

A method for searching for gravitational waves triggered by astronomical observations

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Contents

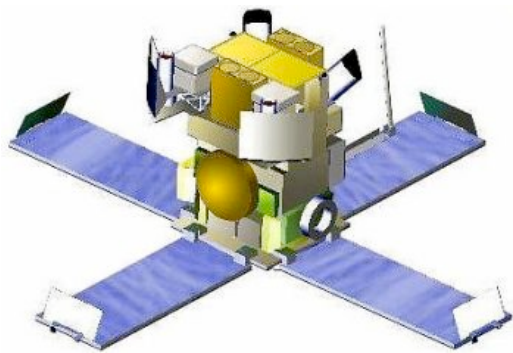
- Gravitational wave search triggered by electro-magnetic observations
- World-wide detector network
- Coherent network analysis
- “RIDGE”--fully coherent network analysis
- Application: monitoring Sco X-1, the strongest X-ray emitted LMXB(low mass X-ray binary).

Triggered search



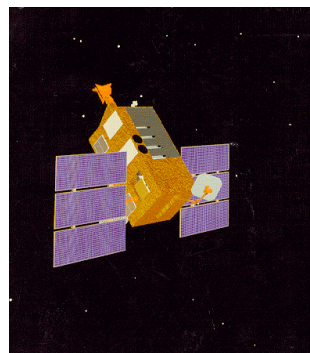
LIGO

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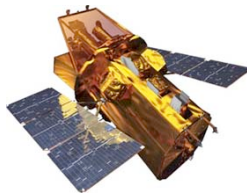
HETE

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RXTE

,



SWIFT



Chandra

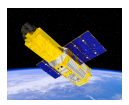


Parkes

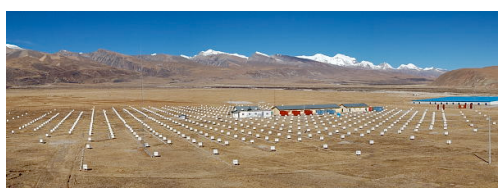
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XMM-Newton

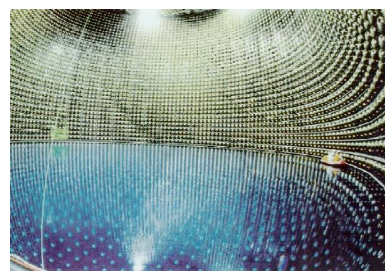


AstroE2



TIBET

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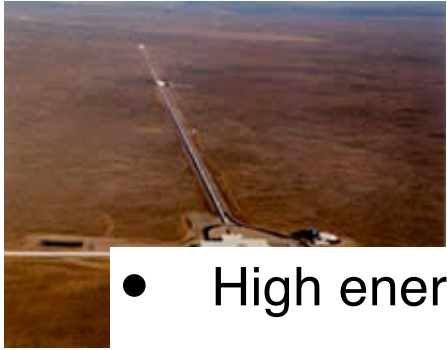
SuperKamiokande

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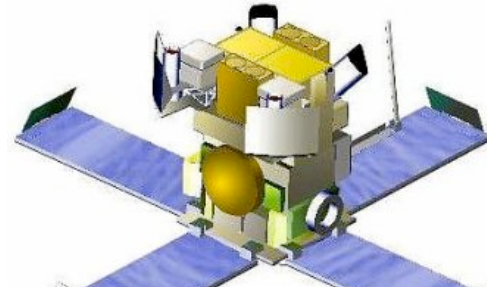


SDSS

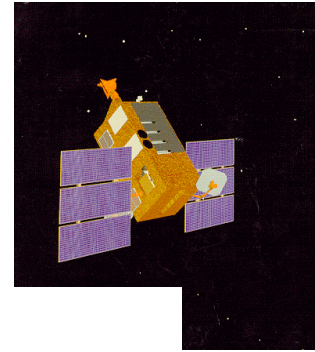
Triggered search



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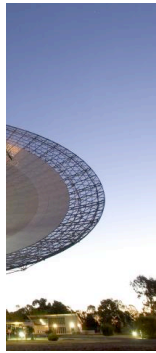


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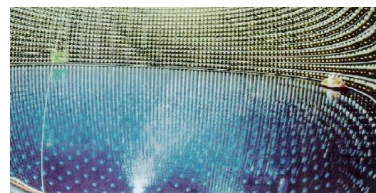
E

- High energy events are potentially G.W. sources for detection.
- The detection of G.W. can be enhanced by coincidences with electromagnetic 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



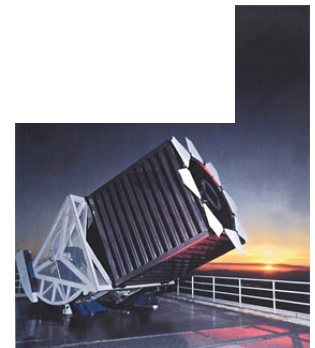
TIBET

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SuperKamiokande

,



SDSS

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



LCGT

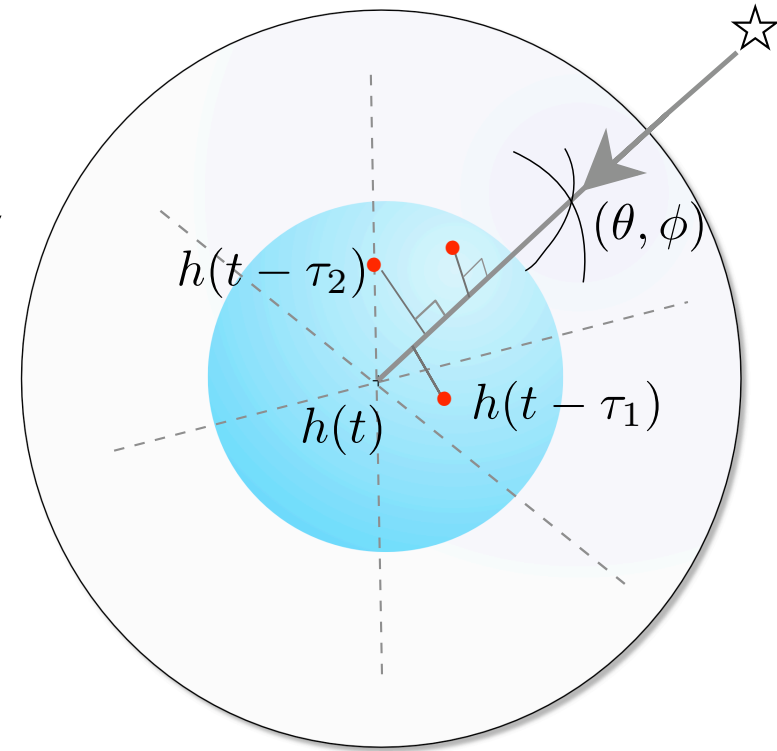


VIRGO

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 G.W. + noise

$$\text{G.W. } \xi_i(t) = F_{i+}(\theta, \phi)h_+(t) + F_{i\times}(\theta, \phi)h_\times(t)$$

Changing (θ, ϕ) , look for

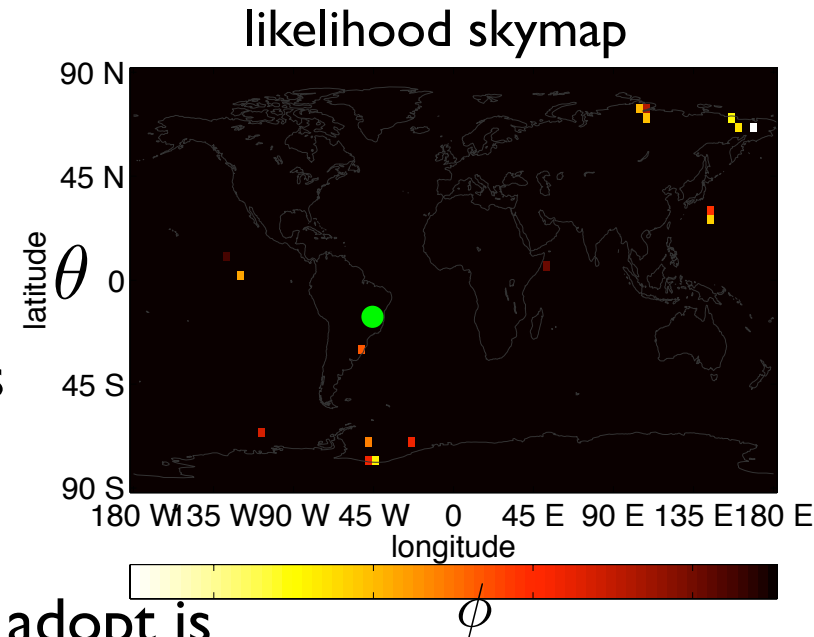
$$L = \sum_{i=1}^d \left(\sum_{t=0}^T \| x_i(t) - \xi_i(t + \tau_i, \theta, \phi) \|^2 \right) \rightarrow \text{minimum}$$

Tikhonov regularization

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

\parallel \parallel
 $F_+(\theta, \phi)$ $F_\times(\theta, \phi)$

- 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



The technique to address this rank deficiency we adopt is

Tikhonov regularization based approach (M. Rakhmanov **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

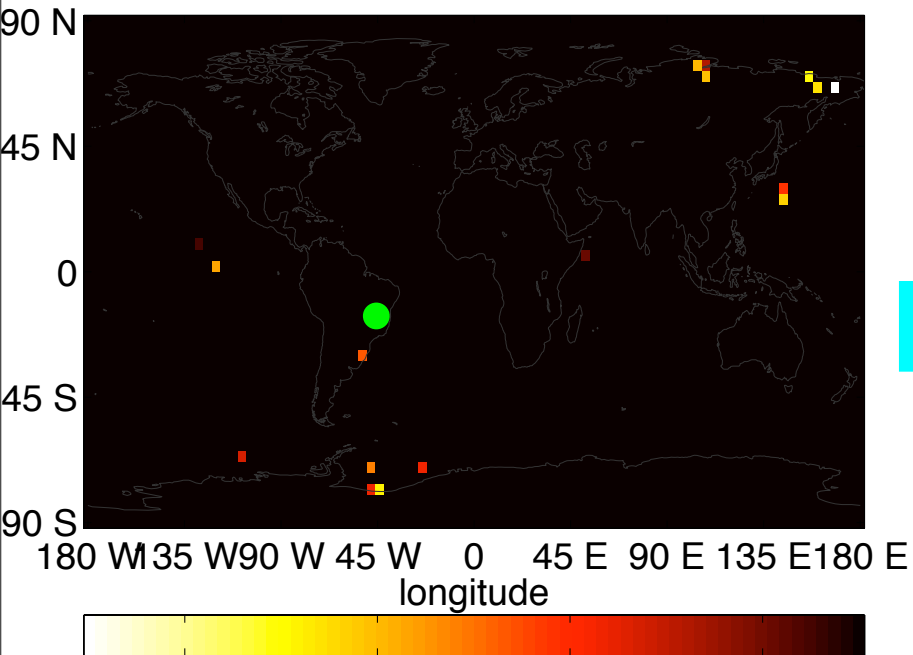
similar approach:

Klimenko et al **PRD 72, 122002 (2005)**

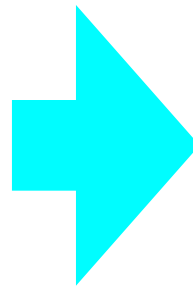
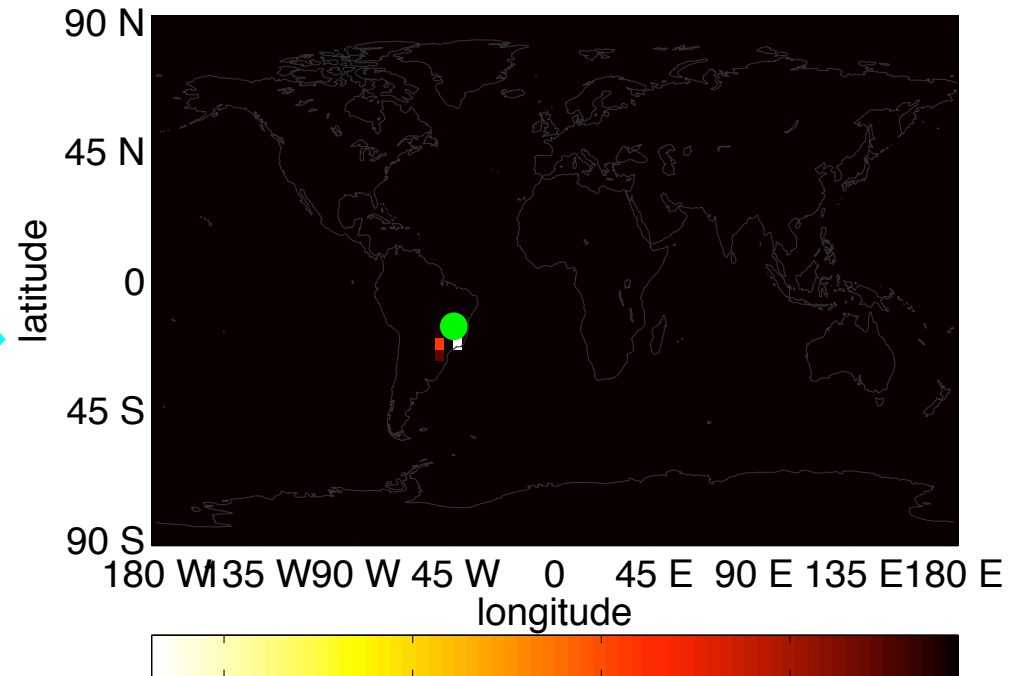
Mohanty et al **CQG 23 (2006)**

Effect of regulator

no regulator



with regulator



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

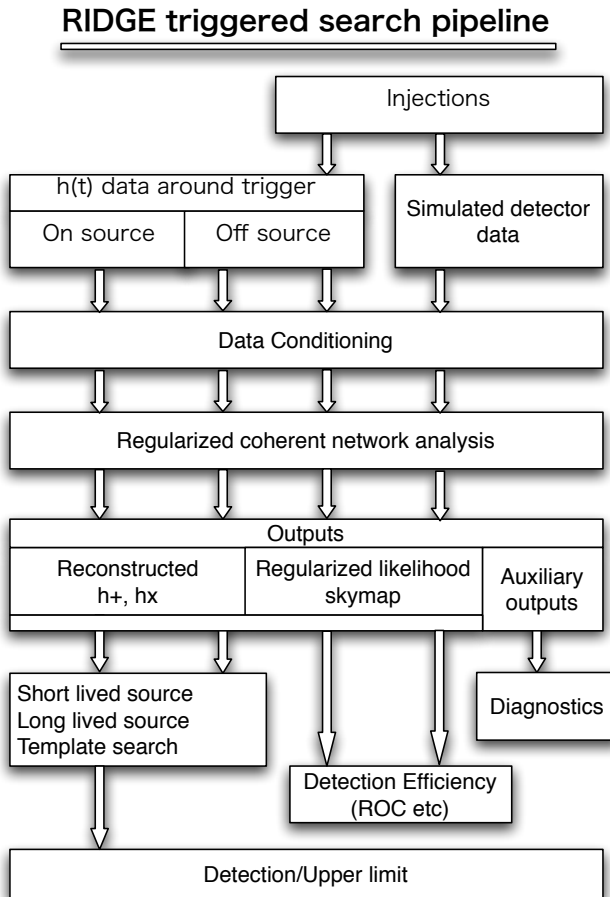
After adding regulator, the values are converged around the true solution.

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

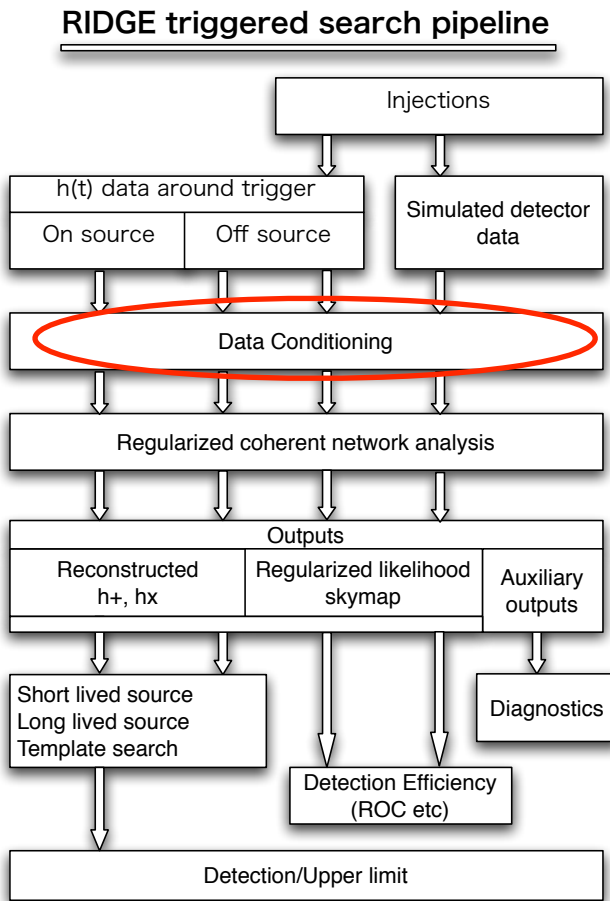
Note:

glitch : A large amplitude noise transient

RIDGE pipeline

-- *fully coherent network analysis pipeline* --

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



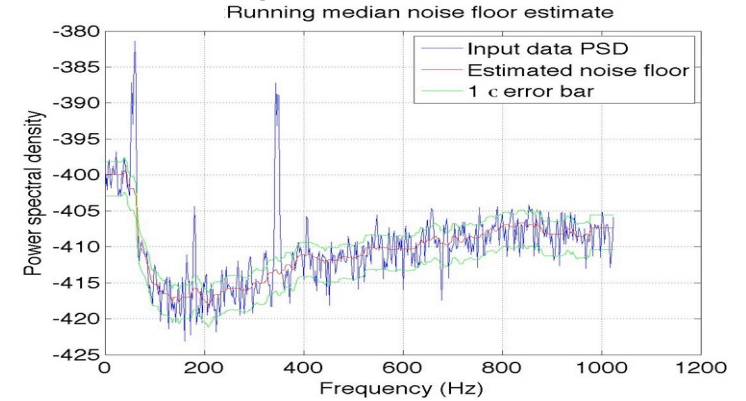
Feature:

- New data conditioning
- Tikhonov-regularized coherent network analysis

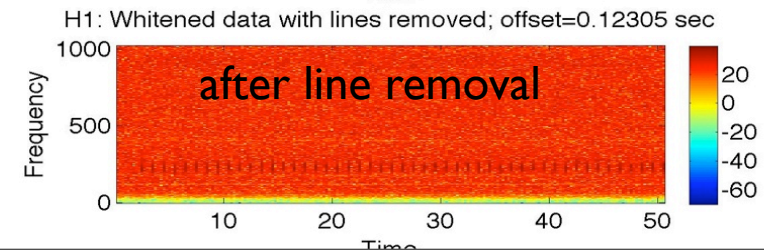
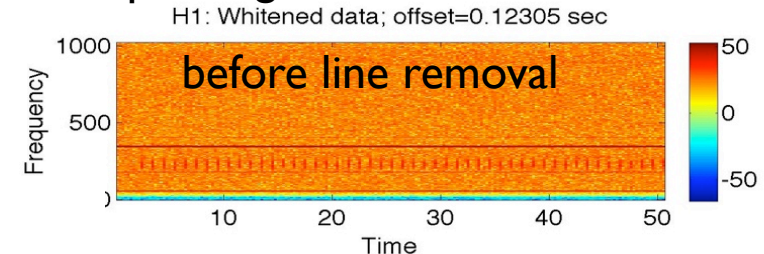
- Time domain noise floor whitening
S. Mukherjee CQG 21 (2004) S1783

- 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

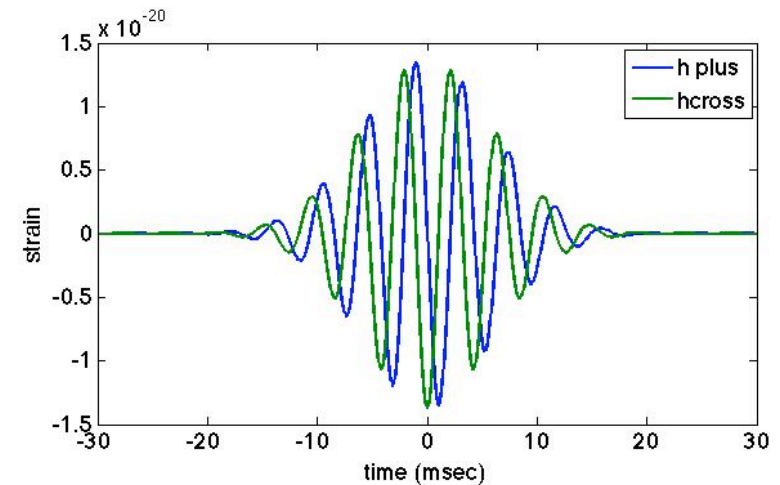
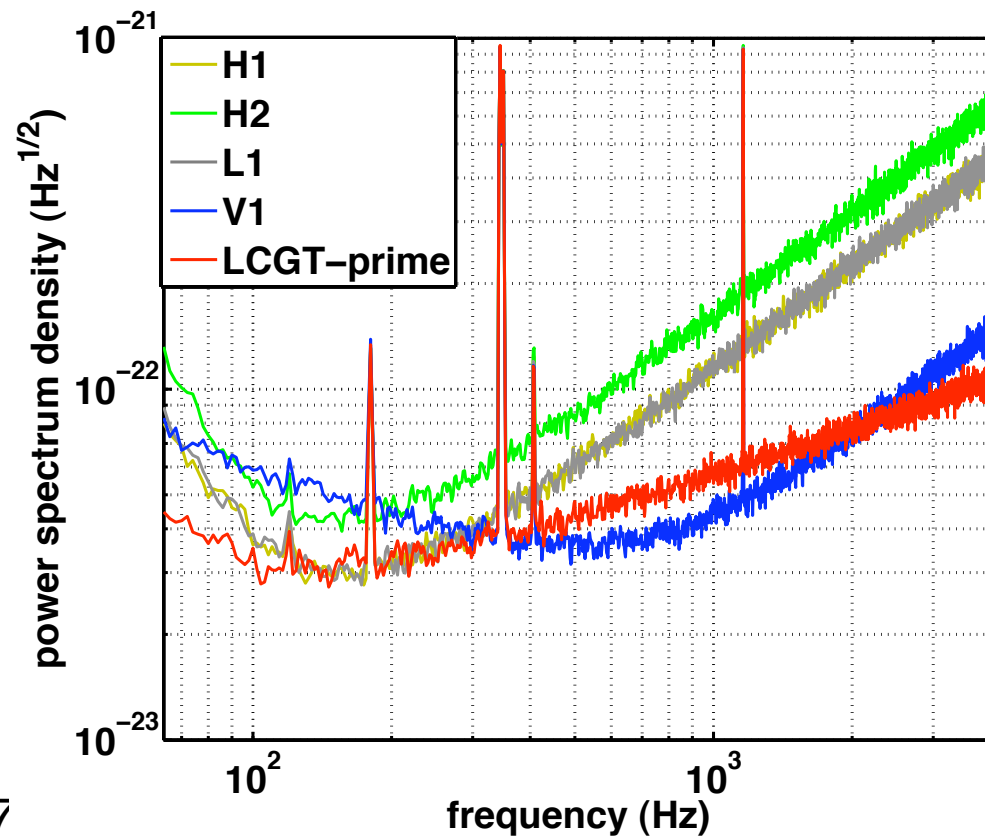
Monte Carlo Simulation

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

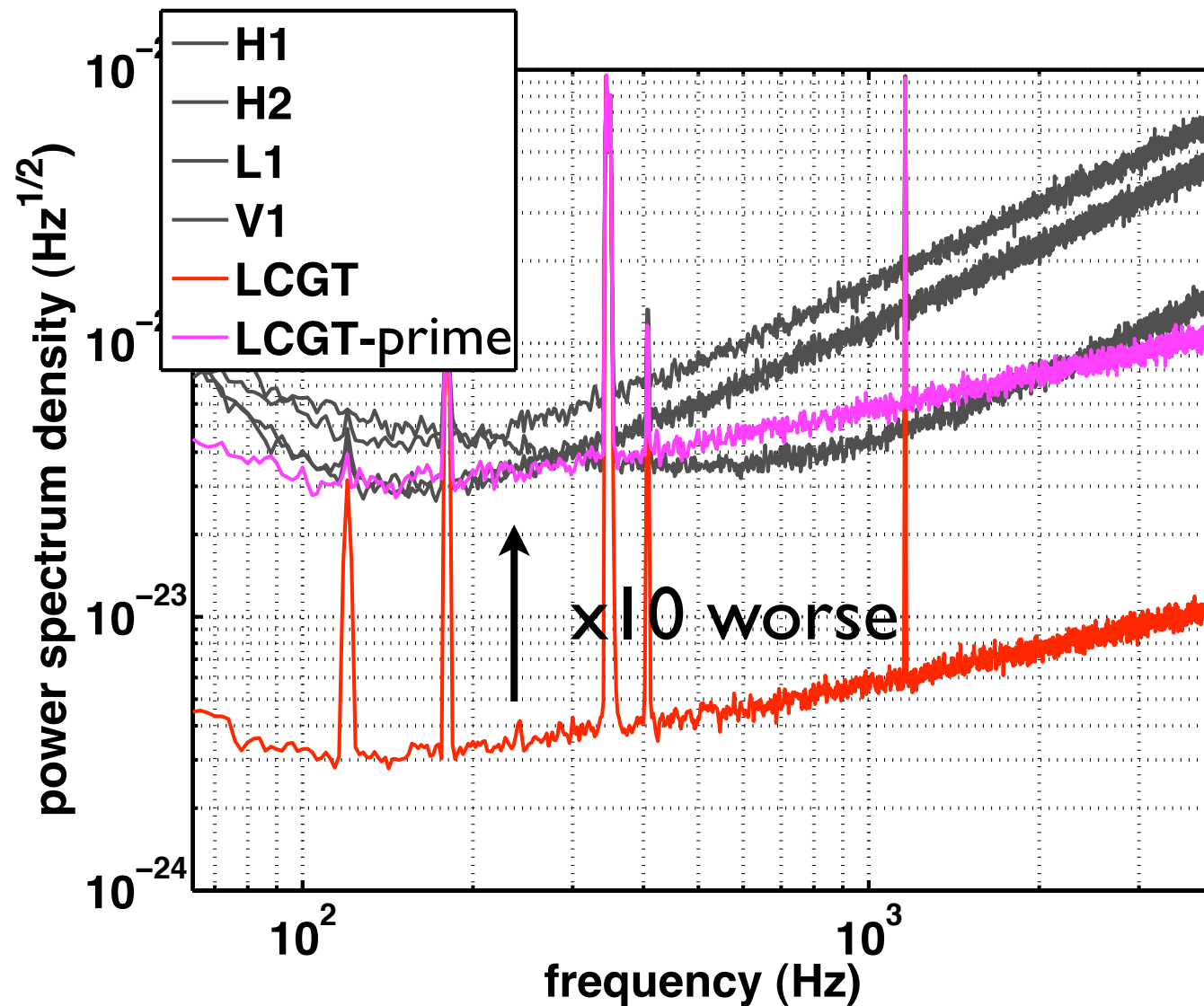
Injected signal:

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



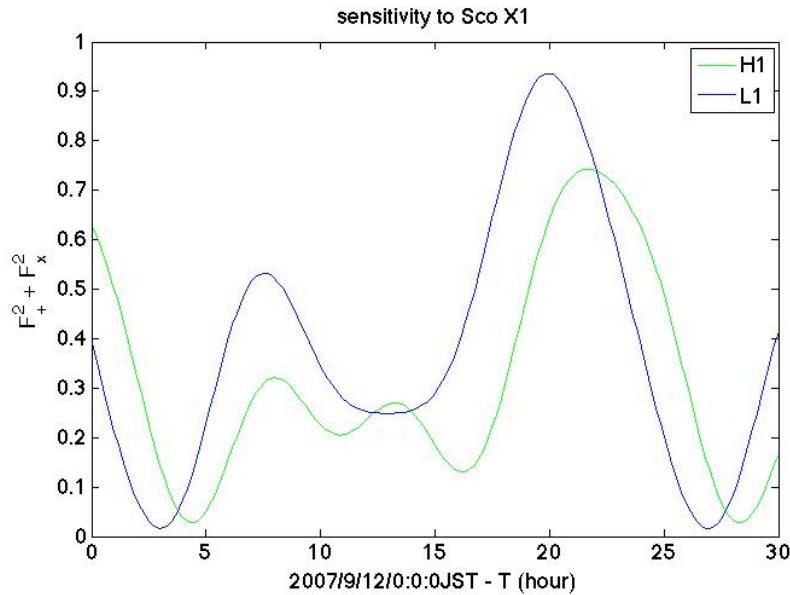
Monte Carlo Simulation

To focus on importance of detector location, use sensitivity $\times 10$ worse than the design sensitivity of LCGT.



Sensitivity to Sco X-1

HI - LI



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:

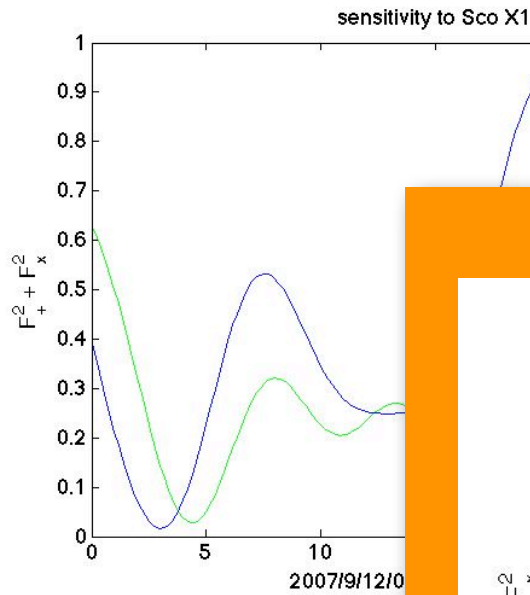
hour from 0:00(JST), today

Due to the rotation of the earth, the response function is 24hr-periodic function.

LIGO only network has sensitivity at the region $T = 17-24$ hr.
However, $T=2-5$ hr, $10-16$ hr, the sensitivity worsens

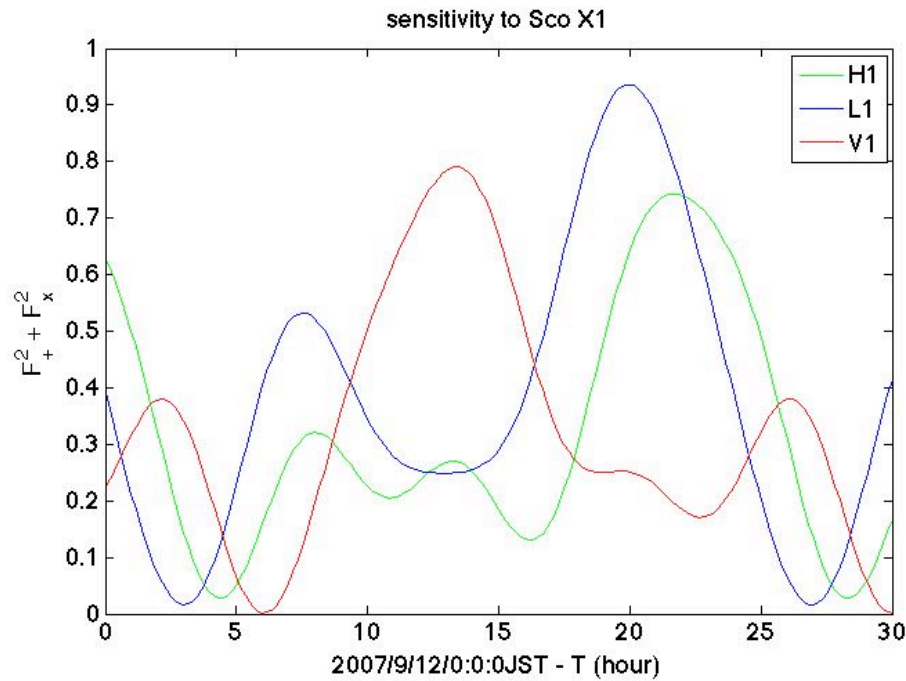
Sensitivity to Sco X-1

H1,H2 - L1



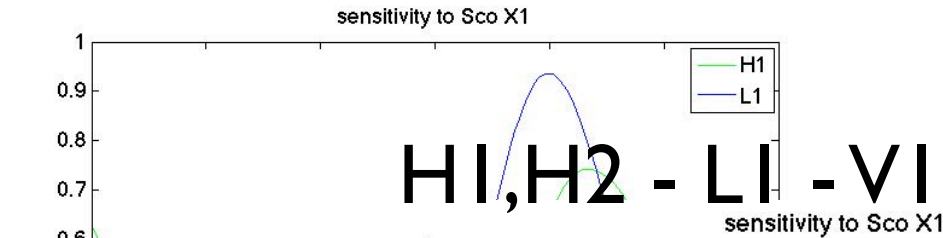
Adding VIRGO to the LIGO network, the sensitivity at the region $T=10-16$ hr is improved.

H1,H2 - L1 - V1



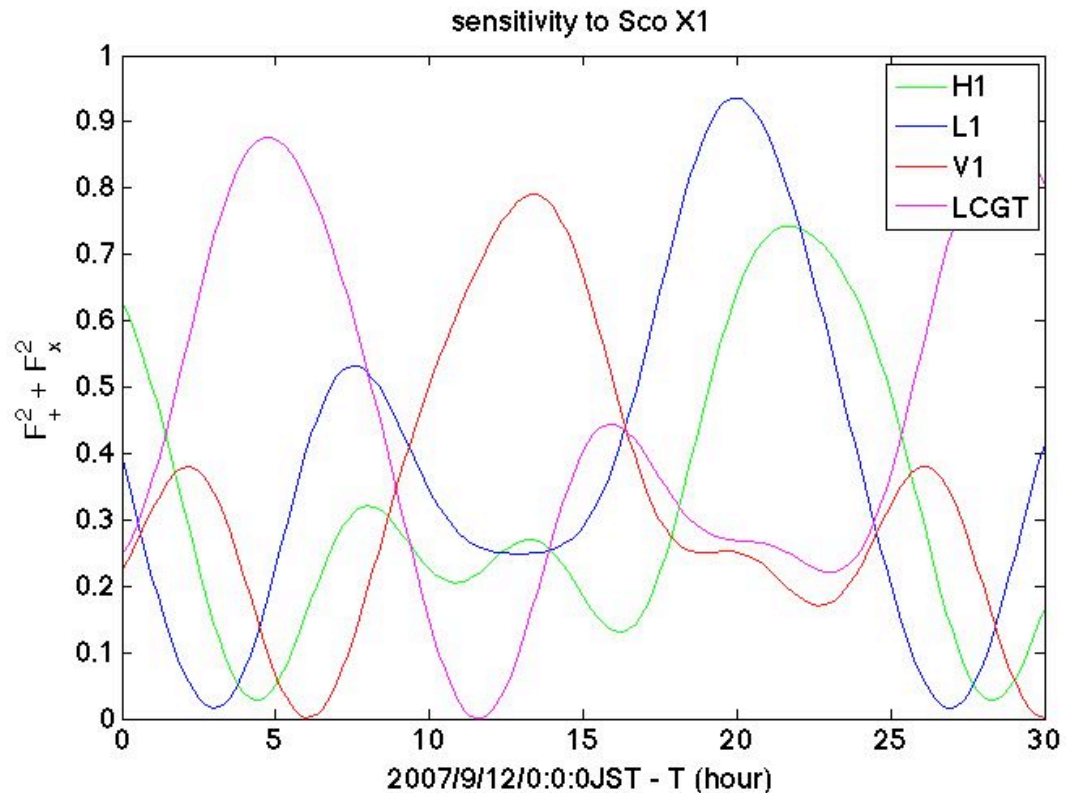
Sensitivity to Sco X-1

HI, H2 - LI



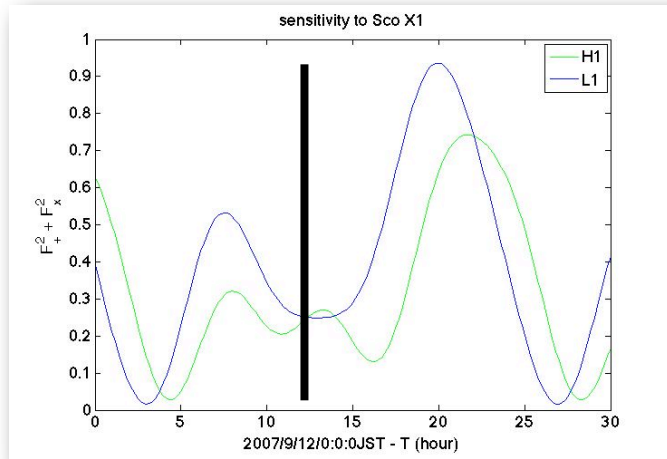
The network covers all region.

HI, H2 - LI - VI - LCGT

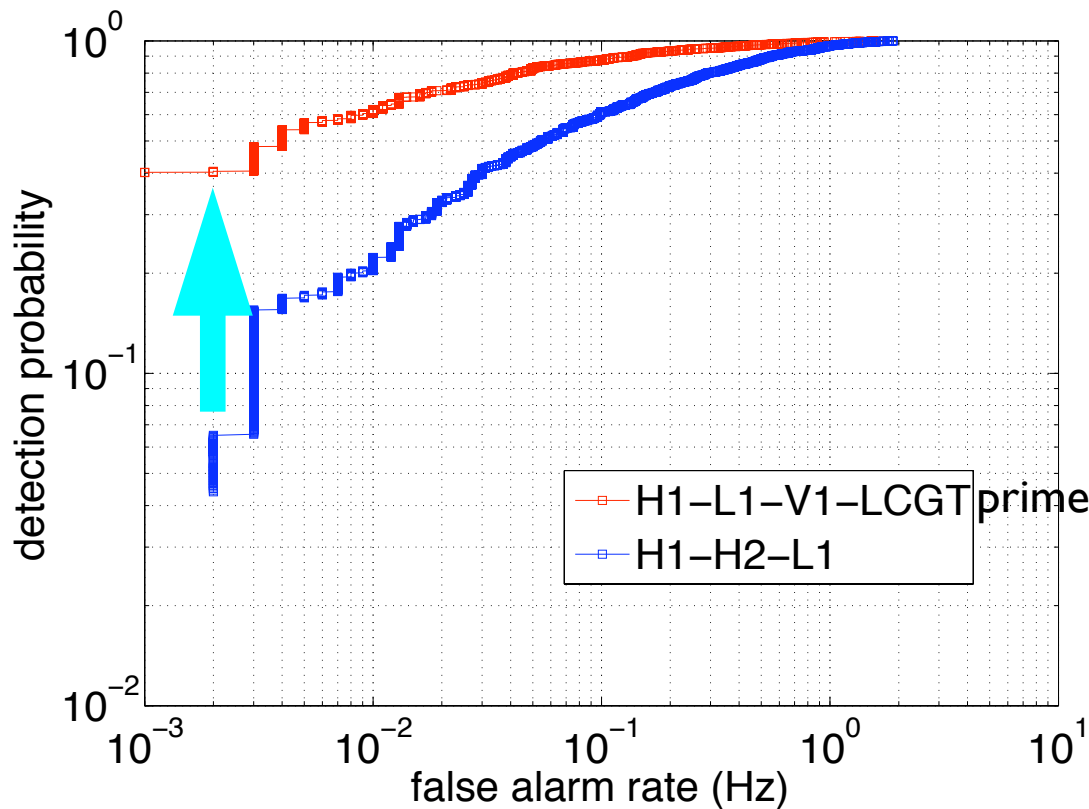
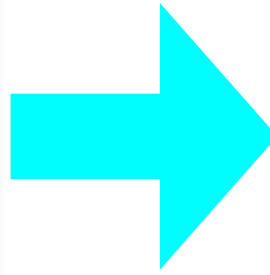
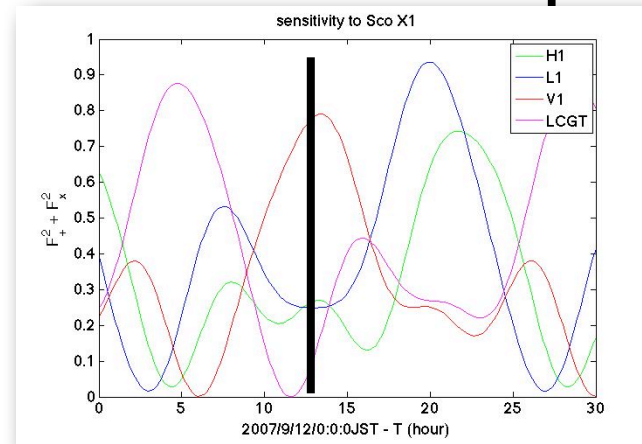


Detection efficiency

H1+H2+L1



H1+L1+V1+LCGT-prime



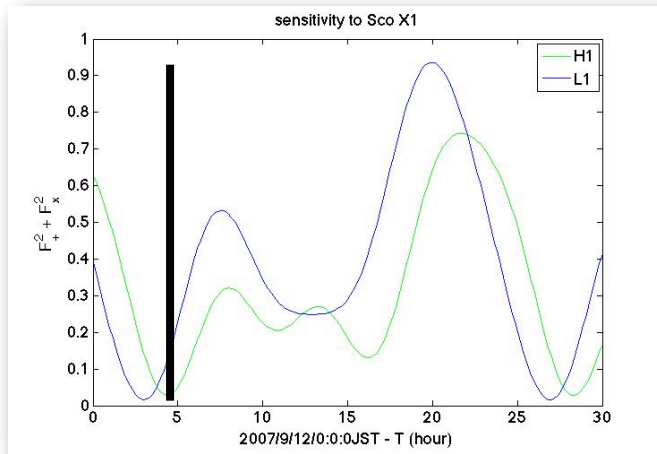
VIRGO compensate the low sensitivity region for LIGO network.

Detection probability
@false alarm rate 0.01Hz

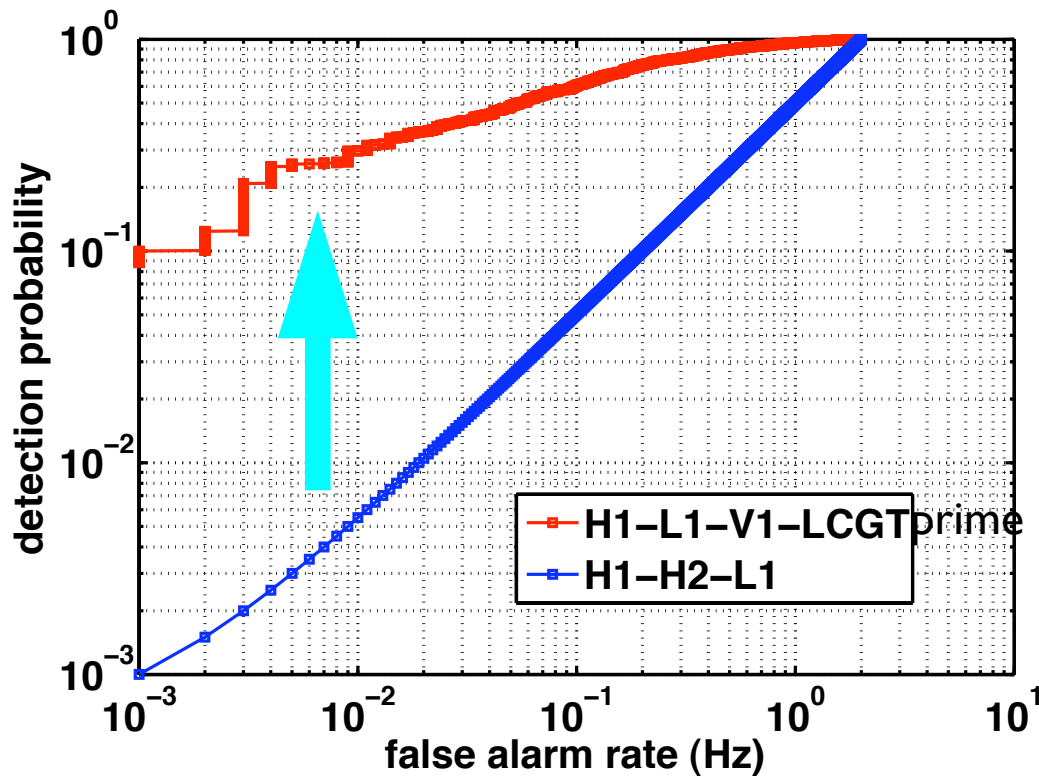
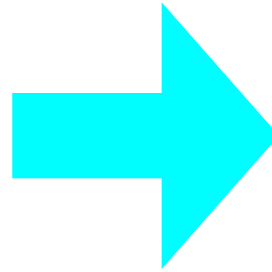
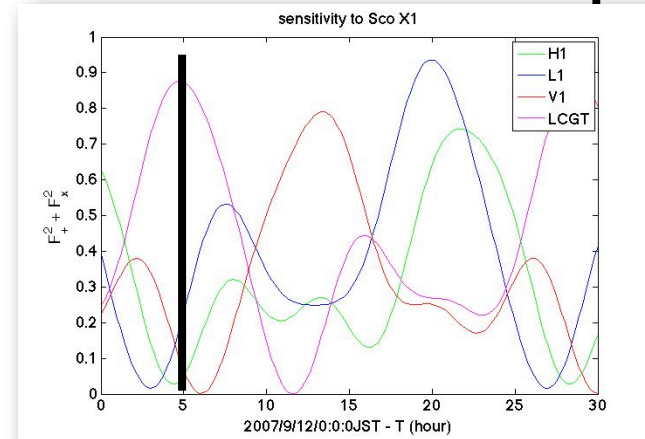
20% -----> 60%

Detection efficiency

H1+H2+L1



H1+L1+V1+LCGT-prime



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

Detection probability
@false alarm rate 0.2Hz

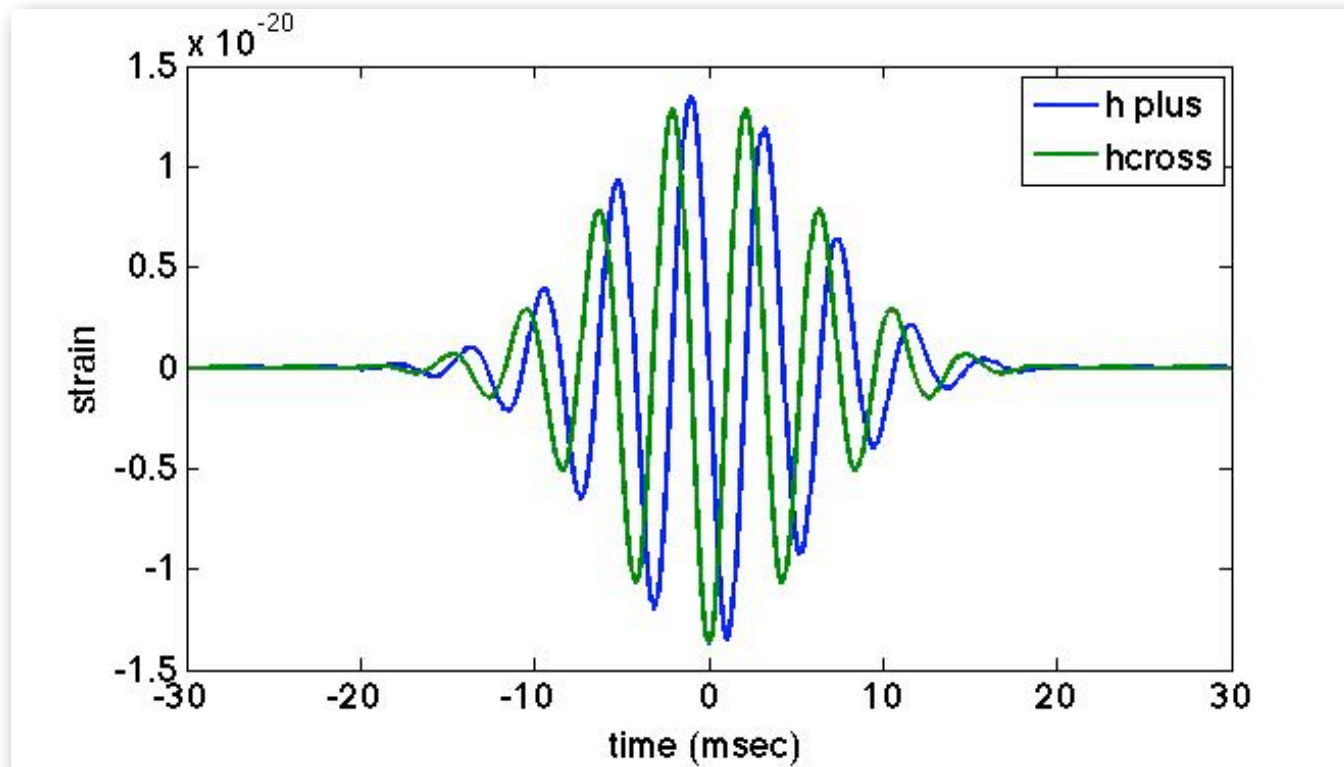
less 10% -----> 80%

Reconstruction of G.W. waveforms

Injected signal:

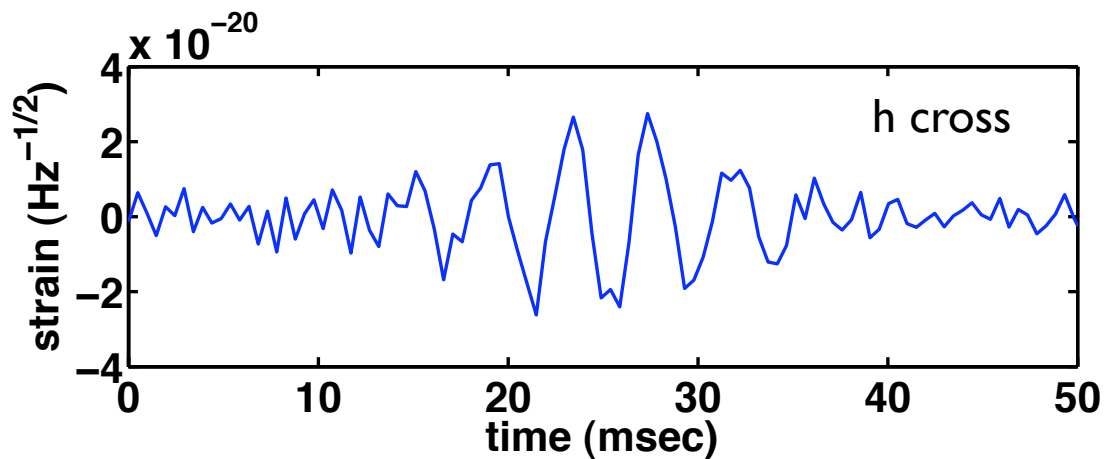
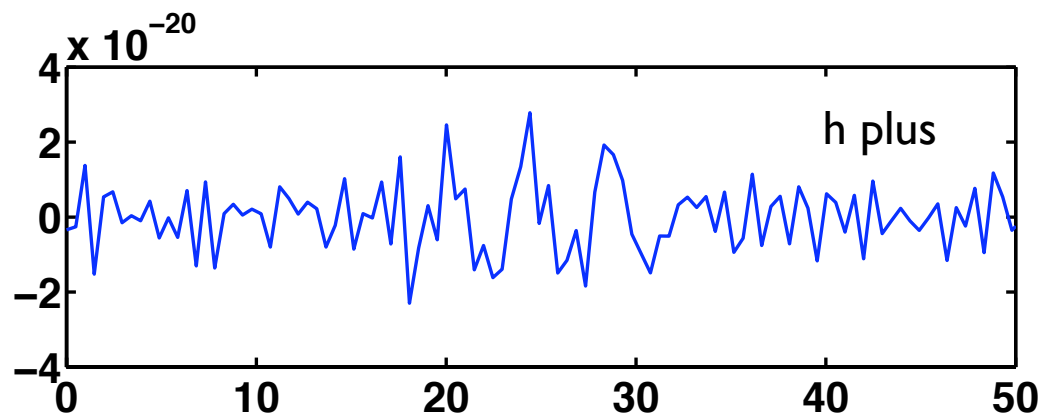
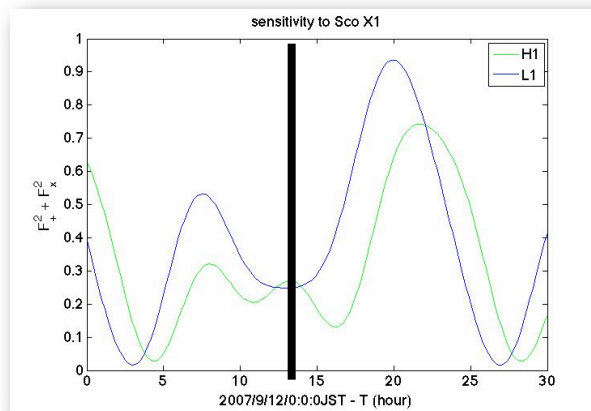
• Sine Gaussian of the central frequency 235Hz

• $h_{rss} = 2.8 \times 10^{-21} \text{ Hz}^{1/2}$



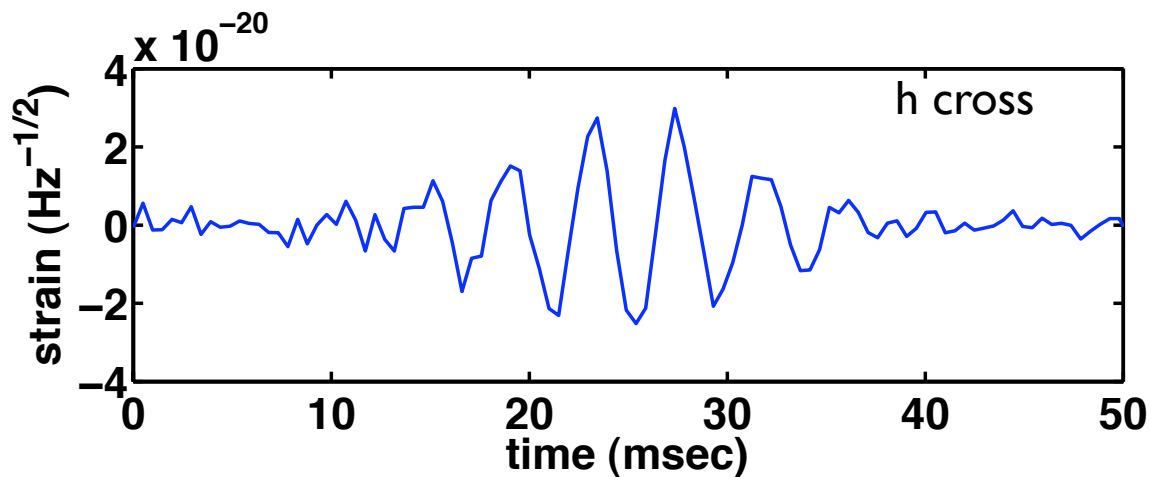
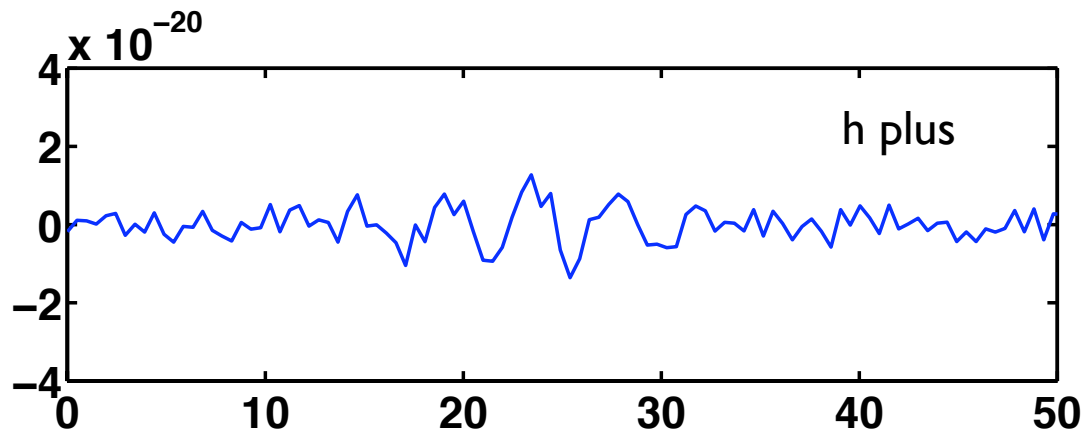
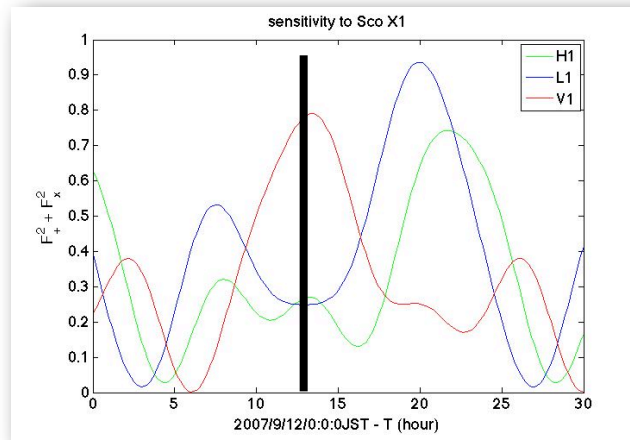
Reconstruction of G.W. waveforms

H1+H2+L1



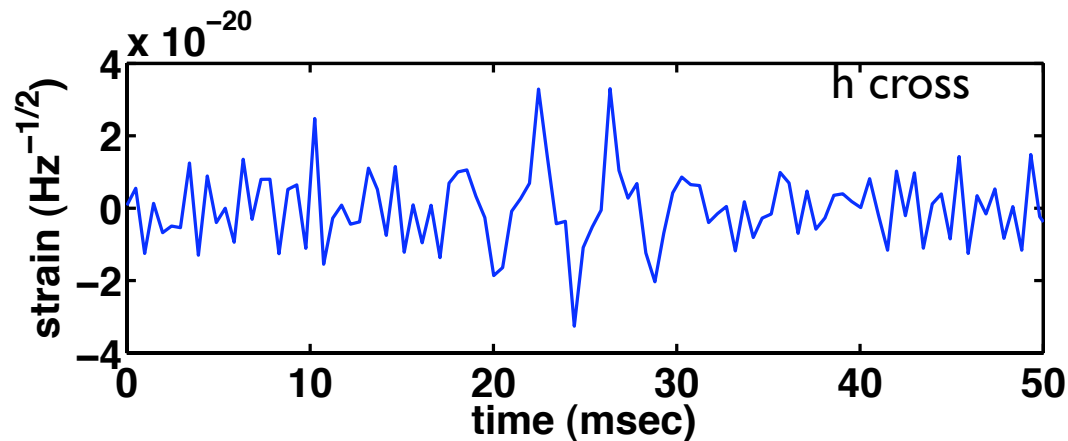
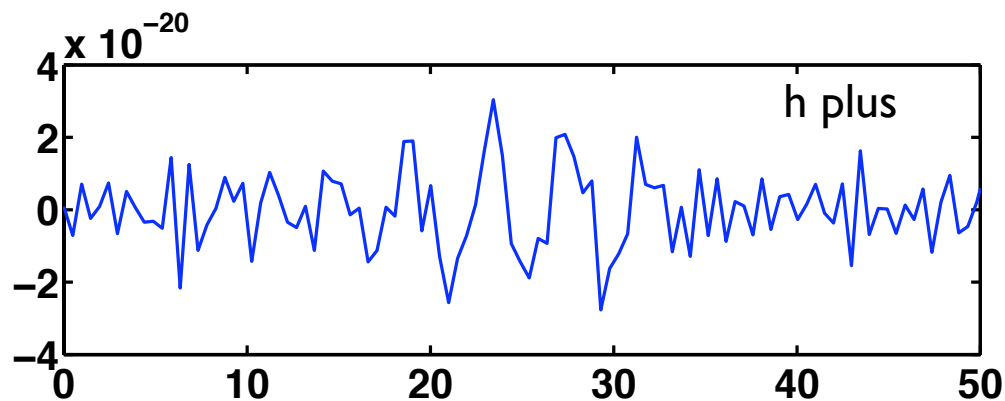
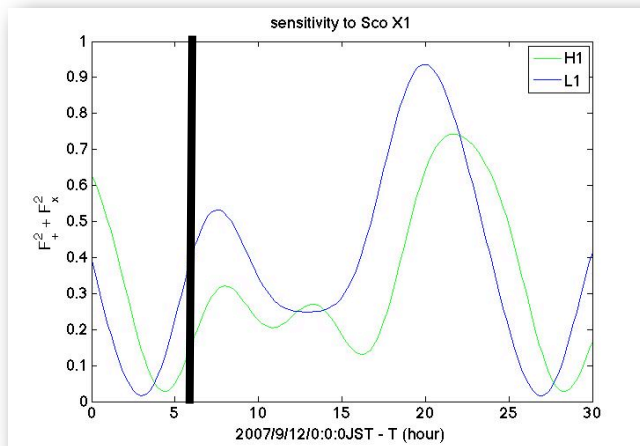
Reconstruction of G.W. waves

H1+H2+L1+V1



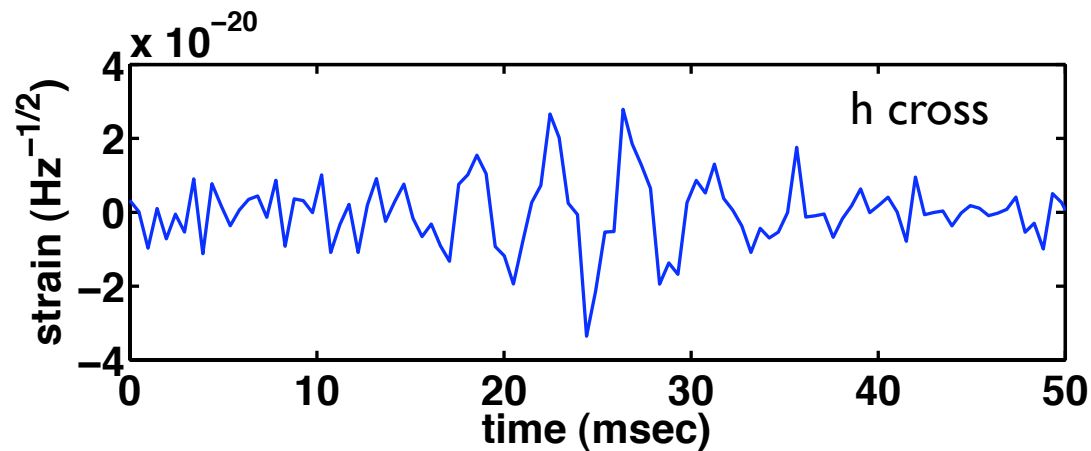
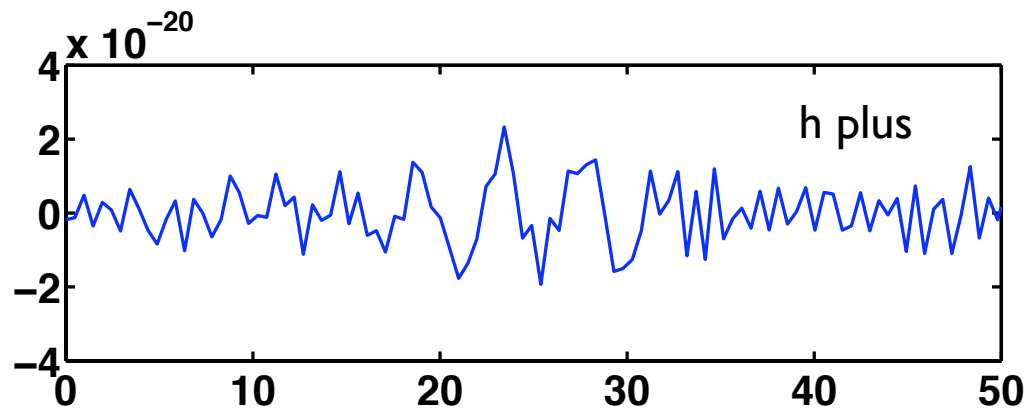
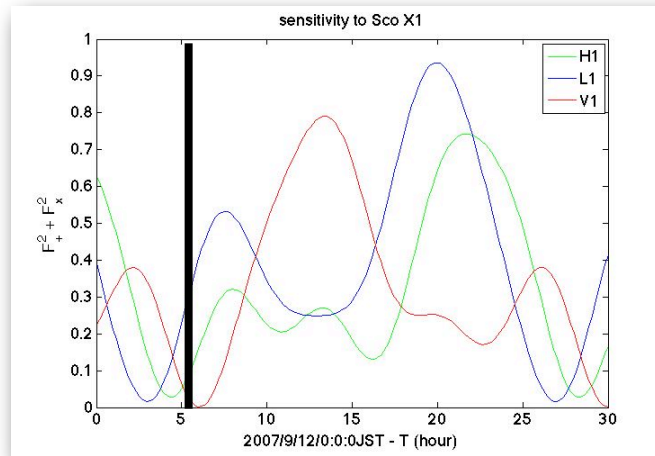
Reconstruction of G.W. waves

H1+H2+L1



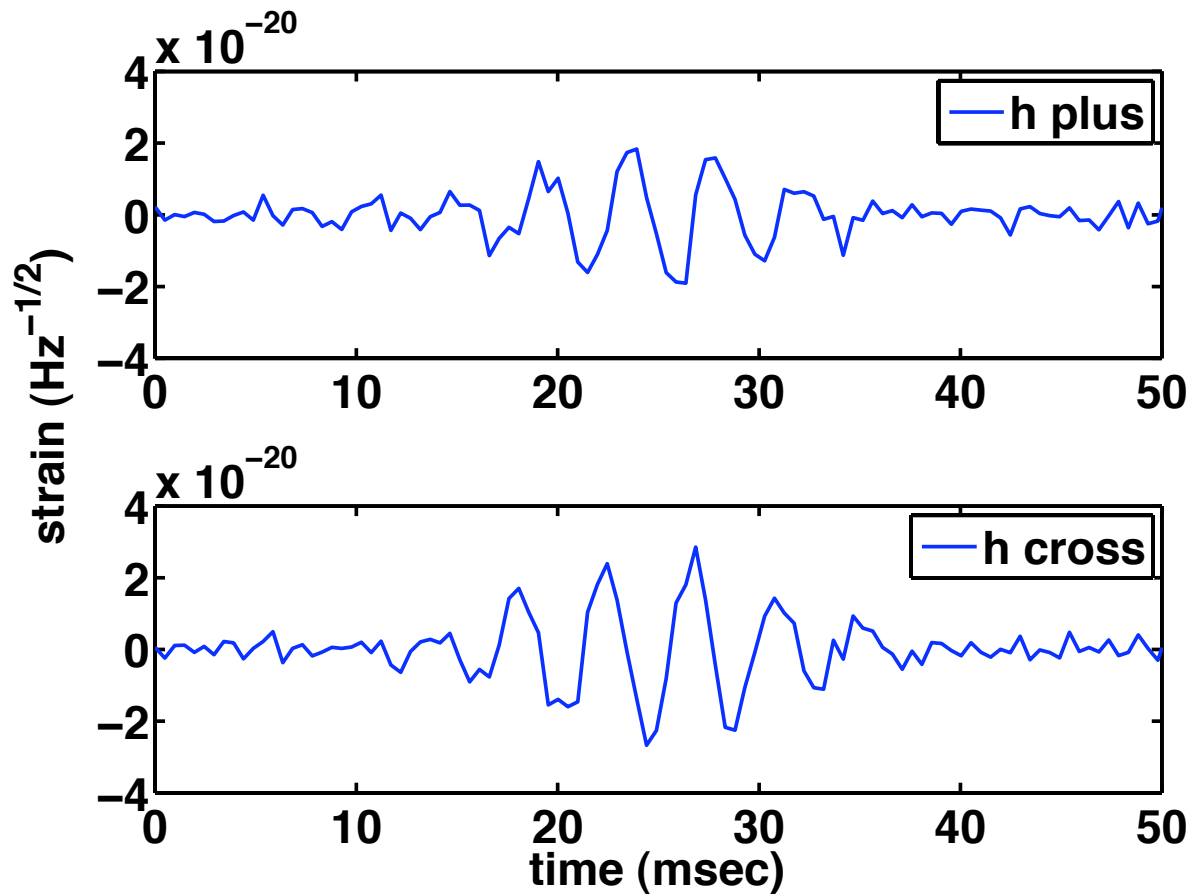
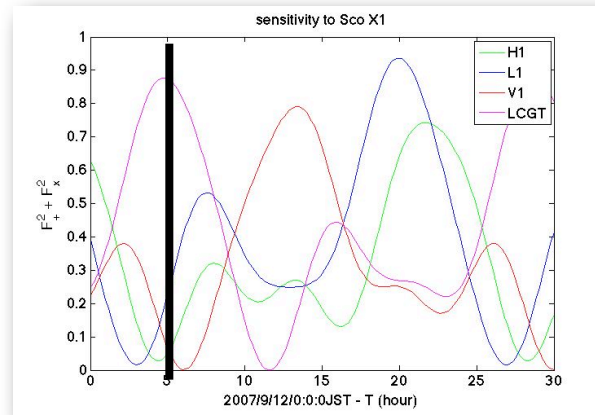
Reconstruction of G.W. waves

H1+H2+L1+V1



Reconstruction of G.W. waves

HI+LI+VI+LCGT-prime



G070616-00-Z

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.

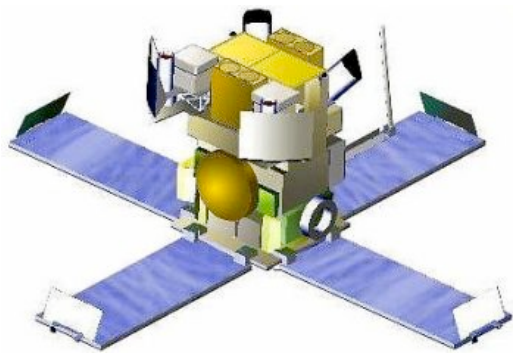
END

Triggered search

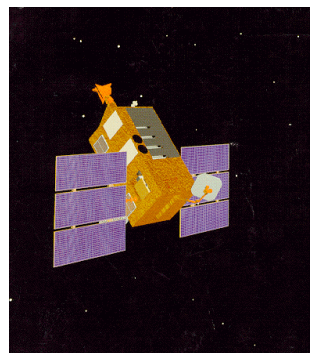


LIGO

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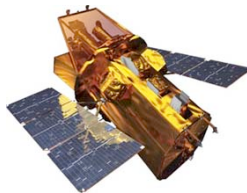
HETE



RXTE

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,



SWIFT



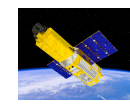
Chandra



Parkes

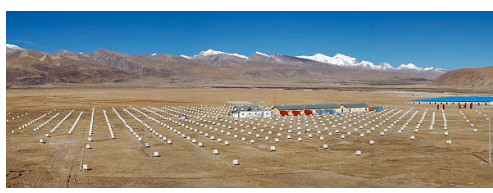


MXE-Newton



AstroE2

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TIBET

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AGASA

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SDSS

Gravitational wave detector network



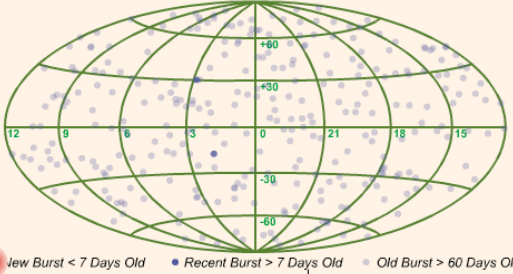
Analysis procedure

-- in case of GRB --

excellent GRB alert system

Gamma-ray Burst Real-time Sky Map

Help



Burst Details

Burst ID: GRB 070724A

Burst date: 2007/07/24

Burst time of day: (UTC) 06:53:50

Detecting Mission: Swift

Burst Description:

GRB 070724A had two peaks-- the first was 0.2 seconds long, and was so FRED (fast rise exponential decay), and the second started 14 seconds later, lasting for 14 seconds. The second peak had a more symmetric rise and decay curve. Although no optical afterglow was detected by Swift, a fading X-ray afterglow was seen, and it had several flares (small brightenings) as it faded.

A very faint near-infrared afterglow was detected using the Very Large Telescope (VLT) on 2007/07/24. It is shown in the accompanying image (it is Object # 1).
[Tell me more about this burst.](#)

Burst List

Burst ID	Date	Time	Mission	RA	Dec
GRB 070724A	2007/07/24	06:53:50	Swift	01:51:13.96	-18:35:40
GRB 070714A	2007/07/14	04:59:29	Swift	02:51:43.8	30:14:28
GRB 070707A	2007/07/07	16:08:40	INTEGRAL	17:52:11	-68:54:42
GRB 070704A	2007/07/04	20:05:57	Swift	23:38:53	66:14:52

<http://grb.sonoma.edu/>

Analysis procedure

-- in case of GRB --

excellent GRB

List of astronomical information and available data

GRB Name	GPS Time	R.A.	Declination	Detectors in Science Mode
051105	815207214.000	265.289	34.92	H2
051105B	815223963.000	9.477	-40.48	H2
051109	815533953.000	330.296	40.837	None
051109B	815560792.000	345.440	38.672	None
051111	815723994.000	348.157	18.367	H2
051113	815930568.000	187.222	-26.391	H2
051114	815976703.000	226.274	60.150	H1,H2
051117	816259893.000	228.405	30.870	H1,H2
051117B	816268987.000	85.225	-19.245	H1,H2,L1
051127	817135616.000	223.736	51.340	H1,H2,L1
051210	818228794.000	330.197	-57.634	H1,H2
051211	818304618.400	104.054	32.679	H1,H2,L1
051211B	818373957.000	345.688	55.079	H1,H2,L1
051213	818493197.000	252.123	-59.207	H1,H2,L1

GPS time

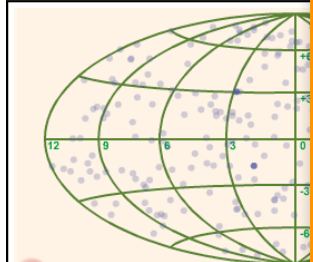
sky position

detectors on science mode

<https://gravity.psu.edu/~psurg/grbs/grblist.html>

Gamma-ray Burst Real

Help



Burst List

Burst ID	Date	Time	Sw
GRB 070724A	2007/07/2410:53:50	Sw	
GRB 070714A	2007/07/1404:59:29	Sw	
GRB 070707A	2007/07/0716:08:40	IN	
GRB 070704A	2007/07/0420:05:57	Sw	

<http://>

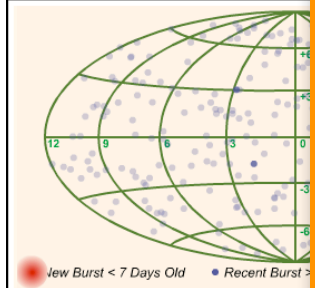
Analysis procedure

-- in case of GRB --

excellent GRB

Gamma-ray Burst Real

Help



Burst List

Burst ID	Date	Time	SW
GRB 070724A	2007/07/24	10:53:50	Sw
GRB 070714A	2007/07/14	04:59:29	Sw
GRB 070707A	2007/07/07	16:08:40	IN
GRB 070704A	2007/07/04	20:05:57	Sw

GRB No
051105
051105E
051109
051109E
051111
051113
051114
051117
051117E
051127
051210
051211
051211E
051213

http://

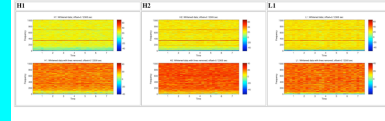
https://gr

```
Terminal — ssh — 40x5
>>
>>
>>
>>
>> RIDGEtrigg('GRB070201')
```

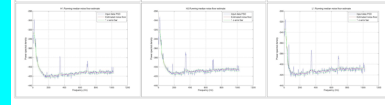
OUTPUT OF RIDGE PIPELINE ON Btriple-20070727

```
GPS time = 86607919 - 86607949
UTC time = 2007-07-27 21:29:19 UTC
TRIP ID = Btriple
Station = 2
Antenna = A
AntennaType = 30
AntennaRad = 30
AntennaOff = 0.2
MagGain = 0.2
AntennaType = 30
AntennaType = 30
More details about these parameters available here:
Link to ridge report for file: link
```

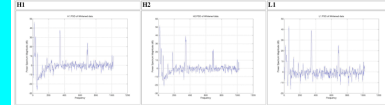
Spectrograms before and after data conditioning



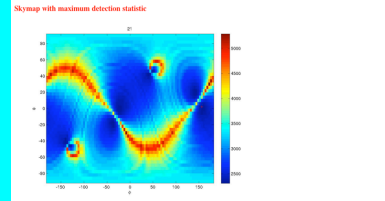
Median noise floor estimate



PSD of whitened data

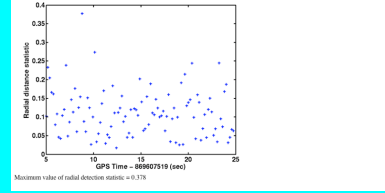


PSD after the stage whitening H1 H2 L1



All other sky maps can be found [here](#).

Plot of Detection Statistic

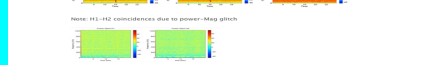


Glitch at gps time 872751329.031

Analysis overview
 Around GPS time 872751329.031 UTC, a significant glitch, which has an L1-112 coincidence with an L1, was detected. We analyzed the data around the time using RIDGE pipeline.
 The analysis data is H1, H2, L1. L1, L2. We use the L1 data for analysis.
 The data analyzed is 10 sec (GPS time 872751314 - 872751324). Every data set is stationary as well as for the spectrogram of the data conditioning before, and the glitch is H1, H2, L1.
 The glitch is the registered sky map for the glitch data not change from typical sky maps from the maximum value of the sky map is over 10 times larger than that of the typical sky maps in the region. One possibility is a power map glitch (see plot in one of the conditioning) here power map glitches are due to site-wide magnetic disturbances, they have a high coincidence, and they don't change the pattern of a likelihood sky map but have a high maximum value of the map. This feature is related to the glitch. The difference between this glitch and power map glitch is that, the typical central frequency of the power map glitch is around 0.15 on the other hand, the central frequency of this signal is bounded (interacted by Black Normal, see the link below). Other possibilities are a hardware glitch (see link, etc).

Event display for this is in the web page <https://glitch.data.gsi.nasa.gov/cgi-bin/plotter/generic/plotter.pl?glitch=872751329.031>

The data conditioning



Here, H1-112 coincidences due to power-map glitch



The detection static



The likelihood sky map corresponding to the glitch



Ref. a typical sky map around this time

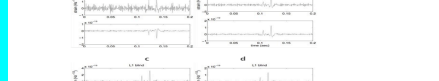


sky map of the power-map glitch

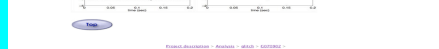


The reconstructed signals where L1 becomes blind

Antenna pattern for H1, L1



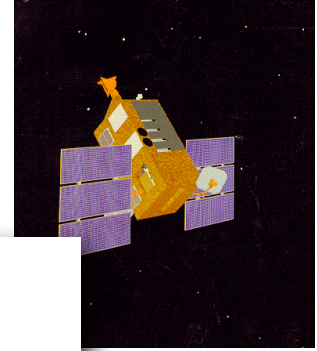
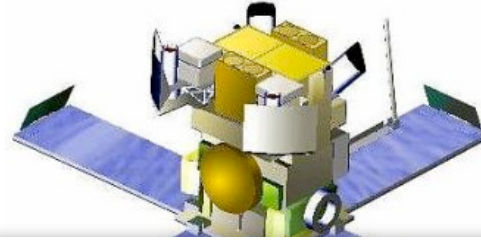
Reconstructed signals



Triggered search



+

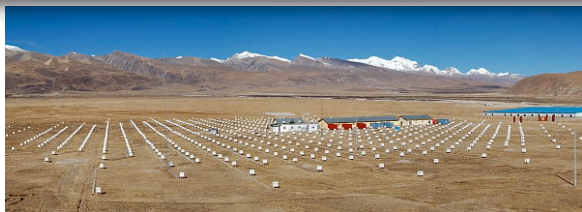


RXTE

- The detection of G.W. can be enhanced by electro-magnetic observations:
GRB, SGR, Pulsar glitch, LMXB, Supernova
- Particularly, pulsar glitches may be predicted theoretically
--> can organize optimal observation.
- Detection efficiency can become increased
 - Time coincidence -- specify data to analyze
--> sophisticated analysis
 - Source location
accurate recovery of waveforms
--> extract astrophysical parameters



arkes



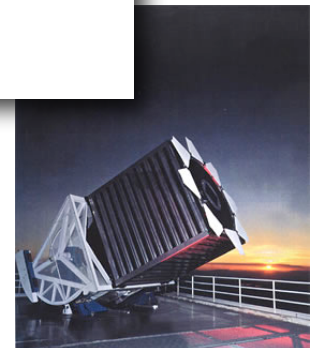
G070616-00-Z TIBET

,



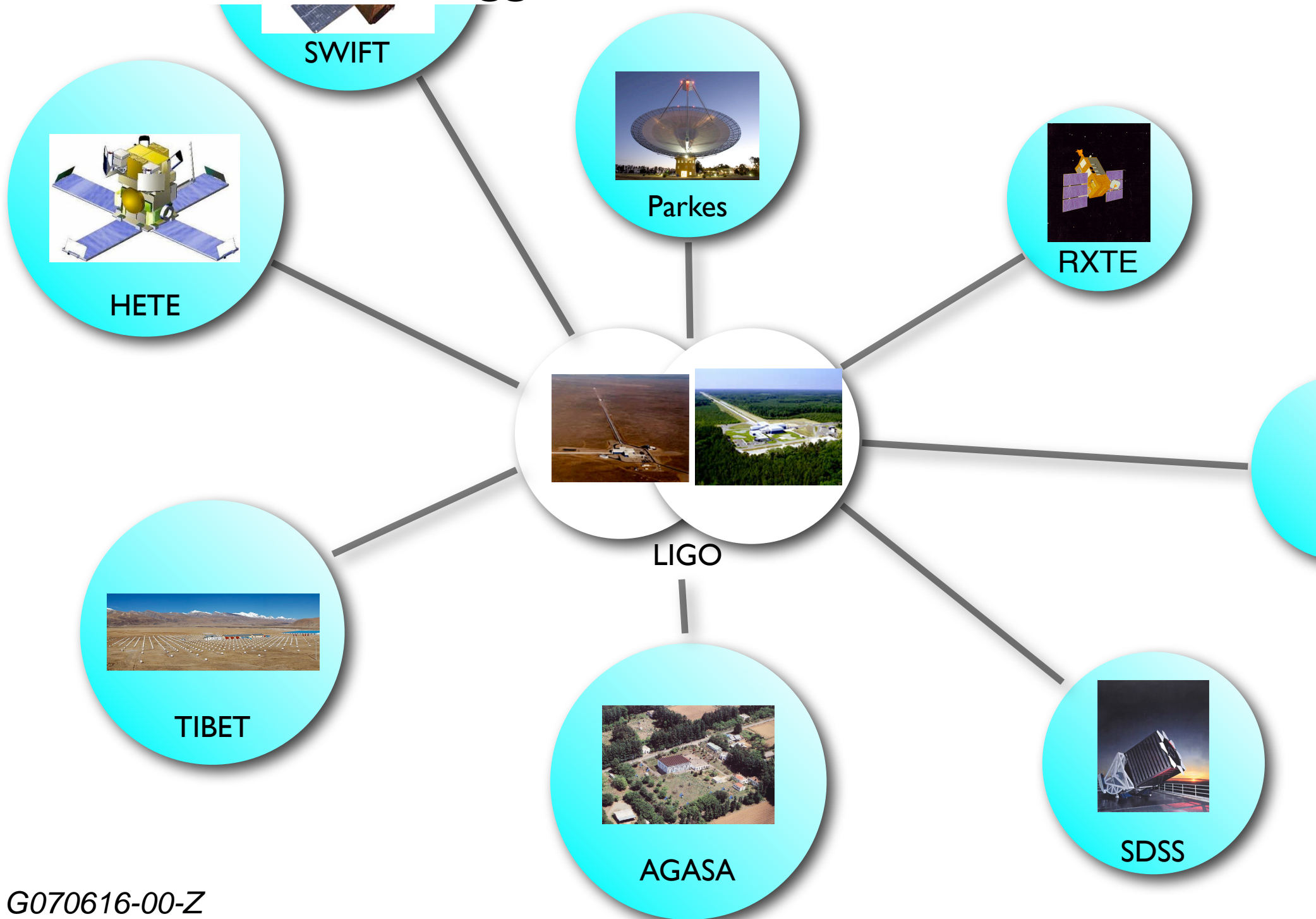
AGASA

,



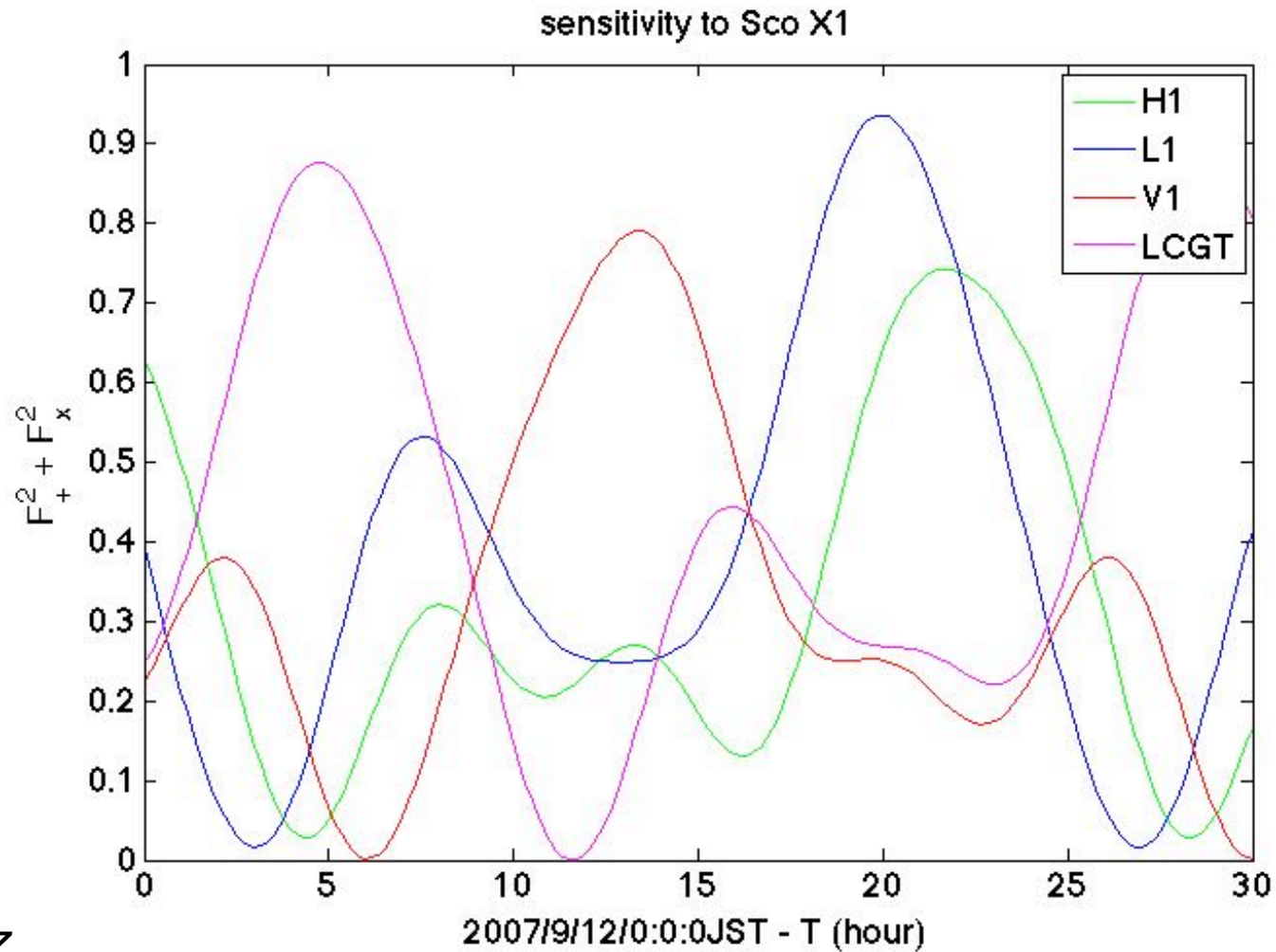
SDSS

Triggered search



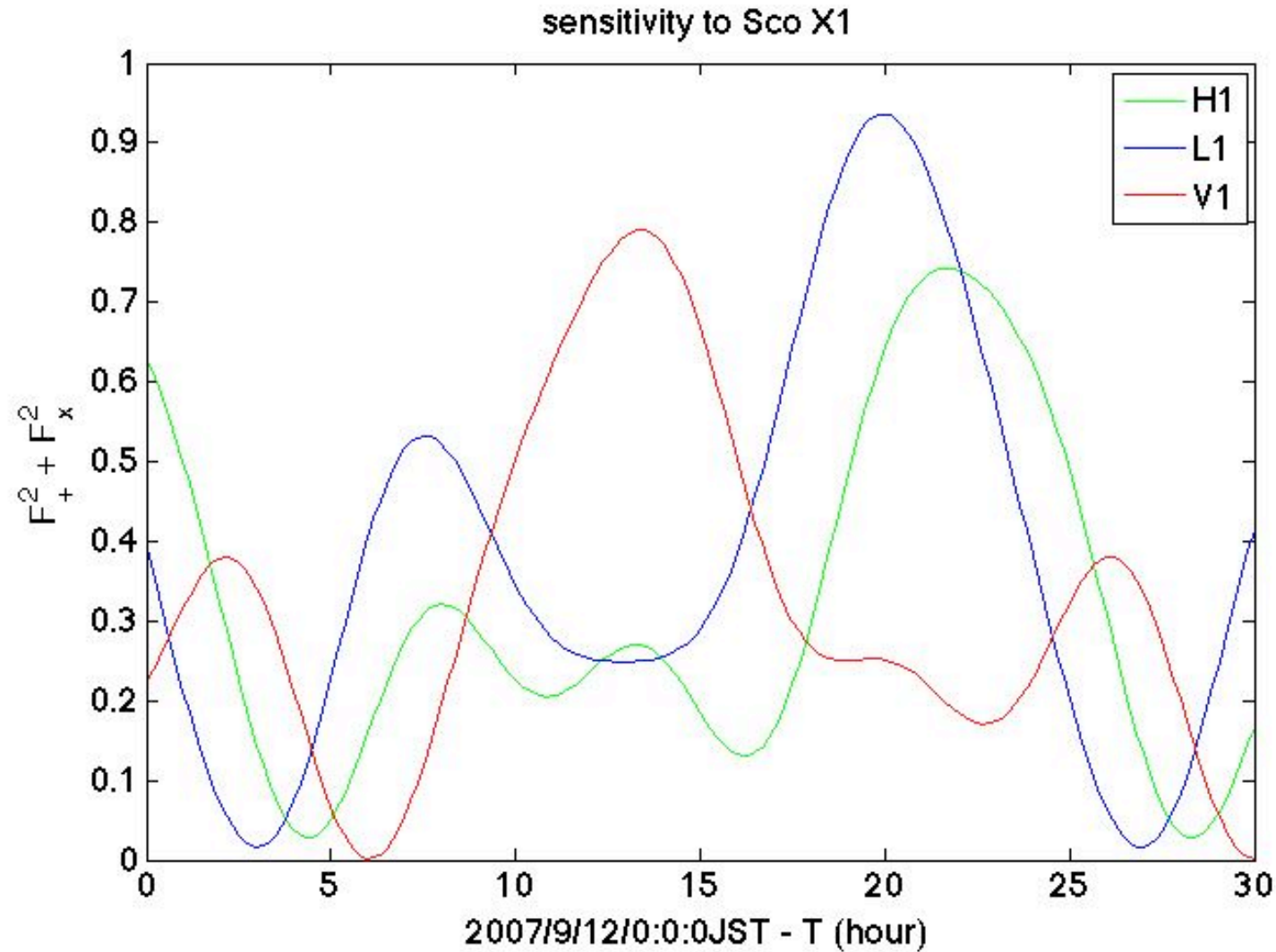
Sensitivity to Sco X-1

HI - LI - VI - LCGT

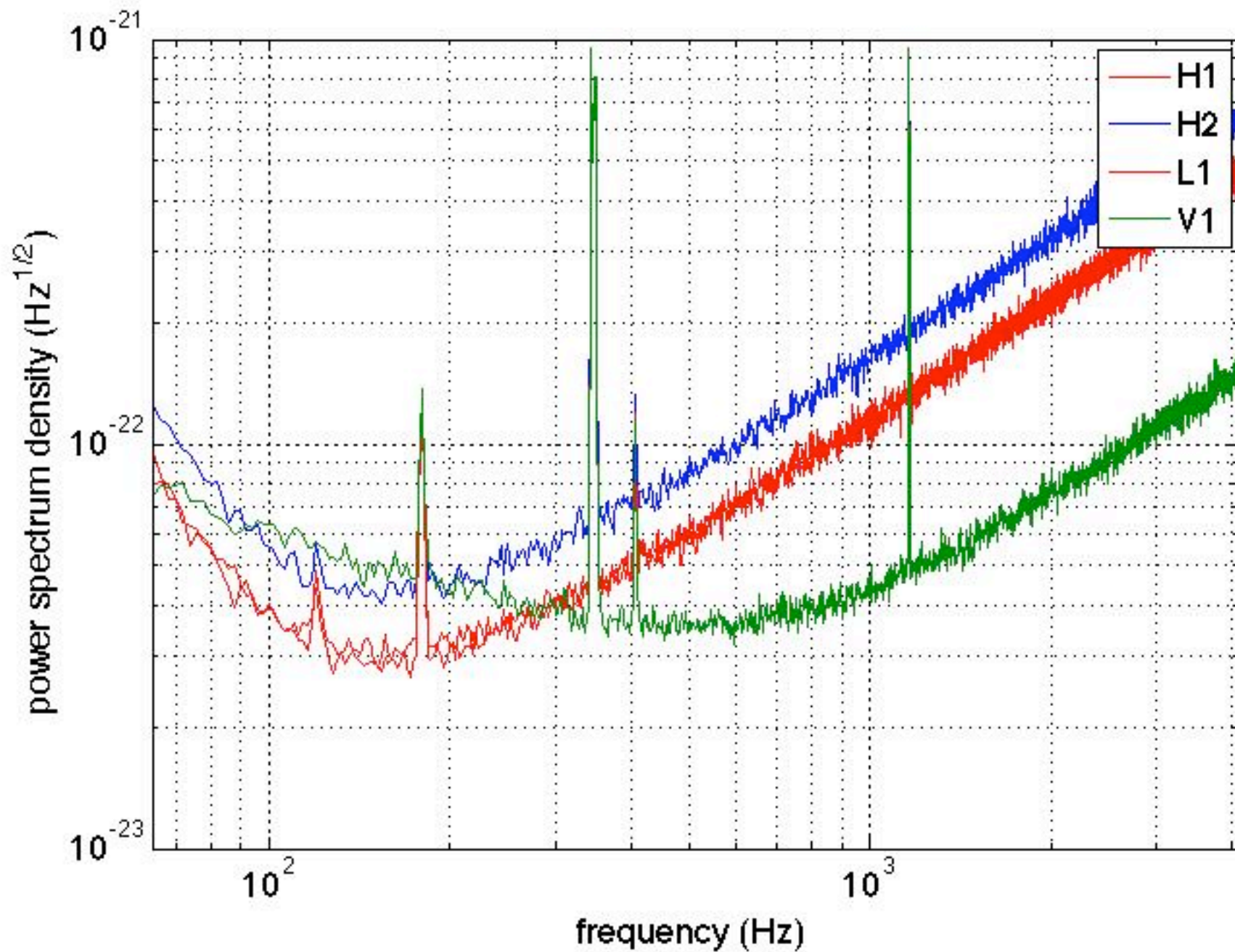


Sensitivity to Sco X-1

HI - LI - VI

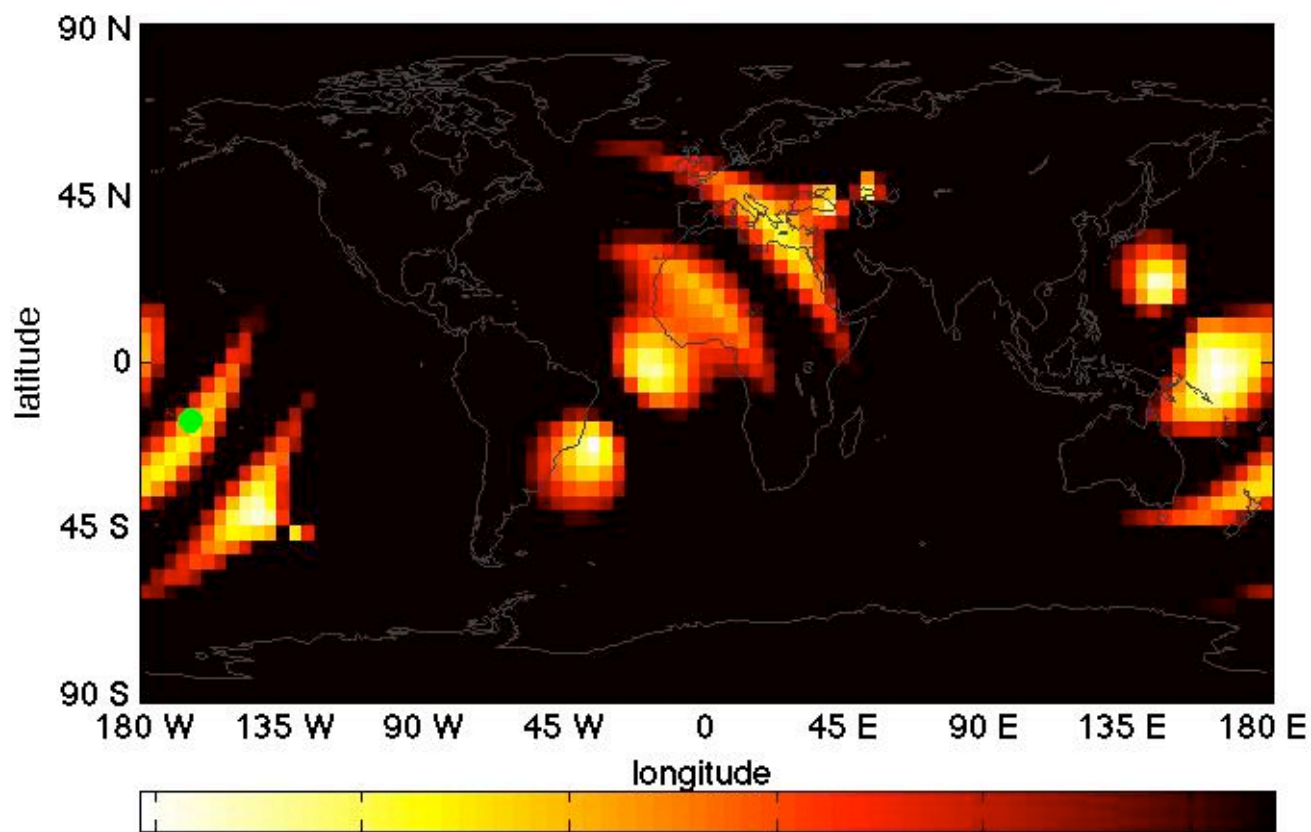
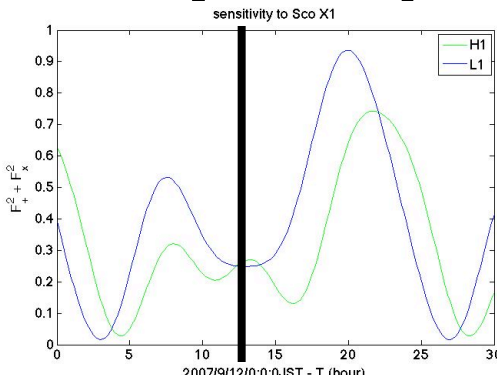


Simulated data



skymap

HI+H2+LI

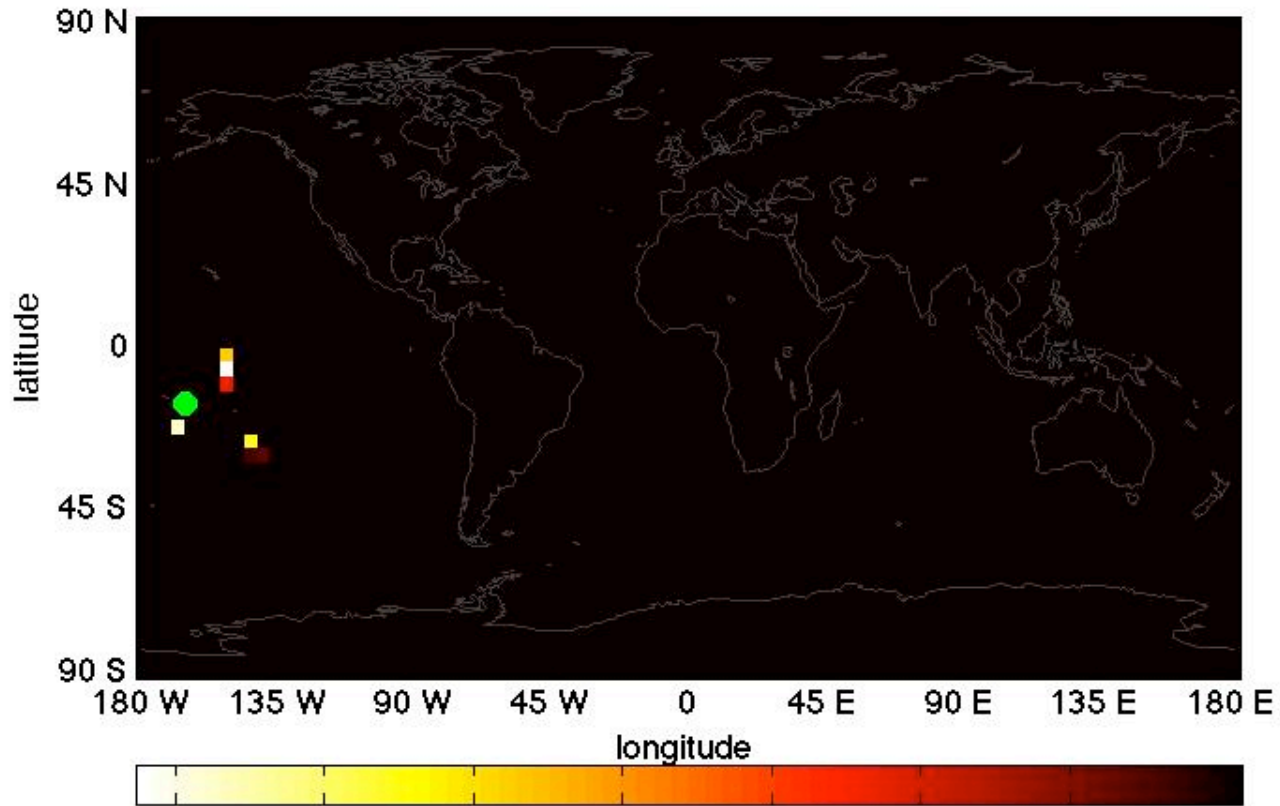
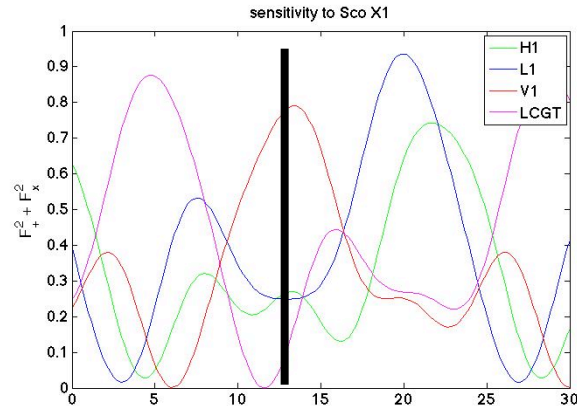


minimum of skymap

1.2 x minimum of skymap

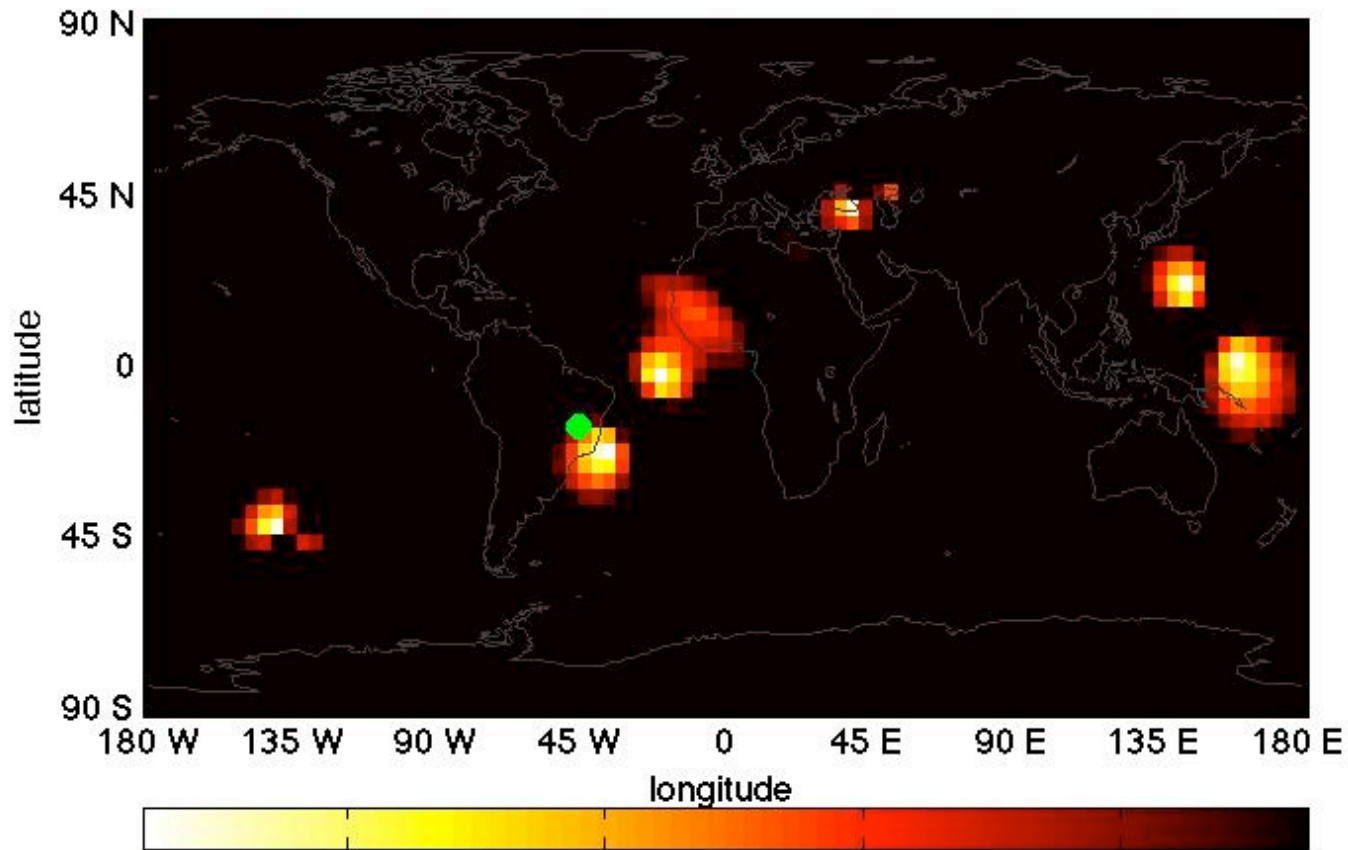
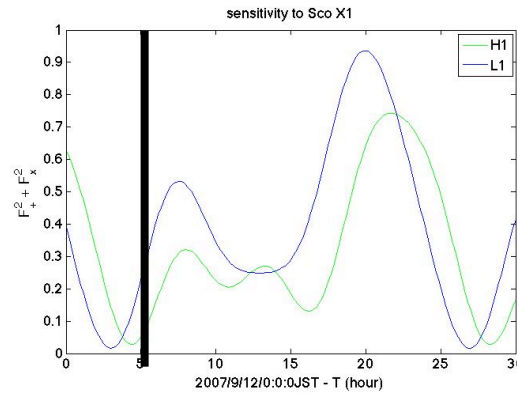
skymap

HI+LI+VI+LCGT



skymap

H1+H2+L1

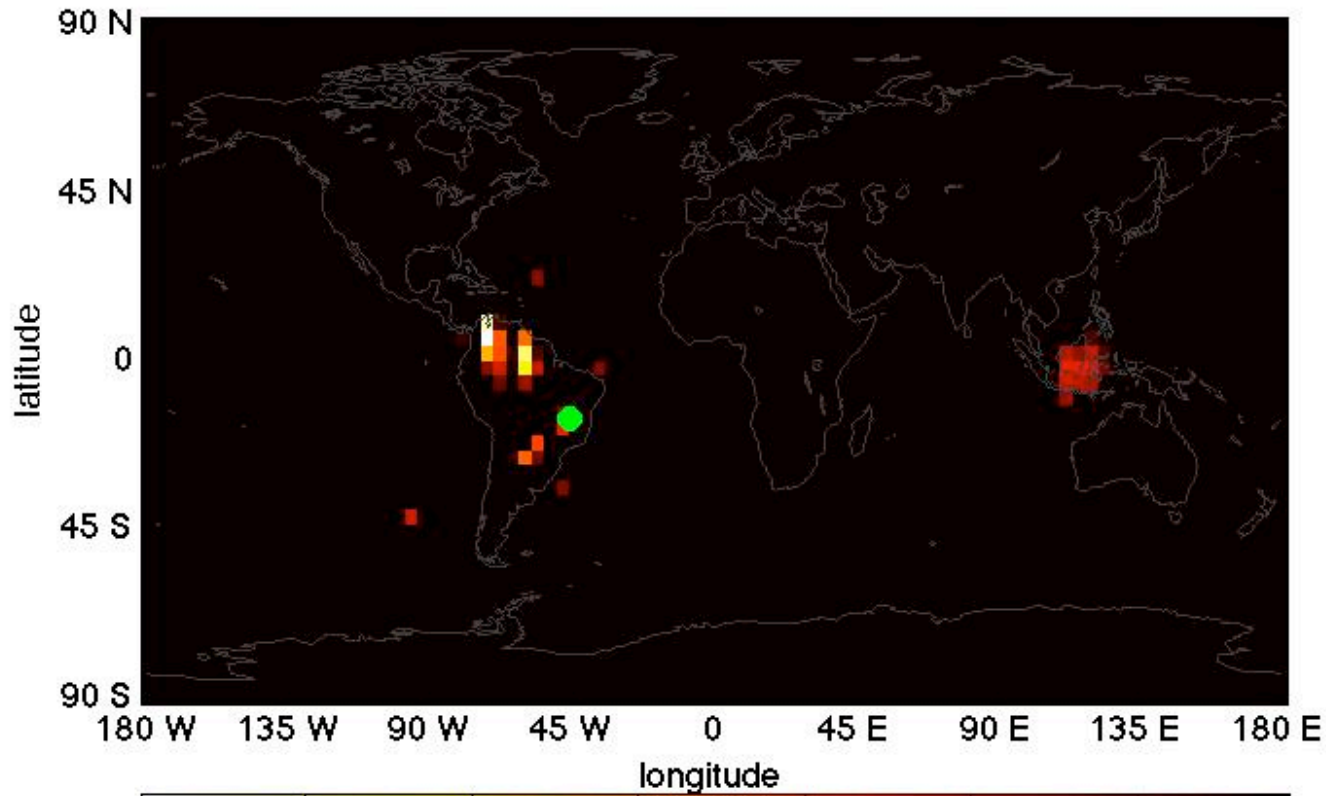
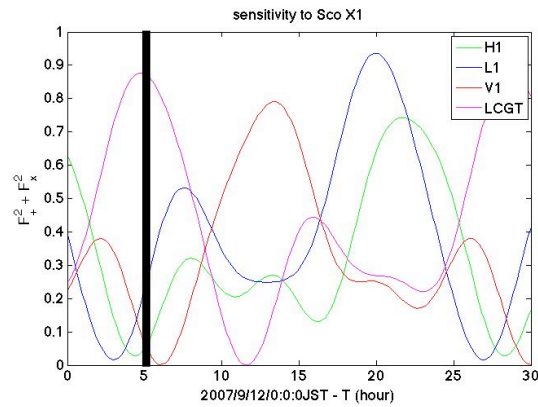


minimum of skymap

1.2 x minimum of skymap

skymap

HI+LI+VI+LCGT



minimum of skymap

1.2 x minimum of skymap