Test for scalar-tensor gravity theory from observations of gravitational wave bursts

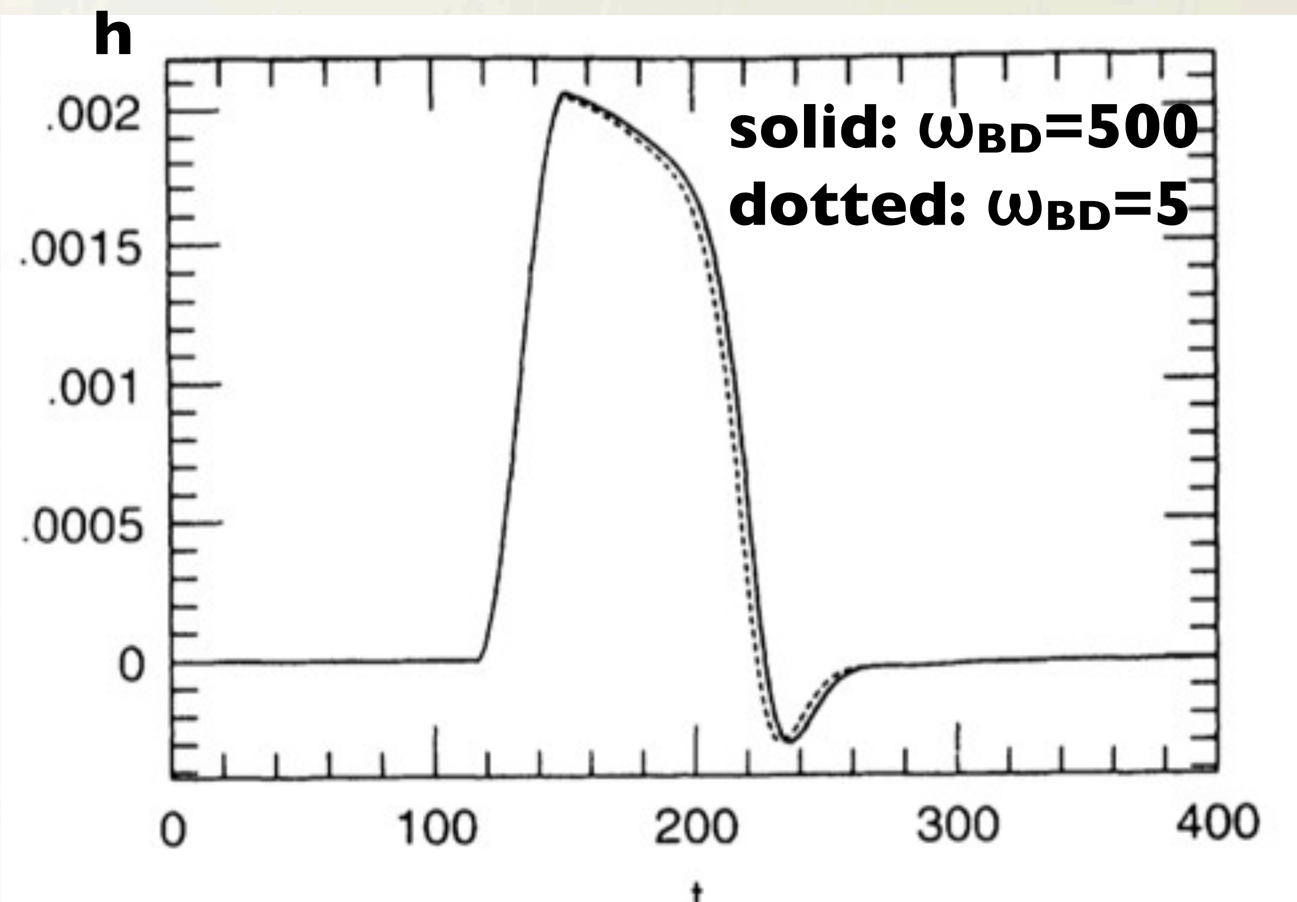
Kazuhiro Hayama(NAOJ-TAMA),
Atsushi Nishizawa(NAOJ-TAMA),
Peter Shawhan(U. Maryland),
Mark Avara (U. Maryland)

Search for scalar gravitational waves

- **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. Tensor GW search might miss some type of sources, e.g. highly spherically symmetric core collapse if scalar-tensor theory is correct.**
- **This talk will focus on search for SGW from Galactic spherically symmetric core collapses in Brans-Dicke theory which is famous scalar-tensor theory which has a coupling parameter ω_{BD}.**

Spherically symmetric core collapse

- There are several scalar gravitational waveforms by numerical simulations for spherically symmetric core collapse (Shibata1994, Saijo 1997, Novak 1998).
- Waveforms by different simulations are consistent with each other.
- In this talk we will use the Shibata's result.
- By scaling amplitudes by ω_{BD}, waveforms are similar for various ω_{BD}. (below)
- The duration depend on the mass of a progenitor.



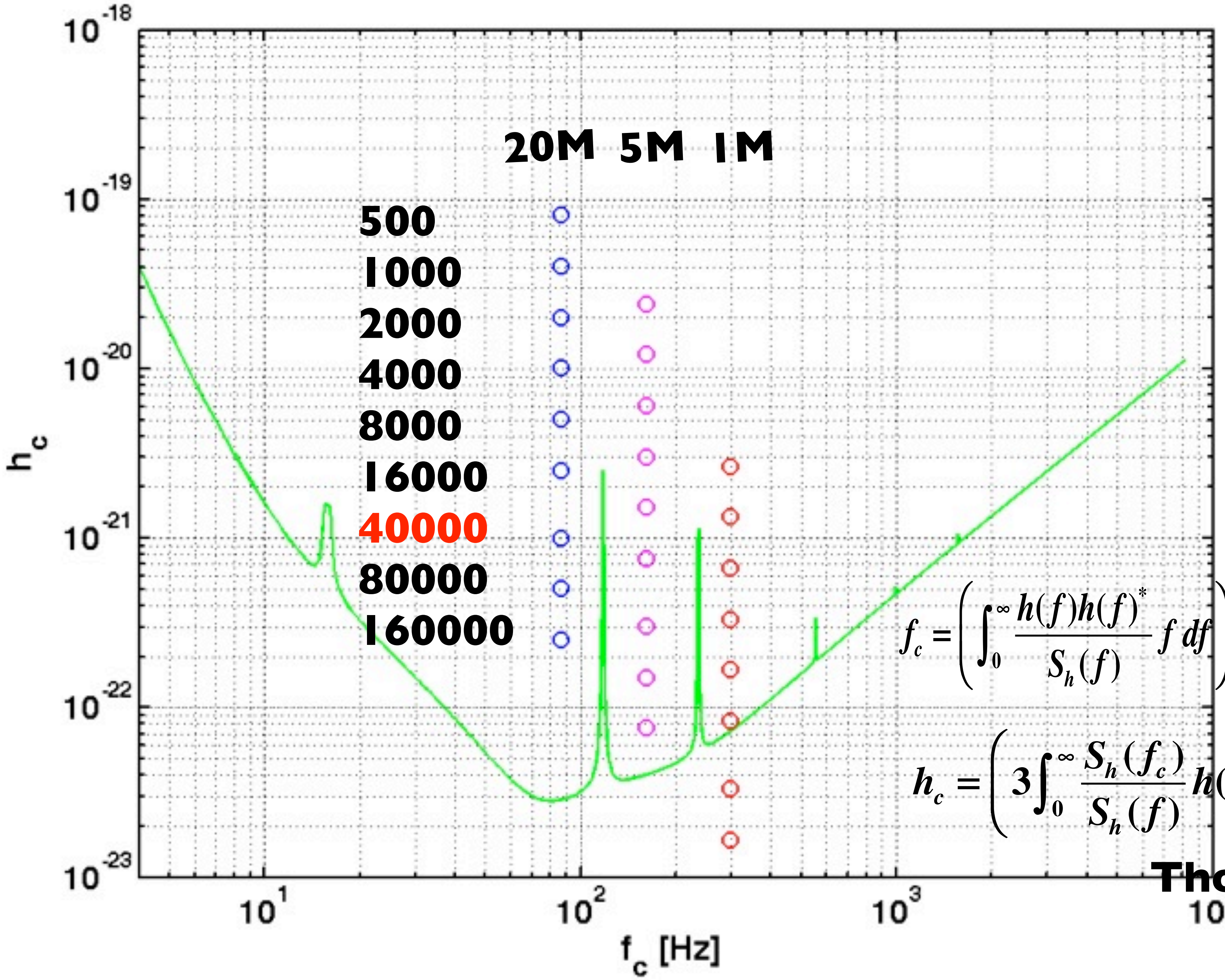
$4.93 \times 10^{-5} (M / M_{\odot})$

Amplitude:

$$\Phi \bullet (\omega_{BD} / 500) \sim 10^{-22} \left(\frac{h}{0.002} \right) \left(\frac{M}{10 M_{\odot}} \right) \left(\frac{10 Mpc}{R} \right)$$

Here we set M=10Mo, R=10kpc

Sensitivity to scalar GWs



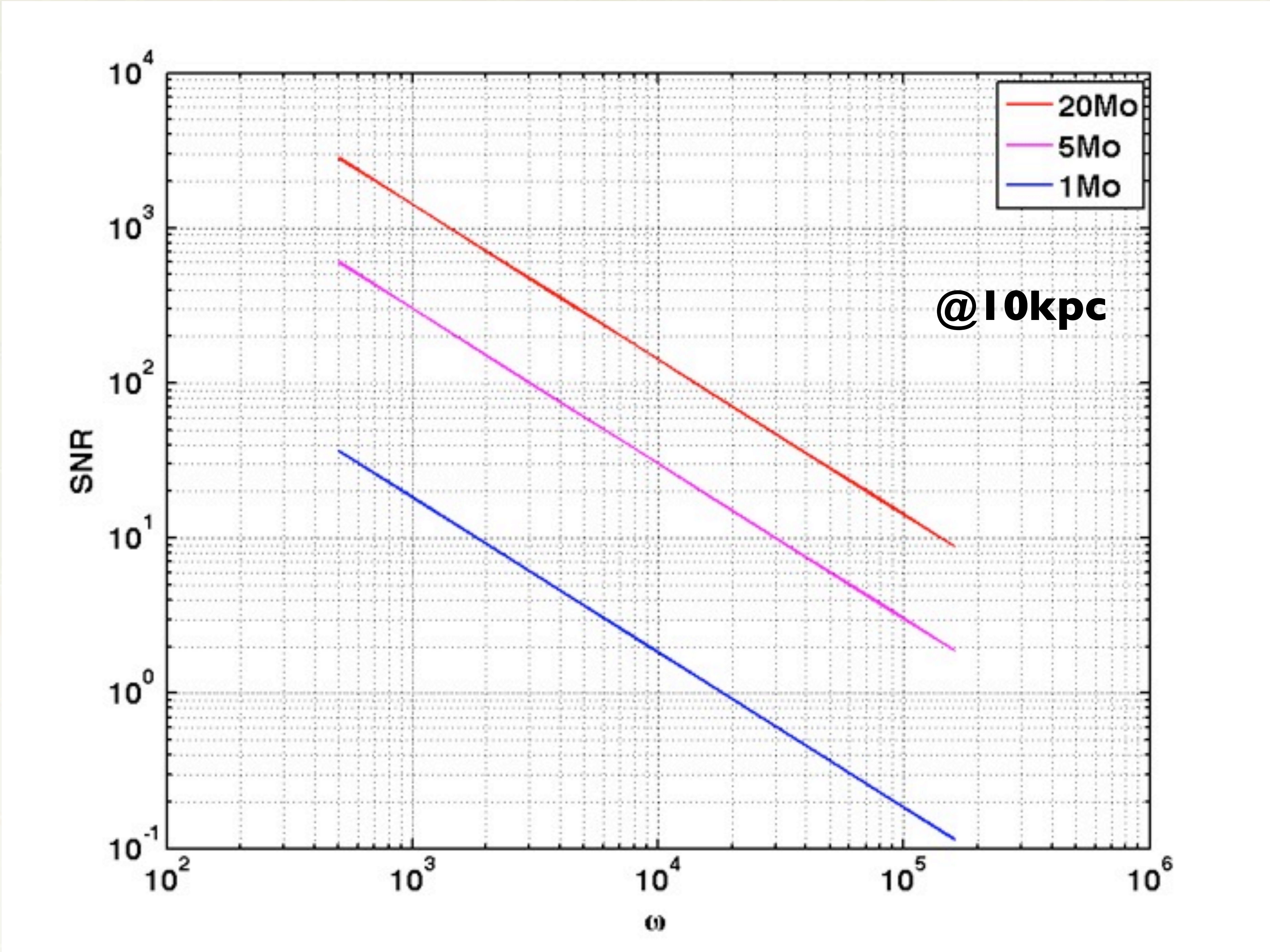
$$f_c = \left(\int_0^\infty \frac{h(f)h(f)^*}{S_h(f)} f\, df \right) \left(\int_0^\infty \frac{h(f)h(f)^*}{S_h(f)} df \right)^{-1}$$

$$h_c = \left(3 \int_0^\infty \frac{S_h(f_c)}{S_h(f)} h(f)h(f)^* f\, df \right)^{1/2}$$

Thorne,K.(1987)

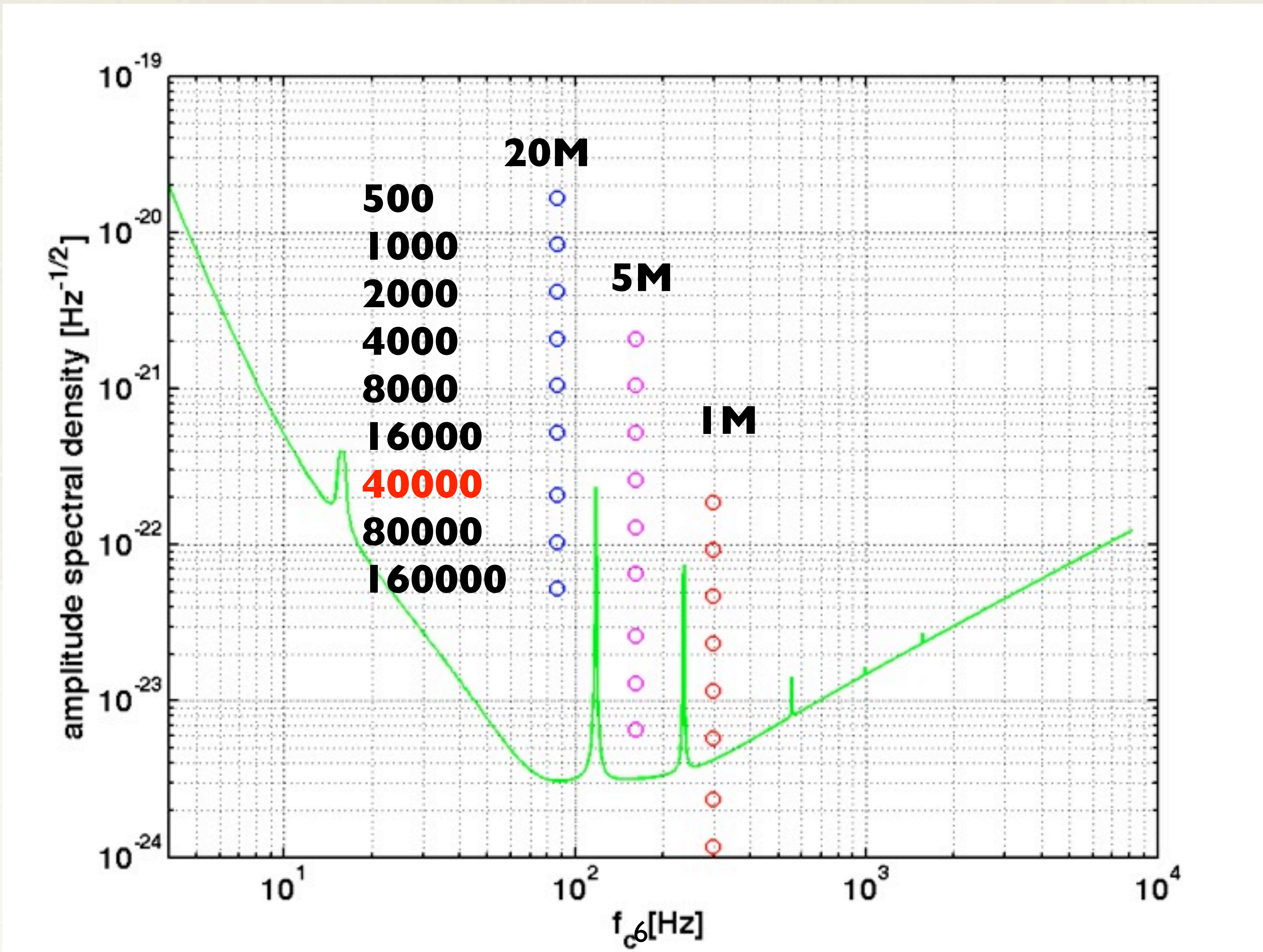
Expected SNR

- We assume optimal direction to a detector in terms of antenna pattern.



Sensitivity to scalar GWs

- **Root mean square of h are plotted in the noise curve plot.**

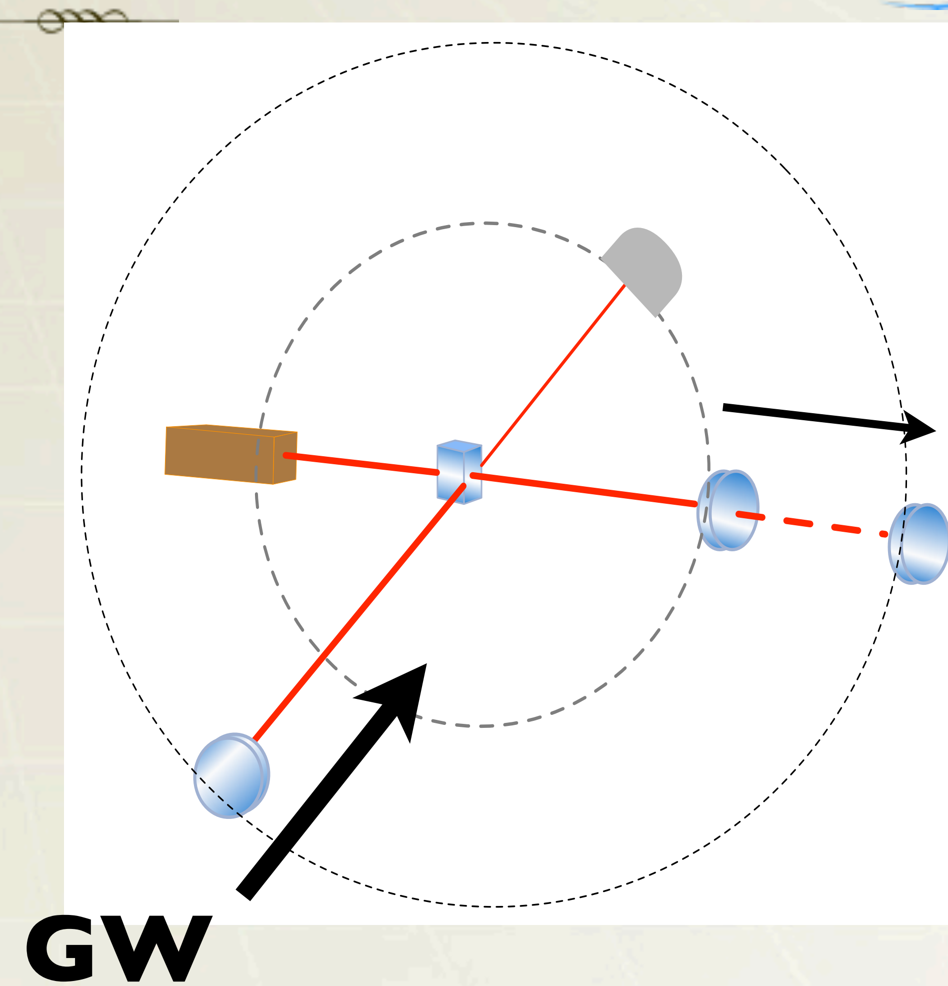


Antenna pattern for scalar GW

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

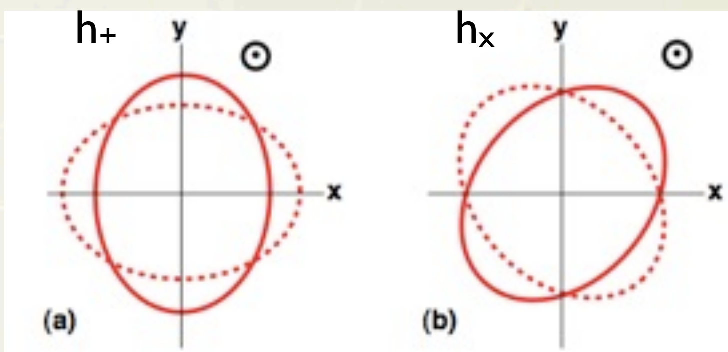
$$
\begin{aligned}
F_{+}(\hat{\Omega}) &= \frac{1}{2}(1+\cos^2\theta)\cos 2\phi \\
F_{\times}(\hat{\Omega}) &= \cos\theta \sin 2\phi \\
F_{\circ}(\hat{\Omega}) &= -\sin^2\theta \cos 2\phi .
\end{aligned}
$$

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



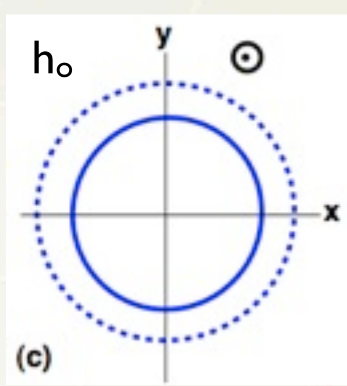
Polarization of tensor, scalar gravitational wave

Tensor GW



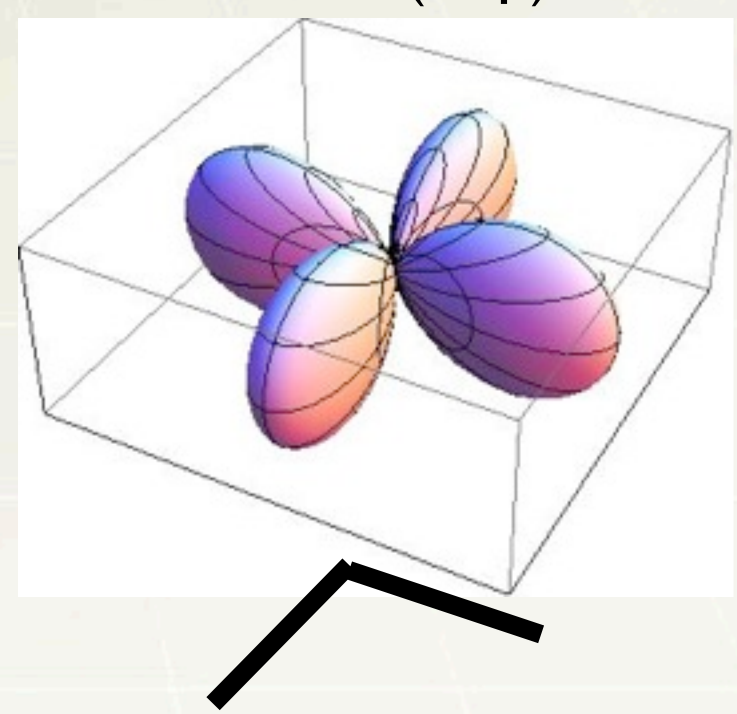
Scalar GW

Spin0



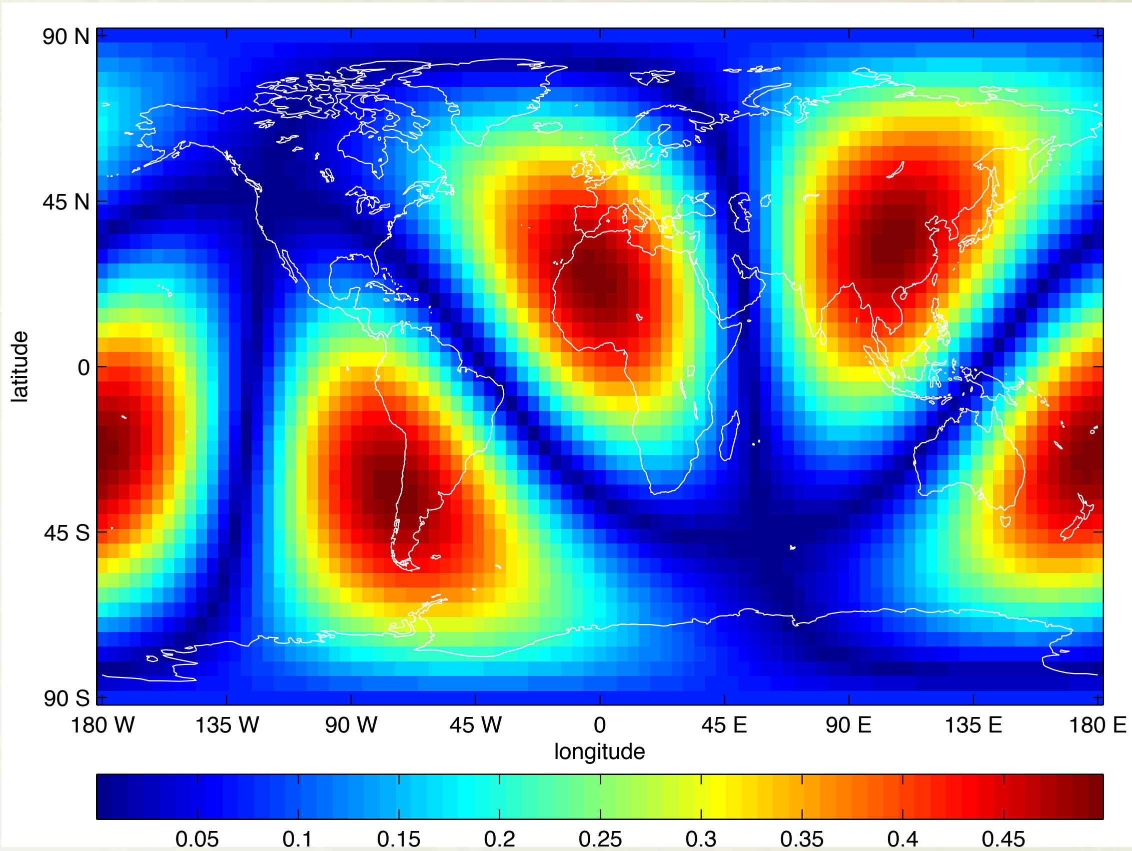
C.Will, Living Review (2006)

$F_{\circ}(\vartheta,\varphi)$

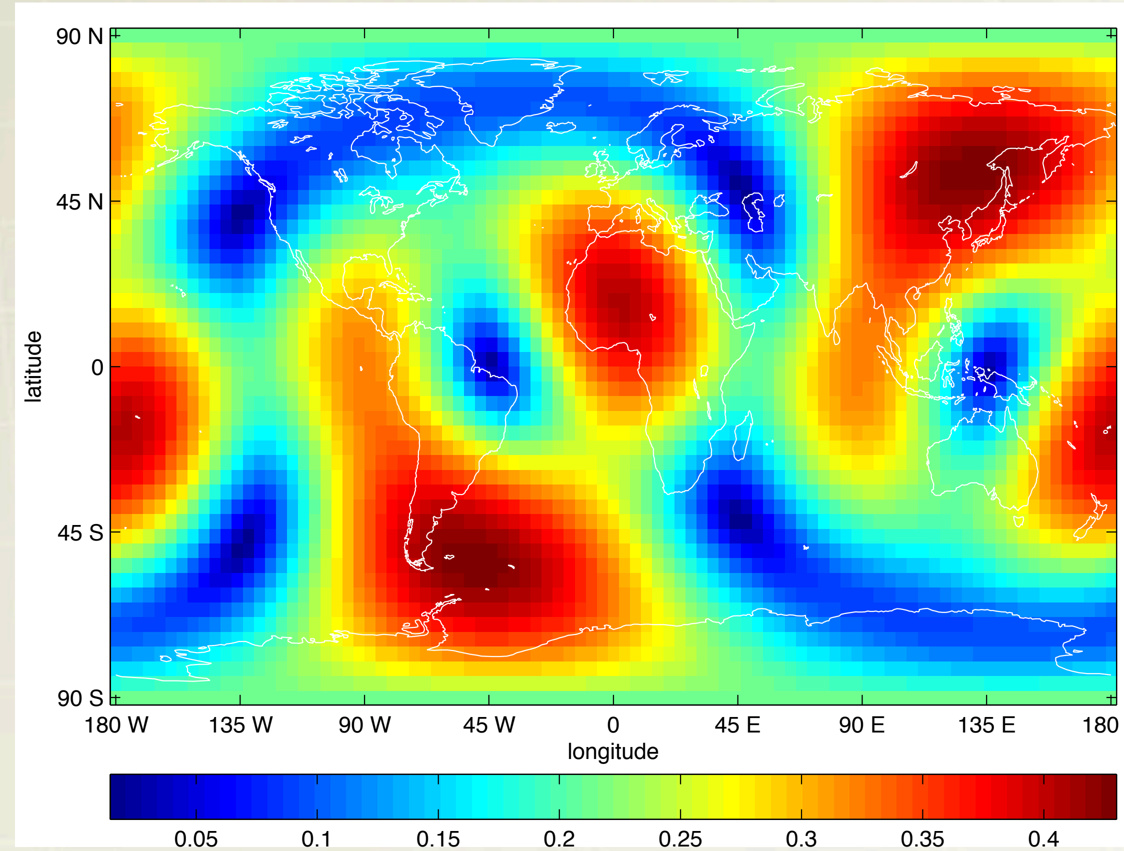


Antenna pattern sky-map

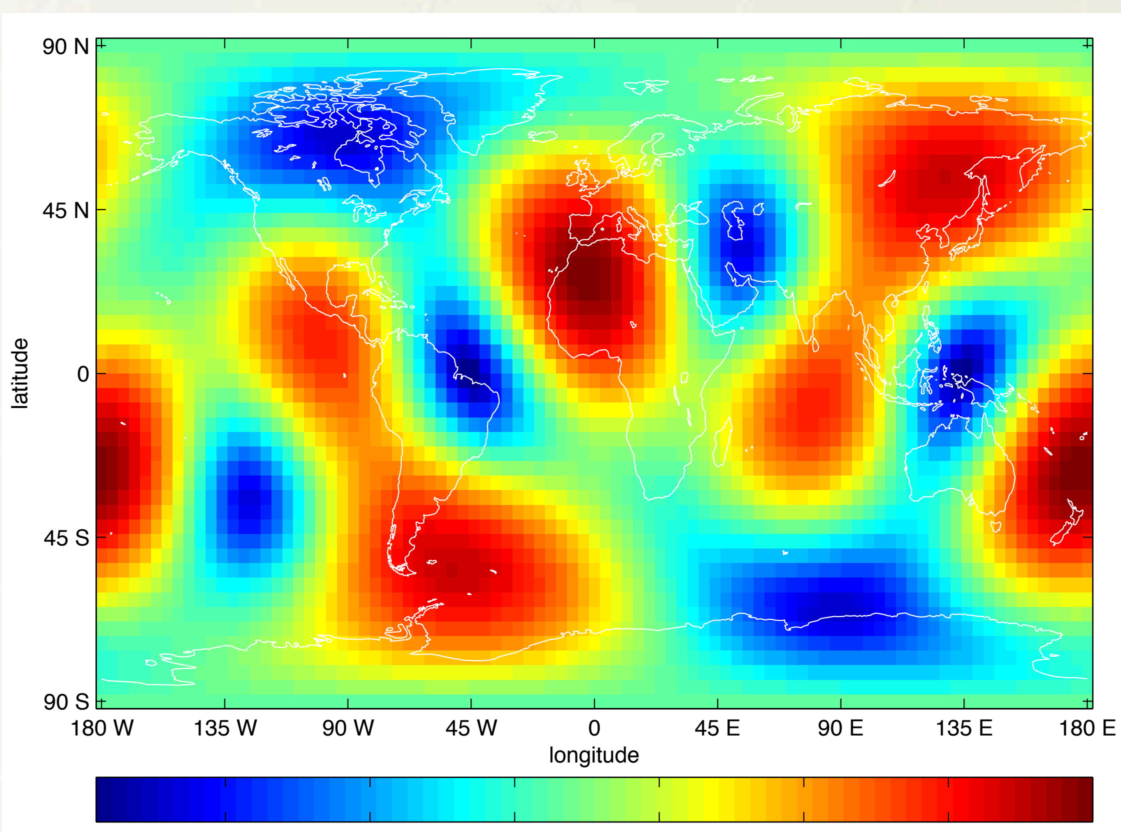
HI



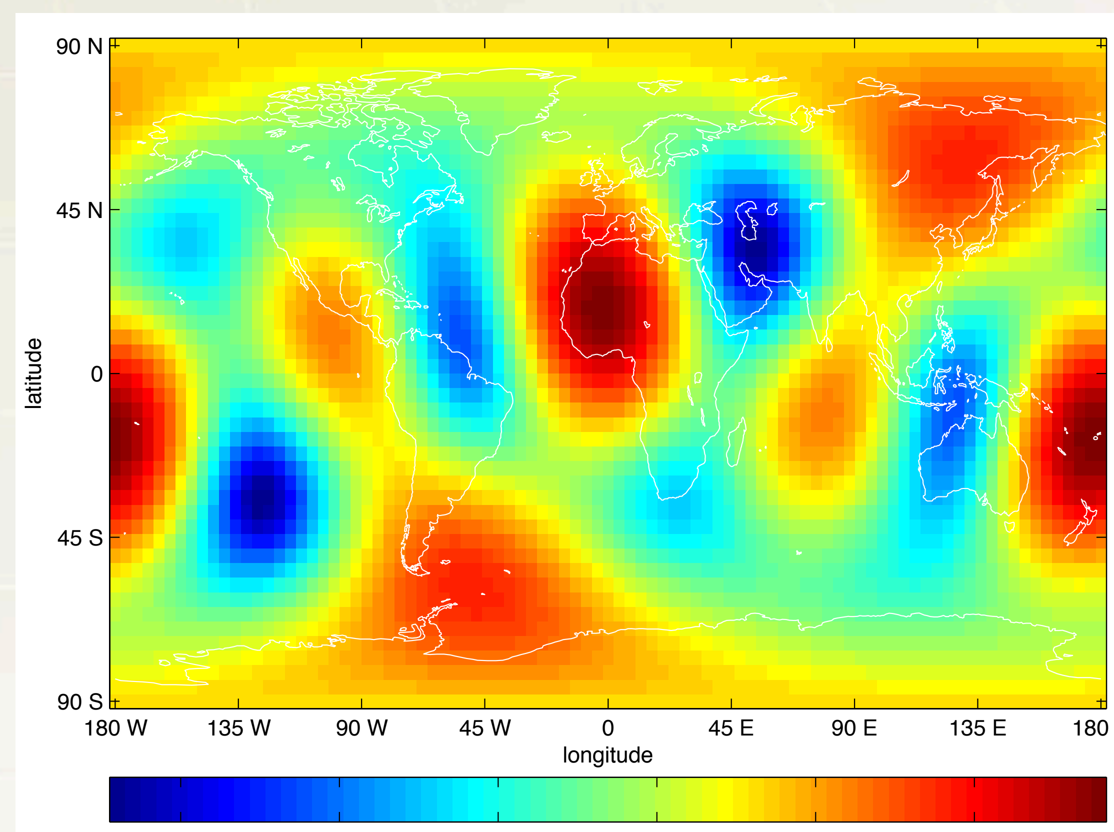
HILIVI



HILIVIKI



HILIVIKIII



Coherent network analysis

Network data of d-detectors can be written as

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

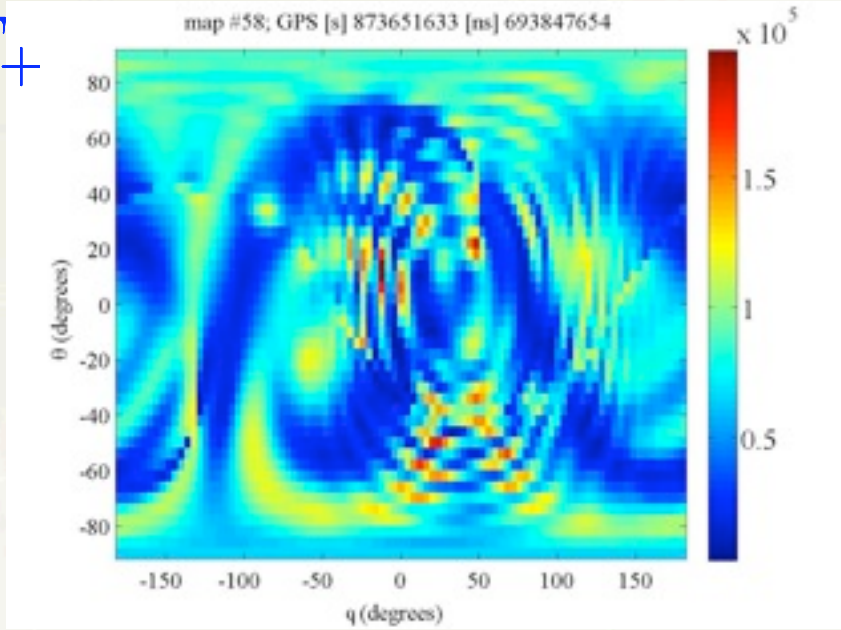
The reconstruction of a gravitational wave is an inverse problem.
Maximum likelihood method to solve the inverse problem:

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

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

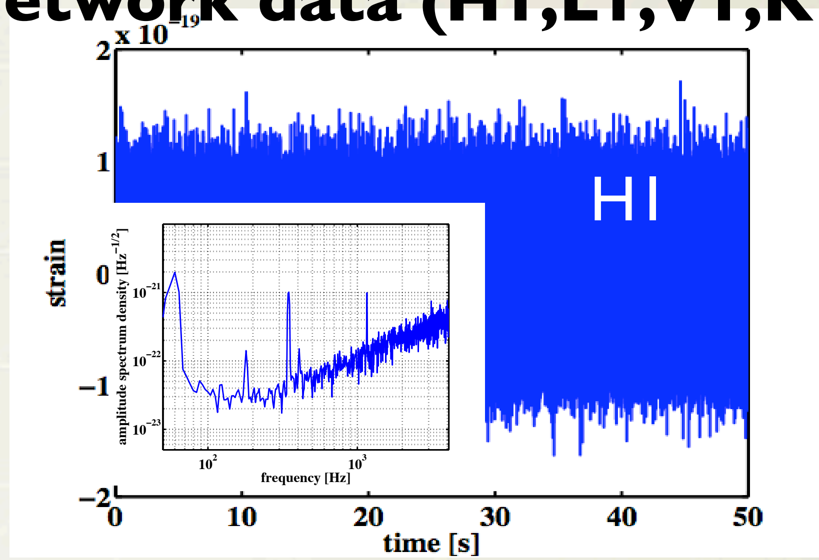
$$\begin{aligned} h_\circ &= \frac{1}{\det(\boldsymbol{M})}(((F_+ \times F_\times)\cdot(F_\times \times F_\circ))\cdot F_+ \\ &- ((F_+ \times F_\times)\cdot(F_+ \times F_\circ))\cdot F_\times \\ &+ ((F_+ \times F_\times)\cdot(F_+ \times F_\times))\cdot F_\circ)\cdot \boldsymbol{x} \end{aligned}$$

Likelihood residual sky-map

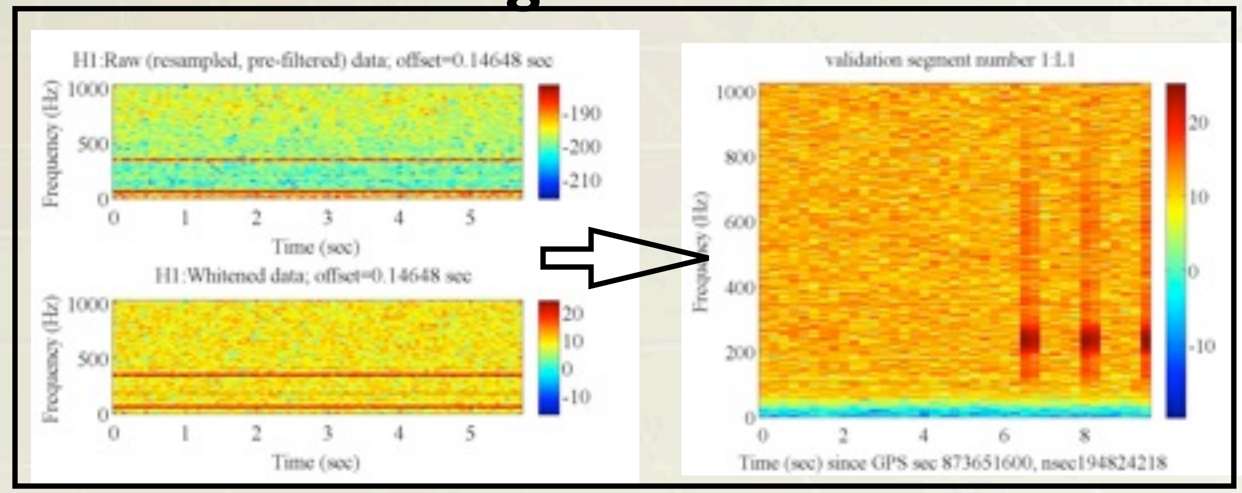


Flow chart of the analysis

Network data (H1,L1,V1,K1, I1)



Data conditioning

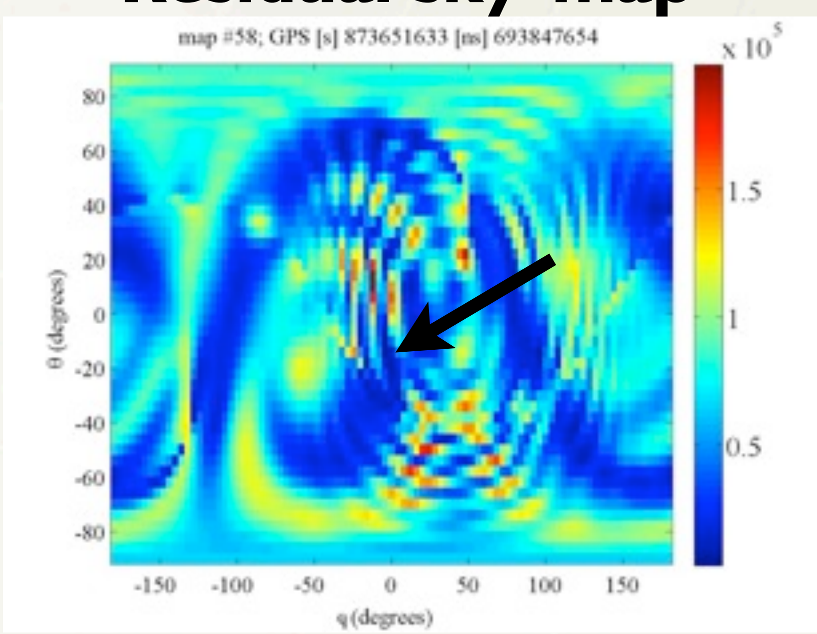


Each data is whitened by linear predictor error filter

Coherent network analysis

Mode separation

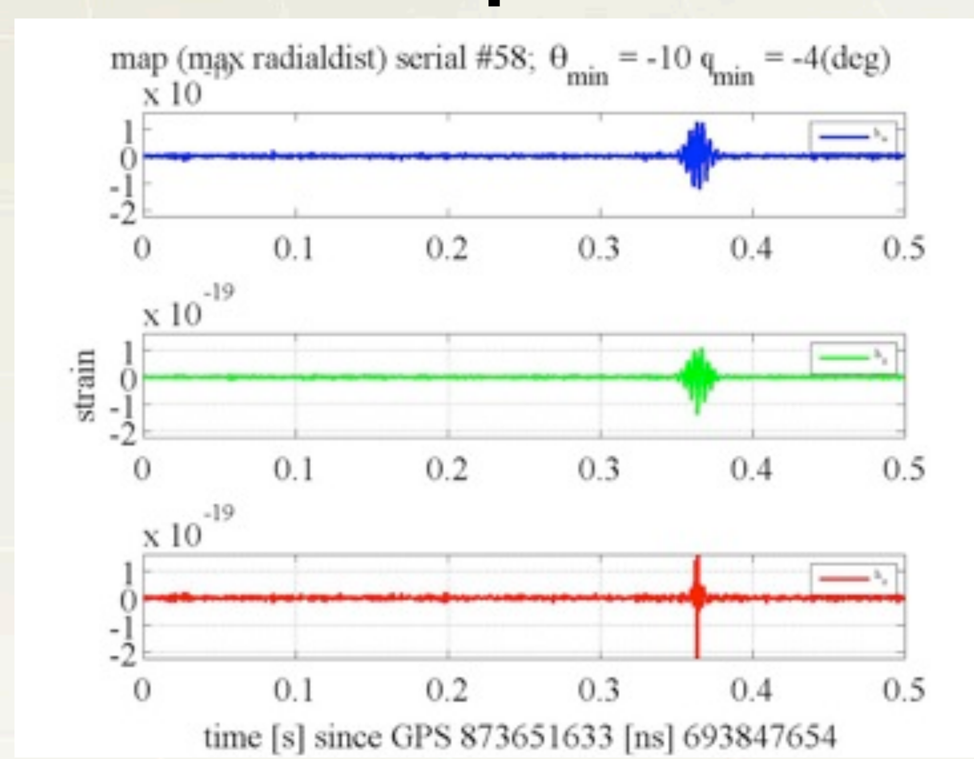
Residual sky-map



h+

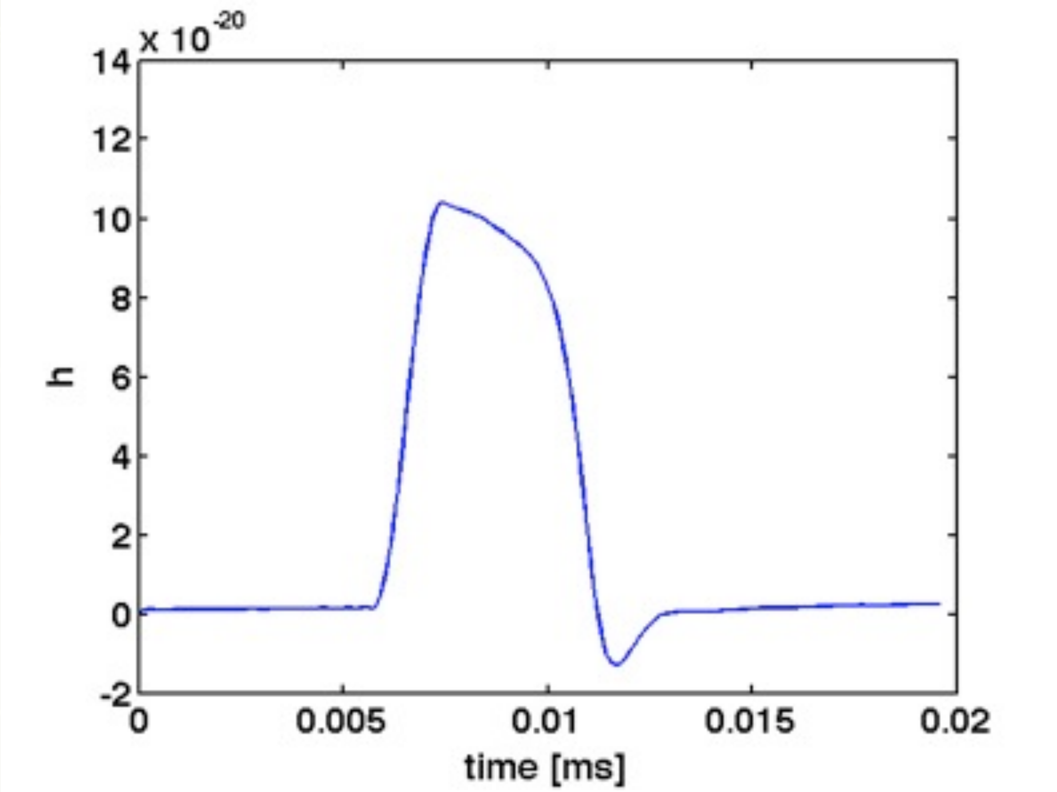
hx

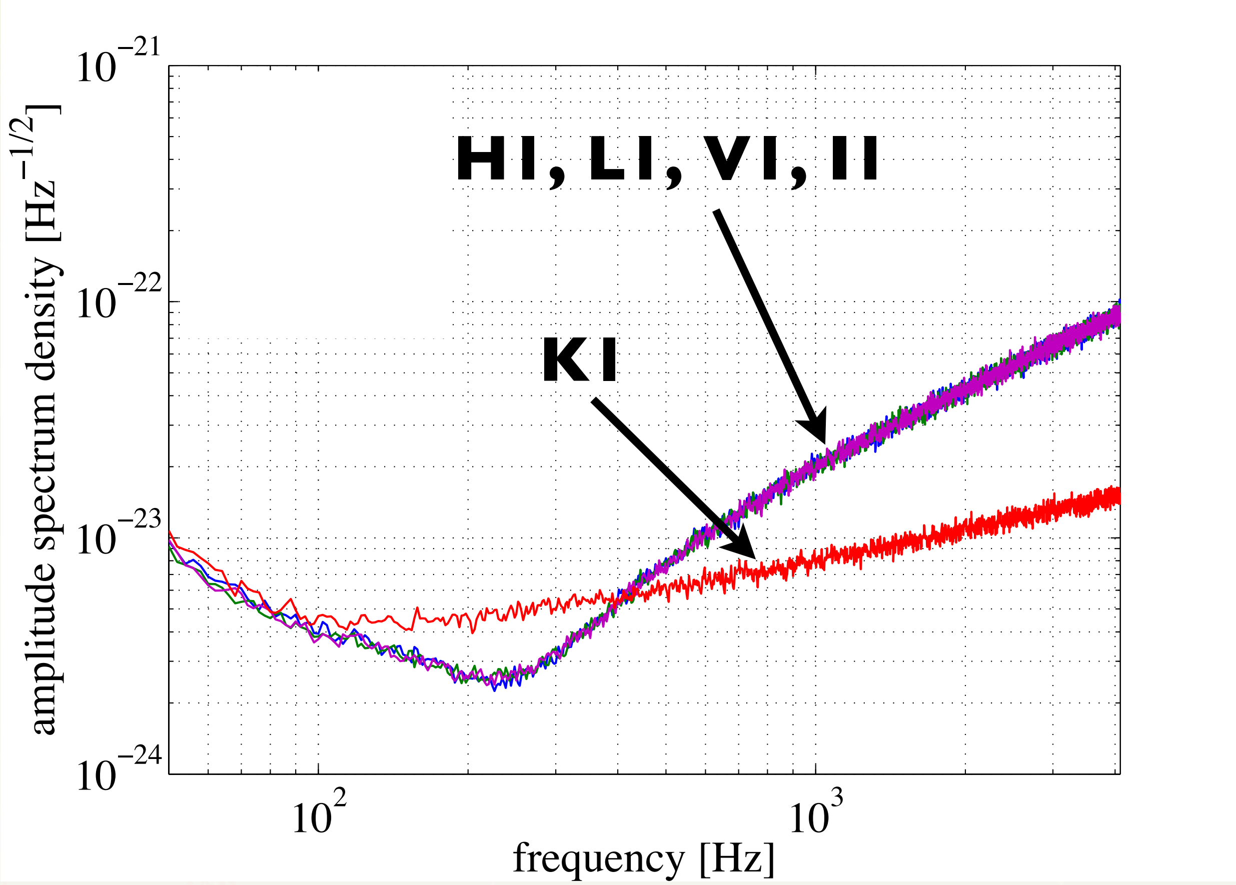
ho



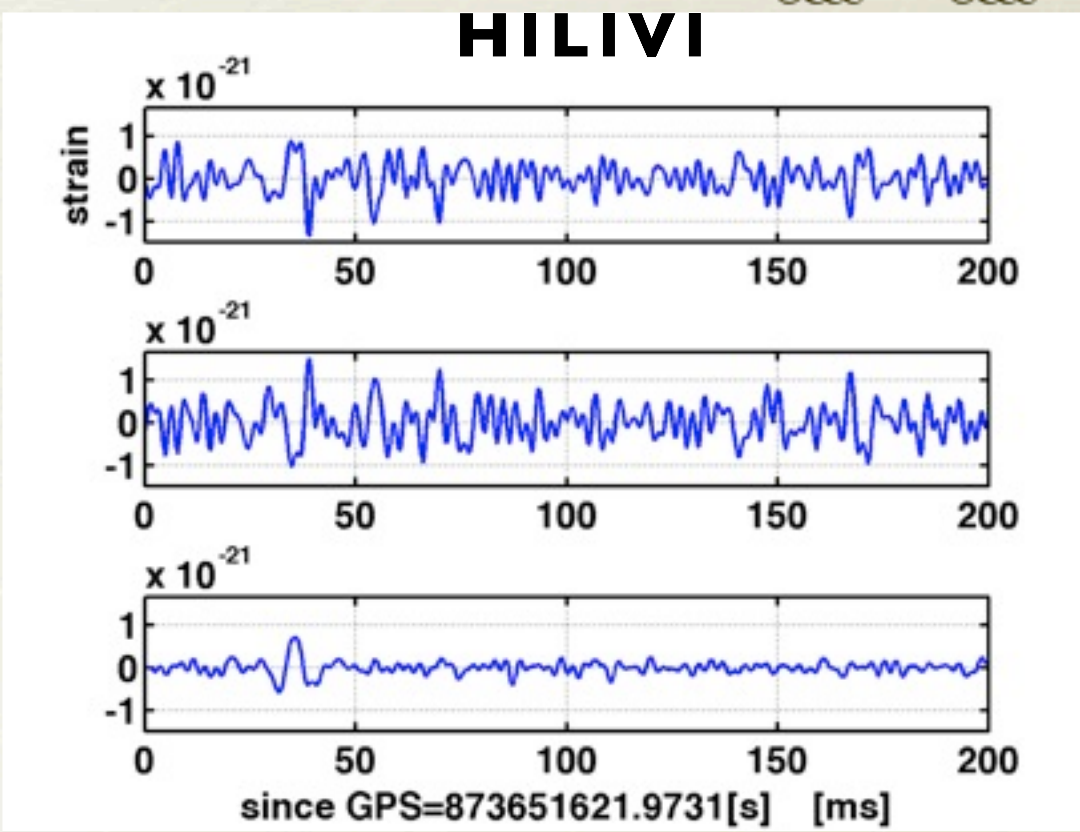
Simulation

- Detector locations used here are LIGO Hanford, LIGO Livingston, Virgo, KAGRA, LIGO-India.
- Data are simulated Gaussian noise with similar to design sensitivities.
- Injected signals are scalar gravitational waveforms described previous slides.
- Progenitor is 10Mo, 10kpc away from the earth.

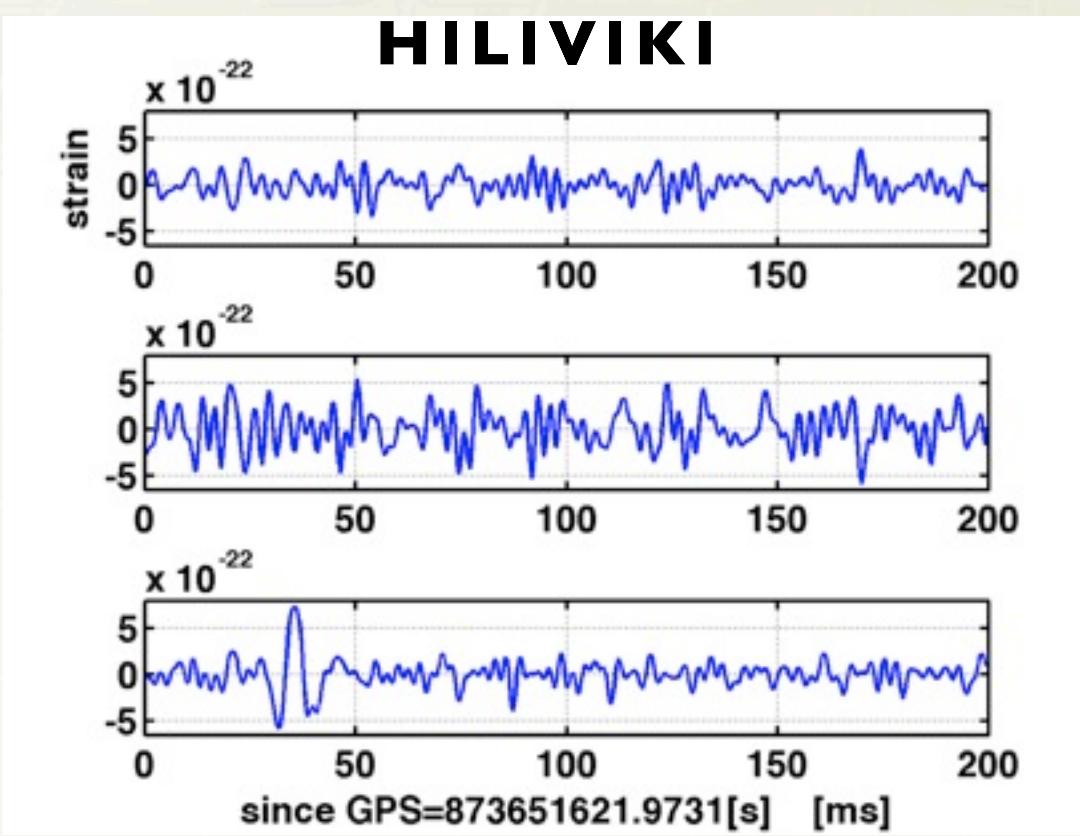


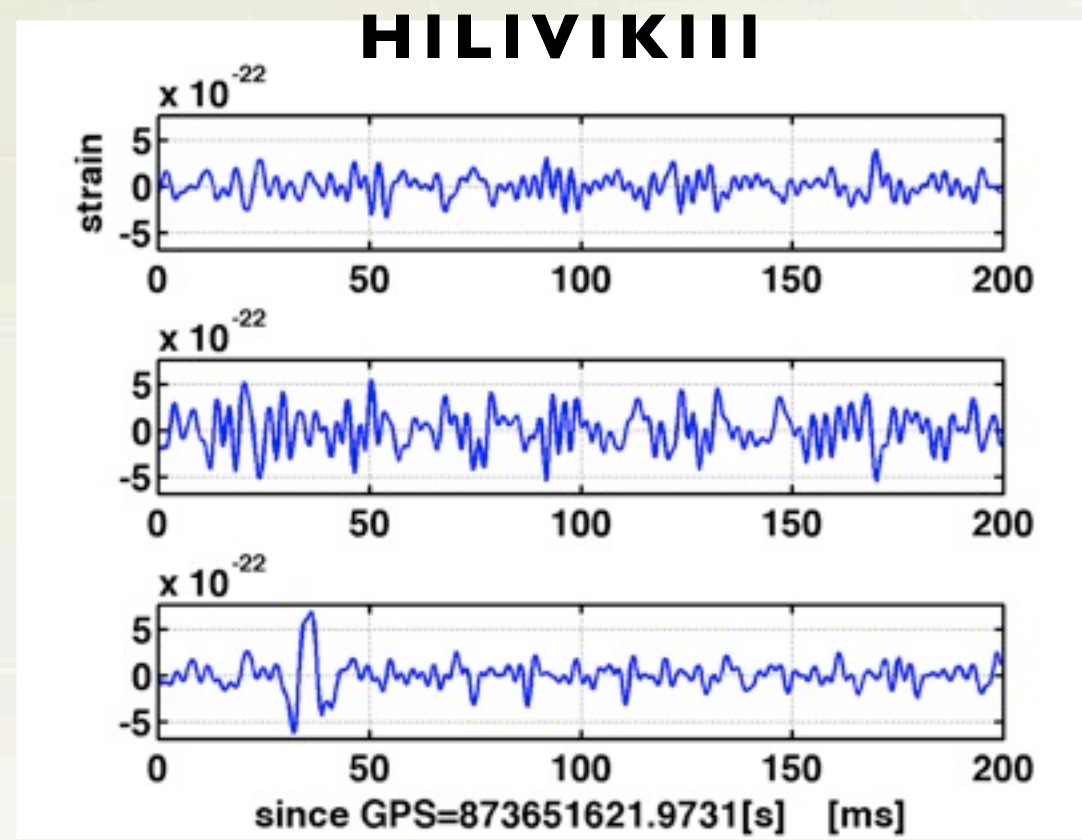


ω_{BD}=40000 (Current limit)



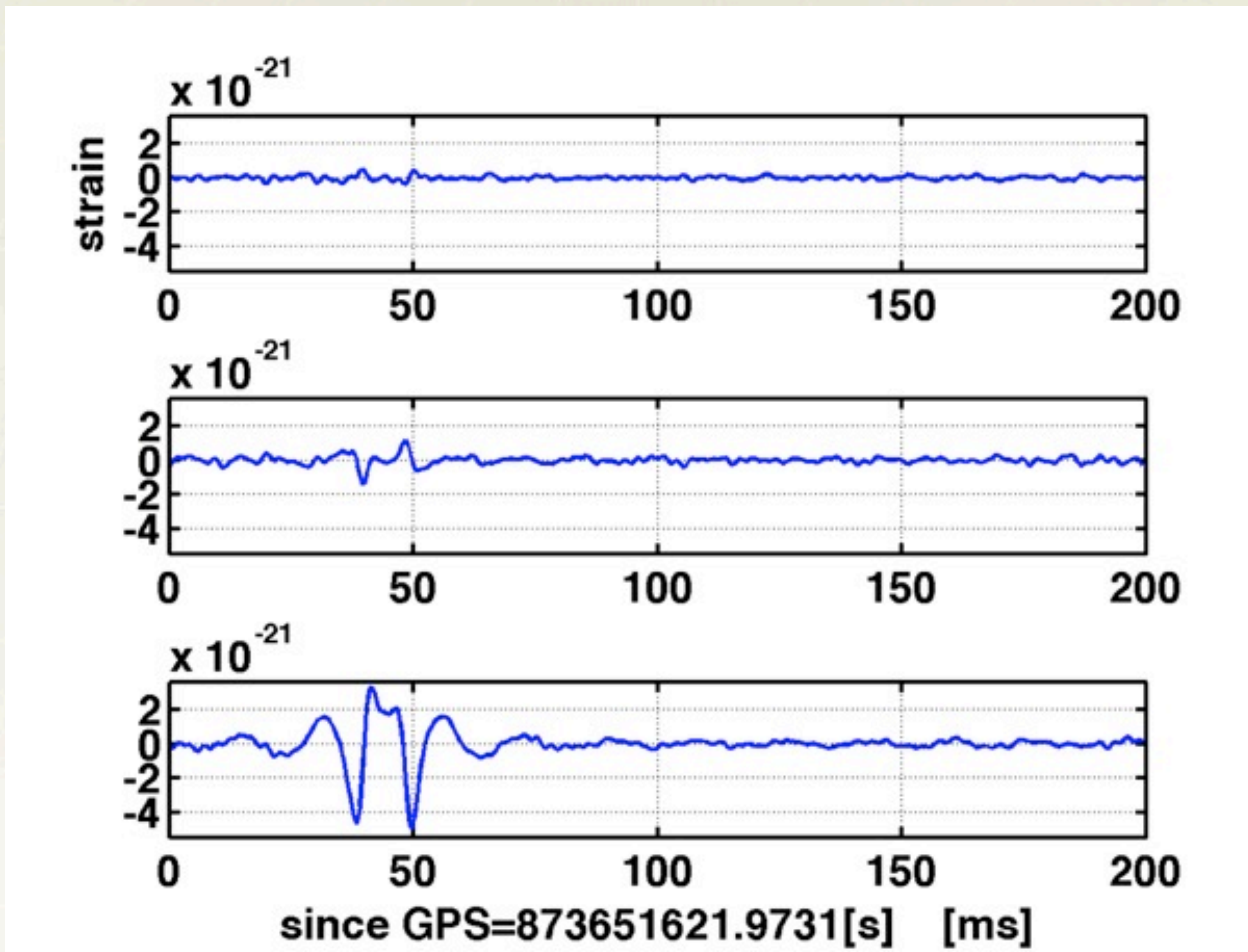
- aa

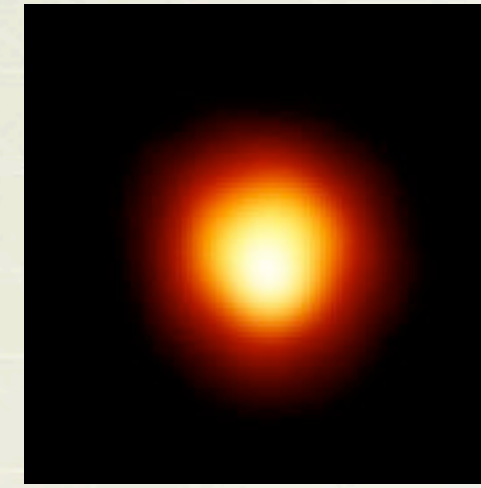




Betelgeuse

- **20Mo, 196.22pc !**
- **ω_{BD}=10x(current limit), 400,000**
- **If Betelgeuse is spherically symmetric core collapsed in Brans-Dicke framework...**





Summary

- We showed that the network of ground-based GW detectors can separate tensor mode and scalar mode of a GW in terms of general alternative theory of gravity.
- A pipeline based on the coherent network analysis is implemented and demonstrated using simulated Gaussian noise.
- Although LIGO-Virgo network cannot determine the direction to a SGW source, KAGRA and Indigo enable to do.
- Gain of detection probability benefits from KAGRA and Indigo.

ω_{BD}=40000 (Current limit)