Search for Black Hole Ringdowns Using TAMA300 Data

Method, Event Selections, Rate, and Upper Limit

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for the TAMA Collaboration

GWDAW-9 2004, Dec 15-18, Annecy, France
Ringdown GWs

Waveform: Damped sinusoid  (Quasi-normal modes)

\[ h(t) = \exp(-\pi f_c t/Q) \sin(2\pi f_c t) \]

central frequency \[ f_c = \frac{3.2 \times 10^4[\text{Hz}]}{M/M_\odot} \left[ 1 - (1 - a)^{0.3} \right] \]

Quality factor \[ Q = 2.0(1 - a)^{-0.45} \]

* Probe for BH direct observation
* BH physics in inspiral-merger, core collapses, ...
* Good SNR expected, ~ 100@10kpc (TAMA sensitivity)
Ringdown GWs

Mass-frequency relation

\[ f_c = \frac{3.2 \times 10^4 \text{[Hz]}}{M/M_\odot} \left[ 1 - (1 - a)^{0.3} \right] \]

GW luminosity \(~3\%\)
(Hughes&Flanagan 1998)
**Matched Filter**

\[ \rho = \int \frac{s(f)h^*(f; f_c, Q)}{S_n(f)} \, df \]

- \( s(f) \): signal + noise
- \( h(f) \): template
- \( S_n(f) \): Weight (noise power)

**Template construction in (fc, Q) plane**
(Nakano, Takahashi, Tagoshi, Sasaki, PRD 2003)

- \( fc = 100 \sim 2500 \) [Hz]
- \( Q = 2 \sim 33.3 \) \((a = 0 \sim 0.998)\)

- 682 templates \((\text{SNR loss} < 2\%)\)

**CPU Time**

\[ T_{50s}^{1} = 130 \left( \frac{N_{\text{tmplt}}}{682} \right) \] [sec]

\[ T_{1000h} = 6.5 \left( \frac{N_{\text{tmplt}}}{682} \right) \left( \frac{16}{N_{\text{CPU}}} \right) \] [days]
## TAMA Observations

<table>
<thead>
<tr>
<th></th>
<th>Year</th>
<th>Lock Time [H]</th>
<th>Eff. Time [H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT6</td>
<td>2001</td>
<td>1042</td>
<td>959</td>
</tr>
<tr>
<td></td>
<td>Aug-Sep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT8</td>
<td>2003</td>
<td>1166</td>
<td>1086</td>
</tr>
<tr>
<td></td>
<td>Feb-Apr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT9</td>
<td>2003/4</td>
<td>472</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>Dec-Jan</td>
<td></td>
<td></td>
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</tbody>
</table>

Eff. Time = (Lock Time) - [4min * 2 * (number of locked segments)]
Detection Probability for Galactic events

Detection Probability

Larger Mass

Lower Mass

Detection Probability

0.1
1

Ringdown frequency $f_c$ [Hz]

0.1
1

DT6, SNR $> 10$

DT6, SNR $> 20$

DT8, SNR $> 10$

DT8, SNR $> 20$

DT9, SNR $> 10$

DT9, SNR $> 20$
Matched Filter Triggers

Trigger rate ~ 1/min (!)
Filter Output Examples:

(a) Simulated event (TAMA data + artificial signal)
- Filter output
- Time [ms]
- $\exp(-\pi f_c t/Q)$
- exponential tail

(b) Spike in data
- Filter output
- Time [ms]
Event Selection

True signal:
* exponential tail \( \tau = Q/\pi f_c \)
* symmetric around the local maximum \( \rho_0 \)

Fake triggers:
* exp rising, no tail

Time Domain Cuts:

- \( \xi^2 \)-cut

\[ \xi^2 \equiv \frac{1}{\rho_0^2} \sum [\rho(t) - \rho_0 \exp(-t/\tau)]^2 \]

- \( \alpha \)-cut

\[ \alpha \equiv \frac{F - B}{F + B} \]

True signal
---> smaller \( \xi^2 \) \( \alpha \)
\[ \xi^2 \equiv \frac{1}{\rho_0^2} \sum \left[ \rho(t) - \rho_0 \exp\left(-t/\tau\right) \right]^2 \]

Event Selection parameter cut
Triggers after selections

Larger Mass

Lower Mass

\[ T_{\text{obs}} \text{ [Hours]} \]
- DT6: 959
- DT8: 1086
- DT9: 430

Triggers (SNR > 20)

Ringdown Frequency [Hz]

DT6 diff
DT6 cum
DT8 diff
DT8 cum
DT9 diff
DT9 cum
Galactic Event Rate

\[ R(f_c) = \frac{N_{\text{trg}}(f_c)}{T_{\text{obs}}} \frac{1}{\epsilon(f_c)} \frac{1}{1 - \text{(false dismissal)}} \]

\[ R < 3.4 \times 10^{-2} \left[ H^{-1} \right] \]

\[ R < 1.8 \times 10^{-1} \left[ H^{-1} \right] \]

\[ R < 4.6 \left[ H^{-1} \right] \]

\[ f_c > 1500 \text{Hz}: \]

\( M < 20 M_{\odot} \)

\( R < 4.6 \left[ H^{-1} \right] \)

\( R < 1.8 \times 10^{-1} \left[ H^{-1} \right] \)

\( R < 3.4 \times 10^{-2} \left[ H^{-1} \right] \)
Summary

* BH ringdown is promising GW source

* Matched filtering code developed

* TAMA has good sensitivity to detect Galactic events, detection probability > 10%

* Galactic event rate < 1 event/day
  * DT9
  * SNR > 20
  * 1500Hz < fc < 2500Hz (10 < M < 20)
Galactic Event Simulation

Event Generator
Position \((R, z, \varphi)\)
Waveform \((f_c, Q)\)
phase \(\phi\), spin axis/rad. pattern

Source info.

TAMA Data

Injection point

Time info.

Matched filter

Template bank

Filter output

\(\text{SNR}\)
\(\text{Detection prob.}\)
\(\text{Waveform param acc.}\)
\(\text{How signals look like?}\)