave detector's potential to model-independently test gravitational theory

  Narikawa & Tagoshi, arXiv:1601.07691

**Study on BH Quasi-Normal Mode (Ringdown waveform)**
- N. Uchikata

  Matched filter for ringdown waveform

- K. Somiya

  GW from BH Quasi-Normal mode

  (—> following talks)
Burst and Detector characterization

Burst signal search is also constructing for KAGRA pipeline.

Detector Characterization is closely related analysis of burst identification.

- Non-Gauss noise treatment


- Evaluate (parameterize) non-gaussianity quantitatively using student-t distribution model

- Using LIGO open data
- Correlation analysis between detector channels


- Advanced study of the correlation of GW channel and environmental channels
- Employ maximal information coefficient (MIC) method
- Employ the model of Virgo’s well-studies case
GW and neutrino coincidence analysis on supernovae
- A03 + A04 + A05

Population III stars may form heavy BH-BH binary and will be detect GW from them
- A05 + A04

- Possible scenario of GW150914 type BBH events

We may possibly observe ringdown GW from dynamical formation of massive BH
- A05 + A04

- Another possibility of massive BH events

Alert of GW events
- A01 + A02 + A04 + A05

Nakamura, Tagoshi, Kanda joined J-GEM.
- We (A04) are planning to upload KAGRA test alert to GRACE-DB.
Collaboration: Neutrino and GW from SNe

Team SKE

SNe Theory (A05)
- Y. Suwa
  - Provide time correlated data, GW and neutrino
  - Suggest signature signals physical phenomenon

GW analysis (A04)
- T. Yokozawa, M. Asano
- N. Kanda
  - KAGRA detector simulations
  - Develop/Optimize GW analysis tools
  - Prepare for realtime observation

Neutrino analysis (A03)
- T. Kayano, Y. Koshio
- M. Vagins
  - R&D of EGADS detector
  - Signal simulations with EGADS and SK

R&D of EGADS detector
Signal simulations with EGADS and SK

KAGRA detector simulations
Develop/Optimize GW analysis tools
Prepare for realtime observation
Neutrino and GW from SNe

GW and neutrino analysis for the dynamics of SNe
- timing analysis could suggest that the core is strongly rotating or not.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GW Eff. (%)</th>
<th>Neutrino Eff. (%)</th>
<th>Detection Eff. (%)</th>
<th>$P_r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 kpc, uniform</td>
<td>74.8</td>
<td>100.0(1)</td>
<td>74.8</td>
<td>0.0</td>
</tr>
<tr>
<td>1.0 kpc, uniform</td>
<td>46.5</td>
<td>46.8(1)</td>
<td>21.9</td>
<td>20.8</td>
</tr>
<tr>
<td>Galactic Center</td>
<td>0.0</td>
<td>97.5(2)</td>
<td>0.0</td>
<td>...</td>
</tr>
<tr>
<td>Galaxy Dist.</td>
<td>1.5</td>
<td>84.6(2)</td>
<td>1.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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</thead>
<tbody>
<tr>
<td>0.2 kpc, uniform</td>
<td>88.0</td>
<td>100.0(1)</td>
<td>88.0</td>
<td>98.4</td>
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<tr>
<td>1.0 kpc, uniform</td>
<td>73.6</td>
<td>40.2(1)</td>
<td>29.5</td>
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<tr>
<td>Galactic Center</td>
<td>21.5</td>
<td>94.8(2)</td>
<td>20.4</td>
<td>75.3</td>
</tr>
<tr>
<td>Galaxy Dist.</td>
<td>26.7</td>
<td>81.7(2)</td>
<td>24.7</td>
<td>76.2</td>
</tr>
</tbody>
</table>

Further study is going: waveform reconstruction from neutrino bursts by Delta-Sigma transformation
- Neutrino detections are discrete events. But, we would like to compare the ‘flux’ in time series with theoretical predictions.
- Delta-Sigma tr. represents as ‘waveform’ of neutrino flux
- Neutrino flux time series will be possibly used for the analysis of SASI or other typical characters of supernovae explosion scenario.

**Theoretical prediction:**
- Population III stars may form blackholes larger than BH from PopI,II starts in later era of universe.

**Data Analysis situation:**
- 20-30 Msolar BH binaries as GW150914 is a good source to detect by ground-based detectors: LIGO, Virgo, KAGRA.

**We may detect more than 100 events/yr in final sensitivity of LIGO, Virgo and KAGRA**

- Likelihood analysis with observed mass distribution could discriminate the PopIII existence.


\[ A.Miyamoto \] (in preparation)
Collaboration: Dynamical formation of massive BH

Gravitational wave from IMBH will be detected.

- BH QNM ringdown waveform has possibility to detect higher mass ($<\text{several } 10^3 \text{ Msolar}$) with KAGRA, LIGO, Virgo.

- Mass distribution of such events might confirm the dynamical formation of massive BH


Expected event rates for KAGRA

(a1) $\text{SNR} = 10$

BH spin=0.9, 0.5, 0.0

7 events/yr

peak at 60M

range 40M-150M

210 events/yr
Summary

A04 have constructed and preparing GW detectors data analysis, especially for KAGRA.
- Computing environment is well constructed.
- KAGRA data transfer in iKAGRA test run was successfully achieved.
- Event pipeline results will be soon.

Various study of data analysis have been done, and are doing continuously.
Moreover, GW150914 gave us great impact on the strategy and/or technical focus on the data analysis.
- i.e., parameter estimation, waveform analysis around BH quasinormal mode, etc.
- Further studies are expected.

We KAGRA expect to find first light (first wave?) of GW in near future, and wish to find mutual follow-ups with counterpart observations.