Activities on the detection of the gravitational wave from core-collapse supernovae
- Status of C01 GW Genesis -

Kazuhiro Hayama (Fukuoka U.)
Kakenhi project on gravitational wave astronomy

A01 Testing gravity theories using gravitational waves
A02 New developments of gravity theory research in gravitational wave physics / astronomy
A03 Theoretical study on binary black hole formation

B01 Physics and Astrophysics with gravitational waves from Binary Neutron star Coalescences, Black Hole Neutron star Coalescences, Pulsars and Magnetars
B02 Gravitational Wave Sources Probed with High Energy Observations
B03 Study of nucleosynthesis in neutron star merger with optical-infrared follow-up observations of gravitational wave sources

C01 Deciphering Physics of Core-Collapse Supernovae via Gravitational-wave Astronomy
C02 Studying supernova explosions via their neutrino emissions
Core Members of C01

Theory

PI: Kei Kotake (Fukuoka University)
CI: (This talk) Tomoya Takiwaki (NAOJ)
PD: (Talk on 24th) Shota Shibagaki (Fukuoka University)

Data-Analysis

CI: Nobuyuki Kanda (Osaka City University)
CI: (Talk on 23rd) Kazuhiro Hayama (Fukuoka University)
PD: Man Leong Chan (Fukuoka University)

Hajime Kawahara (University of Tokyo)
KAGRA project
# KAGRA Data Analysis Working Group

<table>
<thead>
<tr>
<th></th>
<th>Chair</th>
<th>Vice-chairs</th>
</tr>
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<tr>
<td>CBC</td>
<td>Hideyuki Tagoshi</td>
<td>Hyung Won Lee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kipp Cannon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tjonnie Li</td>
</tr>
<tr>
<td>Burst</td>
<td>Kazuhiro Hayama</td>
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<td>Continous Waves</td>
<td>Yousuke Itoh</td>
<td></td>
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<tr>
<td>Stochastic Background</td>
<td>Guo-Chin Liu</td>
<td>Sachiko Kuroyanagi</td>
</tr>
<tr>
<td>Computing and Software</td>
<td>Ken-ichi Oohara</td>
<td>Hirotaka Takahashi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kazuki Sakai</td>
</tr>
<tr>
<td>Detector Characterization</td>
<td>Keiko Kokeyama</td>
<td></td>
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<tr>
<td>Calibration</td>
<td>Yuki Inoue</td>
<td></td>
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Targets of observation

- Detection of GWs from CCSNe
- Physical interpretation of detected GW signals
- Multimessenger observation
  - Multimessenger drill using simulated SNe
    - Unveiling correlation between neutrinos and gravitational waves and its interpretation
    - ...
    - ...

Detection of GWs from core-collapse supernovae have to make detection range more extended need wise way of handling distinct multiple components

KH,Kuroda,Takiwaki,Kotake(2015)

<table>
<thead>
<tr>
<th>Model</th>
<th>Rotating core bounce</th>
<th>Nonaxisymmetric instabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3e</td>
<td>17.9 kpc (+), 11.3 kpc (∗)</td>
<td>17.3 kpc (+), 12.9 kpc (∗)</td>
</tr>
<tr>
<td>R3p</td>
<td>—</td>
<td>39.4 kpc (+), 20.1 kpc (∗)</td>
</tr>
<tr>
<td>R2e</td>
<td>14.0 kpc (+)</td>
<td>16.5 kpc (+)</td>
</tr>
<tr>
<td>R2p</td>
<td>—</td>
<td>35.9 kpc (+), 14.0 kpc (∗)</td>
</tr>
<tr>
<td>R1e</td>
<td>—</td>
<td>16.8 kpc (+), 7.6 kpc (∗)</td>
</tr>
<tr>
<td>R1p</td>
<td>—</td>
<td>5.9 kpc (+), 11.1 kpc (∗)</td>
</tr>
</tbody>
</table>

Kuroda,Takiwaki,Kotake(2016)
Detection of GWs from supernovae

• Signal enhancement
  - Improve coherent network analysis by incorporating new statistical approach such as sparse modeling. (Hayama, Honma, • • •)
  - Looking for appropriate time-frequency representation (Takahashi, Oohara, Kawahara, ...)
  - Use of robust feature (Hayama, Kuroda, Takiwaki, Kotake, (Ueno))
  - Detection statistics (Chan, Hayama)

• Background noise reduction
  - Source tracking approach to optimize background noise level. (Hayama, Mohanty, + (2008))
  - Noise modeling (non-Gaussian (stationary) Yamamoto + (2016), Hayama (in prep))

• Enhancement of detection with neutrino detection
  - Low-threshold coincident search for GWs and Neutrinos (in prep KH, Kotake, Takiwaki, Kuroda)
Physical interpretation of detected GW signals

- **Parameter estimation**
  - position reconstruction by coherent network analysis
  - g-mode (Hayama, Ueno)

- **Physical interpretation**
  - **Time-frequency analysis**
    - mode extraction (Kawahara)
    - precise T-F representation (Kawahara, Takahashi)
  - **Stokes Parameters**
    - infer rotation of core (KH, Kuroda, Nakamura, Yamada (PRL 2016))
    - probe SASI feature (KH, Kuroda, Kotake, Takiwaki (MNRAS Lett 2018))
    - Detection pipeline (Chan, KH)
One-Armed Spiral mode of GW from Rapidly Rotating Core-Collapse Supernovae
Stokes Parameter

To probe the core rotation, we introduce Stokes parameter.

\[
\begin{pmatrix}
\langle h_R(f, \hat{n}) h_R(f', \hat{n}') \rangle & \langle h_L(f, \hat{n}) h_R(f', \hat{n}') \rangle \\
\langle h_R(f, \hat{n}) h_L(f', \hat{n}') \rangle & \langle h_L(f, \hat{n}) h_L(f', \hat{n}') \rangle
\end{pmatrix}
= \frac{1}{4\pi} \delta_D^2(\hat{n} - \hat{n}') \delta_D(f - f')
\times
\begin{pmatrix}
I(f, \hat{n}) + V(f, \hat{n}) & Q(f, \hat{n}) - iU(f, \hat{n}) \\
Q(f, \hat{n}) + iU(f, \hat{n}) & I(f, \hat{n}) - V(f, \hat{n})
\end{pmatrix}
\]

\[h_L := (h_+ + i h_\times)/\sqrt{2}\quad\quad h_R := (h_+ - i h_\times)/\sqrt{2}\]

Hayama+, PRL 2016
At 20kpc
Circular polarization of non-rotating core-collapse supernovae

SFHx

TM1
Detection pipeline
Pipeline: current status

Mervyn Chan (Fukuoka U.)
For Low Latency Analysis of GW data

- GW strain signal $h(t)$ data are derived from KAGRA, LIGO and Virgo almost real-time.
- Detectors’ system push time stream of $h(t)$ every 1 sec.
- We connect this $h(t)$ stream to Burst pipeline cluster at Kashiwa, and to low latency analysis cluster at Osaka.
- Typical latency:
  - LHO, LLO -> Kashiwa: 6~14 sec
  - Virgo -> Kashiwa: 10~16 sec
  - KAGRA tunnel -> Kashiwa: ~3 sec
  (Note: These latency include $h(t)$ reconstruction calculation.)
KAGRA’s Tier-0.5 at Osaka City Univ.

OCU’s ‘ORION’ cluster consists of
1100 cores
partially supported by ‘GW genesis : C01’ grant-in-aid.
324 TB storage
Scientific Linux 7.5
HT condor

Kanda
Pipeline: current status

- DQconvert, for converting data quality flags to data category flags with KAGRA DetChar subsystem.

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
<th>0</th>
<th>1</th>
<th>Comment</th>
<th>CBC</th>
<th>BURST</th>
<th>CW</th>
<th>STOCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Odd Parity</td>
<td>-</td>
<td>-</td>
<td>This is not a data quality information. It is used for checking validation of DQV.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Lock flag</td>
<td>Unlocked</td>
<td>Locked</td>
<td>This bit checks K1:GRD-LSC_LOCK_OK.</td>
<td>CAT1</td>
<td>CAT1</td>
<td>CAT1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SDF flag</td>
<td>Not nominal</td>
<td>Nominal</td>
<td>This bit checks the setting of the IFO control is nominal or not (it may not work during IMC ER because someone will work on downstream of IMC).</td>
<td></td>
<td></td>
<td></td>
<td>CAT2</td>
</tr>
<tr>
<td>3</td>
<td>Science mode</td>
<td>Not Science mode</td>
<td>Science mode</td>
<td>Science mode flag should be turned ON by manually after human check (It is automatically turned off when the lock is lost).</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>not used</td>
<td>-</td>
<td>-</td>
<td>(This will check OMC PD overlap for O3.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>MCE overlap</td>
<td>Overflow</td>
<td>No overflow</td>
<td>This checks MCE coil out of range. (It will check ETMX for O3.)</td>
<td>CAT2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>BS overlap</td>
<td>Overflow</td>
<td>No overflow</td>
<td>This checks BS coil out of range. (It will check ETMY for O3.)</td>
<td>CAT2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>NO Stoch Injection</td>
<td>Injection</td>
<td>No injection</td>
<td>This checks the injection port of the k1calcs, k1calex, and k1caley.</td>
<td>CAT4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>NO CBC Injection</td>
<td>Injection</td>
<td>No injection</td>
<td>This checks the injection port of the k1calcs, k1calex, and k1caley.</td>
<td>CAT4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>NO Burst injection</td>
<td>Injection</td>
<td>No injection</td>
<td>This checks the injection port of the k1calcs, k1calex, and k1caley.</td>
<td>CAT4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>NO DET injection</td>
<td>Injection</td>
<td>No injection</td>
<td>This checks the injection port of the k1calcs, k1calex, and k1caley.</td>
<td>CAT4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>NO CW injection</td>
<td>Injection</td>
<td>No injection</td>
<td>This checks the injection port of the k1calcs, k1calex, and k1caley.</td>
<td>CAT4</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>12</td>
<td>not assigned yet</td>
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<tr>
<td>13</td>
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<tr>
<td>14</td>
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<tr>
<td>15</td>
<td>not assigned yet</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- data category flags: a set of GPS times indicating when the data is reliable for analysis and how long it is for. Data category flags are readable to cWB.
  - 4 categories in total, as defined on the graph.
  - CAT 3 is reserved at the moment.

Mervyn Chan (Fukuoka U.)
The Stokes parameters and the Stokes-parameter-calculation plugin

- The Stokes-parameter-calculation (SPC) plugin:

  External information (sky location, arrival time) from neutrino observations and/or electromagnetic observation

  Triggers → **SPC plugin** → 1. reconstructed h+(t) 2. reconstructed hx(t) 3. reconstructed V-mode in the TF domain

  trigger information: SNRs/ correlated SNRs event likelihood etc

  → Posting trigger information online: SNRs, reconstructed (t), V mode, etc, for review.

Mervyn Chan (Fukuoka U.)
Other activities

- Other collaborative ongoing within KAGRA:
  - predicting seismic activity effects
    - on glitches
    - gravitational wave detector data
    - with detector characterisation group

- Engineering run 2 on July 13th, 2019
  - tested the automatic portion of pipeline.
  - SPC plugin was not tested because there was one detector only.
  - Results posted on cluster page.
    - e.g.

Mervyn Chan (Fukuoka U.)
### Event Candidate 1247035931.555

<table>
<thead>
<tr>
<th>Detector</th>
<th>SNR</th>
<th>hrs</th>
<th>Central Time</th>
<th>Central Frequency</th>
<th>Bandwidth</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>5.3517654705</td>
<td>7.250263±06</td>
<td>1247041558.6489</td>
<td>1071.044434</td>
<td>2.360840</td>
<td>0.039931</td>
</tr>
<tr>
<td>J2</td>
<td>5.3517654705</td>
<td>7.250263±06</td>
<td>1247042115.6489</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Reconstructed Waveforms
2. Spectrograms
3. Scalograms
4. Power Spectral Density

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1. Reconstructed Waveforms

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**Mervyn Chan (Fukuoka U.)**
The SNR of the V mode for sources across the sky

- Simulation
  - waveform: SFHx (Kuroda, et al, 2016)

- Sky locations:
  - uniform distributions on right ascension and declination

- Distances:
  - 10kpc, 5kpc, 2kpc, 2000 injections for each distance

- Detectors:
  - advanced LIGO Hanford, Livingston KAGRA and advanced VIRGO

Mervyn Chan (Fukuoka U.)
SNR of V-mode at 5kpc
SNR of V-mode @ 10kpc

Mervyn Chan (Fukuoka U.)
Web tools for analyzing GW signals

Eguchi, Shibagaki+
System behind the web tool

- Firewall
- SNEGRAF Client (Web Browser)
  - Port 443
- SNEGRAF Service (Java Servlet)
  - Intercommunication
- Web Server
- APACHE
- TCP Socket (One Way)
  - 3-Dimensional Source Position
  - Detection Date
- Session Management Database
  - Keep Client Session Keys
  - Manage File Paths for Each Session
- File Server
  - Waveforms in a CSV Format
  - SVG Files as RIDGE Outputs
- Computing Node(s)
  - RIDGE Proxy
  - Child Process
  - RIDGE

Eguchi, Shibagaki+
Animation of the web tool

Eguchi, Shibagaki+
Analysis of gravitational waves from SASI with Hilbert-Huang Transform

We perform analysis of gravitational waves from standing accretion shock instability (SASI) [1] of a core collapse supernova by using Hilbert-Huang transform (HHT).


- GWs induced by the g-mode and SASI can be clearly extracted.
- A signal whose frequency decreases in time appears. It is considered as GWs from g2-mode.
- We generate a model signal that consists of a chirp signal (200~750Hz) and sine-Gaussian signal of constant frequency (130Hz), and we analyze it by the HHT. Results are shown in Negishiku'n's poster.
Analysis of gravitational waves from SASI with Hilbert-Huang Transform

- The frequency of the SASI has information on the internal situation of the star before the explosion.
- To check the behavior of the SASI frequency of the simulated signal, we use the weighted least-squares fitting of frequency.

Results are shown in Takeda-san's poster.

We plan to apply our proposed analysis method to more realistic case:
- software injection of SN-GW in simulated/real noise data
The frequency of the SASI has information on the internal situation of the star before the explosion.

To check the behavior of the SASI frequency of the simulated signal, we use the weighted least-squares fitting of frequency.

We plan to apply our proposed analysis method to more realistic case:

- software injection of SN-GW in simulated/real noise data

Collaborative work with A01 group
Mode extraction
Wigner-Ville based analysis

Sophisticated time-frequency analysis is useful for unknown GW shapes

It's open source!

https://github.com/HajimeKawahara/juwvid

But, H.K. found that nobody wanted to use Julia.

Now converting it to very boring Python3 (pytfat)

GWs and Neutrino analysis

- Correlation analysis of neutrino and GWs
  Kuroda, Kotake, KH, Takiwaki (2017)

SASI dominant

Convection dominant

No significant correlation between Nu & GW

\[ T_{\text{cor}} \approx 20 \text{km}/(10^8 \text{cm/s}) \approx \text{a few 10 ms} \]

Kuroda, '17
- Low-thresholded detection with help of neutrino detection