Test for scalar-tensor theory from observations of gravitational wave bursts with a network of interferometric detectors

Project page :
http://www.aei.mpg.de/~kahaya/RIDGE-SCALAR/index.html

Kazuhiro Hayama (AEI Hannover)
Atsushi Nishizawa (NAOJ)
Atsushi Taruya (U. Tokyo)

Albert Einstein Institute Hannover
東京大学 THE UNIVERSITY OF TOKYO
NAOJ National Astronomical Observatory of Japan

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Abstract

Testing relativistic gravity theory from gravitational wave observations is important for fundamental physics and cosmology. The constraint of the gravity theory might give a key to the solution of the mysteries of dark matter and dark energy. 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 a coupling parameter, and a resulting scalar gravitational wave. In this talk, focusing on Brans-Dicke model as a scalar-tensor theory, we present how to extract a scalar gravitational wave signal using a network of world wide interferometric detectors. We perform simulations to extract a scalar gravitational wave which has a comparable coupling parameter to the current upper limit by Cassini assuming supernova occur in our Galaxy. In the simulation, we use simulated noise with LIGO-VIRGO-GEO design sensitivity. We discuss new data analysis issue which has to be solved for the detection of the scalar gravitational wave and also discuss the capability of advanced LIGO, LCGT.

Search for scalar gravitational waves in Brans-Dicke Theory

- Main purpose of the search is the detection of a scalar gravitational wave. Particularly, in case of a spherically symmetric core collapse, a tensor gravitational wave cannot emit, only the scalar gravitational wave can emit.
- Even if the scalar gravitational wave is not detected, a constraint of ω_{BD} is possible.
- Current constraint ω_{BD} is $\omega_{BD} > 4\times10^4$ from Cassini (Nature, 2003, astro-ph0709.0082)

How an interferometric detector can detect a scalar gravitational wave?
We assume the scalar gravitational wave h_o comes from z-axis. The geodesic equation of a mirror is

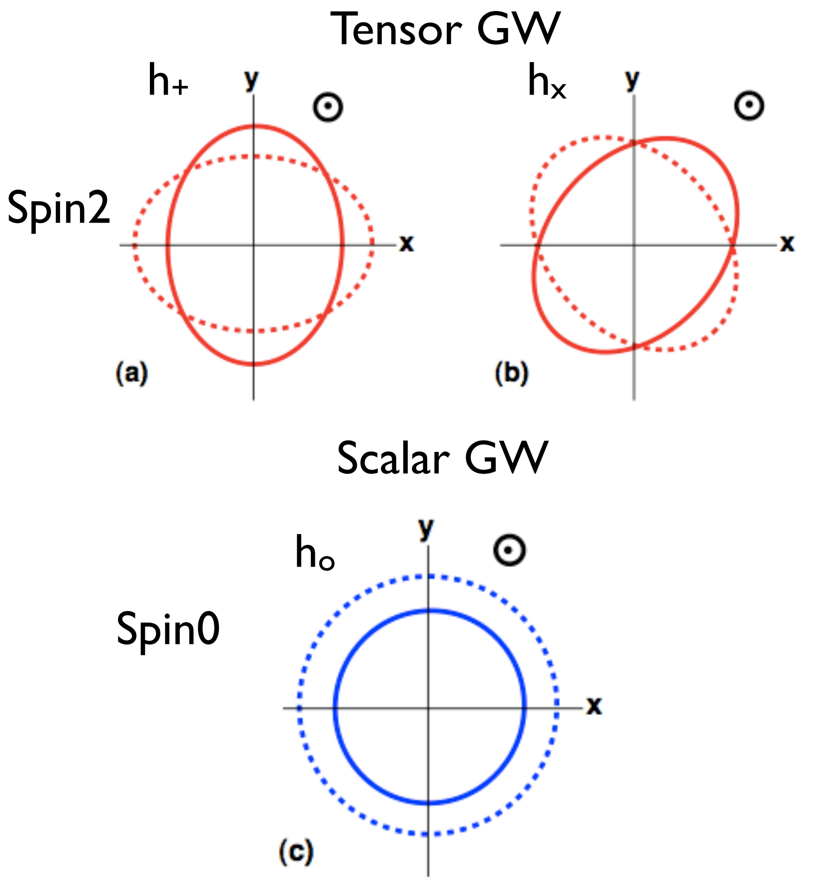
$$\frac{d}{d\tau}\left[(1+h_o)\frac{dx}{d\tau}\right] = \frac{d}{d\tau}\left[(1+h_o)\frac{dy}{d\tau}\right] = 0$$
$$\frac{d}{d\tau}\left[(1+h_o)\frac{dt}{d\tau}\right] = -\frac{1}{2}\frac{\partial_t(1+h_o)}{1+h_o}$$
$$\frac{d}{d\tau}\left[(1+h_o)\frac{dz}{d\tau}\right] = -\frac{1}{2}\frac{\partial_z(1+h_o)}{1+h_o}$$

Introducing u = t - z, performing integration of z, we obtain

$$\Delta z \simeq \frac{1}{2}\int_{-\infty}^{t-z_0} h_o(u)du$$

This shows the scalar gravitational wave moves a mirror in z-axis.

Polarization of tensor, scalar gravitational wave



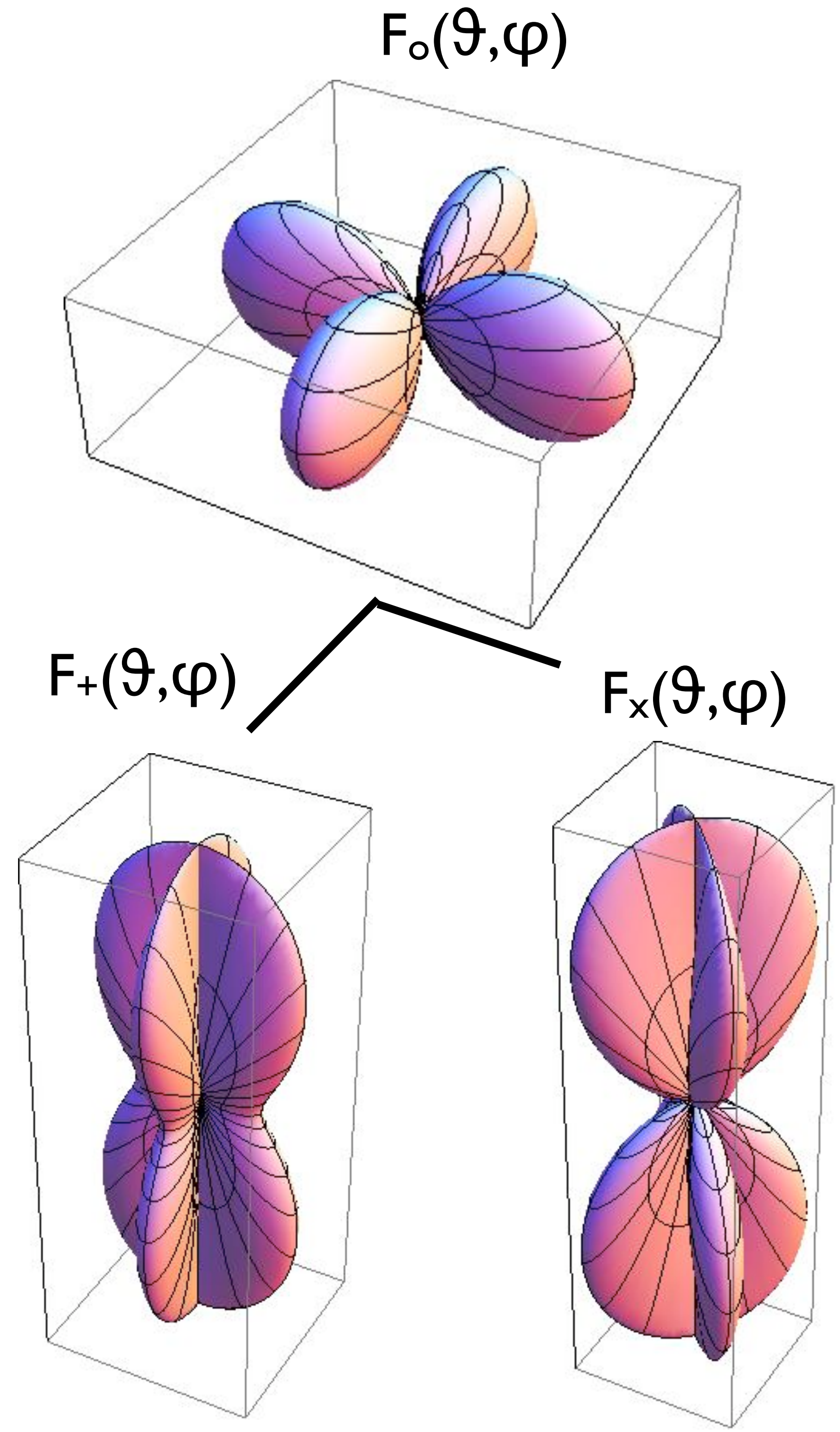
C.Will, Living Review (2006)

Antenna pattern to polarization

Antenna pattern function as a function of sky position (θ,Φ) is written as

$$
\begin{aligned}
F_+(\hat{\Omega}) &= \frac{1}{2}(1+\cos^2\theta)\cos 2\phi \\
F_\times(\hat{\Omega}) &= \cos\theta \sin 2\phi \\
F_\circ(\hat{\Omega}) &= -\sin^2\theta\cos 2\phi.
\end{aligned}
$$

M.Tobar etal(1999), M. Maggiore etal(2000), K.Nakao etal(2001)



Significant characteristics are

- Fo does not have its sensitivity in the source direction while F+,Fx has maximum one.
- On the contrary, Fo has maximum sensitivity in the perpendicular direction.
- The scalar mode is spin0, which means independence of choice of wave coordinate.

antenna pattern of a detector

Antenna pattern functions to all polarization of a detector in the earth-fixed coordinate are calculated as follows:

Detector tensor d is defined as

$$d = \frac{1}{2}[\hat{X} \otimes \hat{X} - \hat{Y} \otimes \hat{Y}]$$

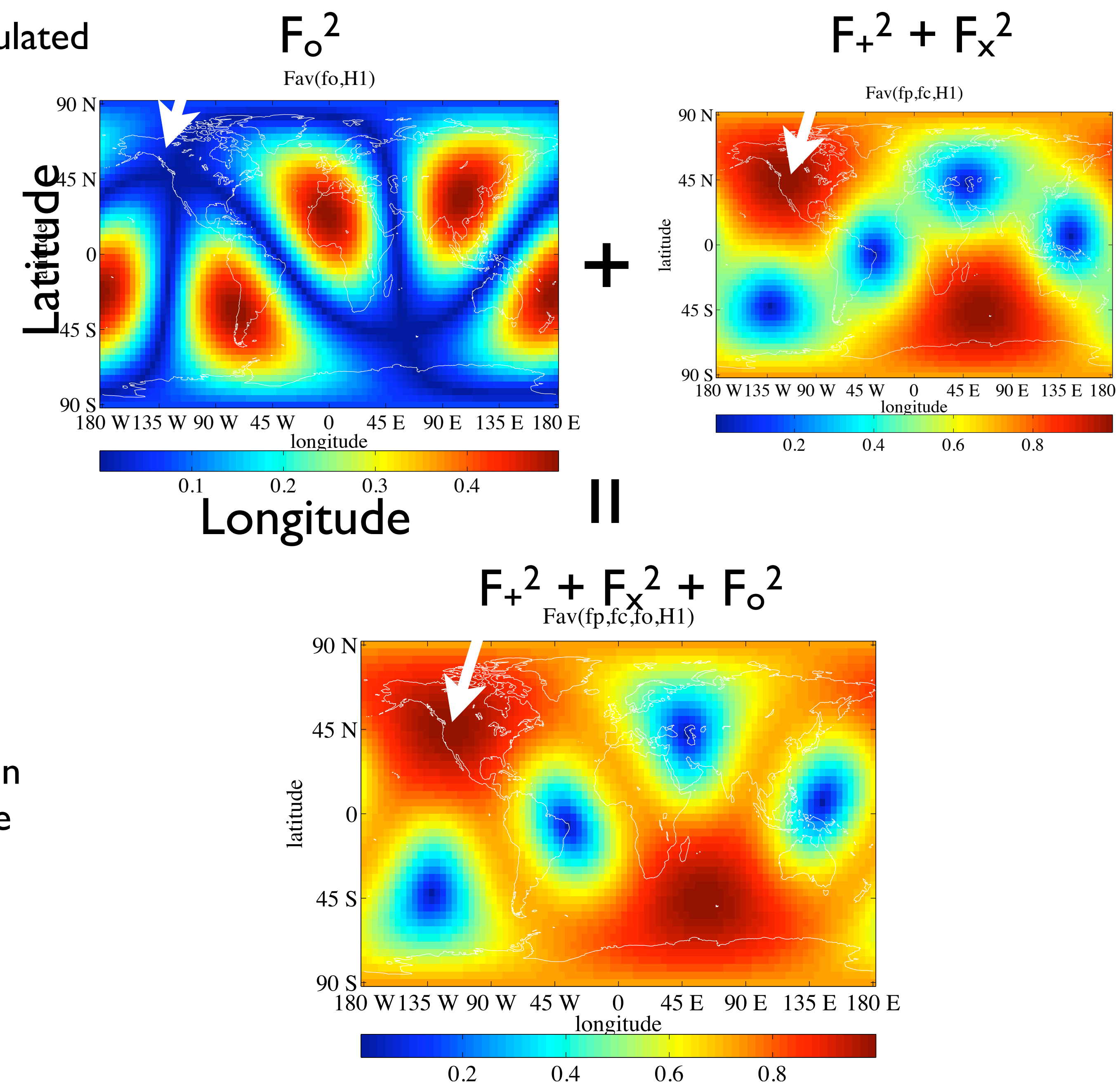
, unit vector X, Y are along with arms of the detector.

Polarization tensors are written by wave coordinate

$$\begin{aligned} e^{+}(\hat{\Omega}) &= \hat{\boldsymbol{e}}_\theta \otimes \hat{\boldsymbol{e}}_\theta - \hat{\boldsymbol{e}}_\phi \otimes \hat{\boldsymbol{e}}_\phi \\ e^{\times}(\hat{\Omega}) &= \hat{\boldsymbol{e}}_\theta \otimes \hat{\boldsymbol{e}}_\phi - \hat{\boldsymbol{e}}_\phi \otimes \hat{\boldsymbol{e}}_\theta \\ e^{o}(\hat{\Omega}) &= \hat{\boldsymbol{e}}_\theta \otimes \hat{\boldsymbol{e}}_\theta + \hat{\boldsymbol{e}}_\phi \otimes \hat{\boldsymbol{e}}_\phi \end{aligned}$$

Antenna pattern functions at a given time when the detector is located a certain location can be expressed as

$$F_A = e^{A}_{ij}(\hat{\Omega}) d^{ij}, \quad A = +, \times, o$$



Search for scalar gravitational waves in Brans-Dicke Theory

- Coherent network analysis can extract scalar gravitational wave with more than 4 world-wide detectors. This approach combines data taking account of the sky position (ϑ,φ), arrival time difference τ(ϑ,φ) 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

$$\begin{bmatrix} x_1 \\ \vdots \\ x_d \end{bmatrix} = \begin{bmatrix} F_{1+} & F_{1\times} & F_{1\circ} \\ \vdots & \vdots & \vdots \\ F_{d+} & F_{d\times} & F_{d\circ} \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \\ h_\circ \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_d \end{bmatrix}$$

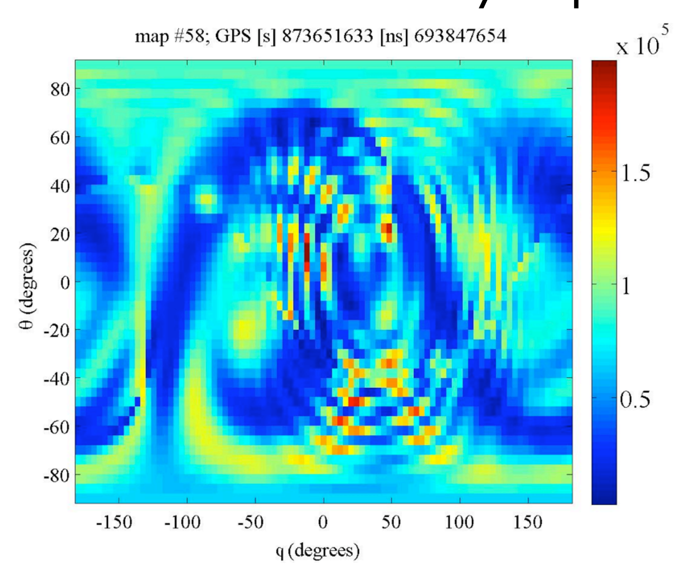
The reconstruction of a gravitational wave is an inverse problem.
Maximum likelihood method to solve the inverse problem:

$$L[\boldsymbol{h}] := \| \boldsymbol{x} - \boldsymbol{F}\boldsymbol{h} \|^2$$

Changing sky position (ϑ,φ), time difference τ(ϑ,φ).
The mathematical formula of the reconstructed scalar gravitational wave is

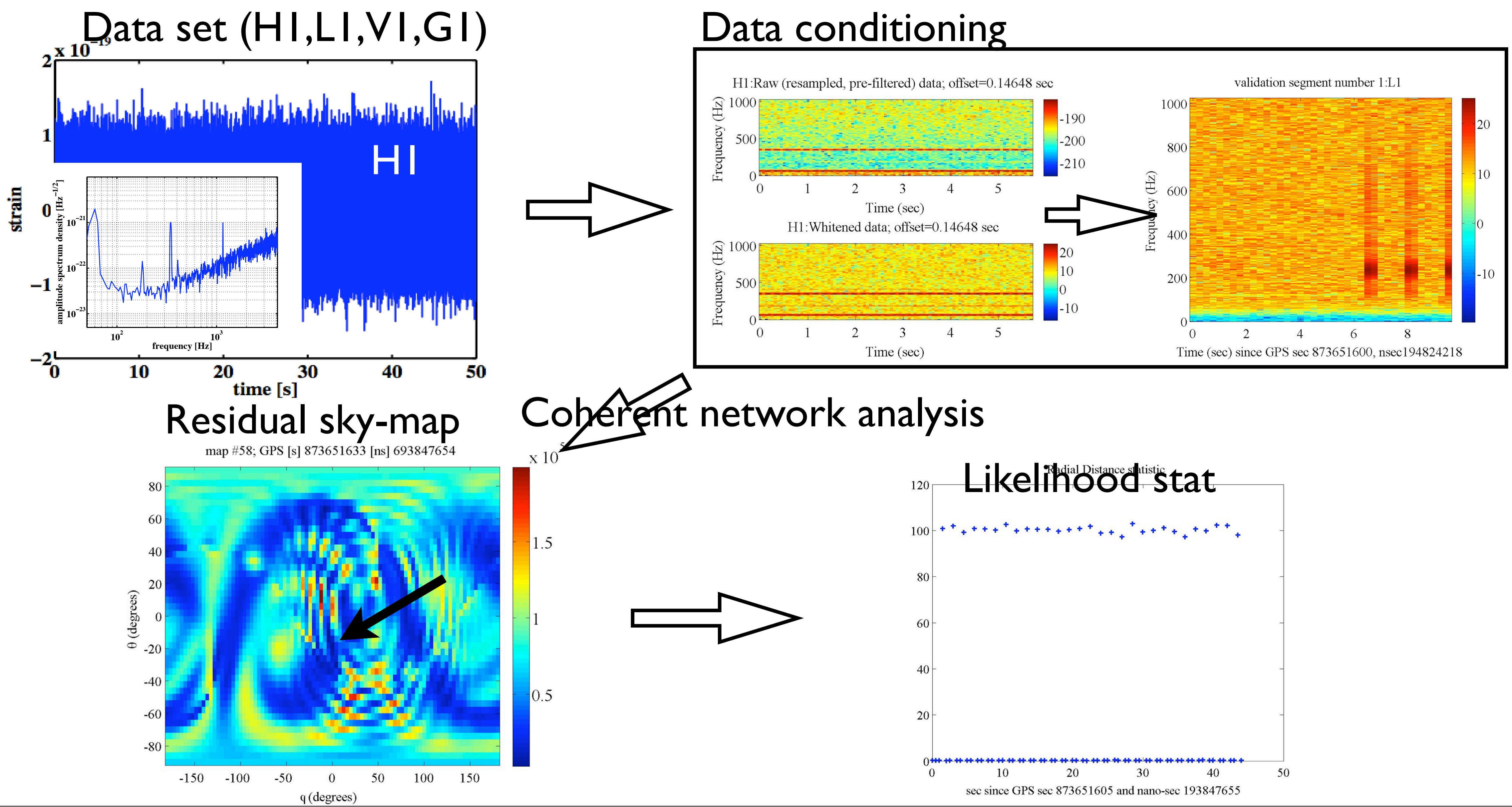
$$\begin{aligned} h_\circ &= \frac{1}{\det(\boldsymbol{M})}(((F_+ \times F_\times)\cdot(F_\times \times F_\circ))\cdot F_+ \\ &- ((F_+ \times F_\times)\cdot(F_+ \times F_\circ))\cdot F_\times \\ &+ ((F_+ \times F_\times)\cdot(F_+ \times F_\times))\cdot F_\circ)\cdot \boldsymbol{x} \end{aligned}$$

Likelihood residual sky-map

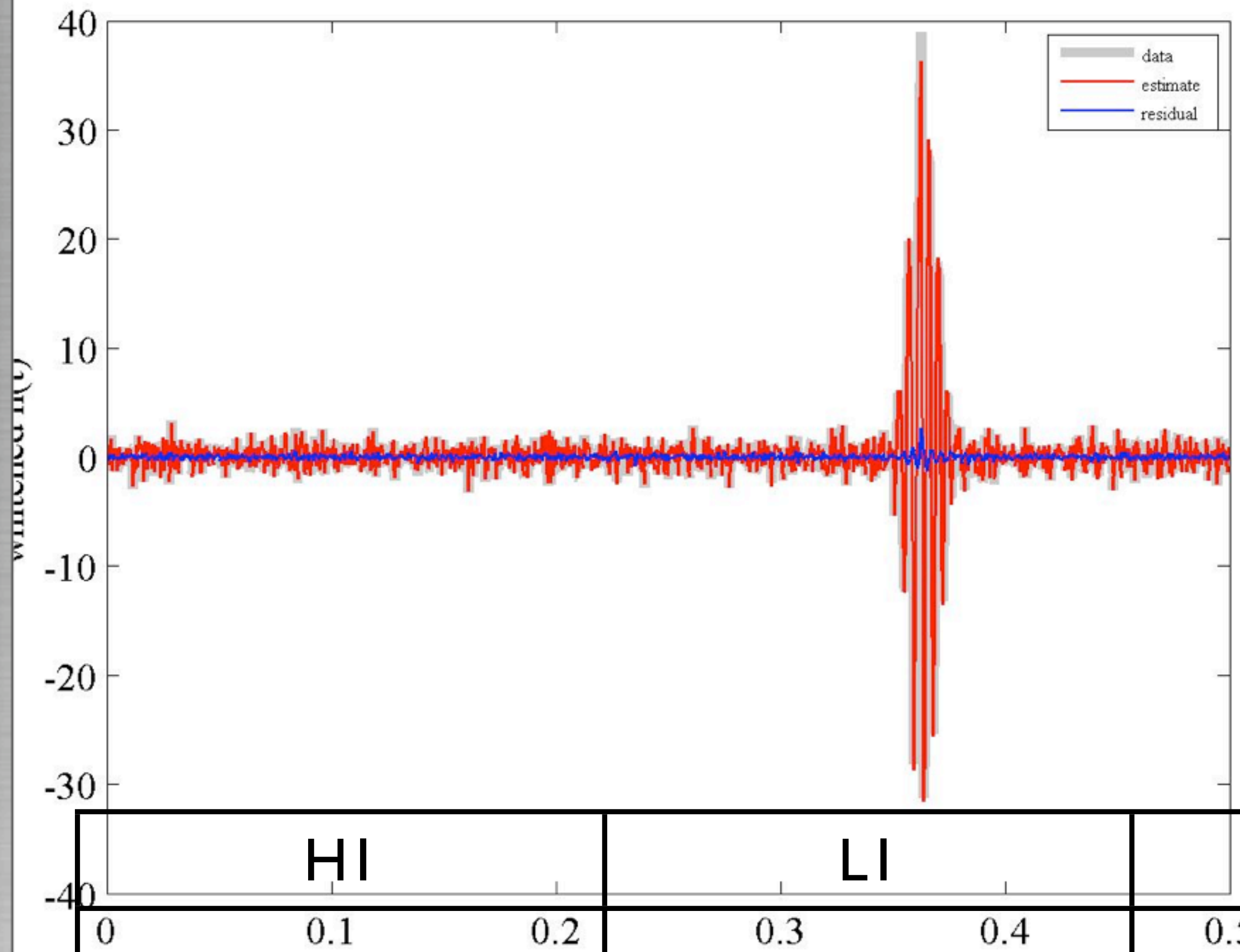


RIDGE-Scalar pipeline

- Full featured coherent network analysis pipeline(Data conditioning, detection stat., Veto analysis)
- One can apply the pipeline to H1,H2,L1,V1,G1 (Here, I used H1,L1,V1,G1 simulated data)
- Analysis result is output by a Web-based event display.

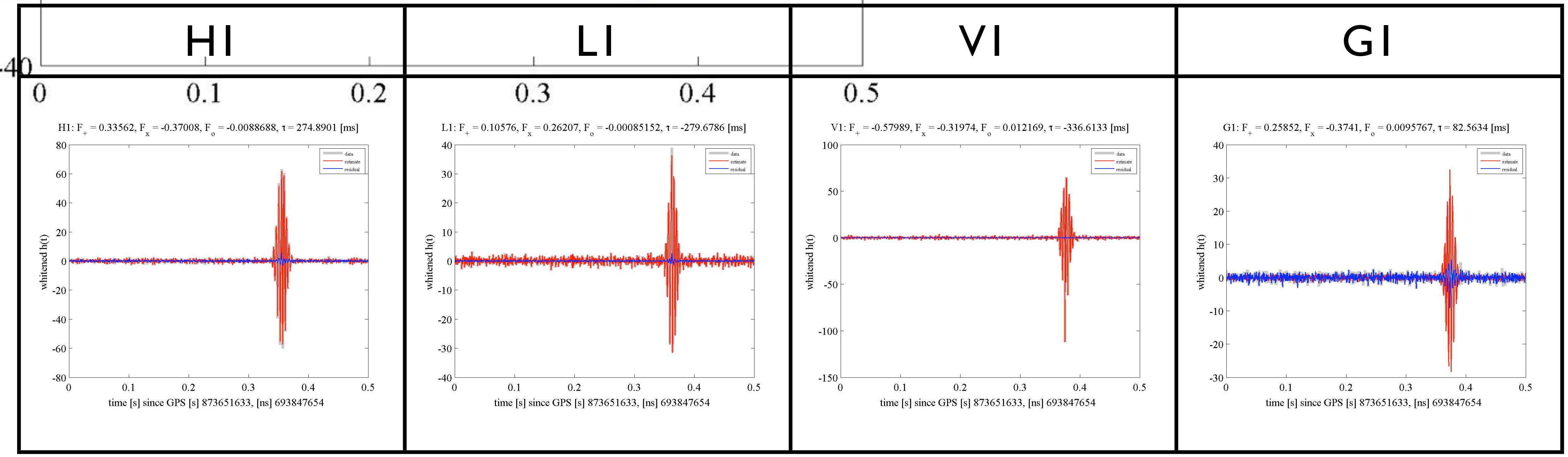


Reconstruction of detector response



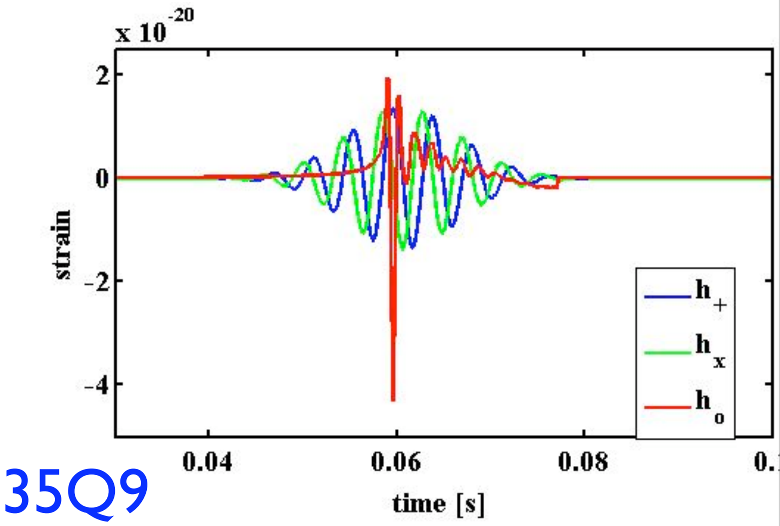
- Red plot: Reconstructed detector response
- Grey plot: Detector response
- Blue plot : Residual

Residual is calculated by subtracting the reconstructed detector response from the detector response. The energy of the residual shows how well the detector response is reconstructed. In this simulation, since simulated GEO data is more noisy than others, the residual is larger.



RIDGE-Scalar pipeline

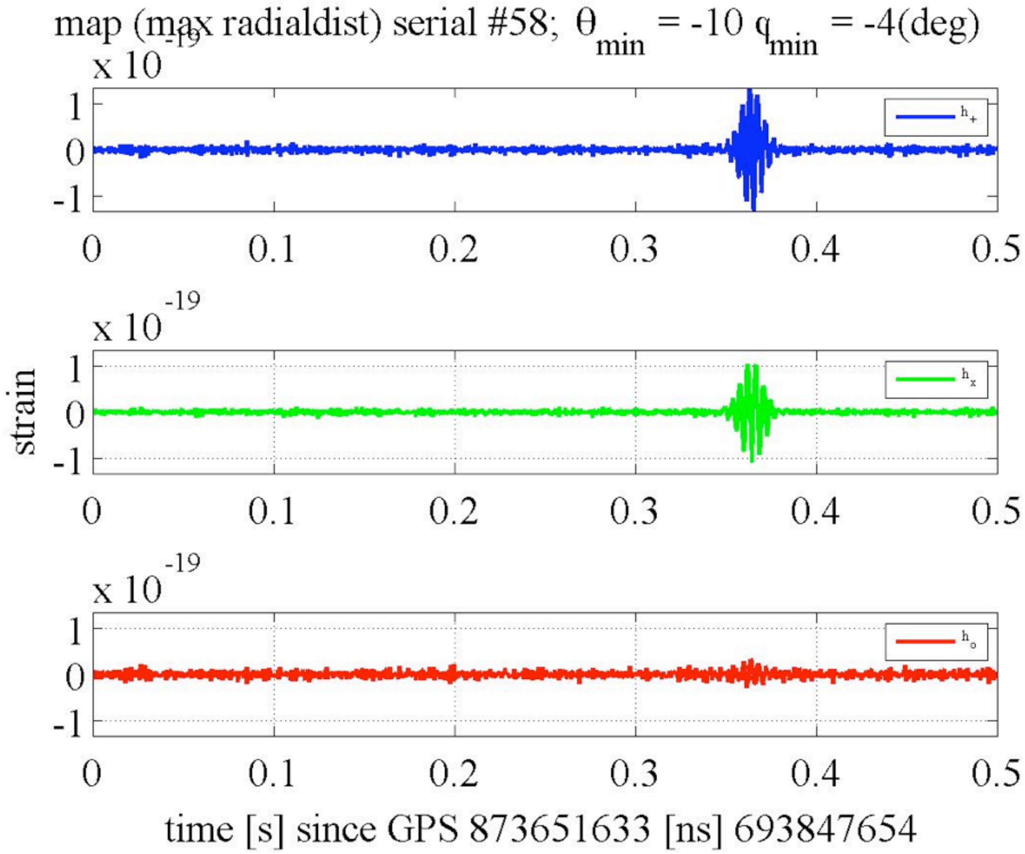
Reconstruction of h_+, $h_\times$, h_o



- 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, ho is reconstructed clearly.

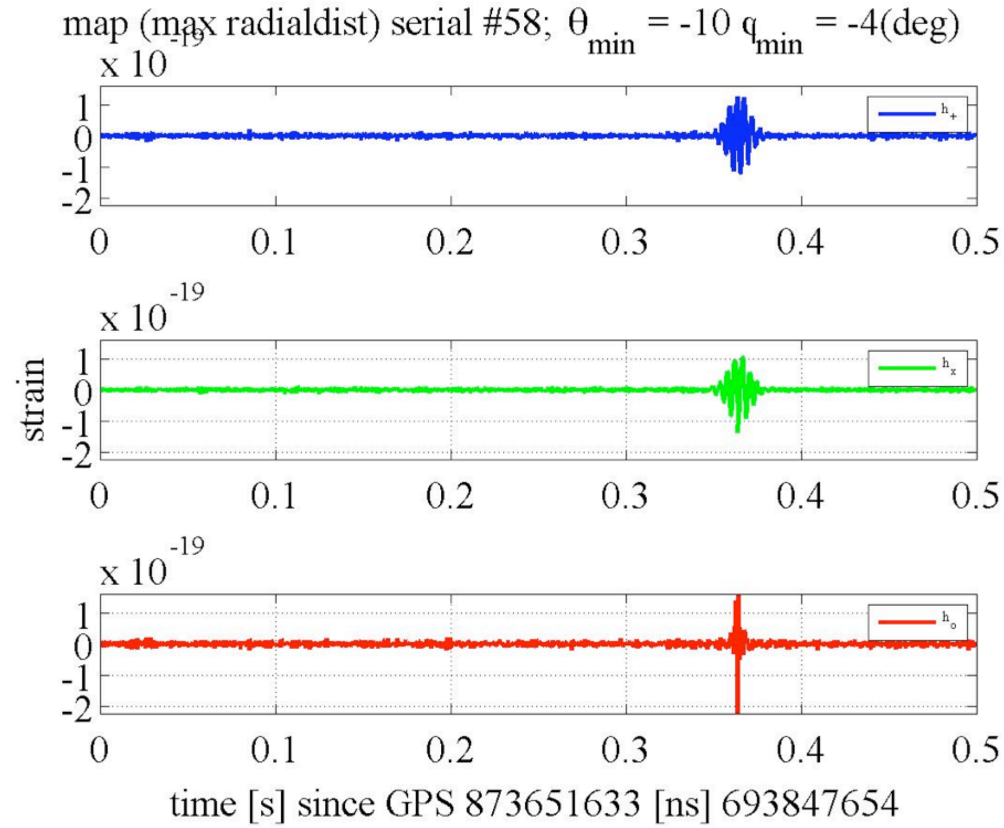
h_+, $h_\times$: SG235Q9

h_o : Not injected

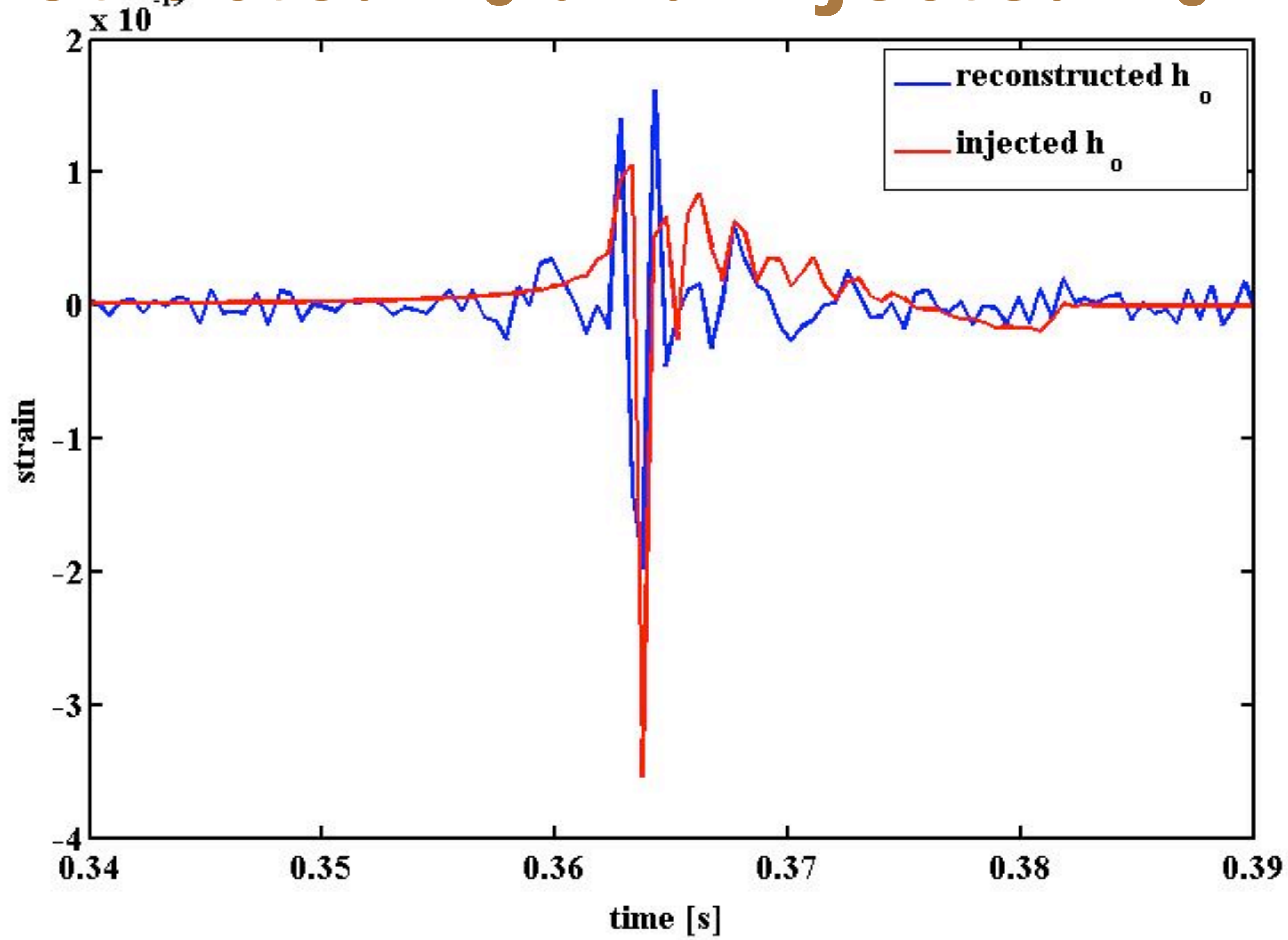


h_+, $h_\times$: SG235Q9

h_o : Spike-like burst



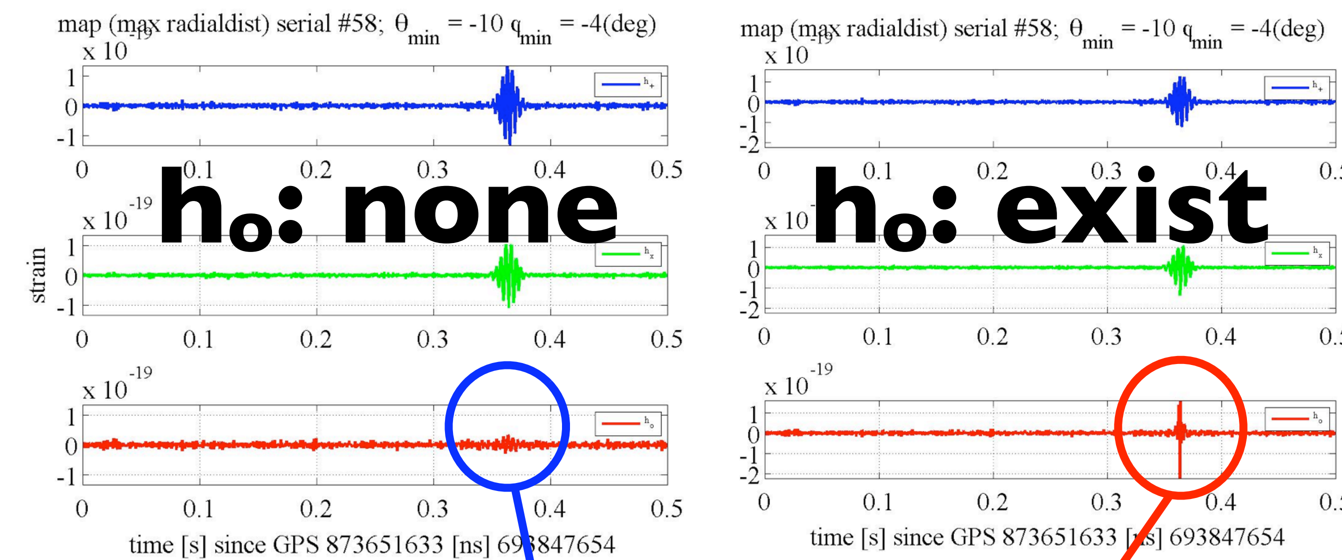
Comparison of reconstructed h_o and injected h_o



Red plot is injected ho signal and blue plot is the reconstructed ho.
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.

Background

We perform an excess power method to calculate detection statistic.



Excess power method

- h_0 is divided into segments (each segment is overlapped 50%
- In each segment, events are extracted in wavelet space by hard thresholding.

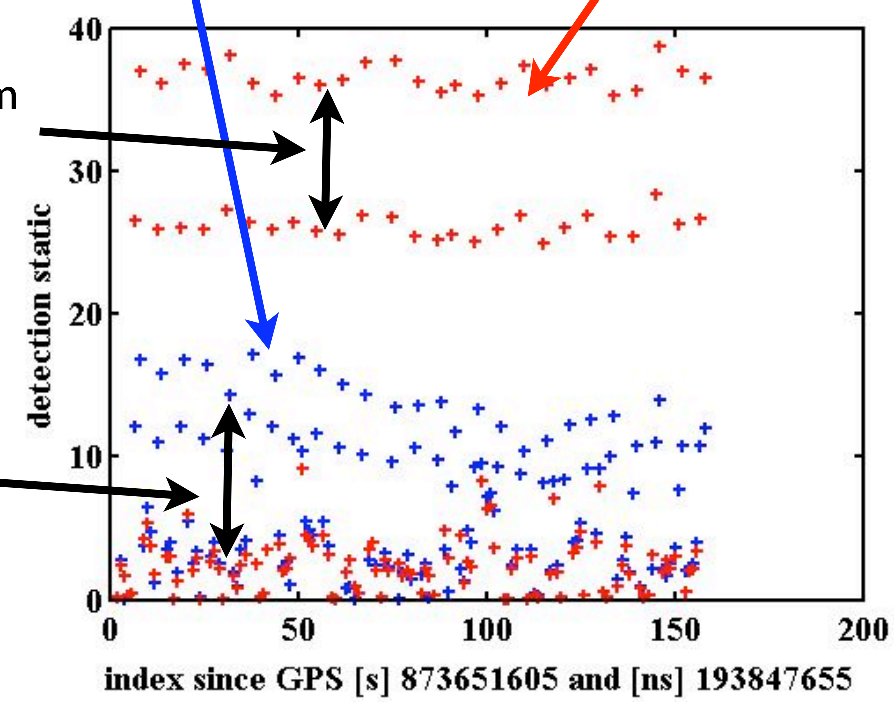
$$\hat{w}_{i,j} = w_{i,j} \ \text{if} \ \text{abs}(w_{i,j}) > T$$
$$0 \ \text{if} \ \text{abs}(w_{i,j}) < T$$

- Calculate statistic defined as

$$\text{static} = \sqrt{\frac{\sum \hat{w}_{i,j}^2}{\sigma^2}}$$

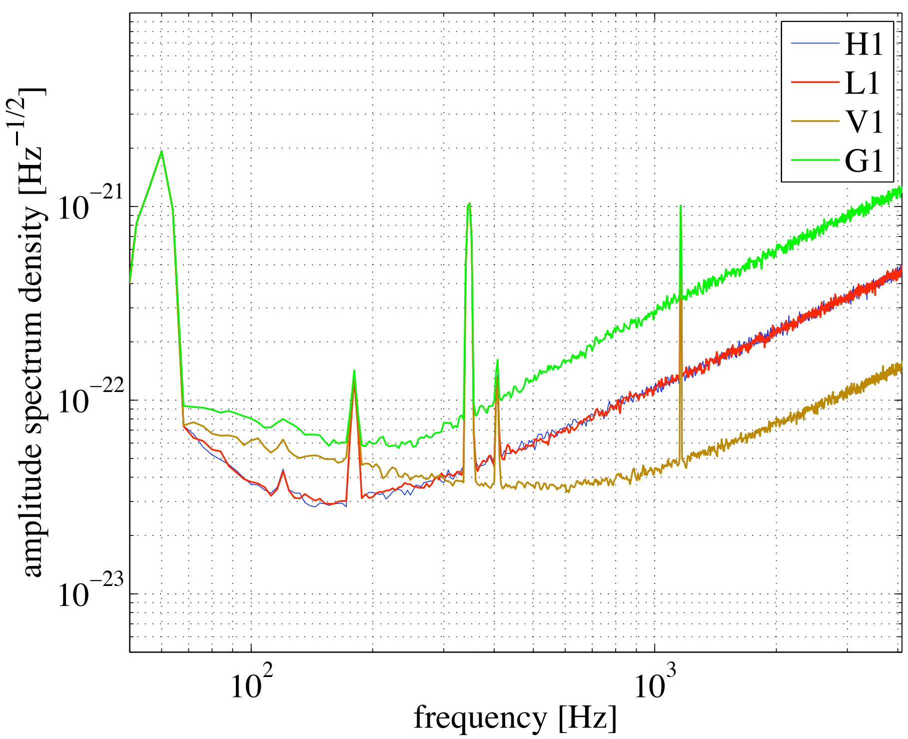
This gap comes from overlap of segments

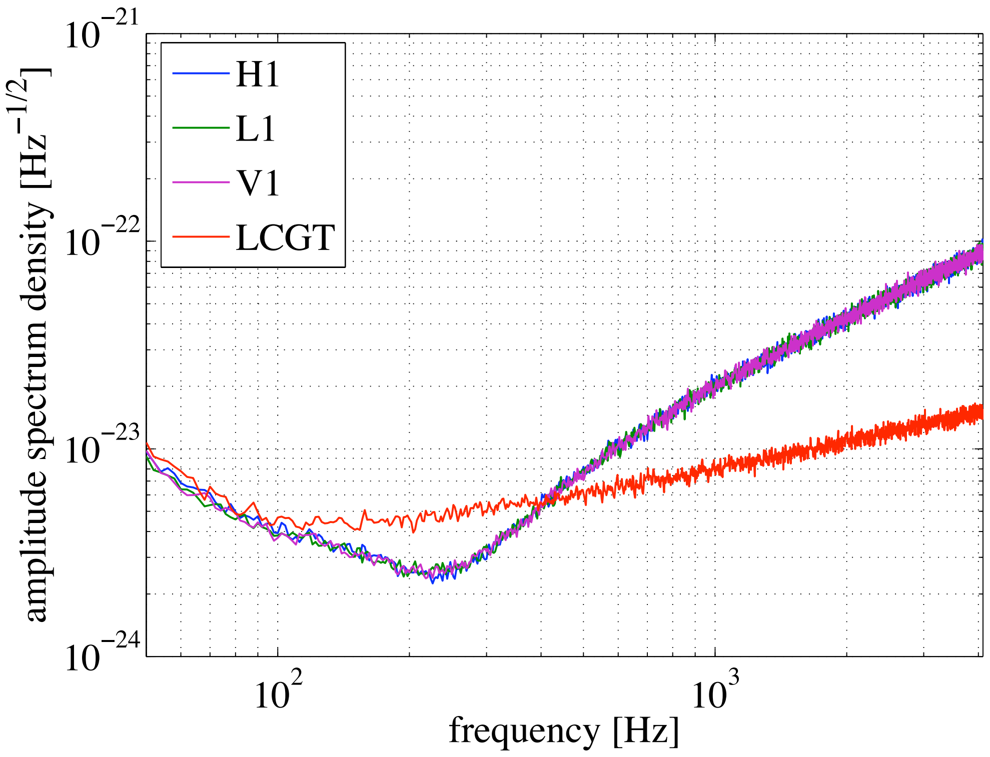
Error of waveform estimation



Simulated data

- Simulations were performed using simulated noise of current detector network (4km LIGO Hanford, Livingston, VIRGO, GEO600) and next generation (4km advLIGO Hanford, Livingston, advVIRGO, LCGT) For advVIRGO, the design sensitivity of advLIGO is used.

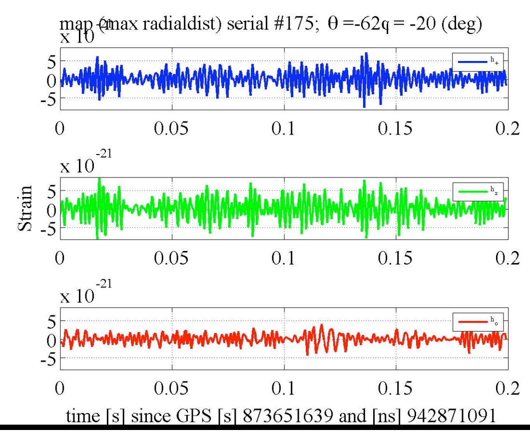




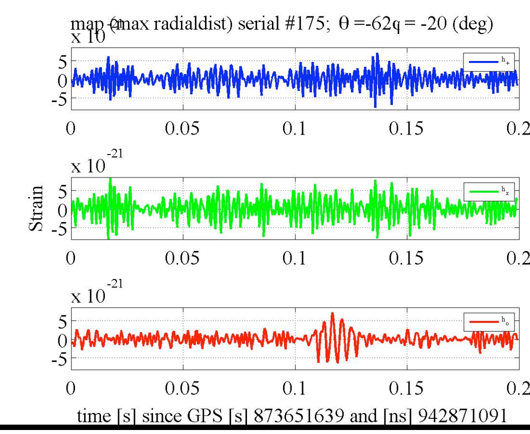
Reconstruction of SGW with some ω_{BD}

We performed simulations to reconstruct scalar gravitational waves with ω_{BD} = 2000,5000,10000,20000. Astrophysical model used is a spherically symmetric core collapse with 10Mo at the distance of 10kpc from the earth. Sine Gaussian with center frequency of 235Hz and Q value of 9 is used as scalar gravitational wave. The maximum amplitude of the signal is set to $3\times10^{-20}\times500/\omega_{BD}$ from Shibata et al(1994). From the result, we found the signal with ω_{BD}<=10000 is detected and reconstructed clearly.

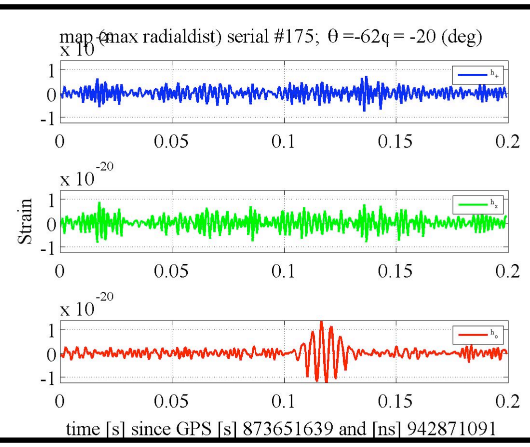
ω_{BD}=20000



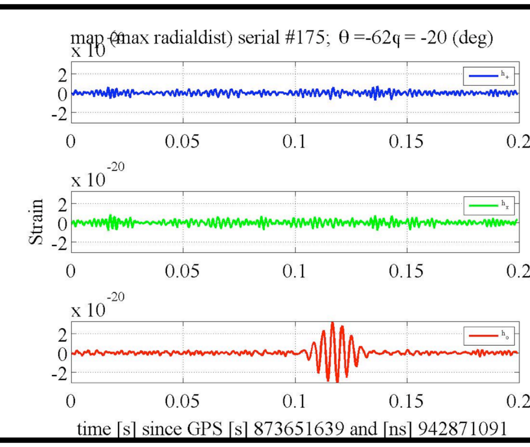
ω_{BD}=10000



ω_{BD}=5000



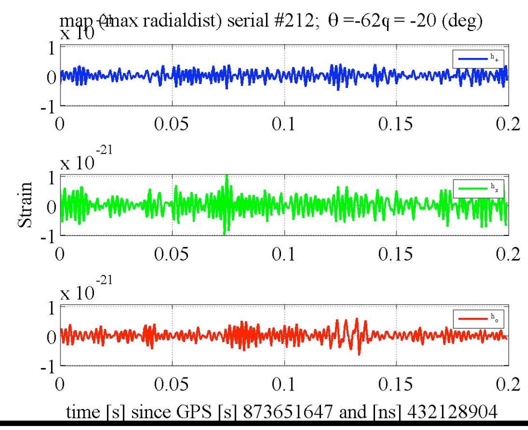
ω_{BD}=2000



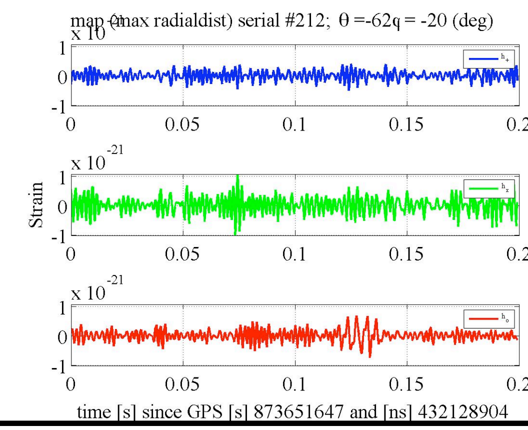
Reconstruction of SGW with some ω_{BD}

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

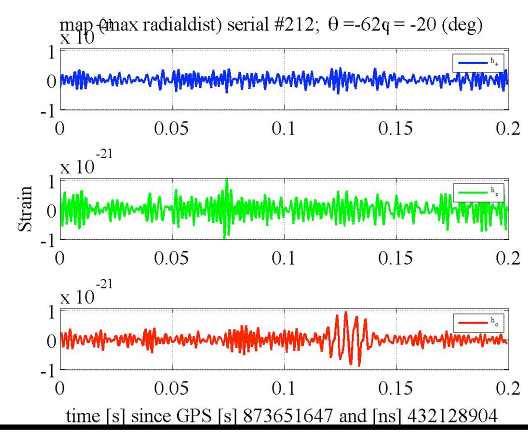
ω_{BD}=160000



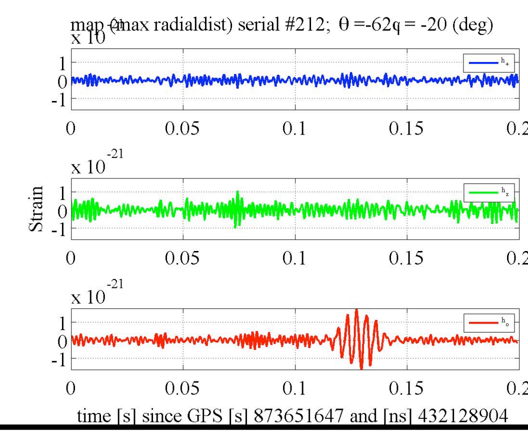
ω_{BD}=120000



ω_{BD}=80000



ω_{BD}=40000



Conclusion

- We discussed test of scalar-tensor theory from gravitational wave observations. Here we picked Brans-Dicke model.
- We implemented a coherent network analysis pipeline for the detection of a scalar gravitational wave with the current network of interferometric detectors.
- From our simulation, current gravitational wave detector network can pose $\omega_{BD} >= 10000$. This constraint is by several factor weaker than from Cassini.
- Next generation of detectors (advLIGO, LCGT) can put constraint much stronger than Cassini if a spherically symmetric core collapse occurs in our Galaxy.
- Estimation error of tensorial modes are mixed into error of the scalar mode. This may limit the lower limit of the coupling parameter.

LIGO-G0900532