Test of scalar-tensor gravity theory from observations of gravitational wave bursts with advanced detector network

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Testing relativistic gravity theory is important for fundamental physics and cosmology e.g. dark matter, dark energy, accelerating the Universe.

One of plausible gravity theories is scalar-tensor theory. Significant difference from the general relativity is the existence of a scalar field which is connected with the gravity field with coupling parameters, and a resulting scalar gravitational wave. Brans-Dicke theory is famous scalar-tensor theory which has a coupling parameter $\omega_{BD}$.

Tensor GW search might miss some type of sources, e.g. highly spherical core collapse if scalar-tensor theory is correct. In this sense, search for SGW is complementary to current GW search.

This talk will focus on search for SGW from Galactic spherical core collapses in Brans-Dicke theory.
Antenna pattern for scalar mode

Antenna pattern function as a function of sky position \((\theta, \Phi)\) is written as

\[
F_+ (\hat{\Omega}) = \frac{1}{2} (1 + \cos^2 \theta) \cos 2\phi \\
F_\times (\hat{\Omega}) = \cos \theta \sin 2\phi \\
F_\circ (\hat{\Omega}) = -\sin^2 \theta \cos 2\phi.
\]


Polarization of tensor, scalar gravitational wave

Tensor GW

- \(h_+\)

Scalar GW

- \(h_\circ\)

Spin 0

Antenna pattern sky-map of scalar mode

HI

\[ \text{Fav(fo, H1)} \]

HLV

HLVA

HLVAJ
Coherent network analysis can extract scalar gravitational wave with more than 3 world-wide detectors. This approach combines data taking account of the sky position \((\theta, \varphi)\), arrival time difference \(\tau(\theta, \varphi)\) coherently, and calculates all polarization components at a certain direction of the sky which is most likely.

#### Mathematical expression of the coherent network analysis

Expression of d-detectors can be taken as

\[
\begin{bmatrix}
  x_1 \\
  \vdots \\
  x_d
\end{bmatrix} =
\begin{bmatrix}
  F_{1+} & F_{1\times} & F_{1o} \\
  \vdots & \vdots & \vdots \\
  F_{d+} & F_{d\times} & F_{do}
\end{bmatrix}
\begin{bmatrix}
  h_+ \\
  h_\times \\
  h_o
\end{bmatrix} +
\begin{bmatrix}
  n_1 \\
  \vdots \\
  n_d
\end{bmatrix}
\]

The reconstruction of a gravitational wave is an inverse problem. Maximum likelihood method to solve the inverse problem:

\[
L[h] := \| x - Fh \|^2
\]

Changing sky position \((\theta, \varphi)\), time difference \(\tau(\theta, \varphi)\).

The mathematical formula of the reconstructed scalar gravitational wave is

\[
h_o = \frac{1}{\det(M)}((F_+ \times F_{\times}) \cdot (F_{\times} \times F_o)) \cdot F_+
\]

\[
- ((F_+ \times F_{\times}) \cdot (F_+ \times F_o)) \cdot F_{\times}
\]

\[
+ ((F_+ \times F_{\times}) \cdot (F_+ \times F_{\times})) \cdot F_o \cdot x
\]
Scalar pipeline

- Full featured coherent network analysis pipeline (Data conditioning, detection stat., Veto analysis)
- One can apply the pipeline to H1, L1, V1, A1, LCGT
- Analysis result is output by a Web-based event display.
Demonstration of pol. reconstruction

Reconstruction of $h_+$, $h_x$, $h_o$

- **As to injection signal, to see $h_o$ clearly, I used spike-like burst as $h_o$.**
- **Although the grid of lat-lon map is coarse (4°x4°) in the simulation, $h_o$ is reconstructed clearly.**

$h_+, h_x : $SG235Q9
$h_o : $Not injected

map (max radial dist) serial #58; $\theta_{min} = -10$ $q_{min} = -4$(deg)

$h_+, h_x : $SG235Q9
$h_o : $Spike-like burst

map (max radial dist) serial #58; $\theta_{min} = -10$ $q_{min} = -4$(deg)

2011年1月29日土曜日
Astrophysical model used is a spherically symmetric core collapse with 10Mo at the distance of 10kpc from the earth. (M. Sibata, 1994)
ROC curve for adv. networks

Simulated GWs is from spherical core collapse at 10kpc. Sky directions are uniformly distributed.

Detection probability vs. false alarm rate for different algorithms: HLVAJ, HLVA, HLV.
Waveform reconstructions for $\omega_{BDs}$

We performed simulations to reconstruct scalar gravitational waves with $\omega_{BD} = 40000, 80000, 120000, 160000$. This simulation uses the design sensitivity of advLIGO for LIGO, VIRGO, and LCGT. Astrophysical model used is the same as the previous simulation.

<table>
<thead>
<tr>
<th>$\omega_{BD}=160000$</th>
<th>$\omega_{BD}=120000$</th>
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<tbody>
<tr>
<td>$h_+$</td>
<td>$h_+$</td>
</tr>
<tr>
<td>$h_x$</td>
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<table>
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<tr>
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<tr>
<td>$h_0$</td>
<td>$h_0$</td>
</tr>
</tbody>
</table>
ROC curve for $\omega_{BD}$

- Detection probability
- False alarm rate

Current constraint by Cassini

- 40000
- 100000
- 160000
We discuss search for scalar GW from Galactic spherical core collapse in Brans-Dicke theory with various adv det. network.

Although depending sky location and models, it is possible to put stronger constraint on $\omega_{BD}$.

LCGT and LIGO-Australia play an important role for search for scalar gravitational waves.

We need numerical simulations of scalar GW in S-T theory.
Red plot is injected $h_0$ signal and blue plot is the reconstructed $h_0$. The difference at the low frequency region comes from the data conditioning step. Detector noise at low frequency is very high, such region is cut at the step.