Testing 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

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Motivation

- 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.
- In general, Scalar-tensor theories has a term of matter in the action in which physical metric:

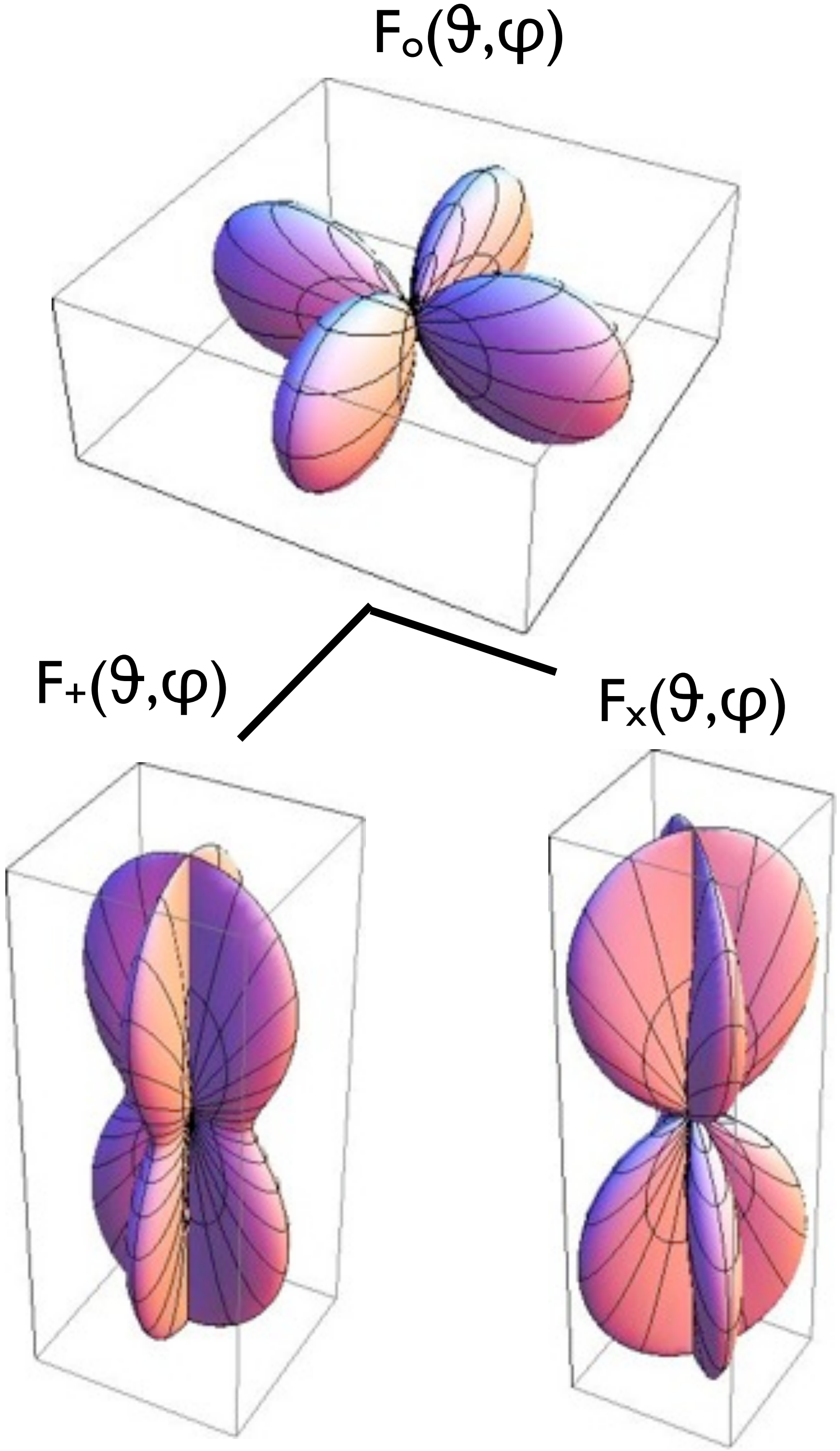
$$\tilde{g}_{\mu\nu} := A^2(\phi) g^*_{\mu\nu}$$

$$A(\phi) = e^{\alpha_0(\phi-\phi_0)+\frac{1}{2}\beta_0(\phi-\phi_0)^2}$$

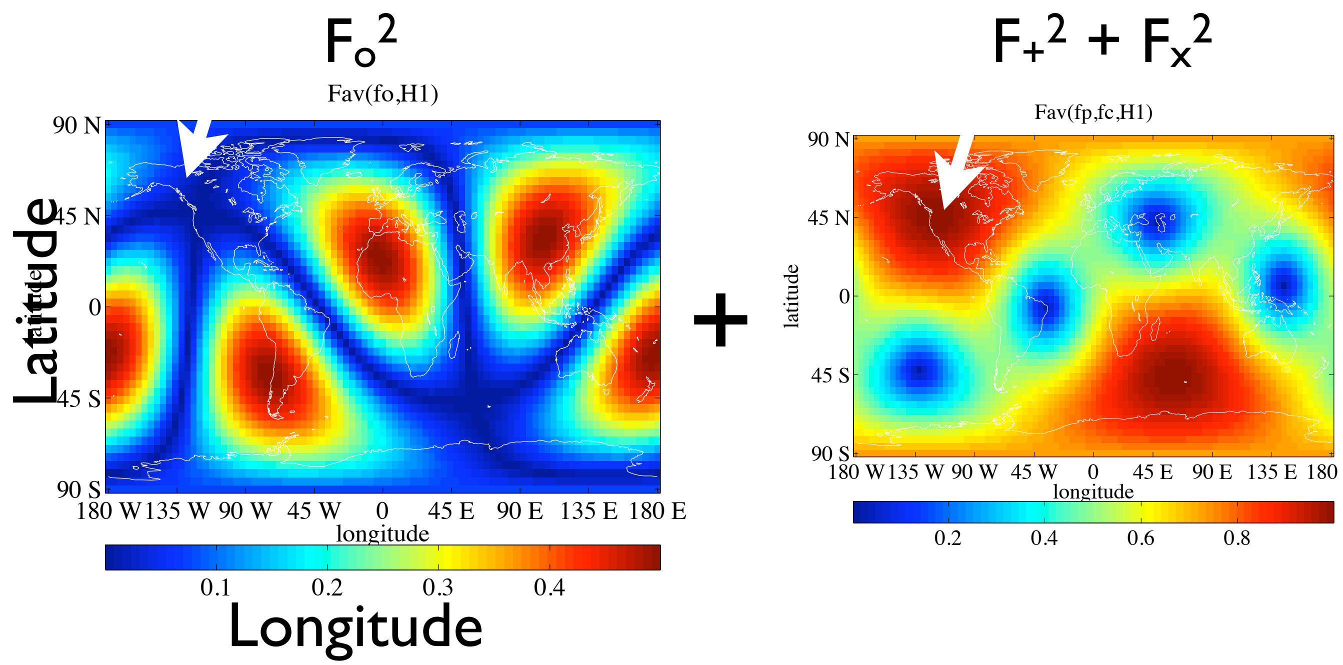
α_0 and β_0 are parameters which characterize

  - α_0 : weak gravity field (test in solar system, $\alpha < 3.5\times10^{-3}$ by Cassini)
  - β_0 : strong gravity field (can constrain by GW observation ($\beta = 0$ in Brans–Dicke))
- Tensor GW search might miss some type of source, e.g. highly spherical core collapse.. In this sense, search for SGW is complementary to current GWsearch.
- we present how to extract a scalar gravitational wave signal using a network of world wide interferometric detectors.

Antenna pattern to polarization



Antenna pattern sky-map (LIGO Hanford)



- SGWs have Maximum sensitivity to the direction in which TGWs don't have sensitivity.
  ----> complementary to TGW search

Search for scalar gravitational waves

- 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 (ϑ,φ), arrival time difference τ(ϑ,φ) coherently, and calculates all polarization components on a sky position which has largest likelihood statistic.

Mathematical expression of the coherent network analysis

Expression of d-detectors can be taken as

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

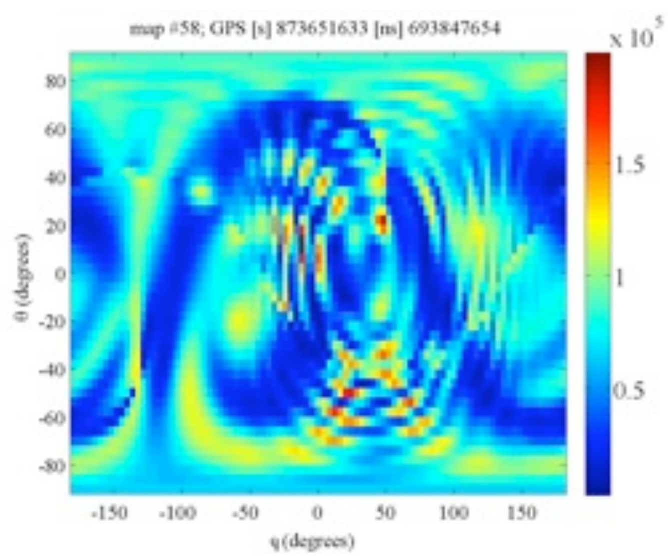
The reconstruction of a gravitational wave is an inverse problem.
Maximum likelihood method to solve the inverse problem:

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

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

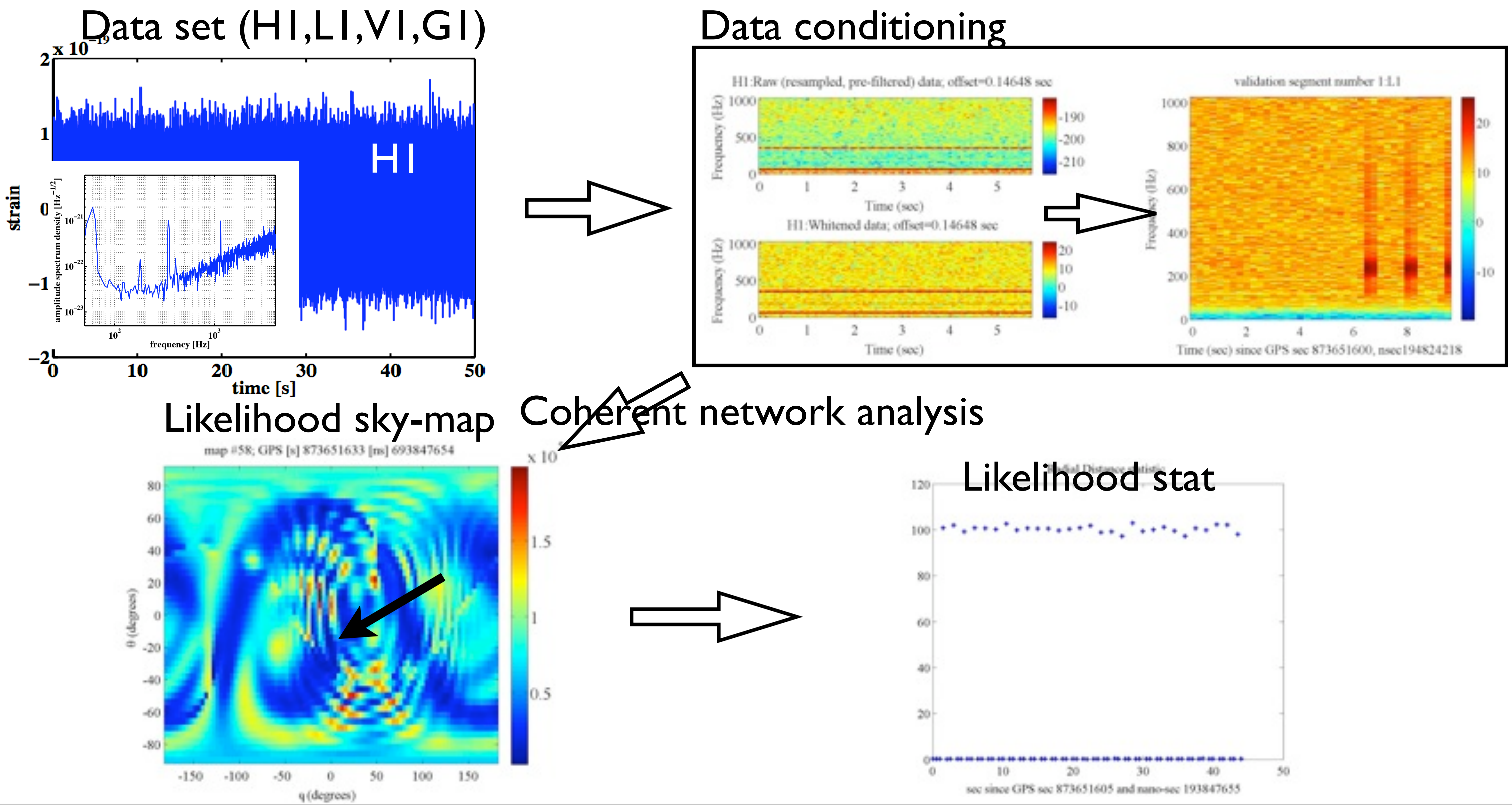
$$\begin{aligned} h_\circ &= \frac{1}{\det(\boldsymbol{M})}\big(((F_+ \times F_\times)\cdot(F_\times \times F_\circ))\cdot F_+ \\ &- ((F_+ \times F_\times)\cdot(F_+ \times F_\circ))\cdot F_\times \\ &+ ((F_+ \times F_\times)\cdot(F_+ \times F_\times))\cdot F_\circ\big)\cdot \boldsymbol{x} \end{aligned}$$

Likelihood residual sky-map



Scalar pipeline

- Full featured coherent network analysis pipeline(Data conditioning, detection stat., Veto analysis)



Reconstruction of pol. modes

Reconstruction of h_+, h_x, h_o

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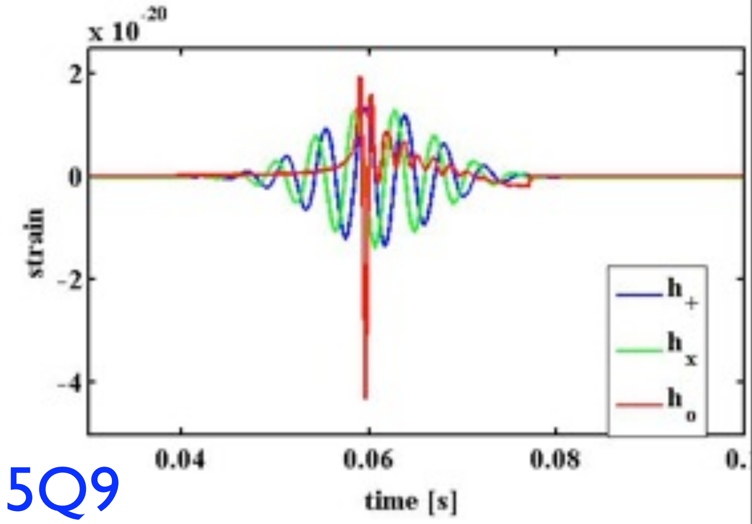
- Although the grid of lat-lon map is coarse (4°x4°) in the simulation, ho is reconstructed clearly.

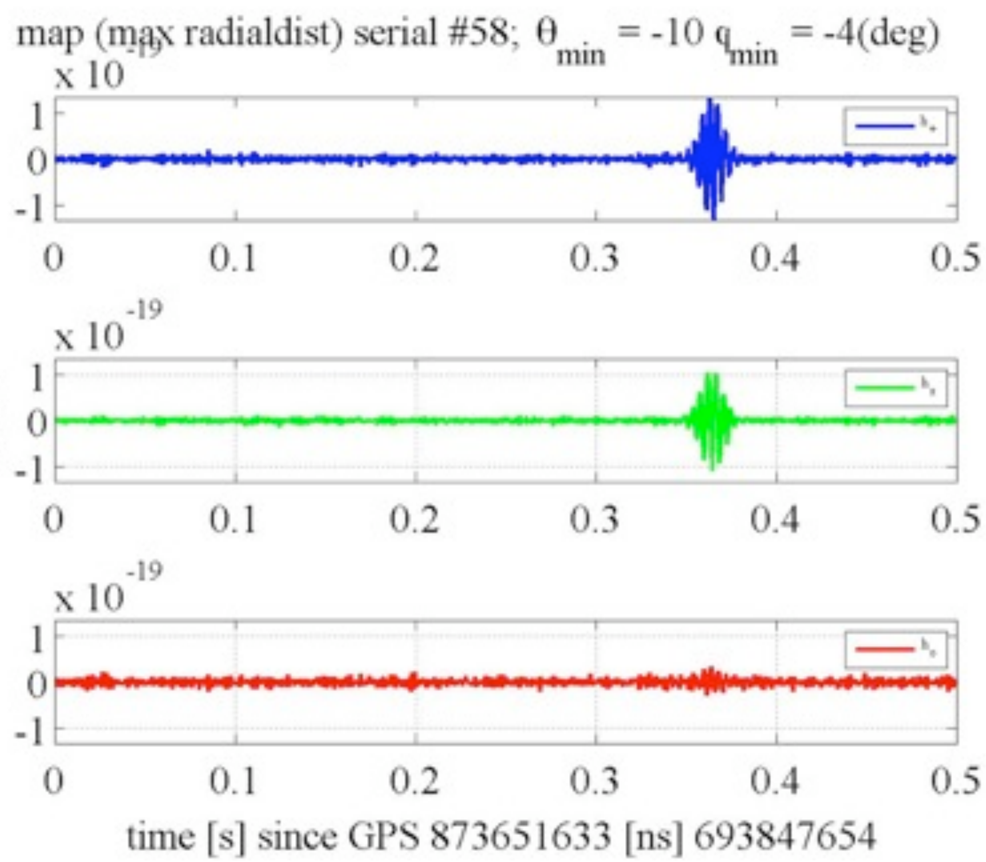


h_+, h_x : SG235Q9
h_o : Not injected

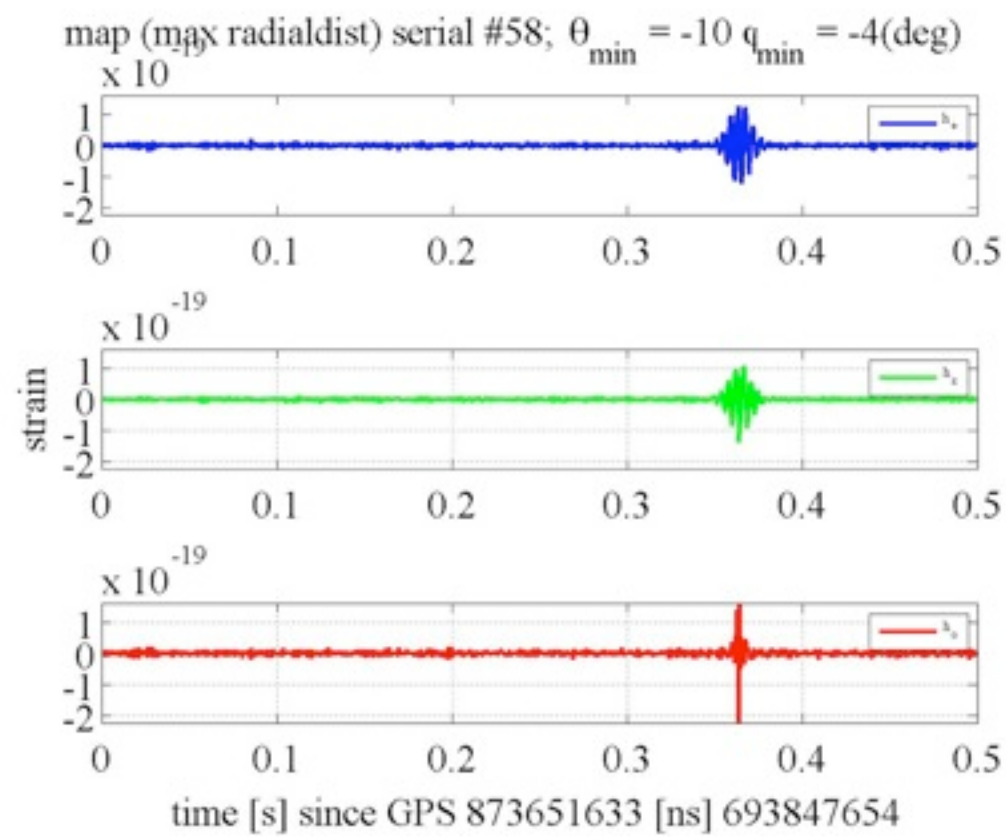
h_+

h_x

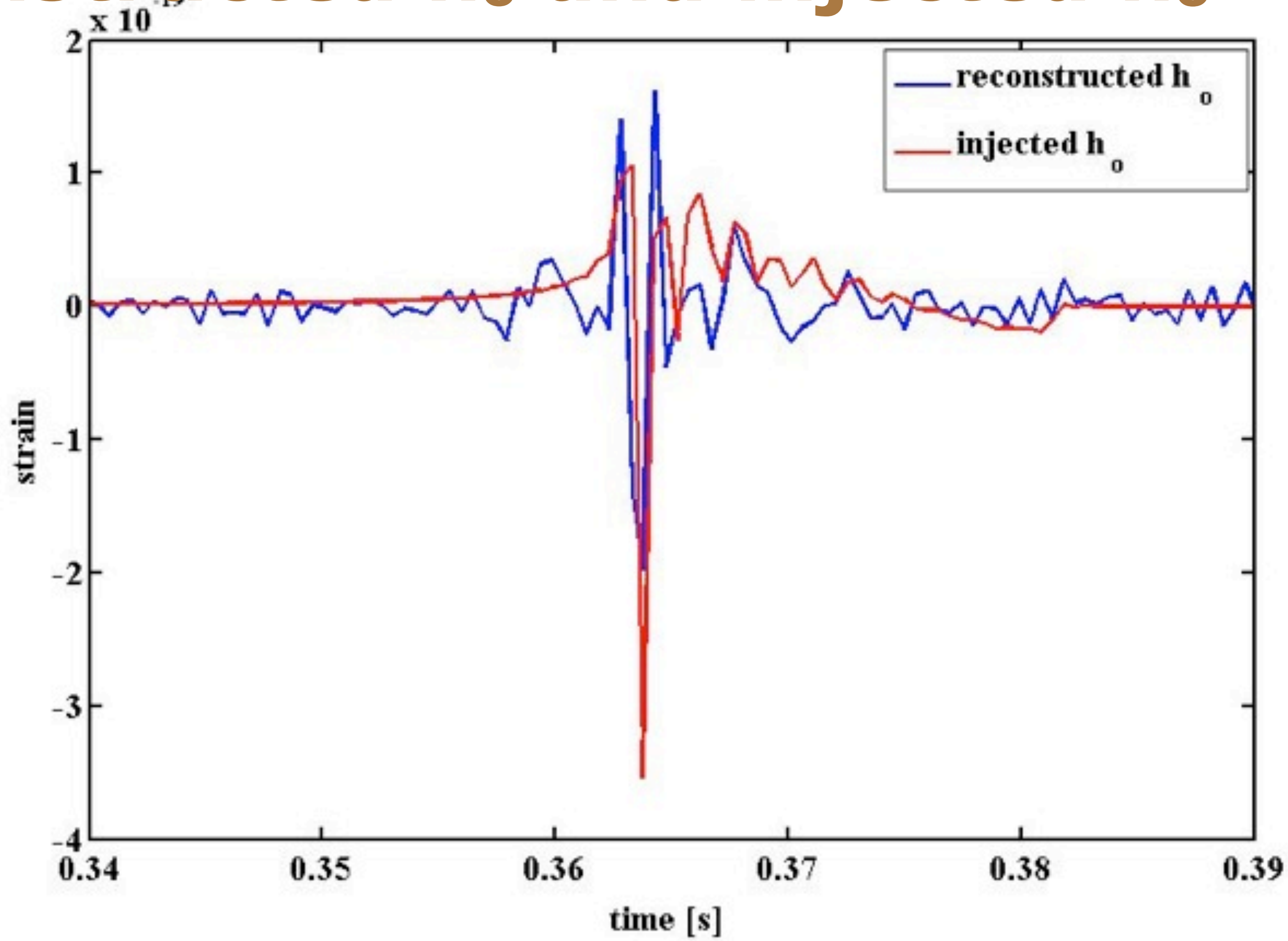
h_o



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



Comparison of reconstructed h_o and injected h_o

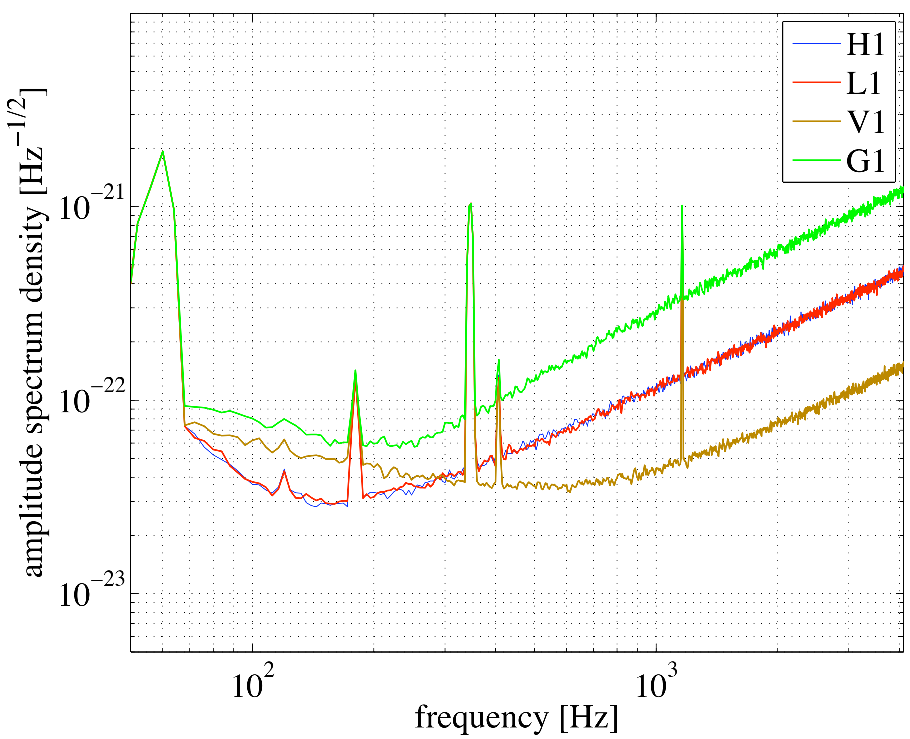


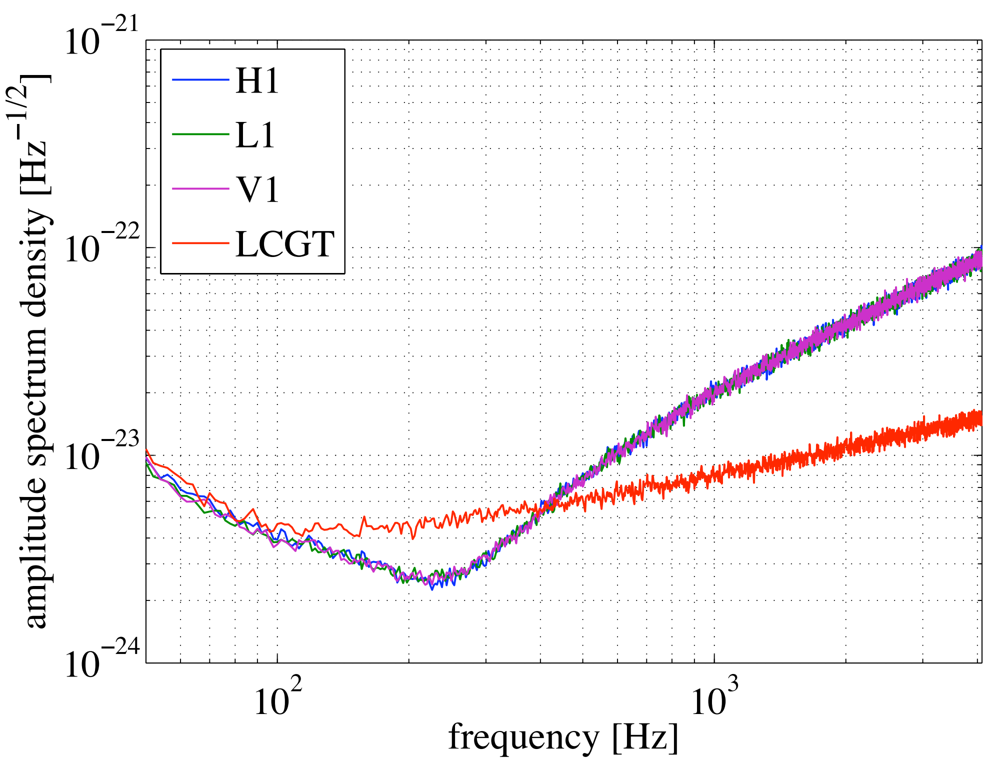
Red plot is injected ho signal and blue plot is the reconstructed ho.
The difference at the low frequency region comes from the data conditioning step.
Detector noise at low frequency is very high, such region is cut at the step.

Reconstruction simulation

- 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.

- We consider scalar GW in Brans-Dicke case (α_0 and β_0)
($\alpha_0^2 = \frac{1}{3+2\omega_{BD}}$, $\beta_0=0$)

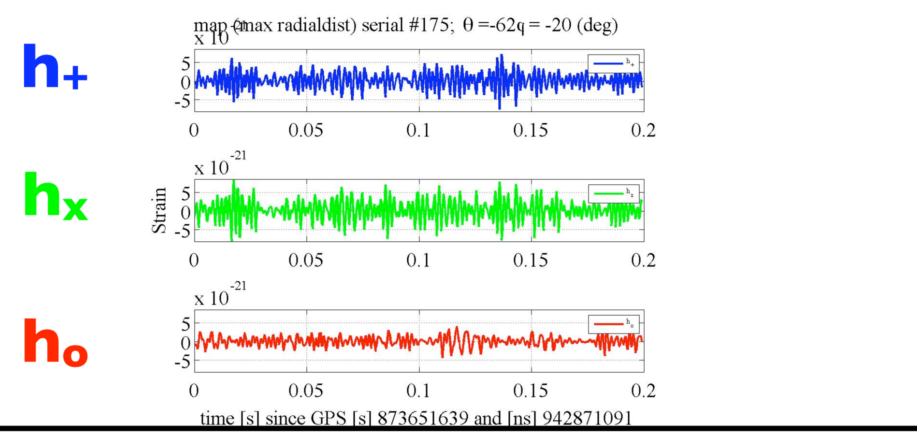




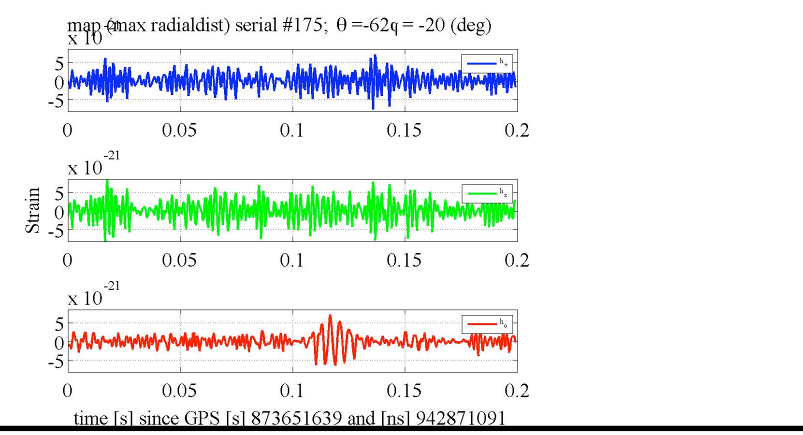
Reconstruction of SGW (current detectors)

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 can detected and reconstructed clearly.

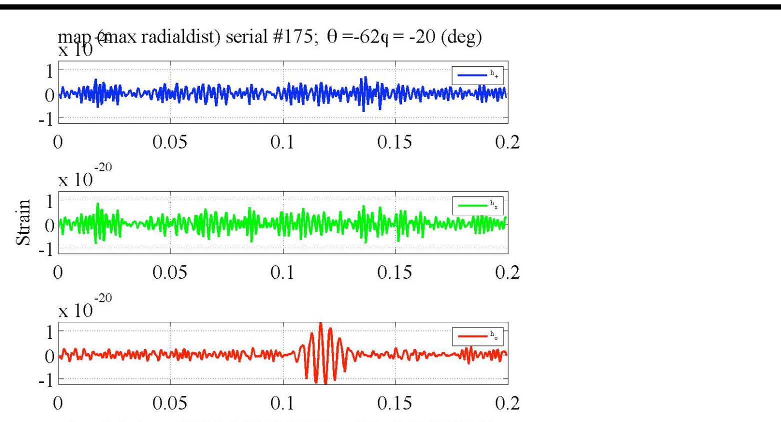
ω_{BD}=20000



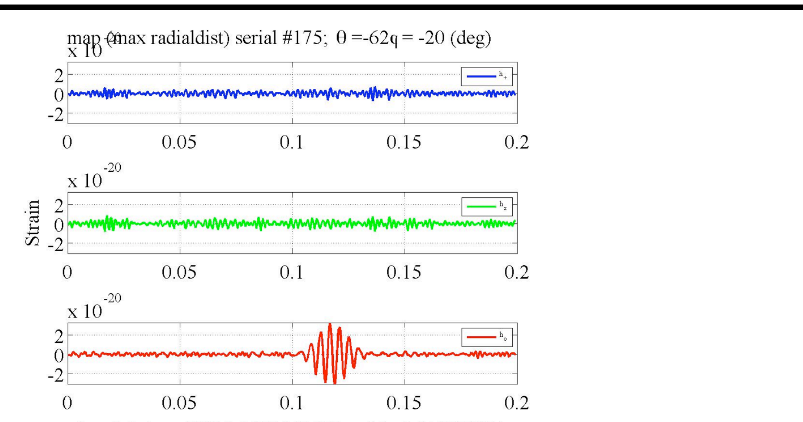
ω_{BD}=10000



ω_{BD}=5000

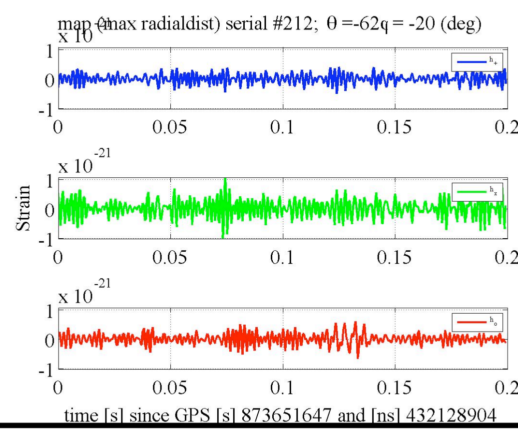
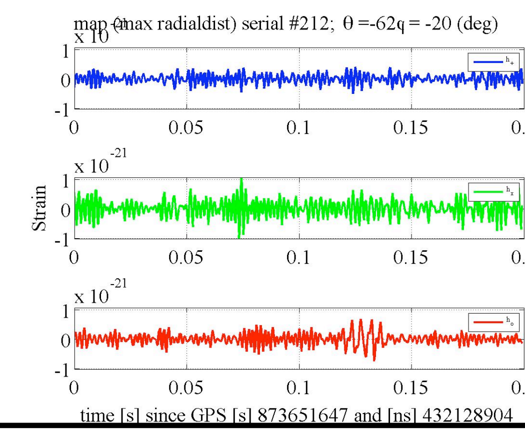
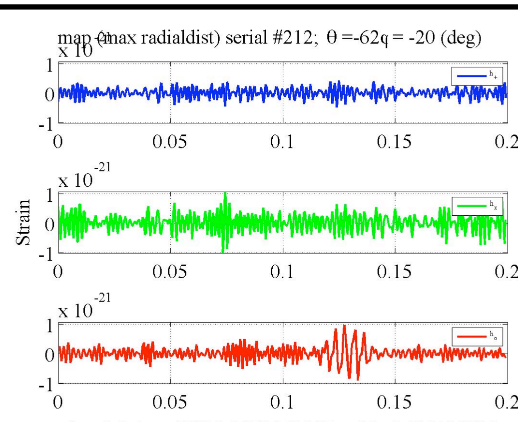
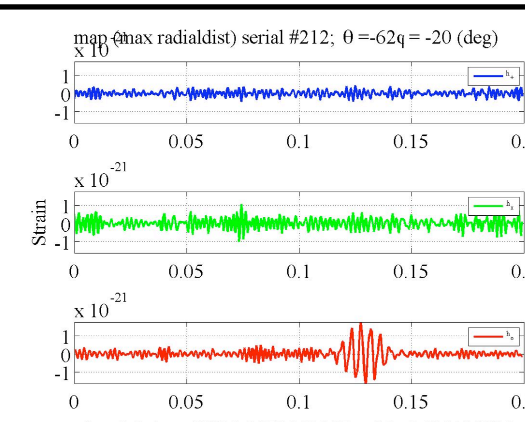


ω_{BD}=2000



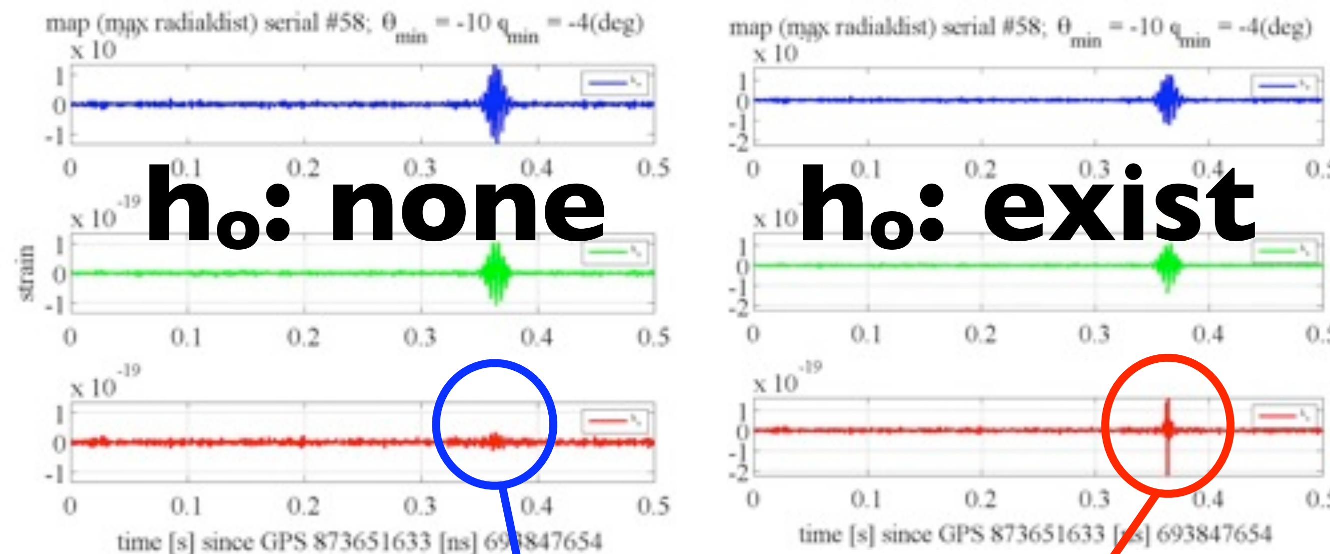
Reconstruction of SGW(advanced detectors)

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
h_+ h_x h_o 	
ω_{BD}=80000	**ω_{BD}=40000**
	

Detection statistics

We perform an excess power method to calculate detection statistic.



Excess power method

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

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

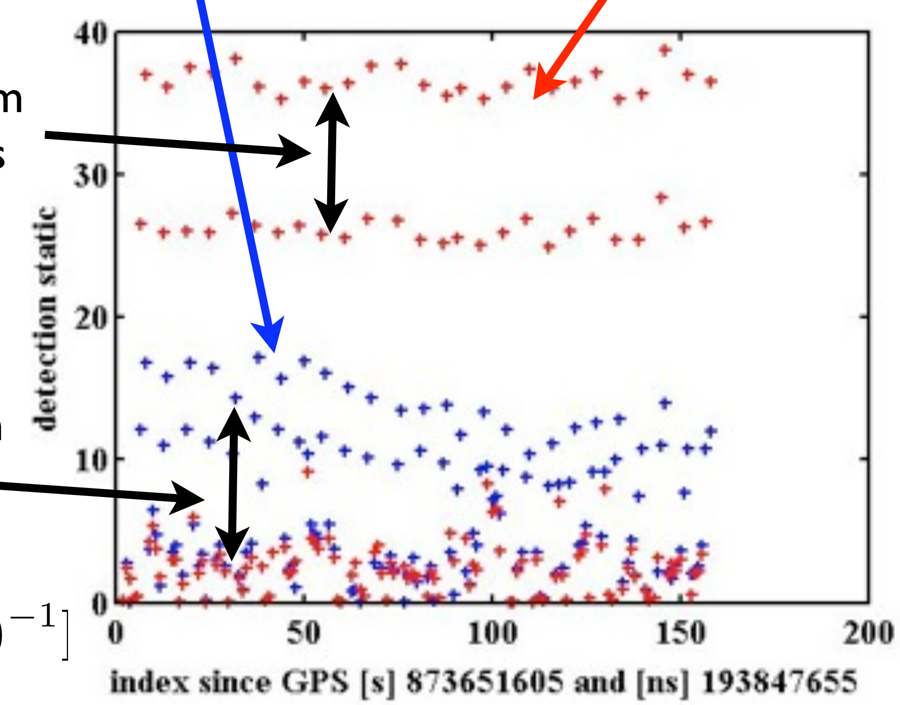
- Calculate statistic defined as

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

This gap comes from overlap of segments

Error of waveform estimation

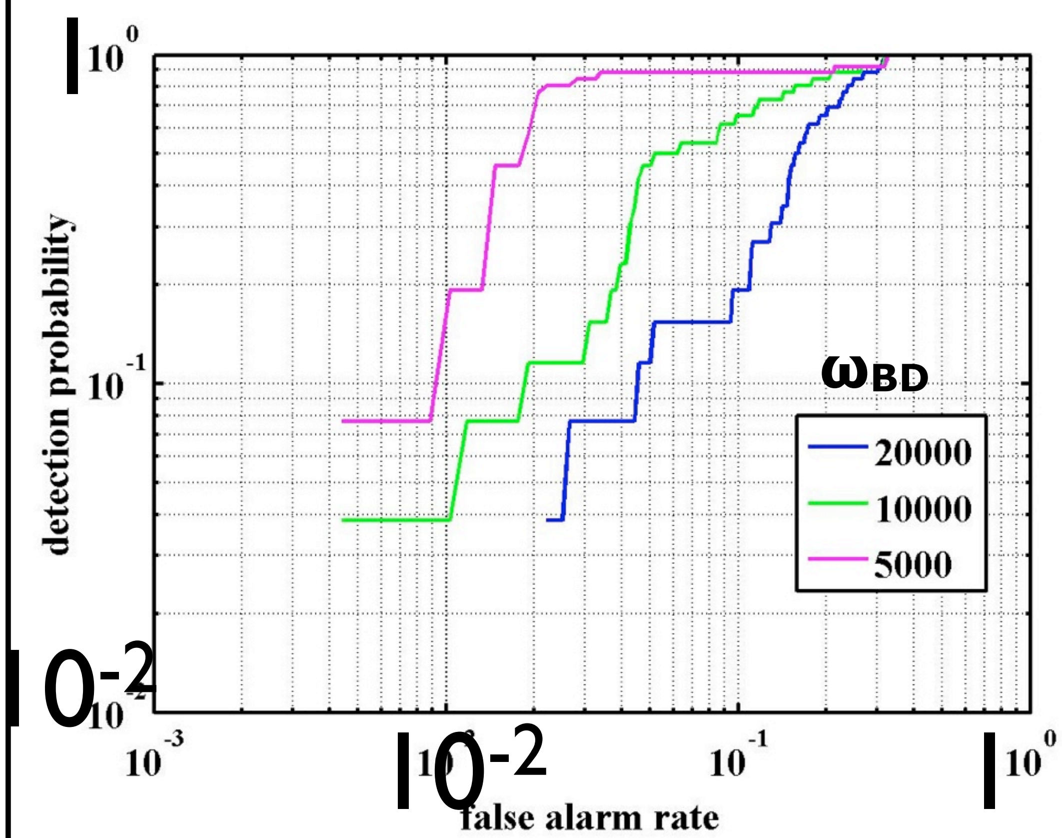
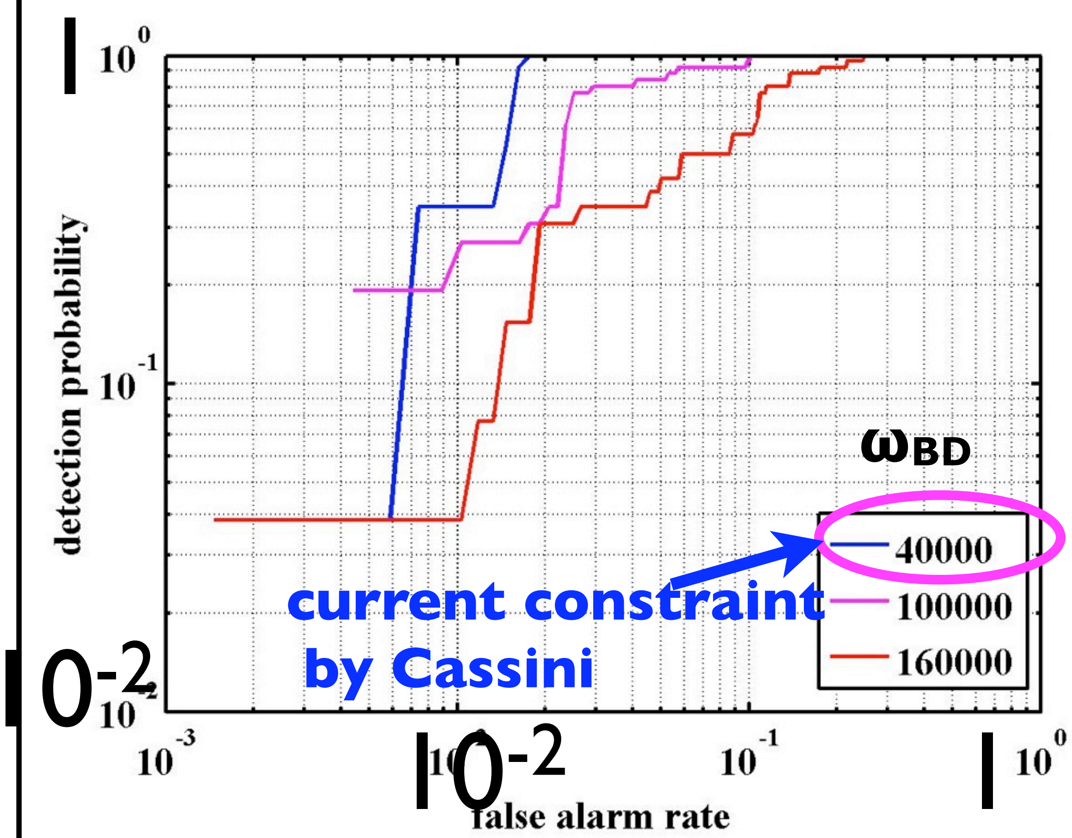
$$E\{\| h - E\{h\} \|^2\} = \sigma^2 \text{Tr}[(\text{A}^{\text{T}}\text{A})^{-1}]$$



Detection Efficiency

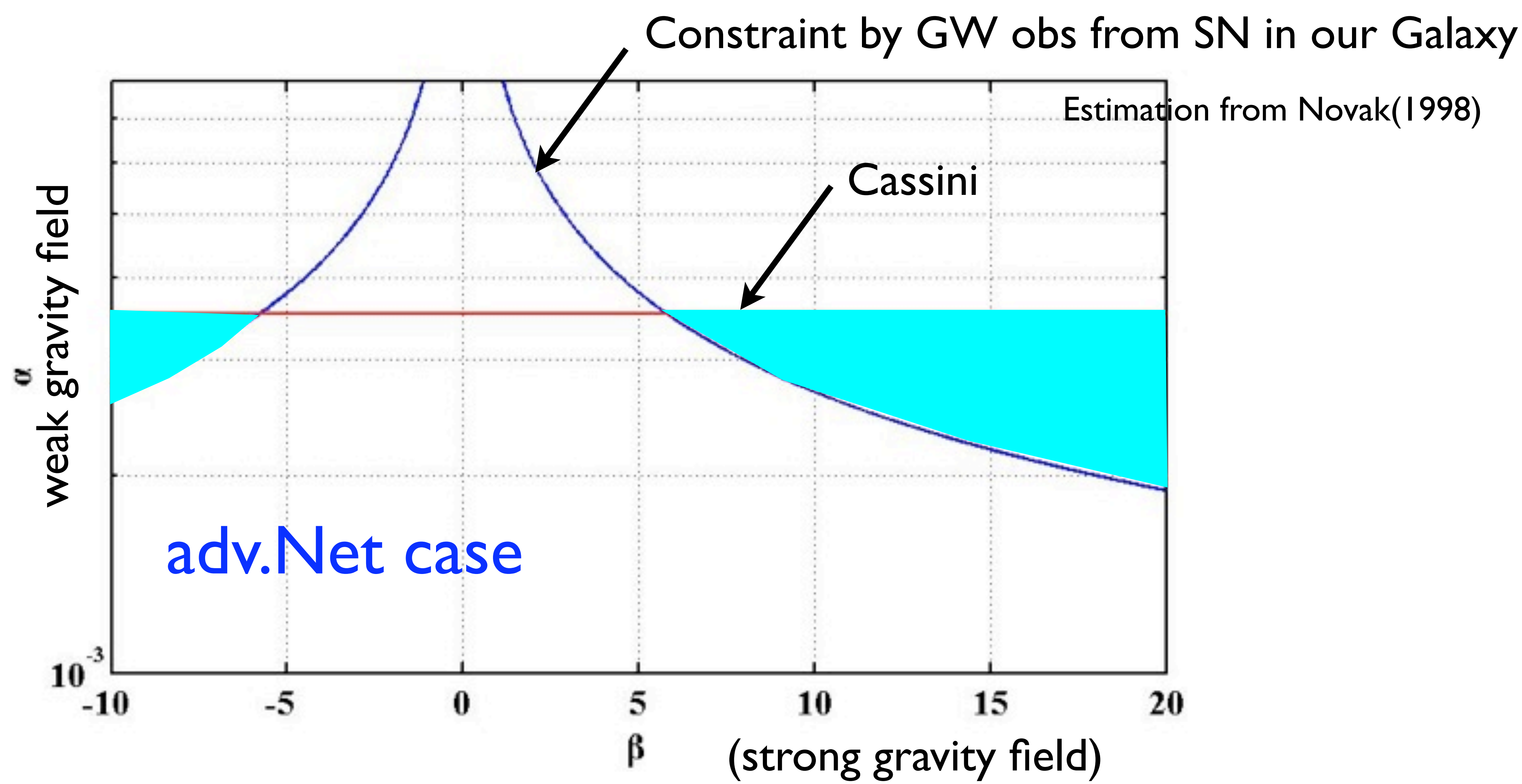
- For ω_{BD}=40000(Cassini), 90% det. prob. at false alarm prob.=0.18 using advNet
- For ω_{BD}=5000, 80% det. prob. at false alarm prob.=0.2 using currNet

ROC curve

currNet (H1-L1-V1-G1)	advNet (advH1-advL1-advV1-LCGT)
	

α–β map

General Scalar-tensor theory which is charactyerized by α and β...



β is constrained by the use of the constraint of α by Cassini.

Summary

- We discussed test of scalar-tensor theory from gravitational wave observations.
- We implemented a coherent network analysis pipeline for the detection of a scalar gravitational wave with simulated data from a network of interferometric detectors.
- α
  Next generation of detectors (advLIGO,advVIRGO,LCGT) can put constraint much stronger than Cassini when a spherically symmetric core collapse occurs in our Galaxy.
- β
  Obs. in Solar system cannot constrain it. GW observation is a good tool.

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

$$\frac{d}{d\tau}\left[(1+h_o)\frac{dx}{d\tau}\right] = \frac{d}{d\tau}\left[(1+h_o)\frac{dy}{d\tau}\right] = 0$$

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

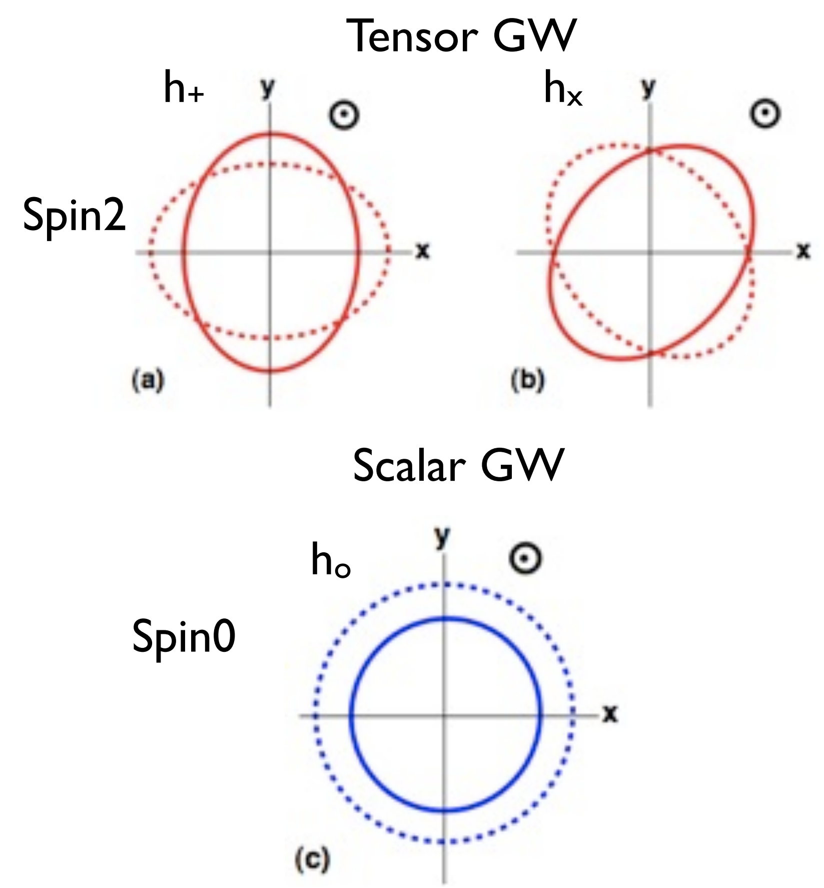
$$\frac{d}{d\tau}\left[(1+h_o)\frac{dz}{d\tau}\right] = -\frac{1}{2}\frac{\partial_z(1+h_o)}{1+h_o}$$

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)