A method for searching for gravitational waves triggered by astronomical observations

Kazuhiro Hayama, Soumya Mohanty
(University of Texas at Brownsville)
Malik Rakhmanov
(Southeastern Louisiana University)
Shantanu Desai
(Pennsylvania State University)
Tiffany Summerscales
(Andrews University)

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Contents

- Gravitational wave search triggered by electro-magnetic observations
- World-wide detector network
- Coherent network analysis
- “RIDGE”--fully coherent network analysis
- Application: monitoring Sco X-1, the strongest X-ray emitted LMXB(low mass X-ray binary).

Triggered search

LIGO

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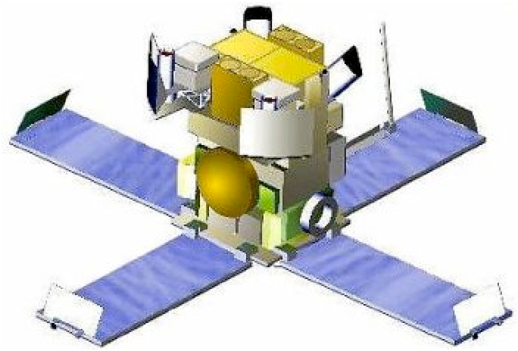

HETE

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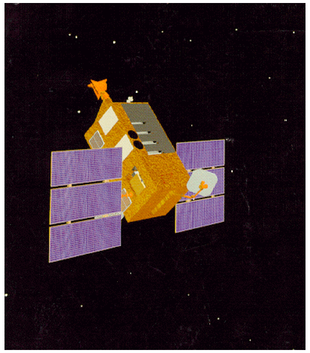

RXTE

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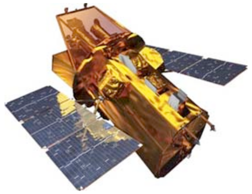
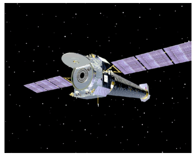


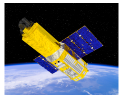
SWIFT

Parkes

XMM-Newton



Chandra



AstroE2

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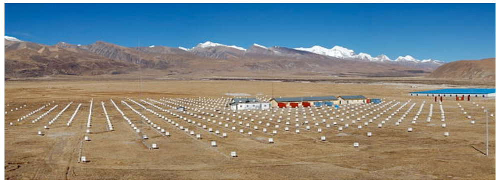

TIBET

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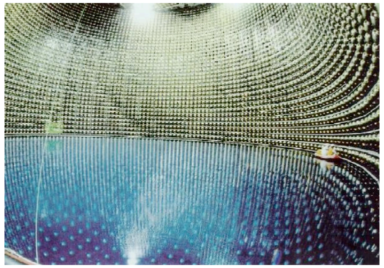

SuperKamiokande

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SDSS

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Triggered search


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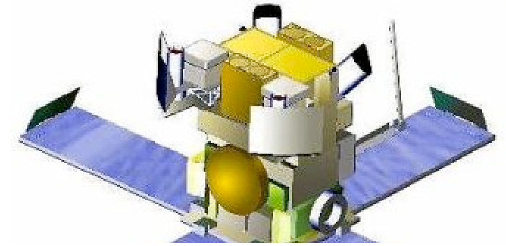
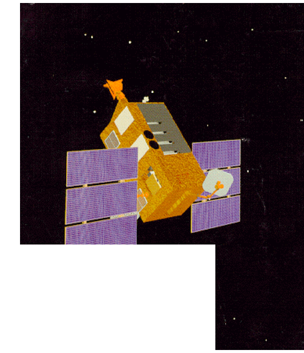
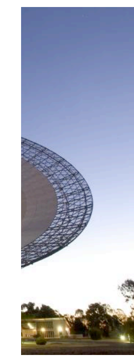



- High energy events are potentially G.W. sources for detection.
- The detection of G.W. can be enhanced by coincidences with electro-magnetic observations:
  GRB, SGR, Pulsar glitch, LMXB, Supernova



- Particularly, when a pulsar glitch is observed, we may predict when it occurs next theoretically(Ito(1983))

  --> can adjust the observation schedule to the predicted event.
- Detection efficiency can be increased
  - Time coincidence -- specify data to analyze
    --> sophisticated analysis
  - Source location
    accurate recovery of waveforms
    --> extract astrophysical parameters-Newton

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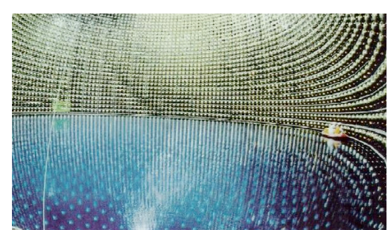

SuperKamiokande

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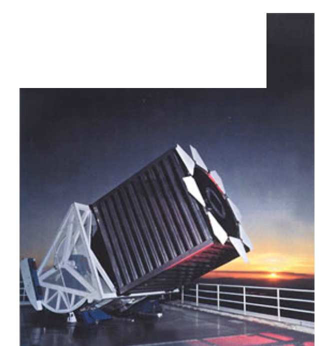

SDSS

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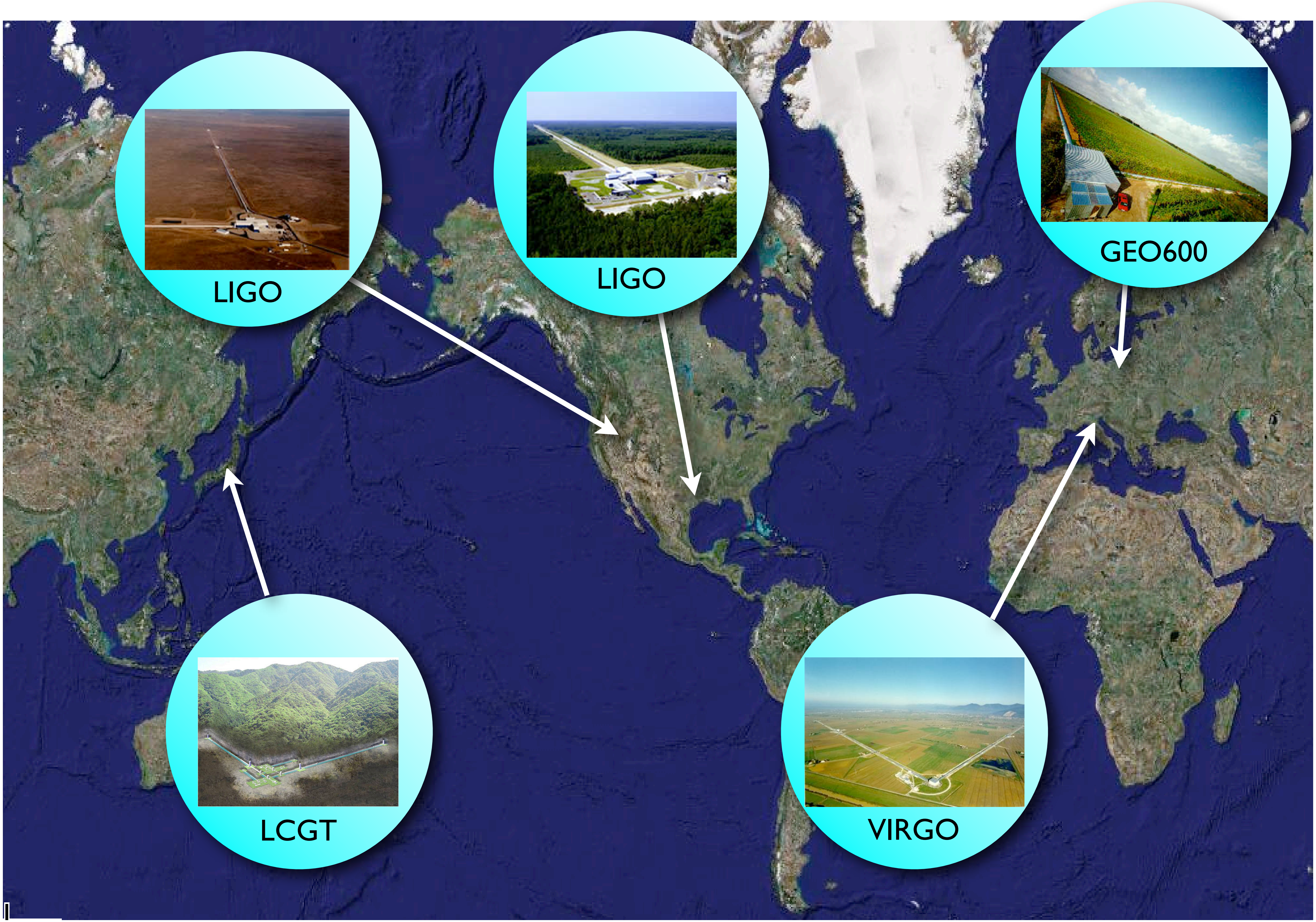
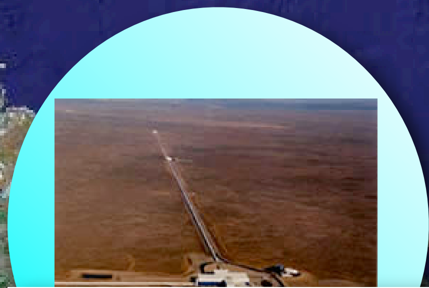
Gravitational wave detector network



Gravitational wave detector network



•When gravitational waves arrive at the earth, the signals are encoded into output of each detector.

•For data analysis to extract the signals,

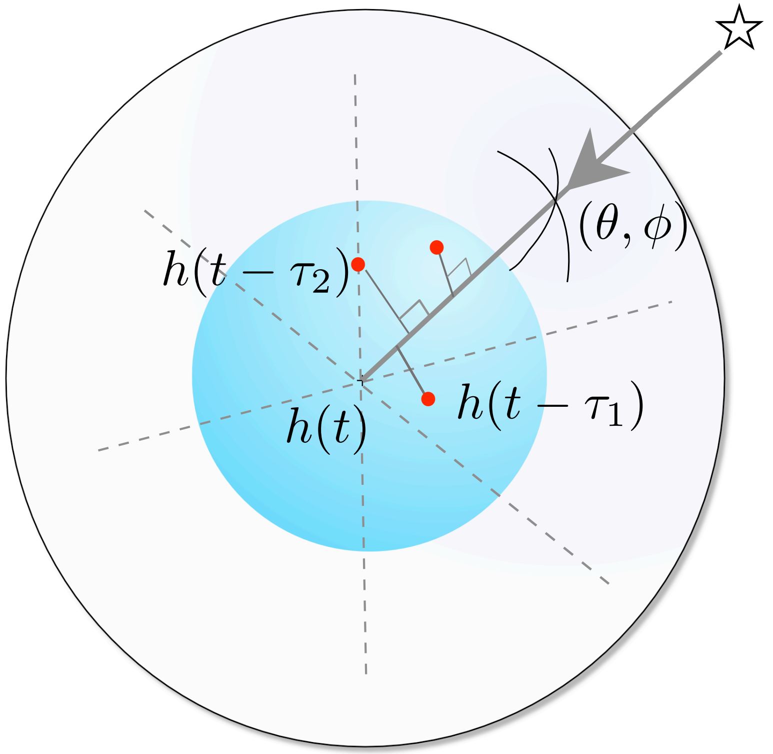
- how to combine these data streams from the detectors?
- how to recover the signal waveforms to obtain astronomical information?

One approach is coherent network analysis

Coherent network analysis

Natural way to handle networks of detectors

- Use arbitrary # of detectors
- Statistics combines all data streams coherently
- Recovery of polarization waveforms and sky position



$$\begin{bmatrix} x_1(t) \\ \vdots \\ x_d(t) \end{bmatrix} = \begin{bmatrix} F_{1+}(\theta,\phi) & F_{1\times}(\theta,\phi) \\ \vdots & \vdots \\ F_{d+}(\theta,\phi) & F_{d\times}(\theta,\phi) \end{bmatrix} \begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ \vdots \\ n_d(t) \end{bmatrix}$$

data = response x gw + noise

gw $\xi_i(t) = F_{i+}(\theta,\phi)h_+(t) + F_{i\times}(\theta,\phi)h_\times(t)$

Changing (θ, ϕ) , look for

$$L = \sum_{i=1}^{d} \left(\sum_{t=0}^{T} \| \, x_i(t) - \xi_i(t + \tau_i, \theta, \phi) \, \|^2 \right) \rightarrow \text{minimum}$$

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Tikhonov regularization

$$\begin{bmatrix} x_1(t) \\ \vdots \\ x_d(t) \end{bmatrix} = \begin{bmatrix} F_{1+}(\theta,\phi) & F_{1\times}(\theta,\phi) \\ \vdots & \vdots \\ F_{d+}(\theta,\phi) & F_{d\times}(\theta,\phi) \end{bmatrix} \begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ \vdots \\ n_d(t) \end{bmatrix}$$

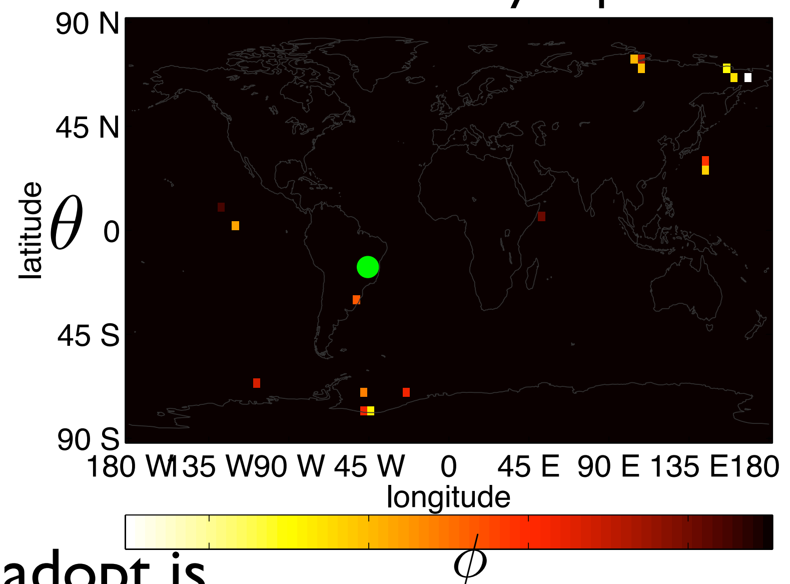
$$\| \quad F_+(\theta,\phi) \qquad \| \quad F_\times(\theta,\phi)$$

- Detection of G.W. is an inverse problem
- Due to the degree of freedom of the response matrix, the problem becomes ill-posed

(When $F_\times(\theta,\phi) \propto F_+(\theta,\phi)$, matrix becomes rank deficient.)

- The error in the best-fit solution is amplified

likelihood skymap



The technique to address this rank deficiency we adopt is Tikhonov regularization based approach **(M. Rakhmaonv CQG 23,S673 (2006))**

$$L_g = \sum_{i=1}^{d} \left(\sum_{t=0}^{T} \| \, x_i(t) - \xi_i(t,\theta,\phi,\tau_i) \, \|^2 \right) + g\Omega[h]$$

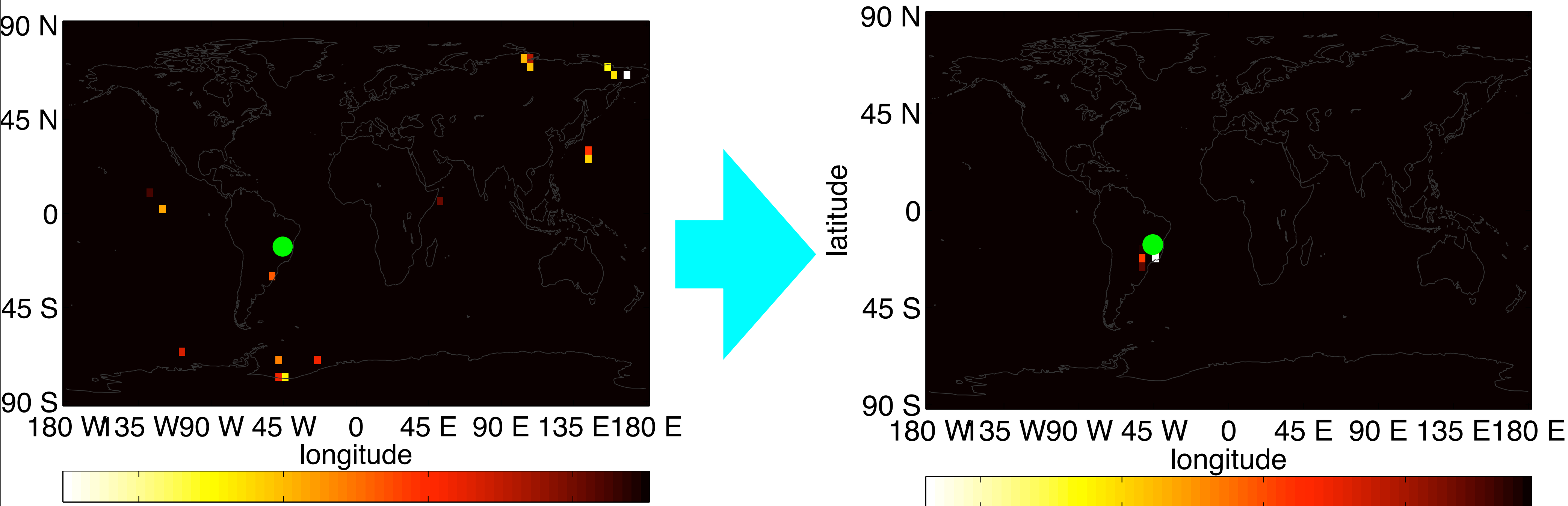
Impose regulator on standard maximum likelihood statistic

similar approach:
Klimenko et al PRD 72, 122002 (2005)
Mohanty et al CQG 23 (2006)

Effect of regulator

no regulator

with regulator



Without regulator, likelihood values beyond a given threshold are scattered widely.

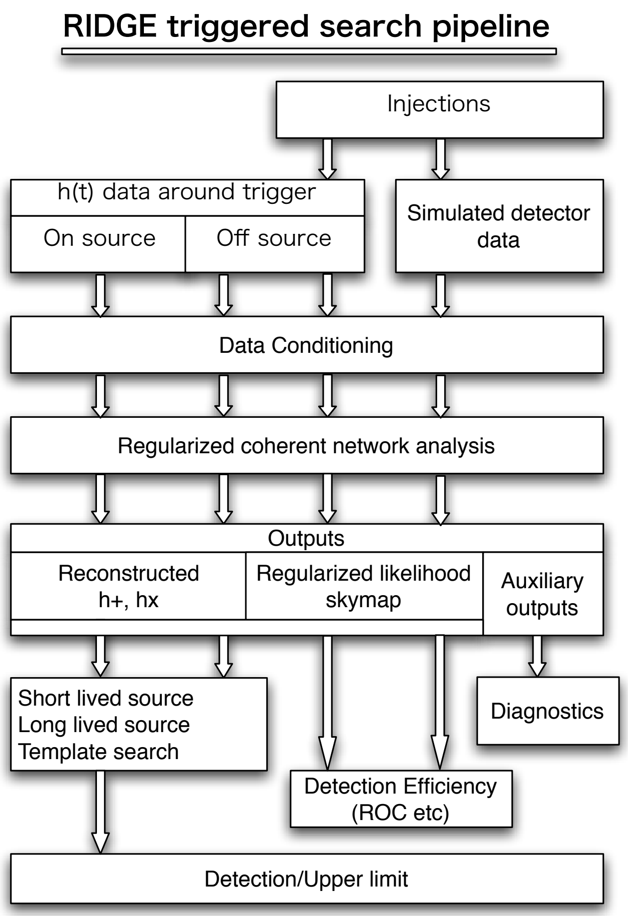
After adding regulator, the values are converged around the true solution.

RIDGE pipeline

-- *fully coherent network analysis pipeline* --

Project Page: http://phys.utb.edu/~kazu/RIDGE

Flow chart



- Target : triggered/untriggered search
- Pipeline consists of
  - data conditioning
  - coherent network analysis
- The codes have been fully implemented.
- Currently analyzing LIGO/GEO/VIRGO data:
  - Search for G.W. bursts
  - Understanding various glitches

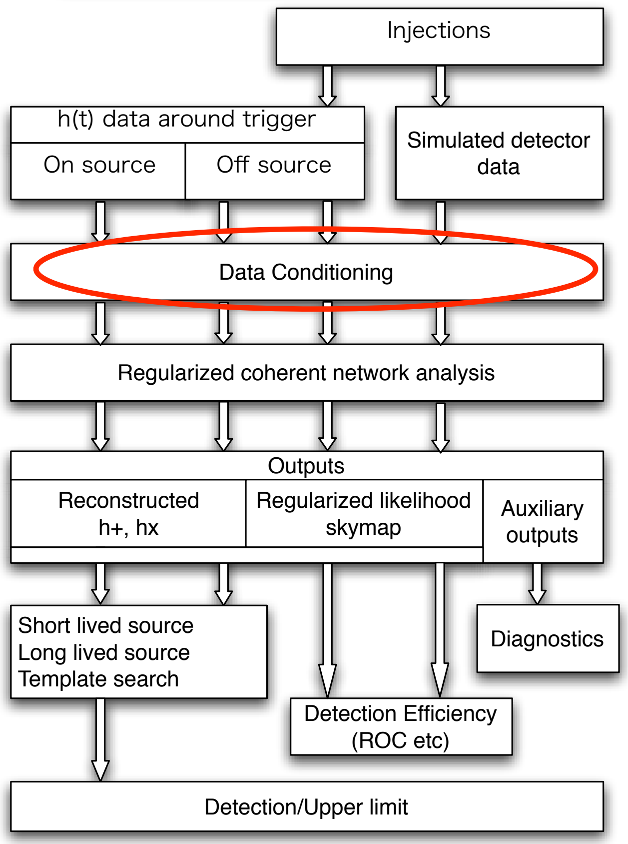
Note:
glitch :A large amplitude noise transient

RIDGE pipeline

-- *fully coherent network analysis pipeline* --

Project Page: http://phys.utb.edu/~kazu/RIDGE

RIDGE triggered search pipeline



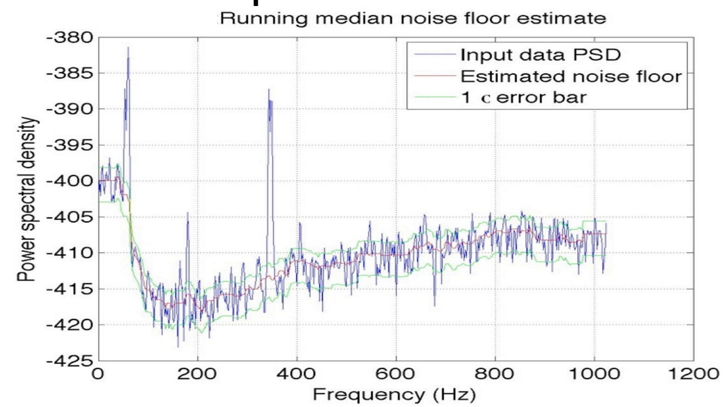
Feature:

- New data conditioning
- Tikhonov-regularized coherent network analysis

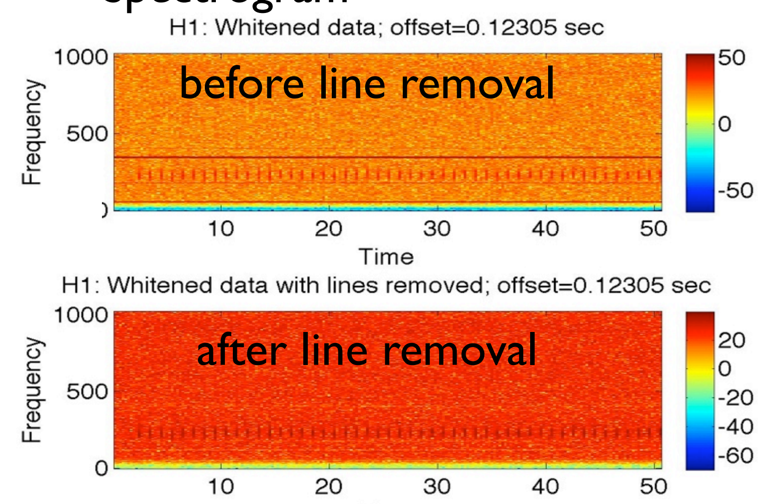
- Time domain noise floor whitening
  S. Mukherjee CQG 21 (2004) S1783

- Remove lines by Median Based Line Tracker
  S. Mohanty CQG 19 (2002) 1513

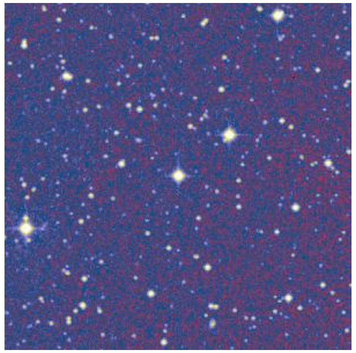
Power spectrum of simulated data



Spectrogram



One application of RIDGE



Monitoring Sco X-1

-- *with some combinations of detectors* --

- Sco X-1 is the strongest X-ray source, and has frequent X-ray outbursts
- G.W. observation can derive constraints on accretion or r-mode
- Sensitivities of detectors to Sco X-1 changes in time due to the rotation of the detector antenna patterns.
- Which detector combination is effective for detection?
  - Detection efficiency
  - Signal recovery
  - Here we consider H1-H2-L1,H1-H2-L1-V1,H1-L1-V1-LCGT combination

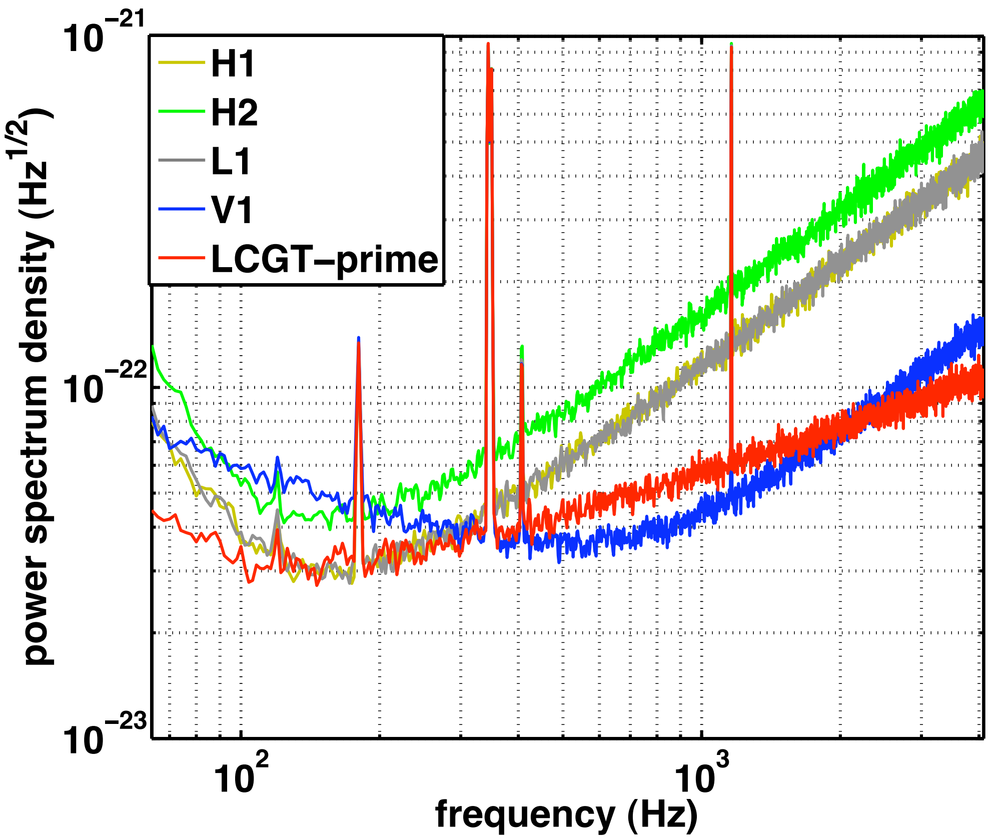
Monte Carlo Simulation

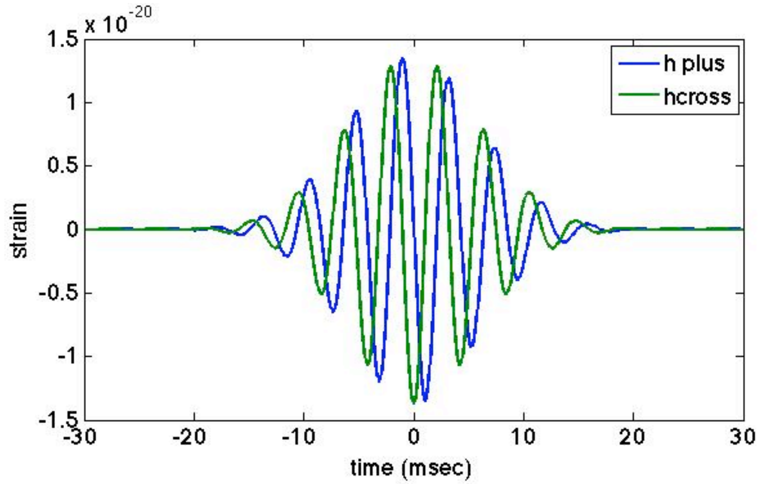
5 simulated data

- H1,H2,L1,V1 design sensitivity
- LCGT-prime: x10 worse than design
- Gaussian noise
- 16384Hz sampling
- 2000sec
- Lines are at same position for all ifo

Injected signal:

- SineGaussian(235Hz)
- Skylocation: ScoX1
- hrss=2×10^{-21} $Hz^{-1/2}$





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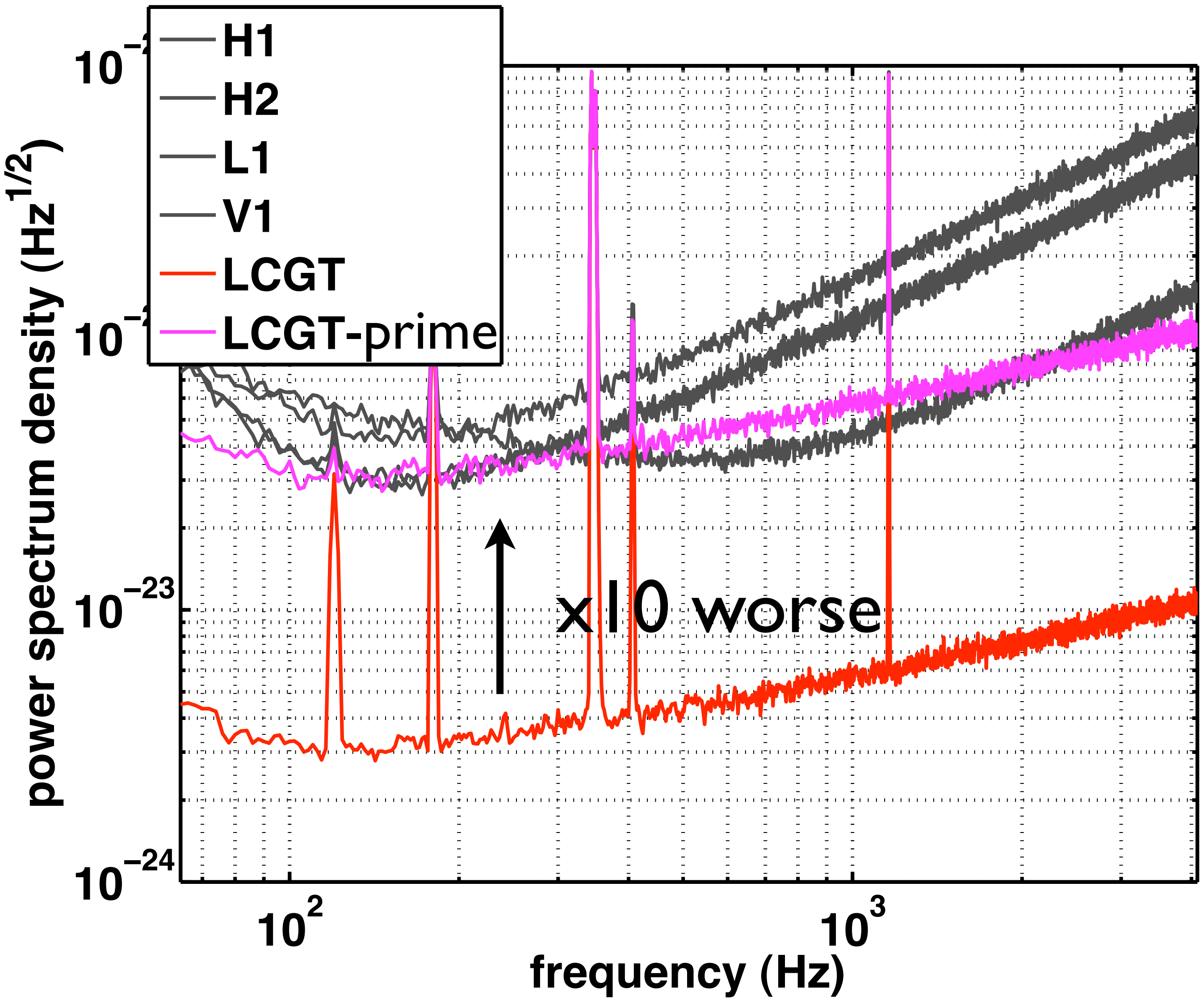
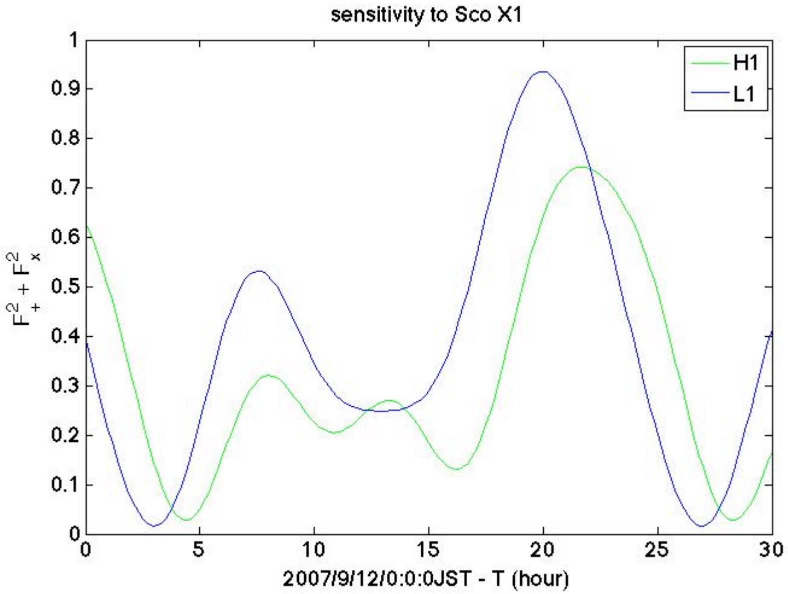
Monte Carlo Simulation

To focus on importance of detector location, use sensitivity x10 worse than the design sensitivity of LCGT.



Sensitivity to Sco X-1

H1 - L1



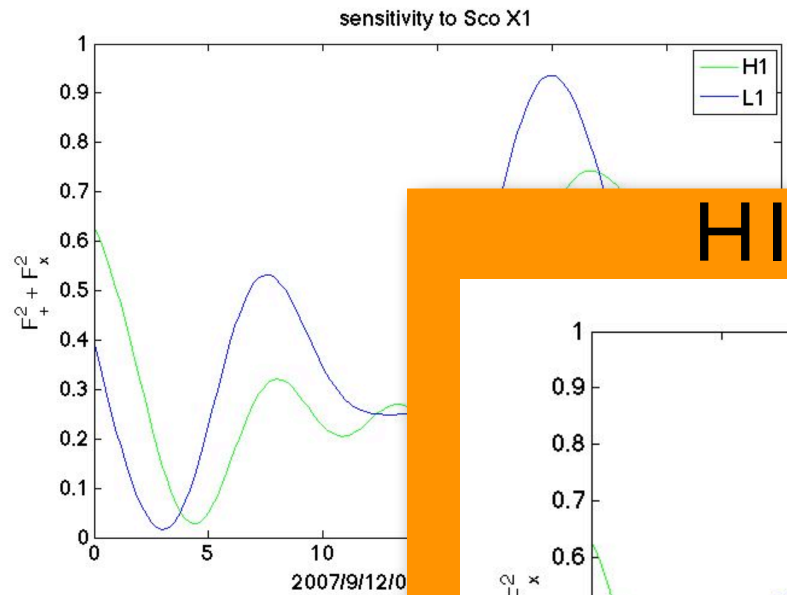
y-axis:
detector response : $F_+(\theta_s, \phi_s)^2 + F_\times(\theta_s, \phi_s)^2$
to the location of Sco X-1(θ_s, ϕ_s)

x-axis:
hour from 0:00(JST), today

Due to the rotation of the earth, the response function is 24hr-periodic function.
LIGO only network has sensitivity at the region T = 17-24hr.
However, T=2-5hr, 10-16hr, the sensitivity worsens

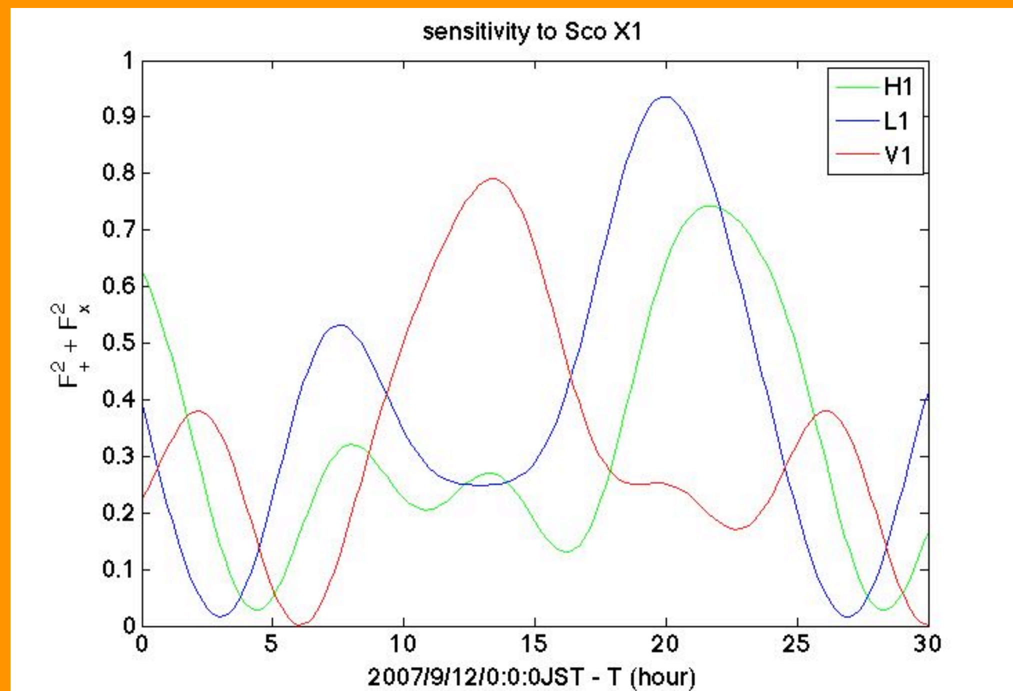
Sensitivity to Sco X-1

H1,H2 - L1



Adding VIRGO to the LIGO network, the sensitivity at the region T=10-16hr is improved.

H1,H2 - L1 - V1



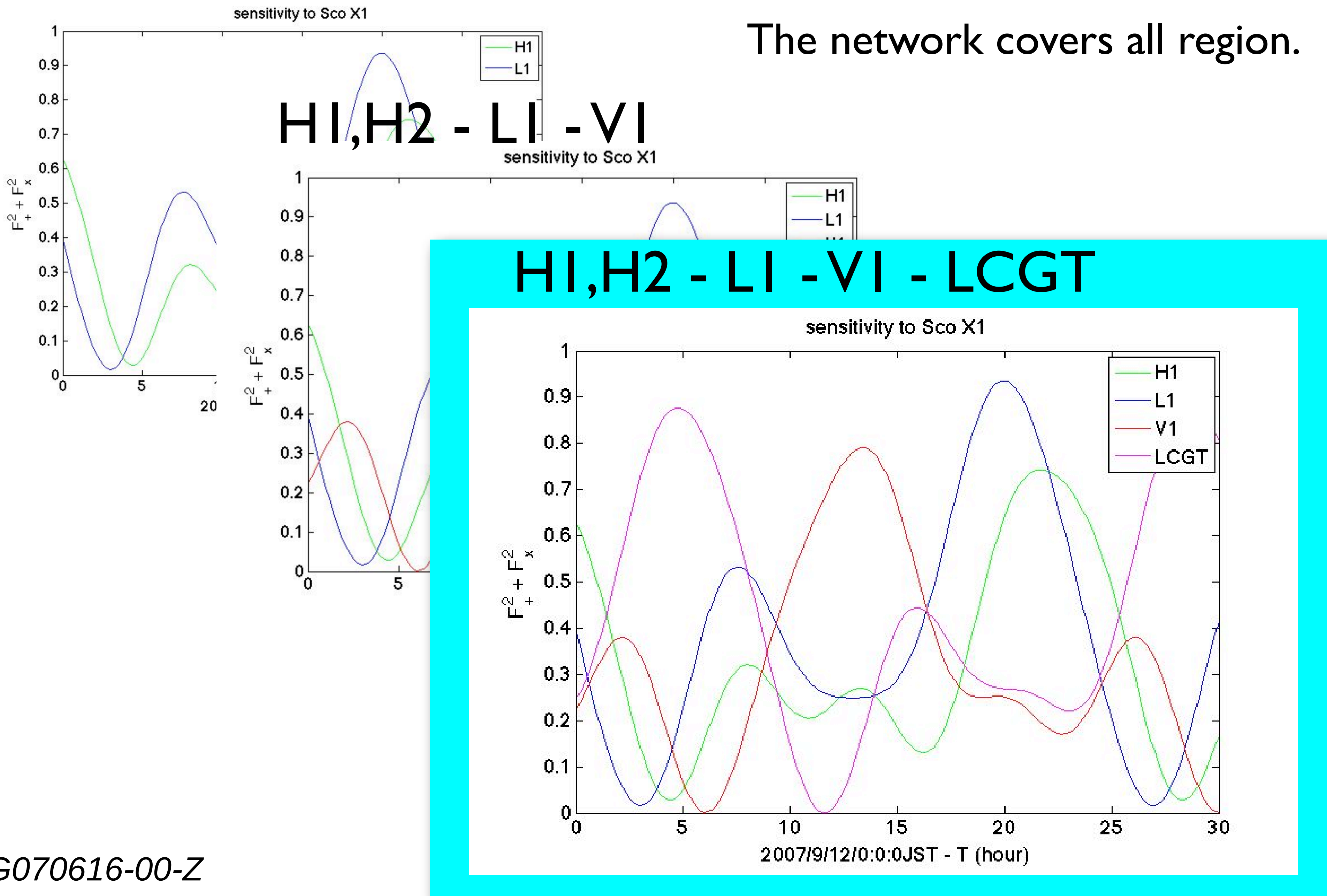
Sensitivity to Sco X-1

H1,H2 - L1

The network covers all region.

H1,H2 - L1 - V1

H1,H2 - L1 - V1 - LCGT



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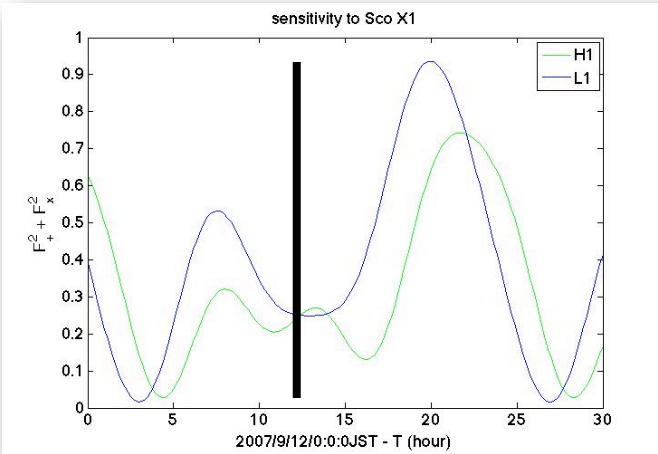
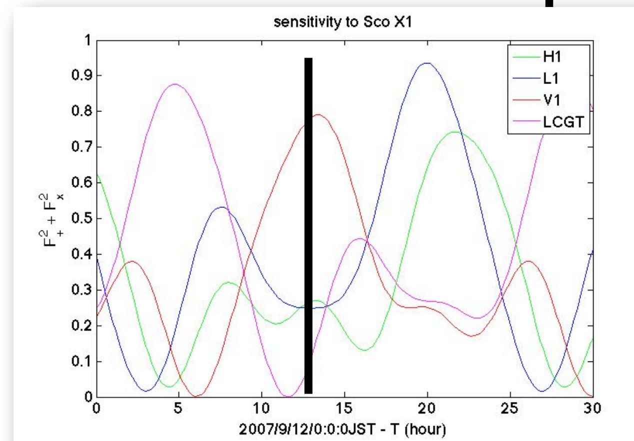
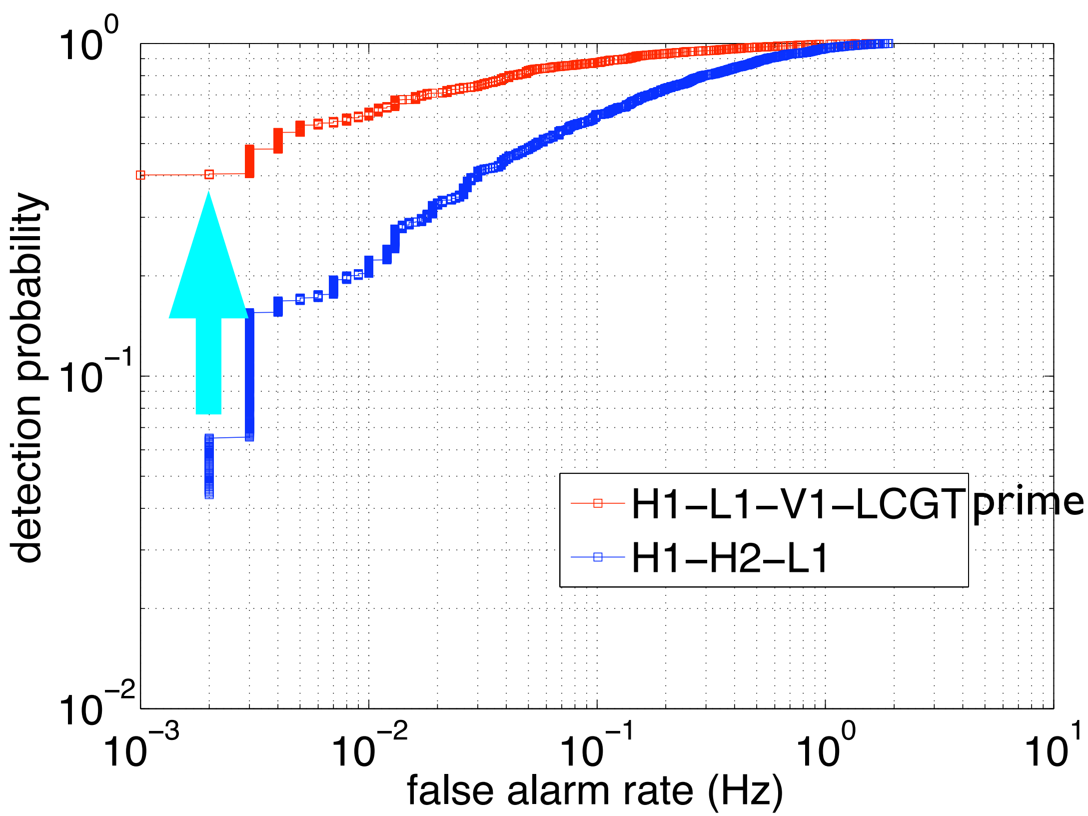
Detection efficiency

H1+H2+L1



H1+L1+V1+LCGT-prime





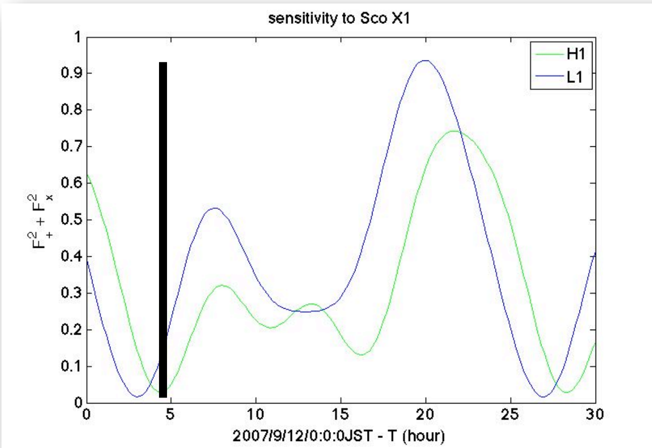
VIRGO compensate the low sensitivity region for LIGO network.

Detection probability
@false alarm rate 0.01Hz

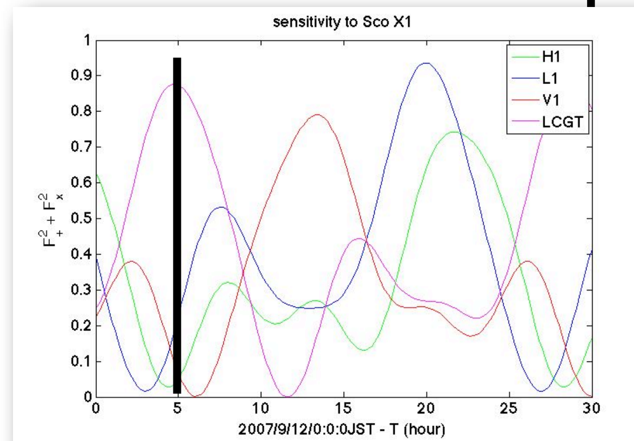
20% -------> 60%

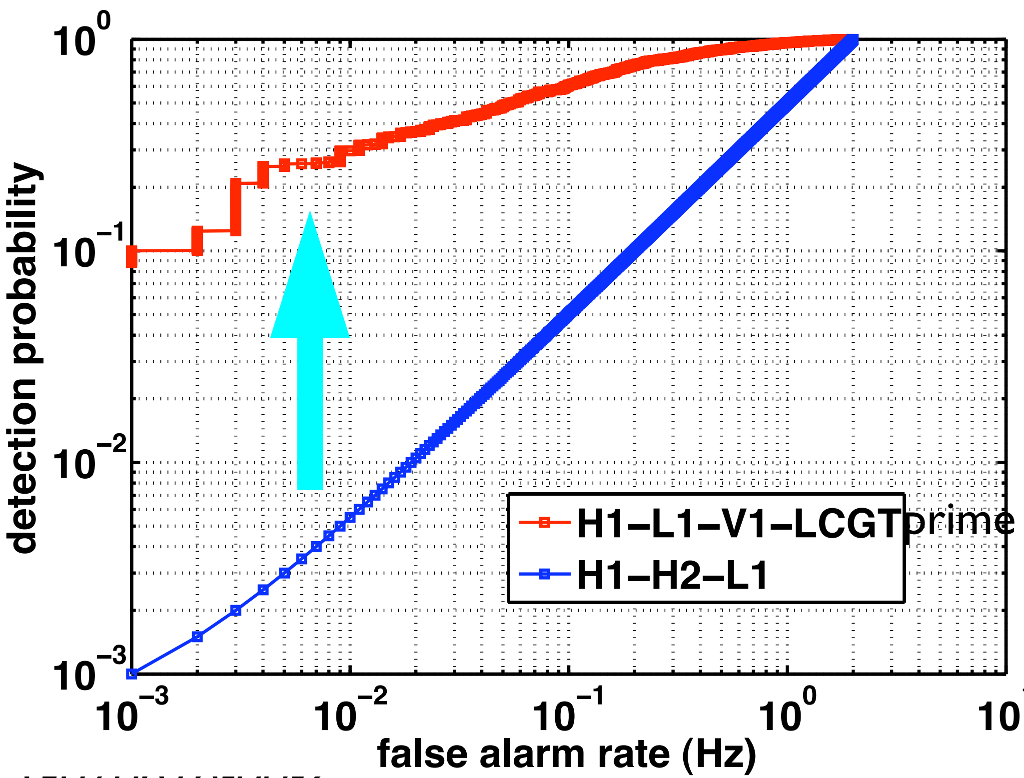
Detection efficiency

H1+H2+L1



H1+L1+V1+LCGT-prime





LCGT compensates the low sensitivity region for LIGO-VIRGO network.

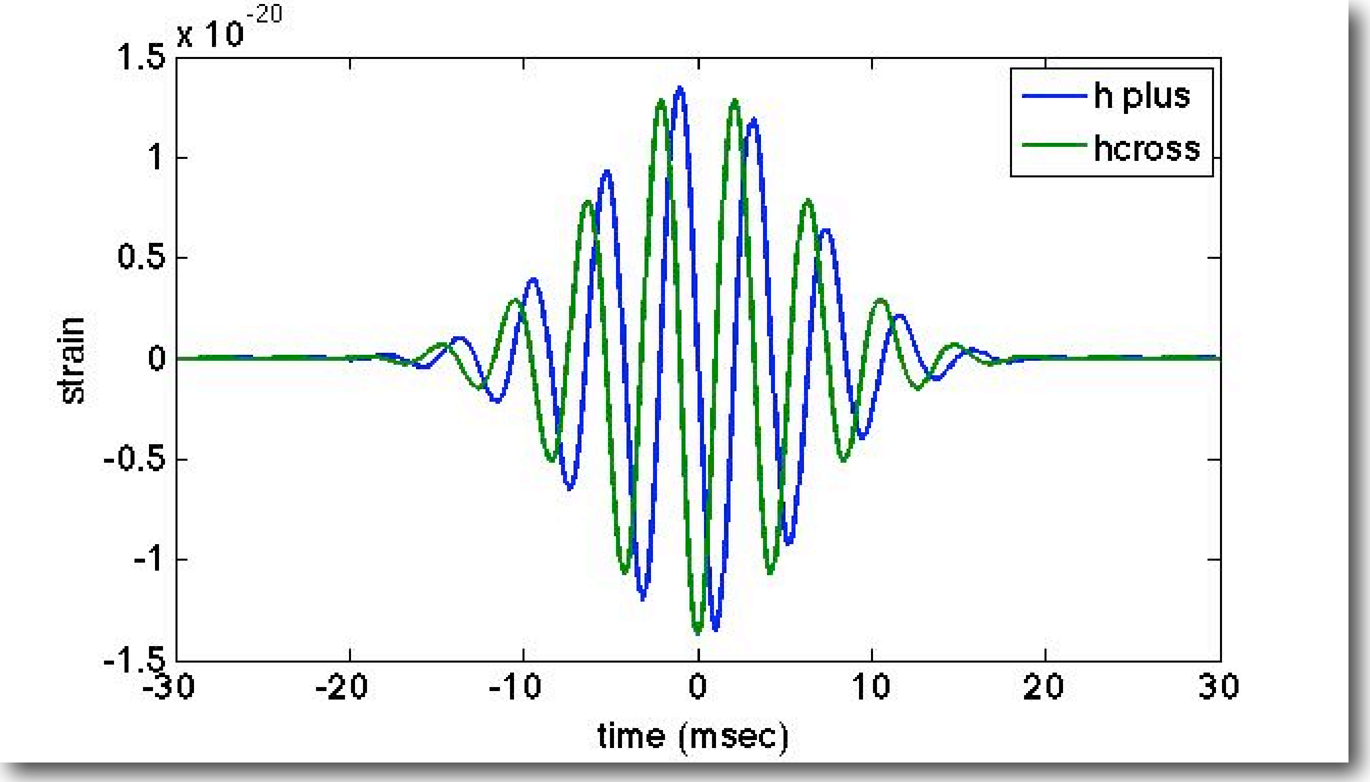
Detection probability
@false aralm rate 0.2Hz

less 10% -------> 80%

Reconstruction of G.W. waveforms

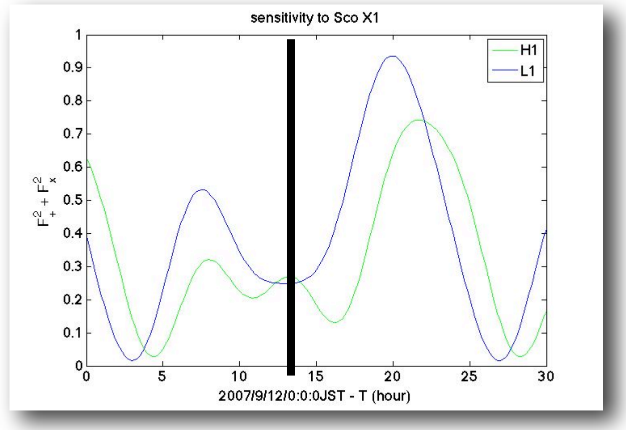
Injected signal:

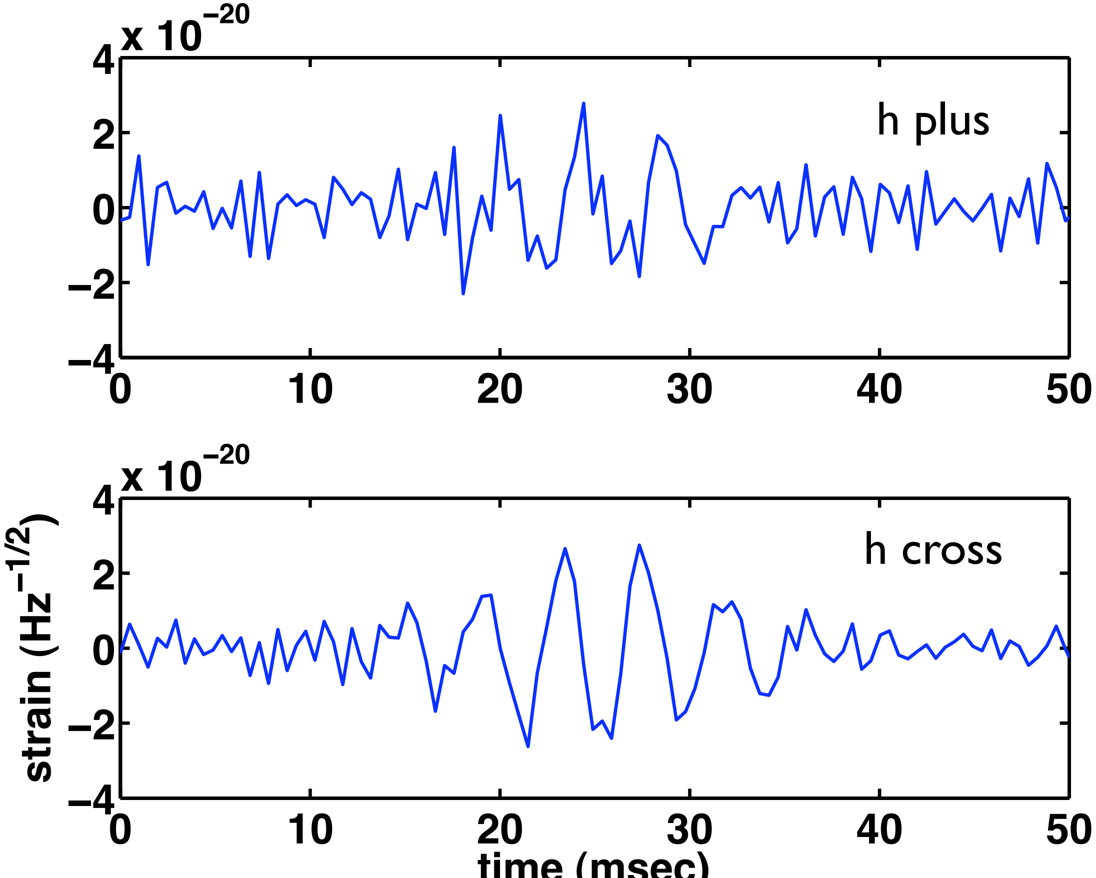
- Sine Gaussian of the central frequency 235Hz
- hrss=2.8×10^{-21} $Hz^{1/2}$



Reconstruction of G.W. waveforms

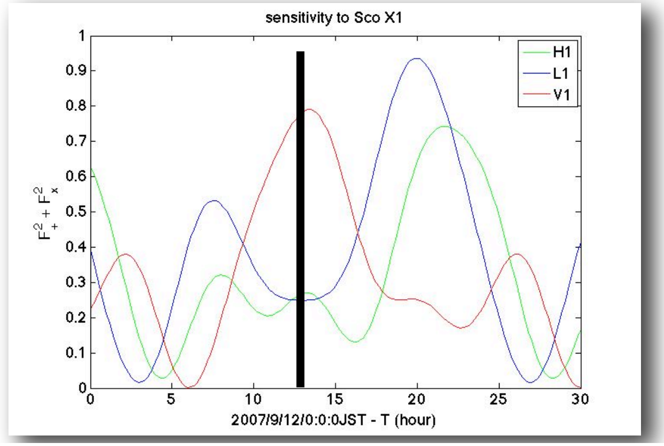
H1+H2+L1

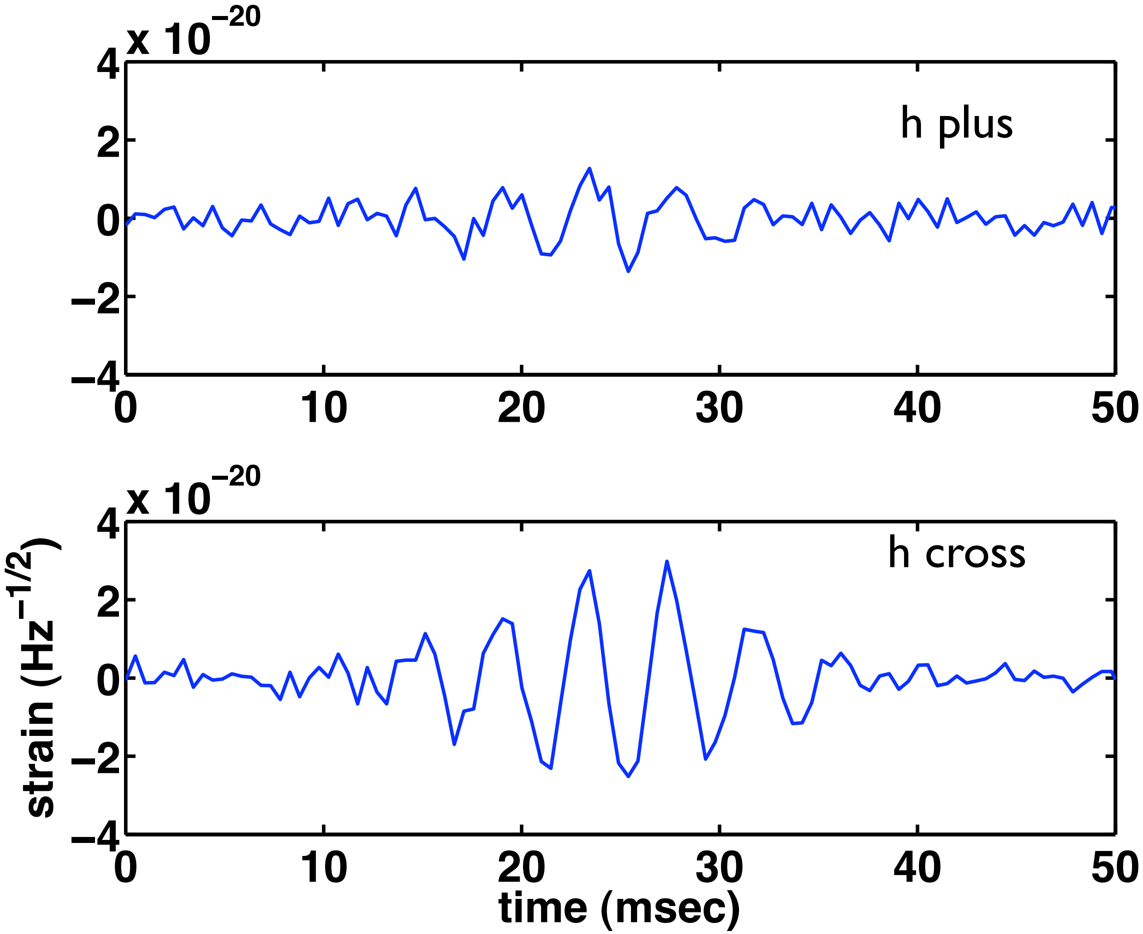




Reconstruction of G.W. waves

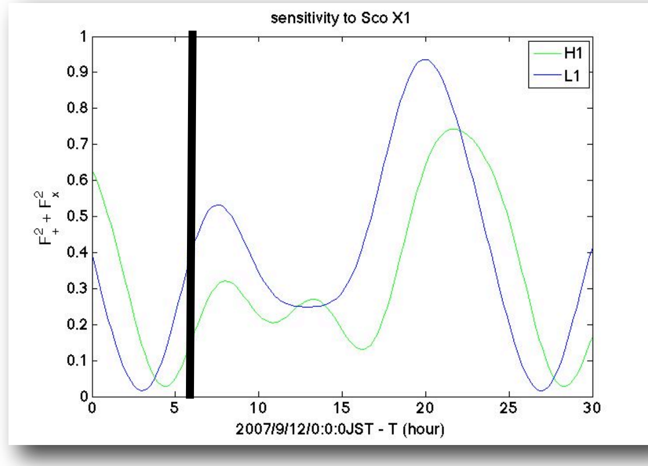
H1+H2+L1+V1

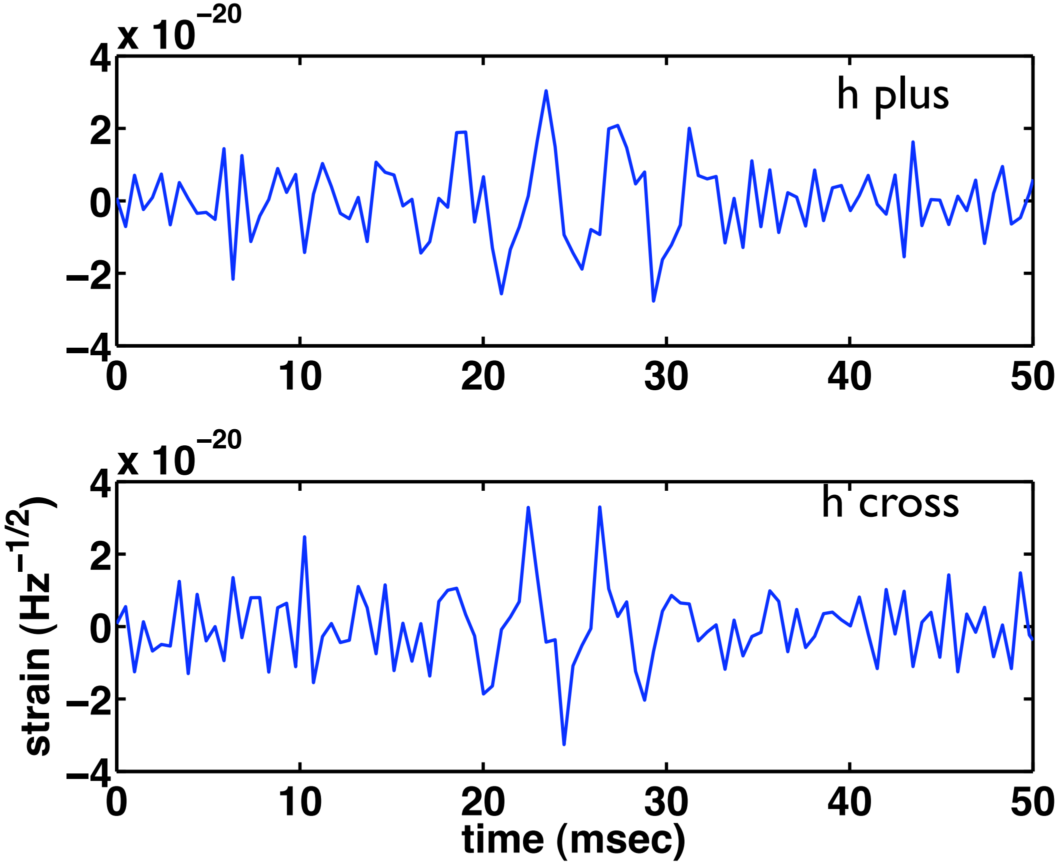




Reconstruction of G.W. waves

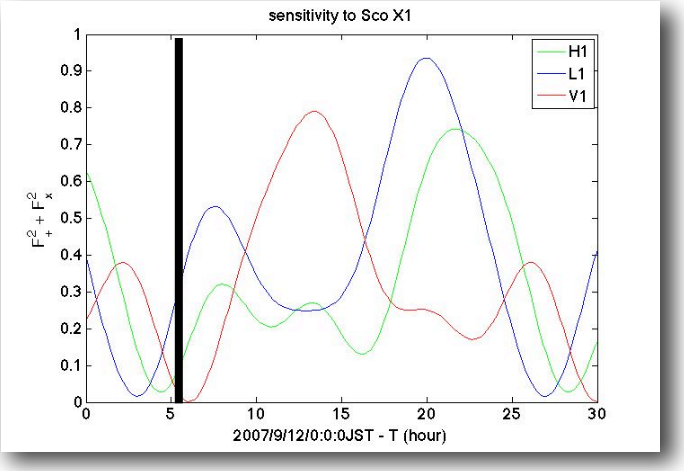
H1+H2+L1

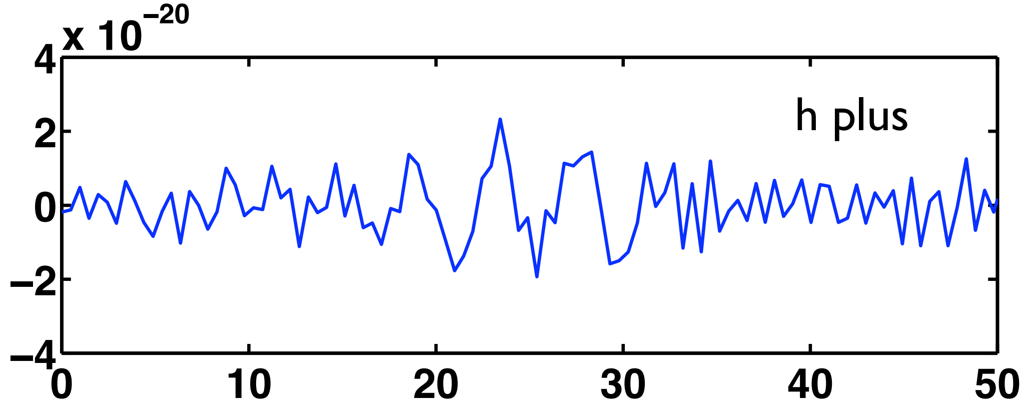


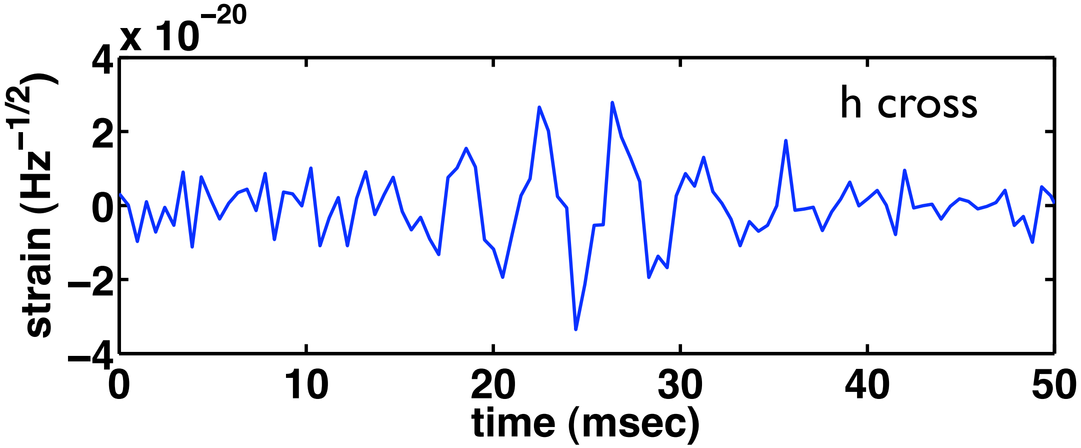


Reconstruction of G.W. waves

H1+H2+L1+V1







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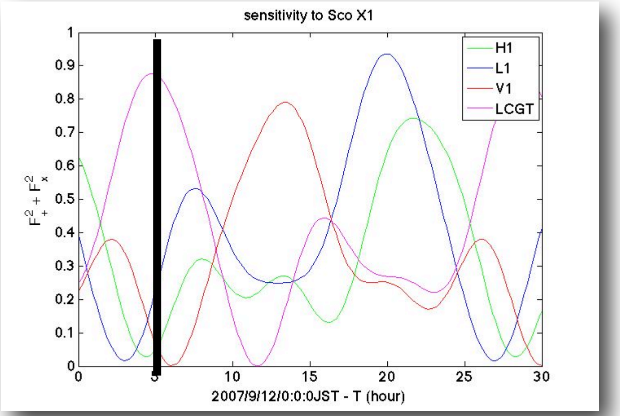
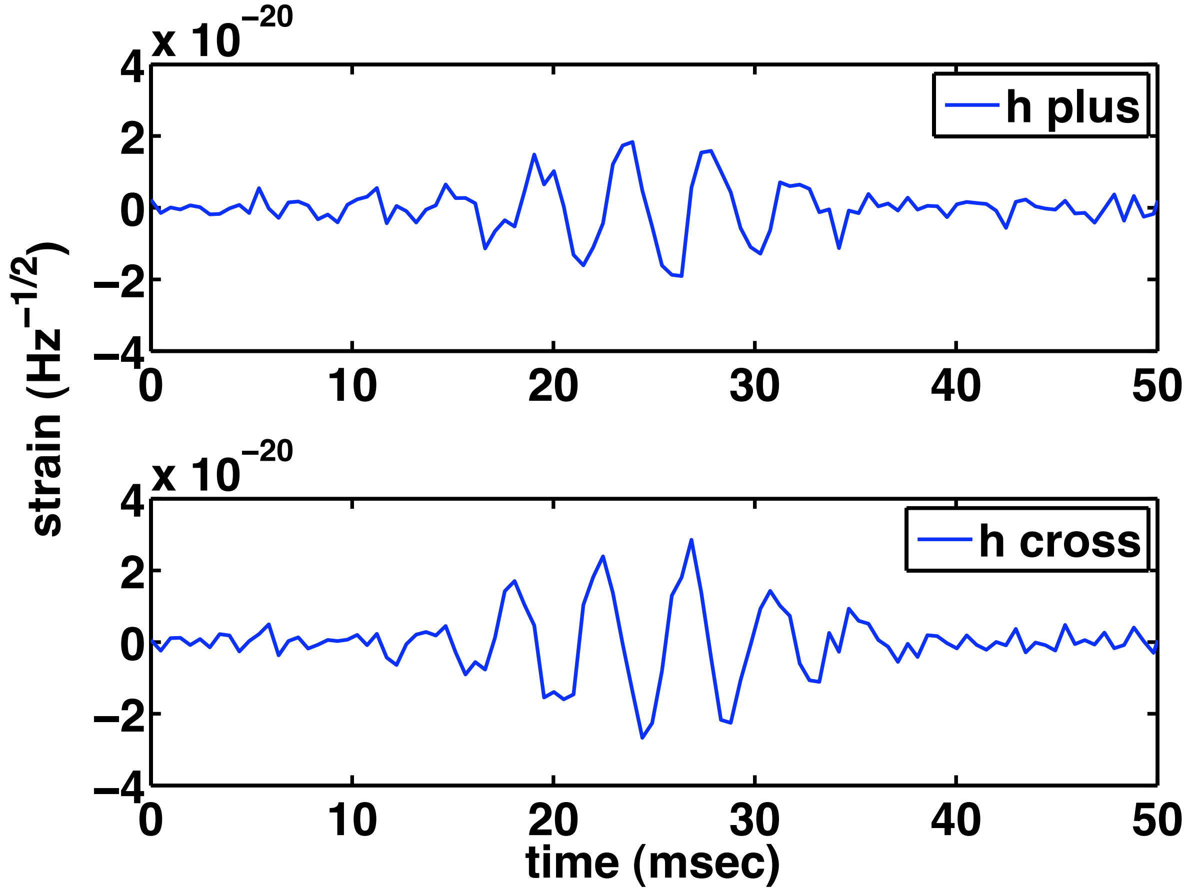
Reconstruction of G.W. waves

H1+L1+V1+LCGT-prime





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Summary, current status and future plan

Summary

- The fully coherent network analysis pipeline called "RIDGE" has been developed.
- Coincidence analysis with electro-magnetic observations give us
  - timing information --> more sophisticated analysis
  - source location --> accurate signal recovery and constrain astrophysical parameters
- Sensitivities of some detector combinations and signal recovery are presented

Current status

- Pulsar glitches during S5 are being analyzed
- Start monitoring Sco X-1
- Various detector noise transients are being analyzed

Future plan

- Set upper limit on some sources
- Understand detector-originated glitches
- Collaboration with various astronomers needed

-- Building alert system which enables quick analysis.

END