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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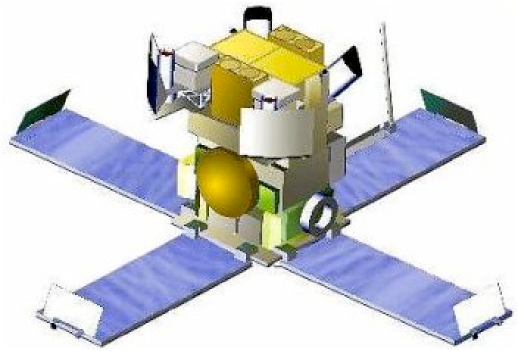

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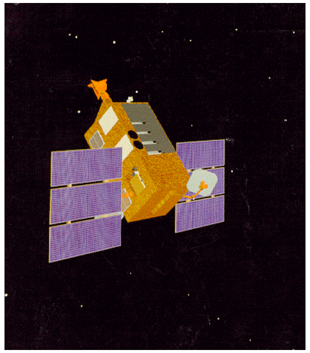

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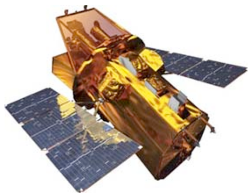
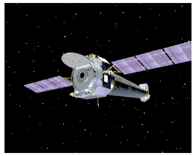


SWIFT

Parkes

XMM-Newton



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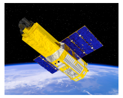

AstroE2

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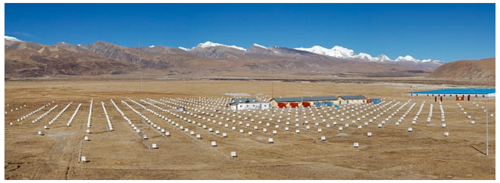

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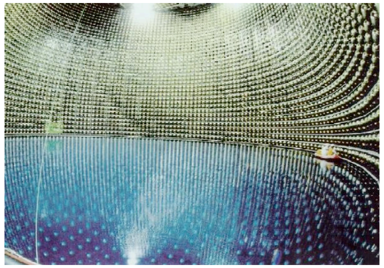

SuperKamiokande

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SDSS

Triggered search

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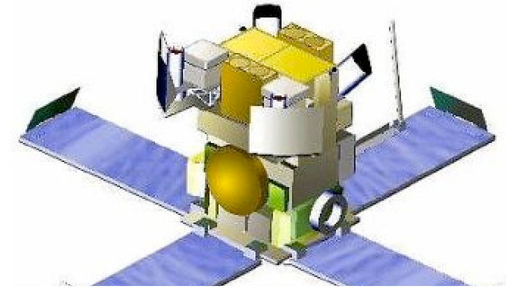

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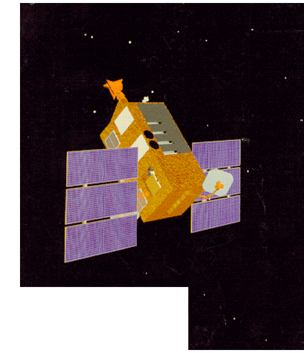

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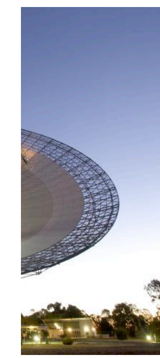

- High energy events are potentially G.W. sources for detection.
- The detection of G.W. can be enhanced by coincidences with electro-magnetic observations:
  GRB, SGR, Pulsar glitch, LMXB, Supernova
- Particularly, when a pulsar glitch is observed, we may predict when it occurs next theoretically(Ito(1983))

  --> 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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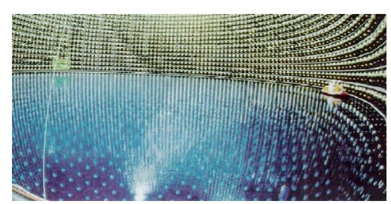

SuperKamiokande

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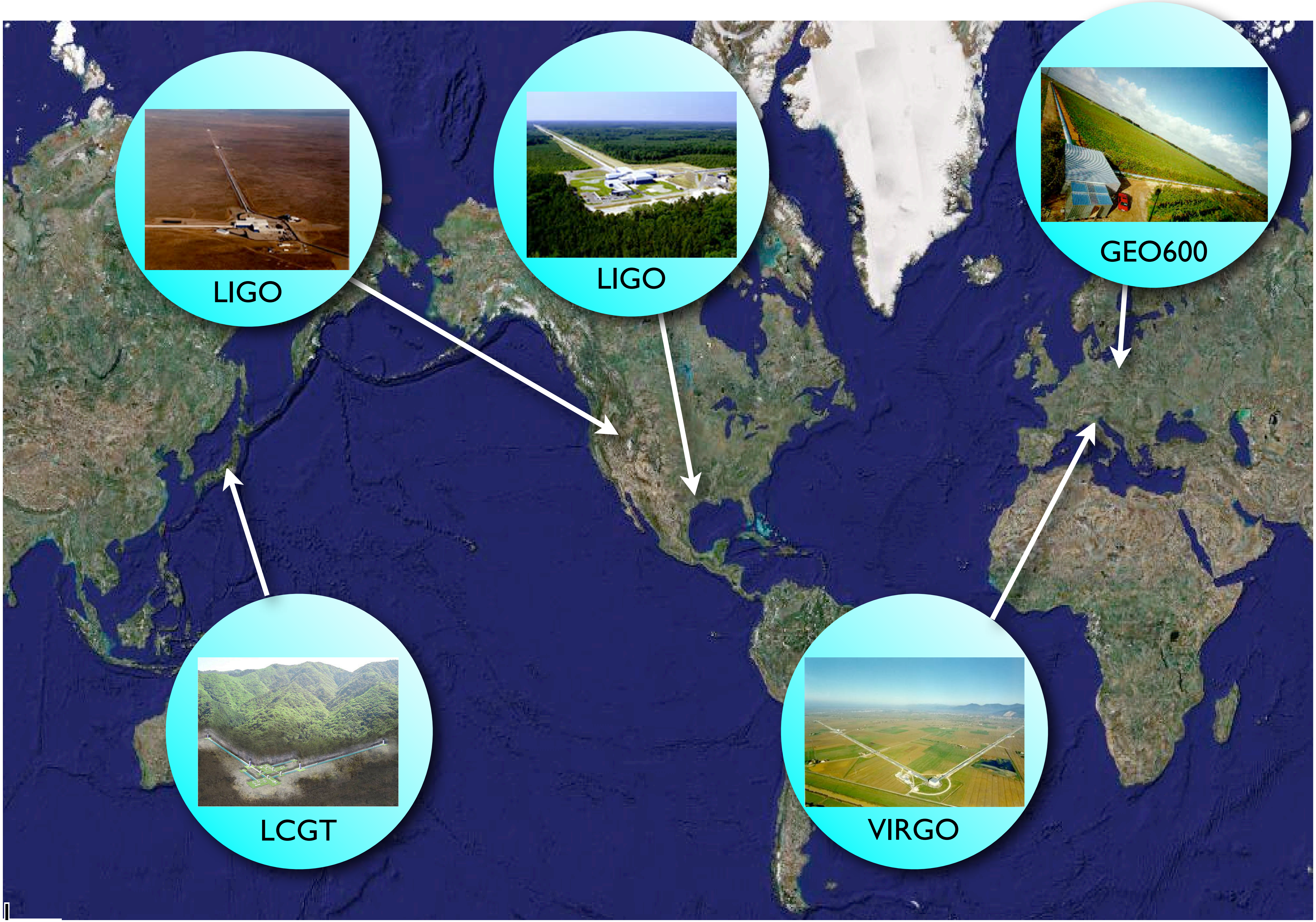
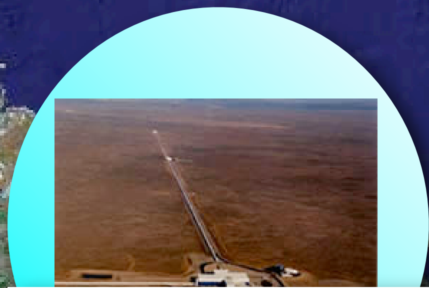
SDSS

Gravitational wave detector network



Gravitational wave detector network



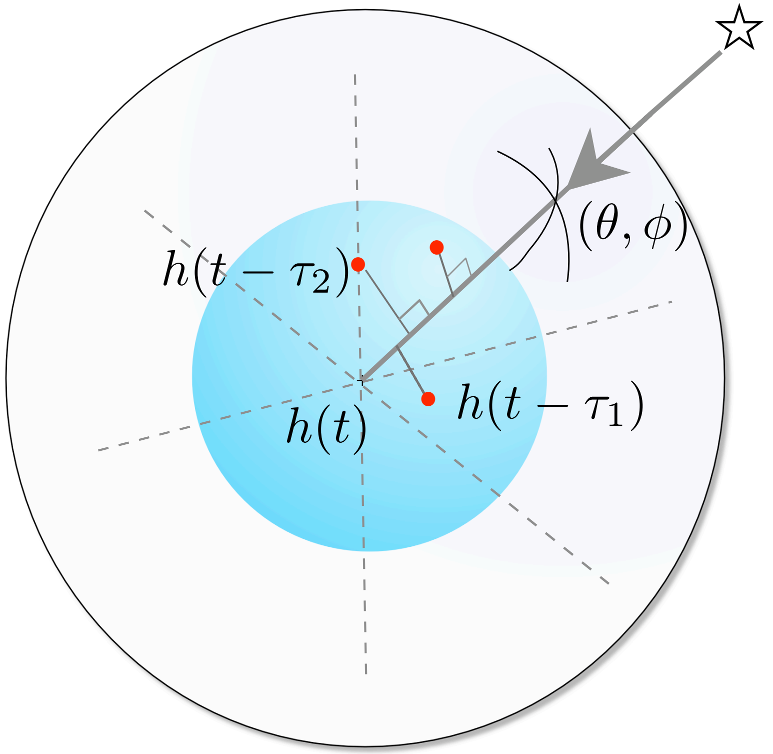
- When gravitational waves arrive at the earth, the signals are encoded into output of each detector.
- For data analysis to extract the signals,
  - how to combine these data streams from the detectors?
  - how to recover the signal waveforms to obtain astronomical information?

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 G.W. + noise

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

Changing (θ,ϕ) , look for

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

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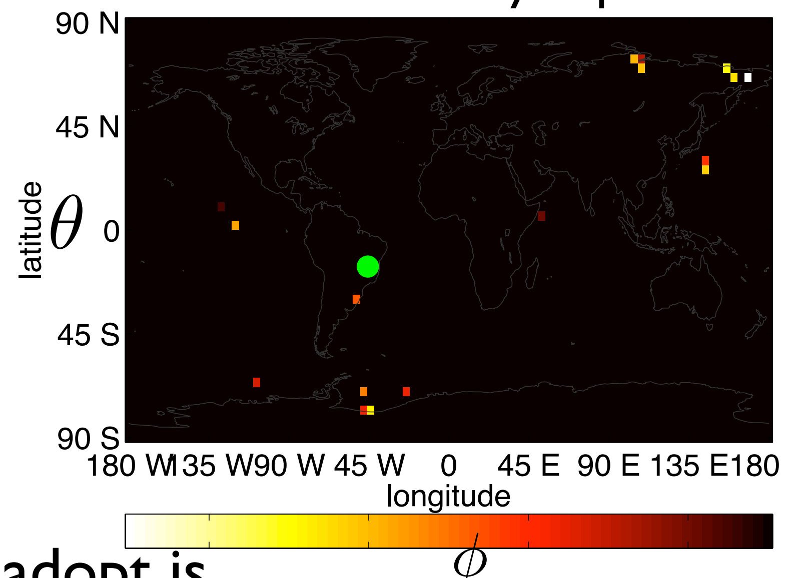
Tikhonov regularization

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

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

- 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)

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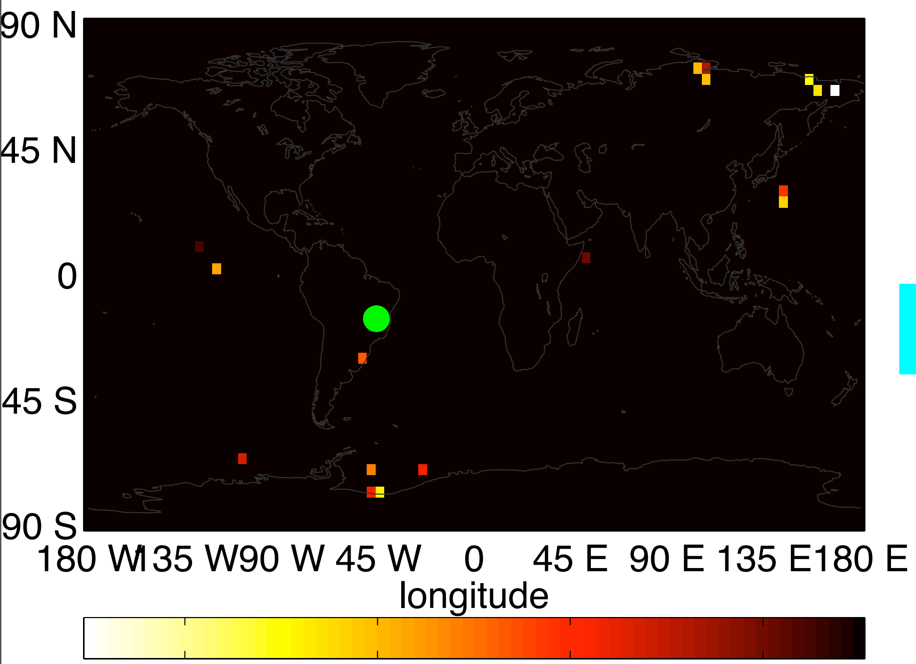
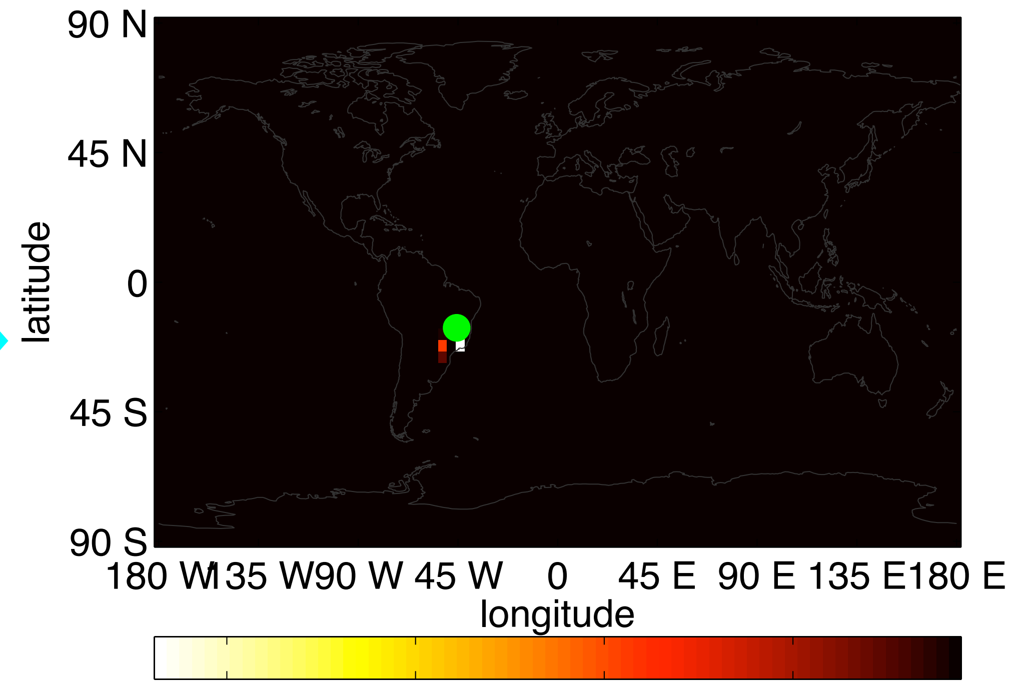
Effect of regulator

no regulator



with regulator



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

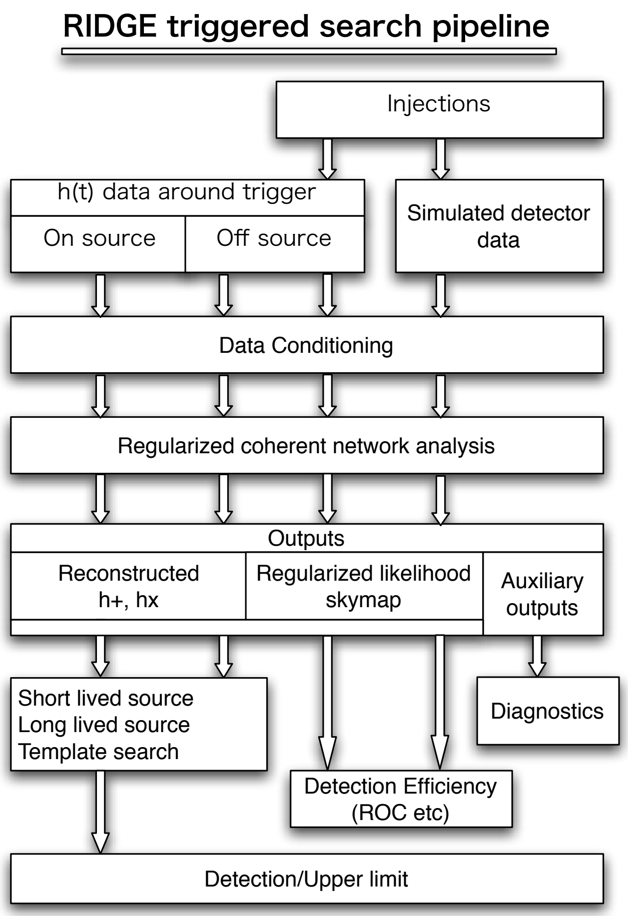
After adding regulator, the values are converged around the true solution.

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

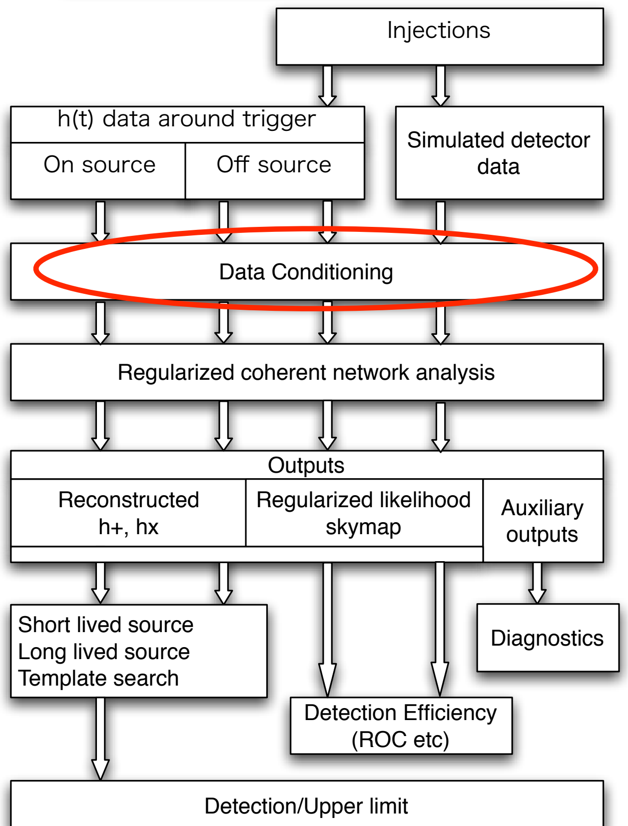
Note:
glitch :A large amplitude noise transient

RIDGE pipeline

-- fully coherent network analysis pipeline --

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

RIDGE triggered search pipeline



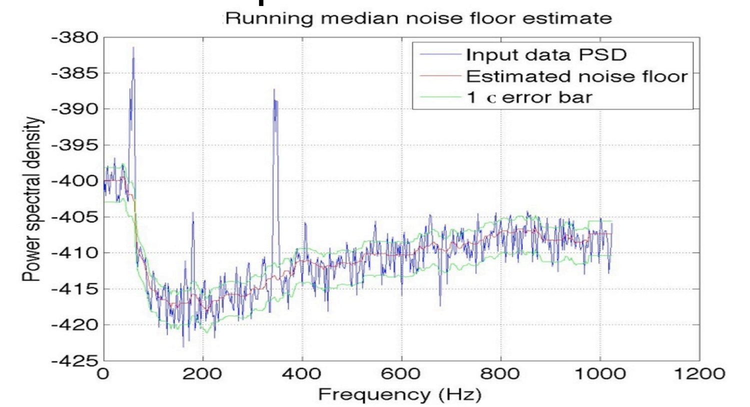
Feature:

- New data conditioning
- Tikhonov-regularized coherent network analysis

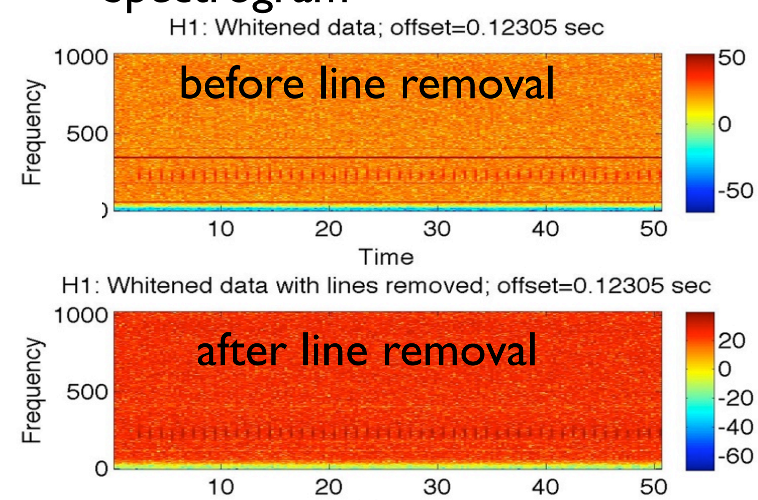
- Time domain noise floor whitening
  S. Mukherjee CQG 21 (2004) S1783

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

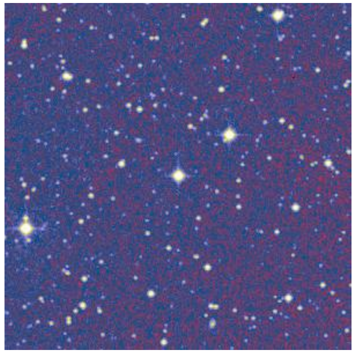
Power spectrum of simulated data



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

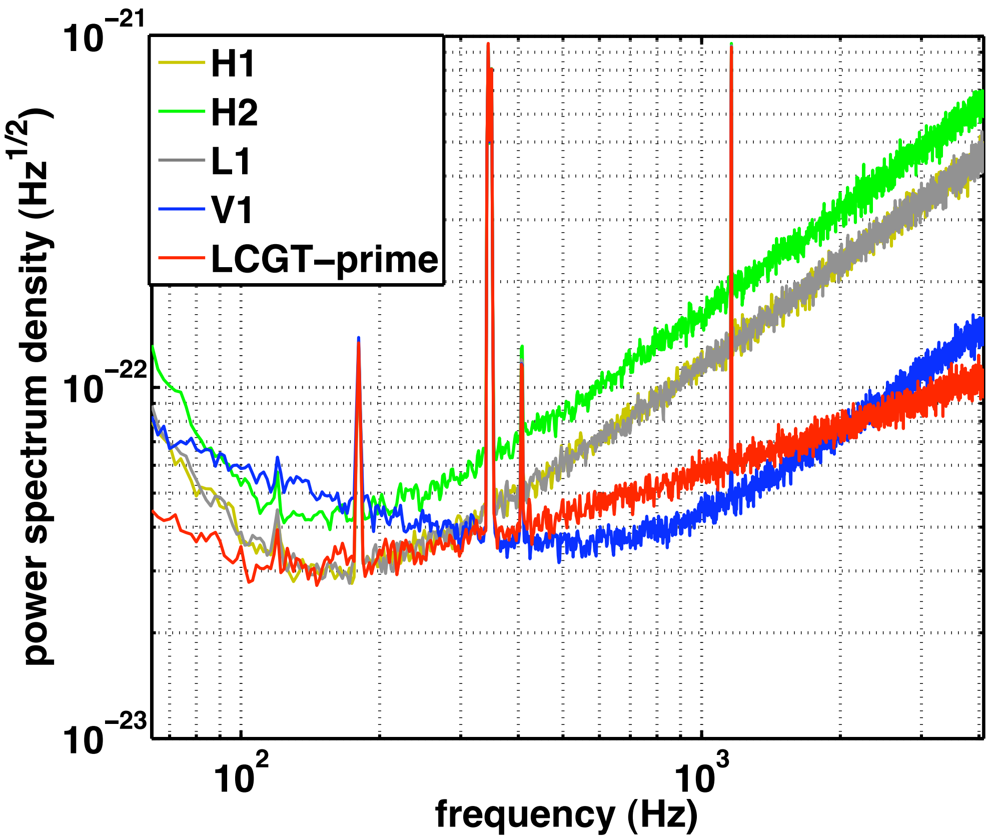
Monte Carlo Simulation

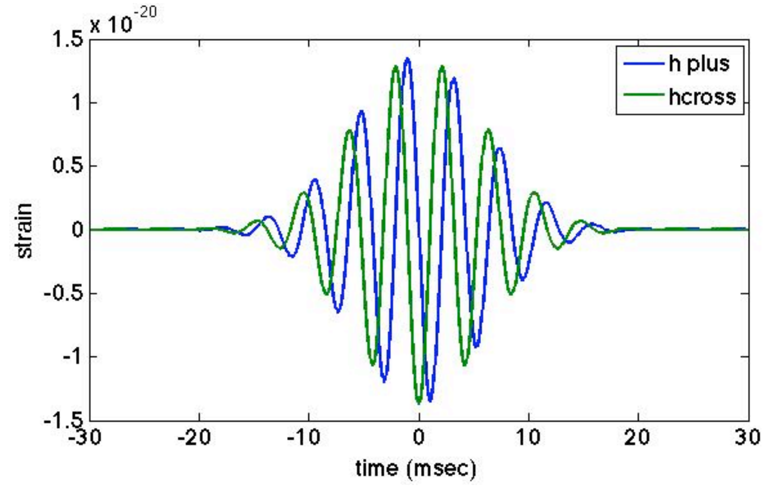
Simulated data

- 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:

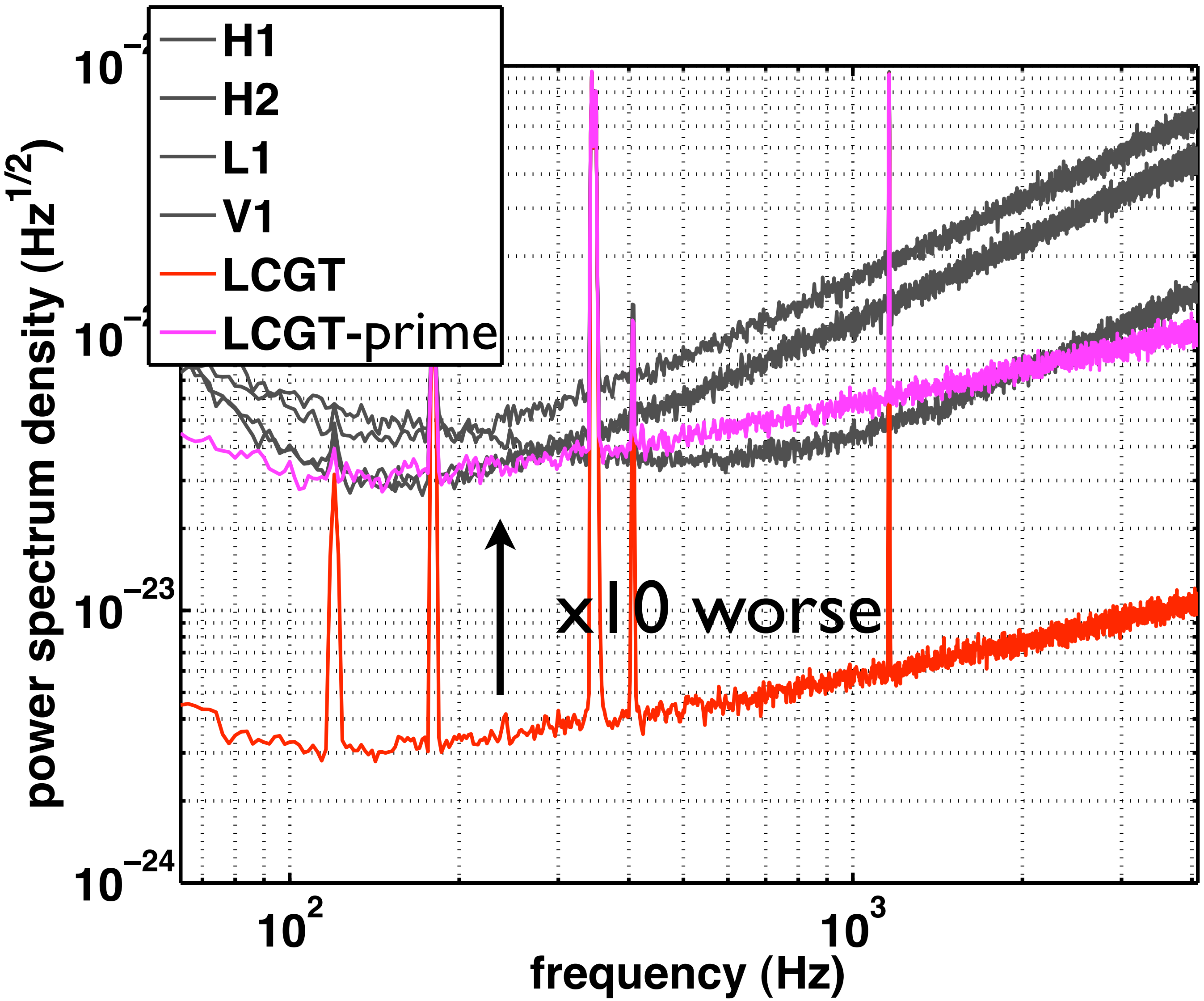
- SineGaussian(235Hz)
- Skylocation: ScoX1
- hrss=2×10^{-21} $Hz^{1/2}$





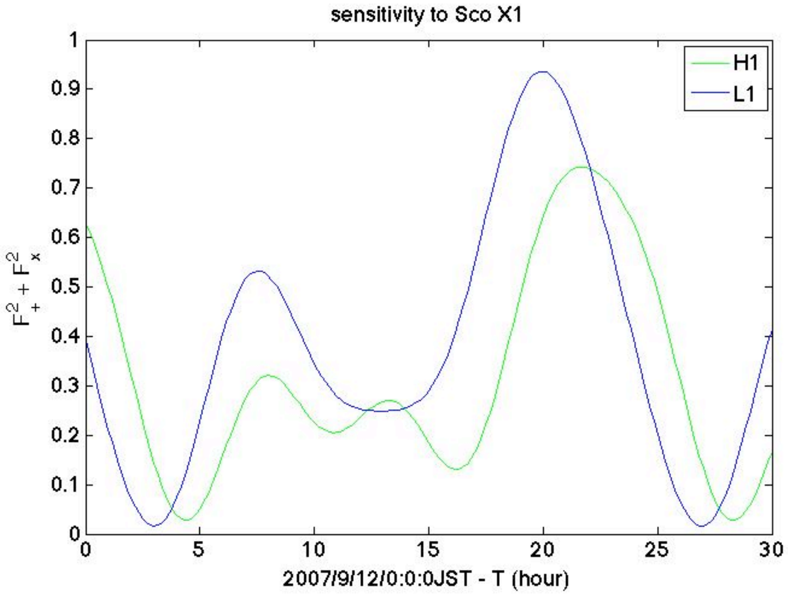
Monte Carlo Simulation

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



Sensitivity to Sco X-1

H1 - L1



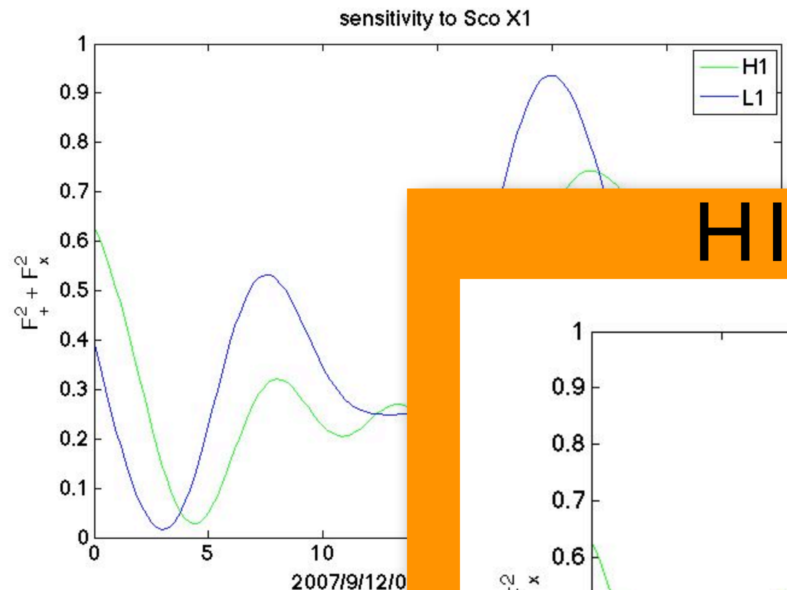
y-axis:
detector response : $F_+(\theta_s, \phi_s)^2 + F_\times(\theta_s, \phi_s)^2$
to the location of Sco X-1(θ_s, ϕ_s)

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

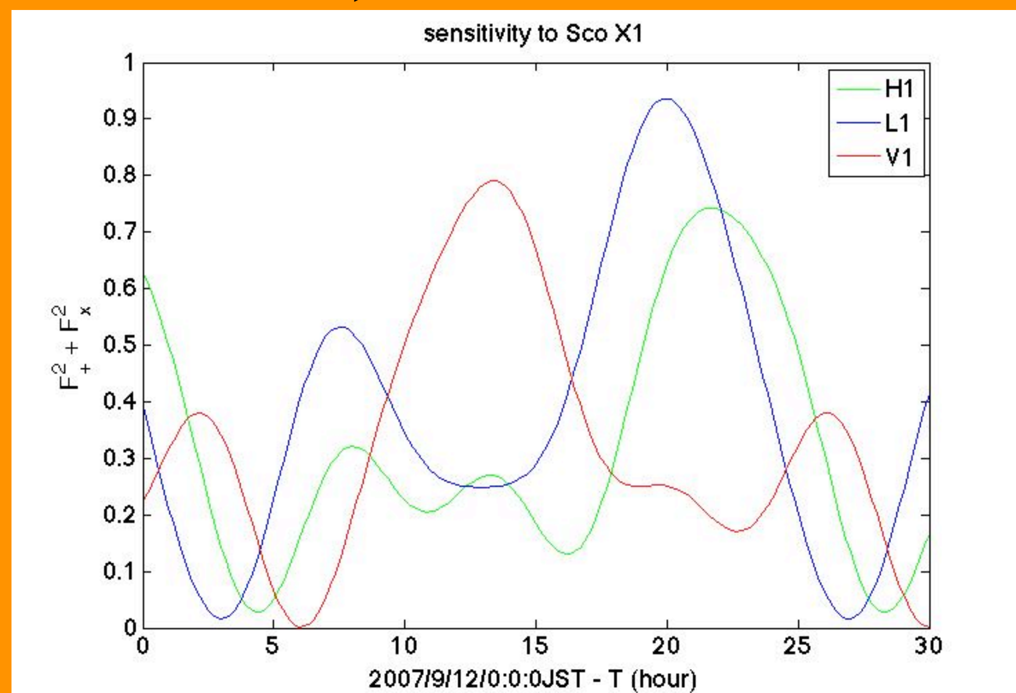
Sensitivity to Sco X-1

H1,H2 - L1



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

H1,H2 - L1 - V1



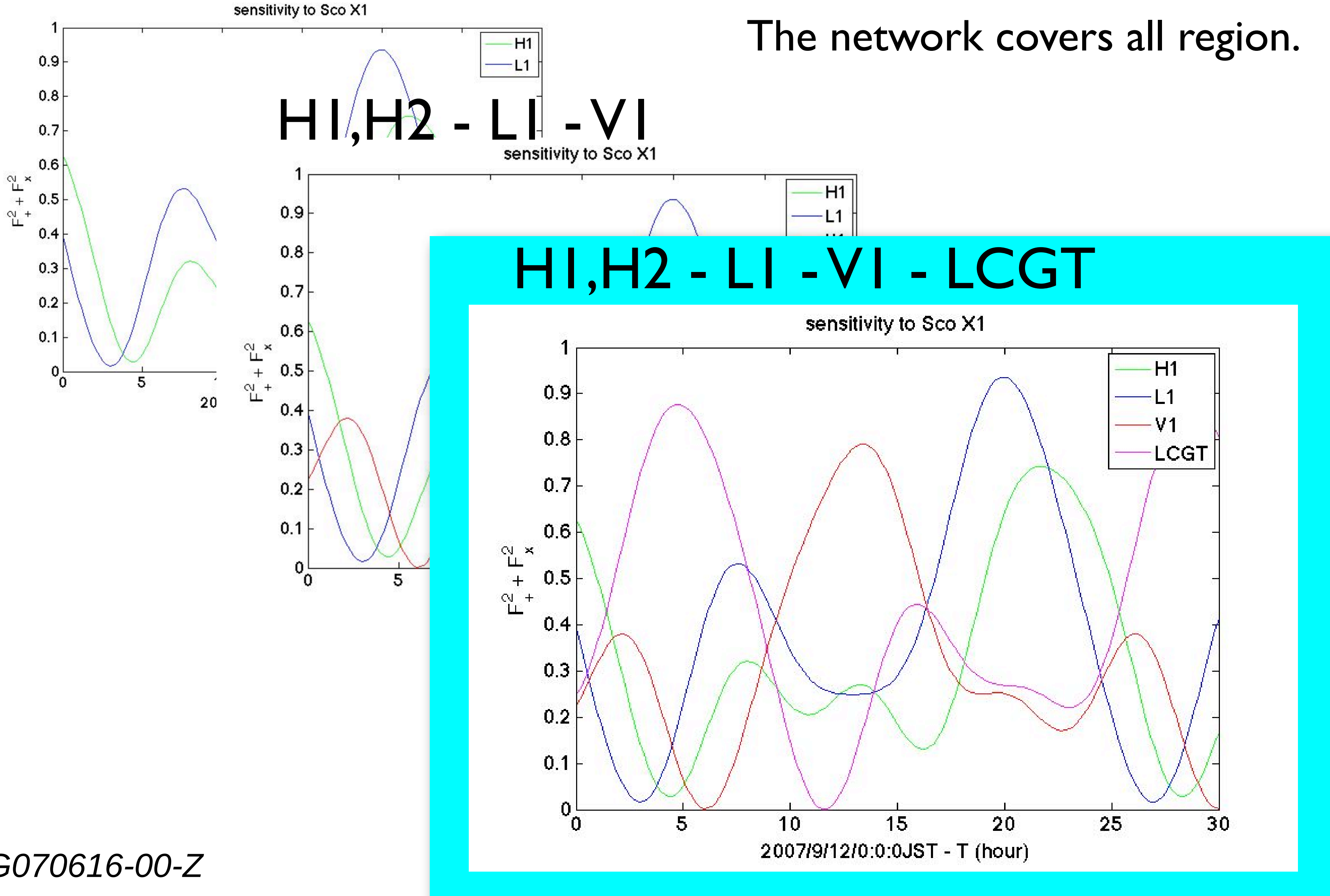
Sensitivity to Sco X-1

H1,H2 - L1

The network covers all region.

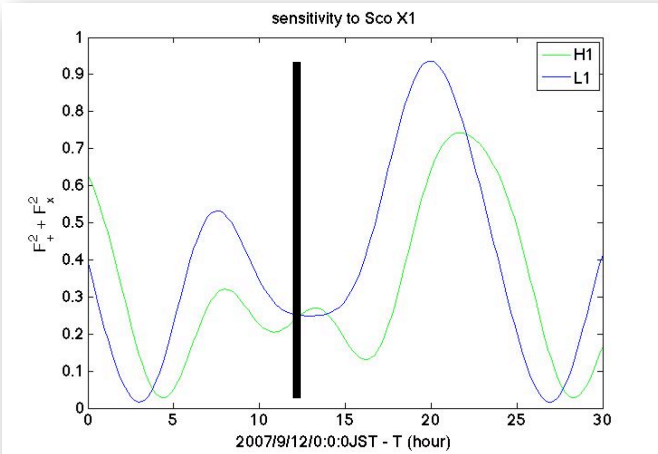
H1,H2 - L1 -V1

H1,H2 - L1 -V1 - LCGT

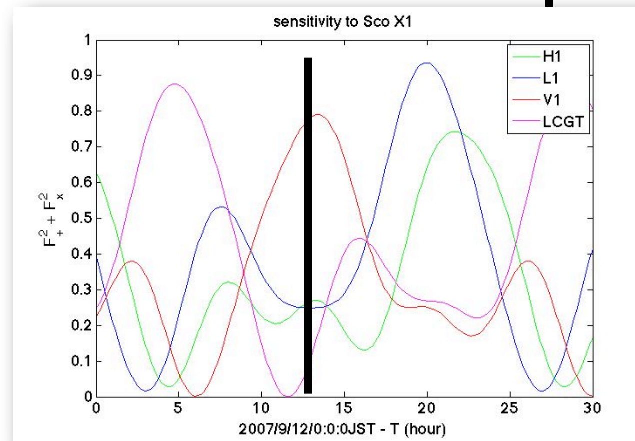


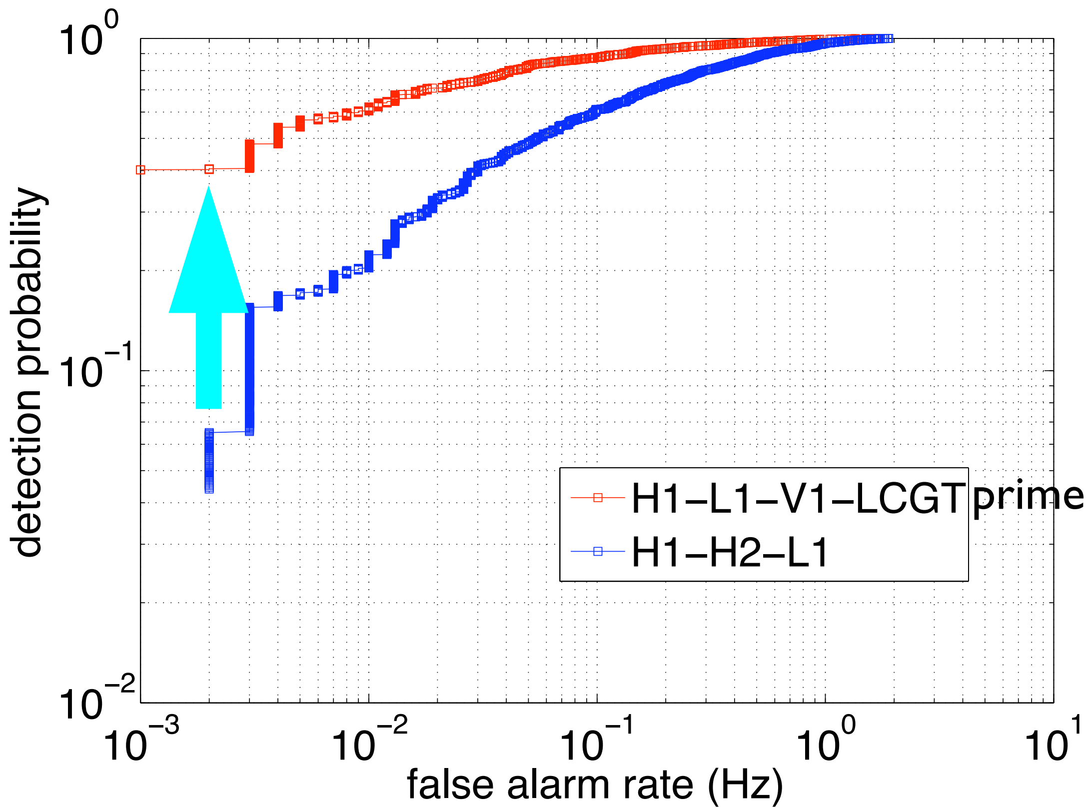
Detection efficiency

H1+H2+L1



H1+L1+V1+LCGT-prime





VIRGO compensate the low sensitivity region for LIGO network.

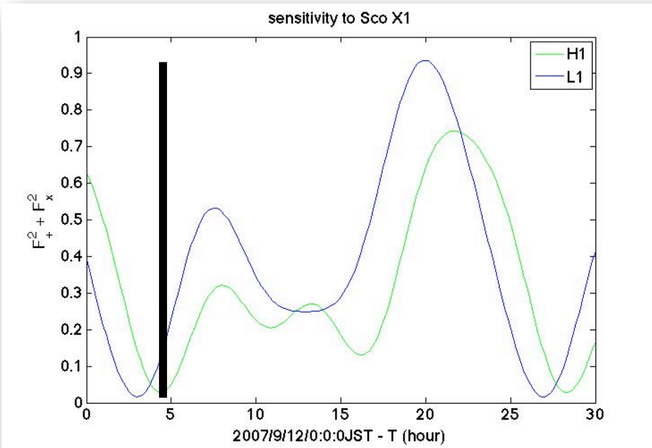
Detection probability
@false alarm rate 0.01Hz

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

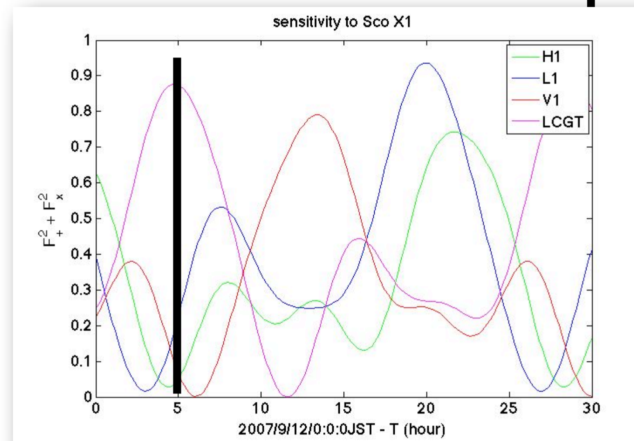
G(

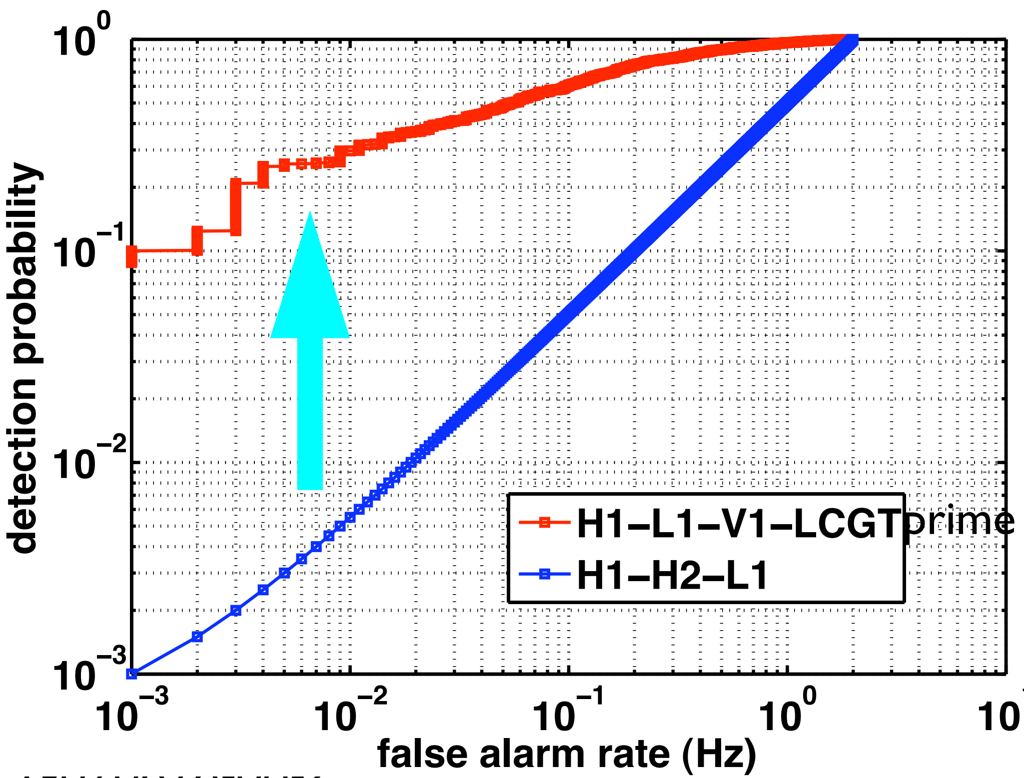
Detection efficiency

H1+H2+L1



H1+L1+V1+LCGT-prime





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

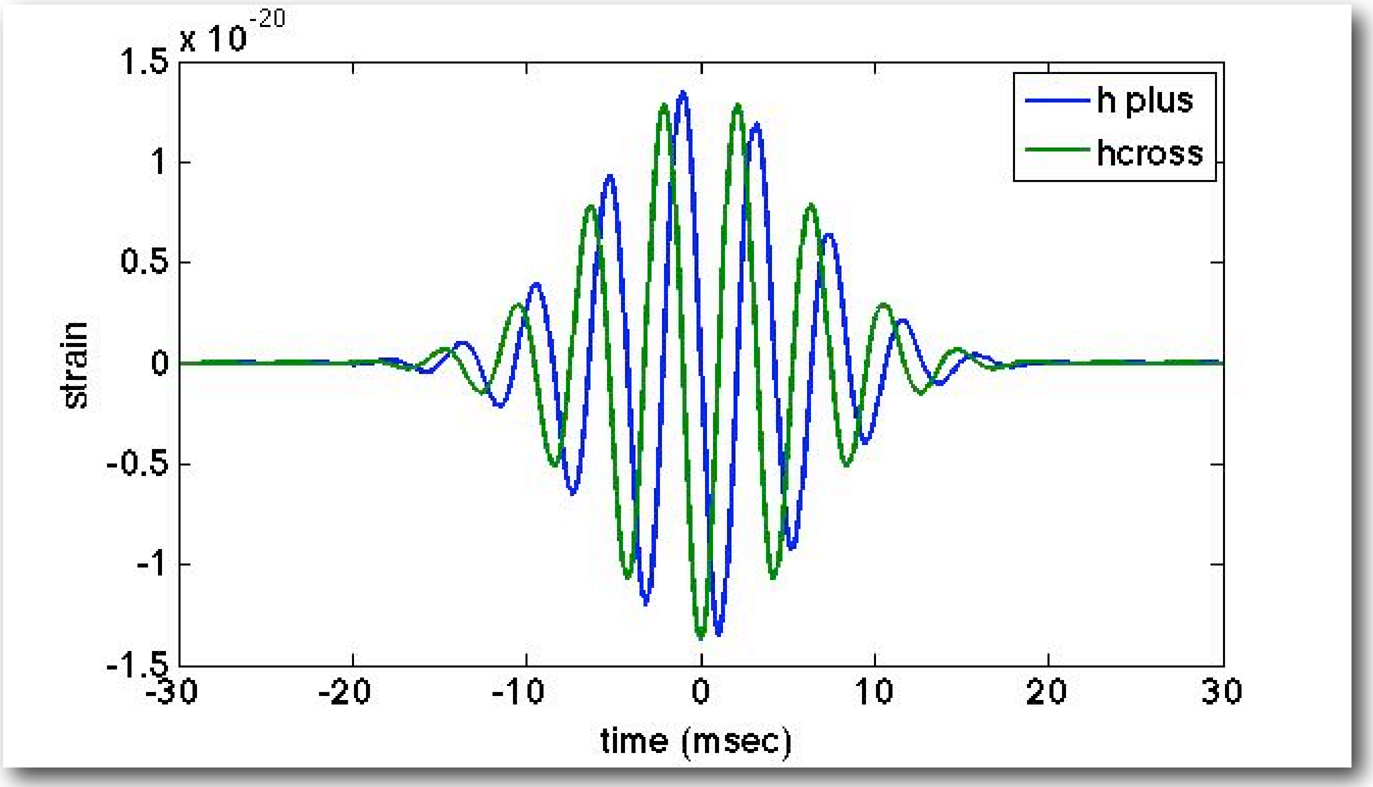
Detection probability
@false aralm rate 0.2Hz

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

Reconstruction of G.W. waveforms

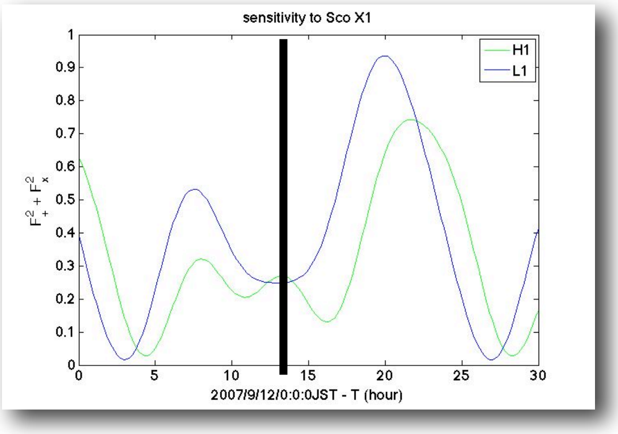
Injected signal:

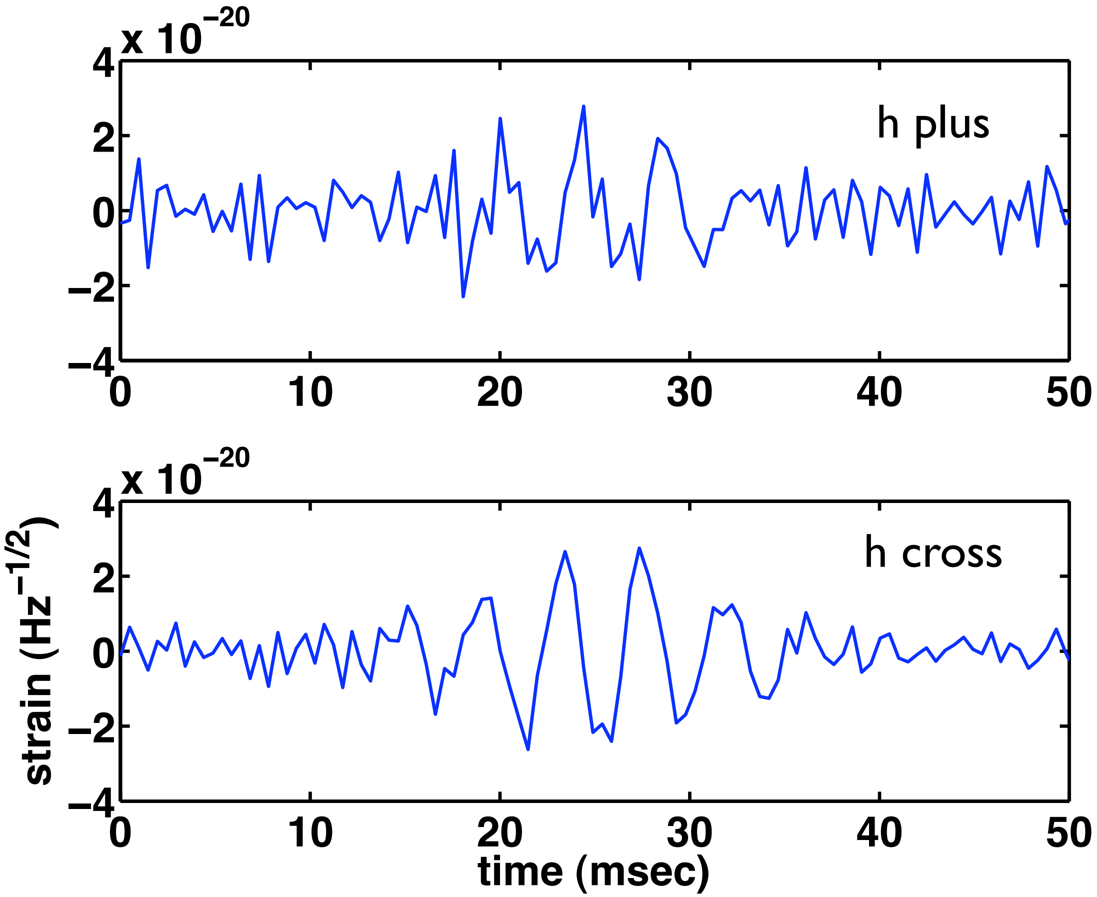
- Sine Gaussian of the central frequency 235Hz
- hrss=2.8×10^{-21} $Hz^{1/2}$



Reconstruction of G.W. waveforms

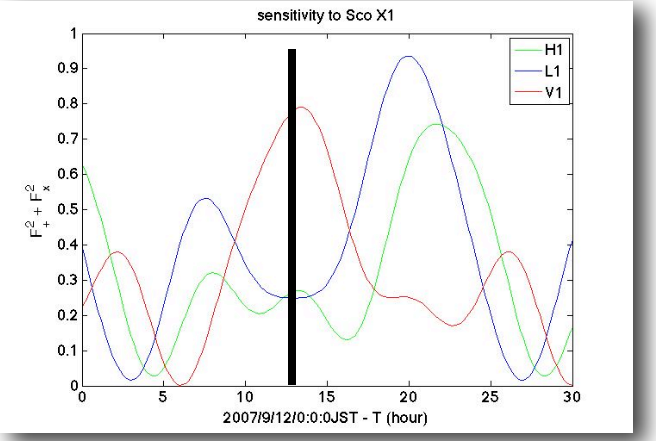
H1+H2+L1

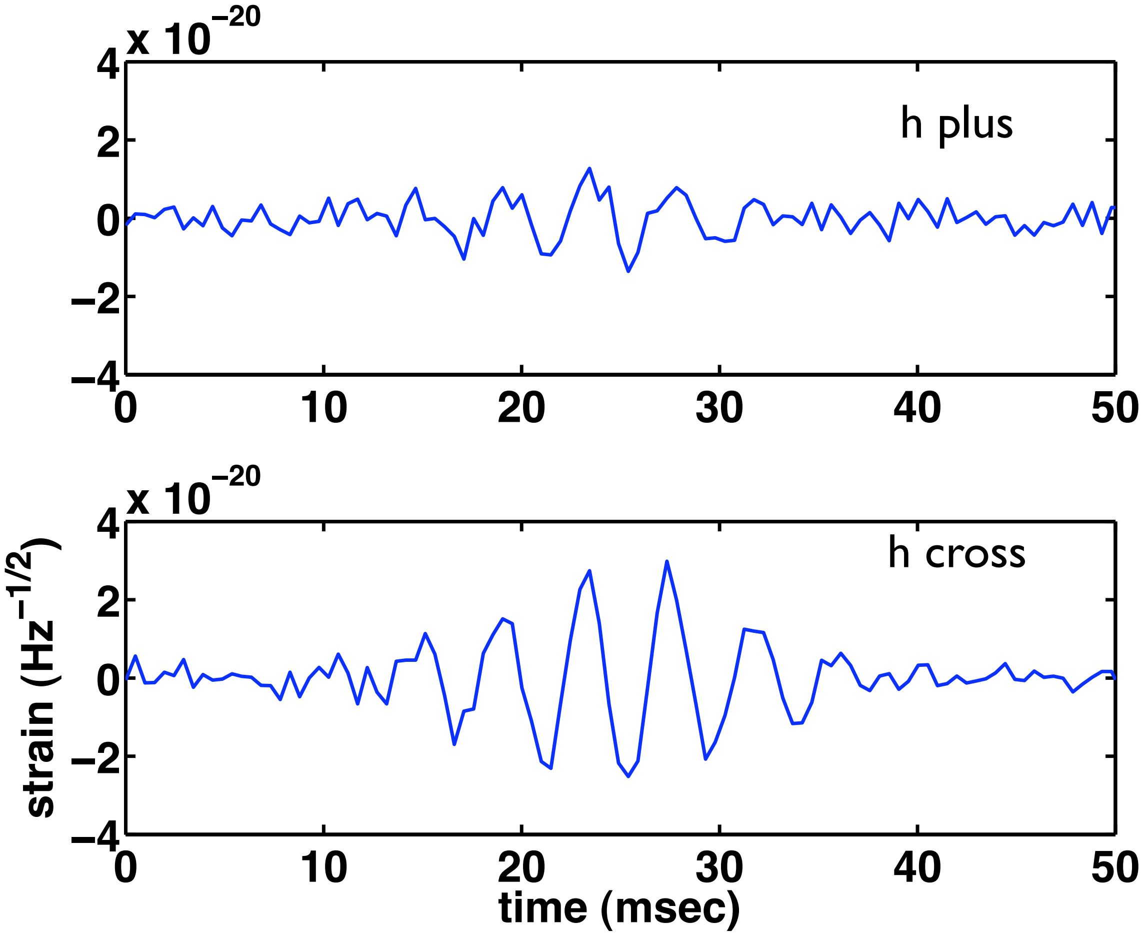




Reconstruction of G.W. waves

H1+H2+L1+V1





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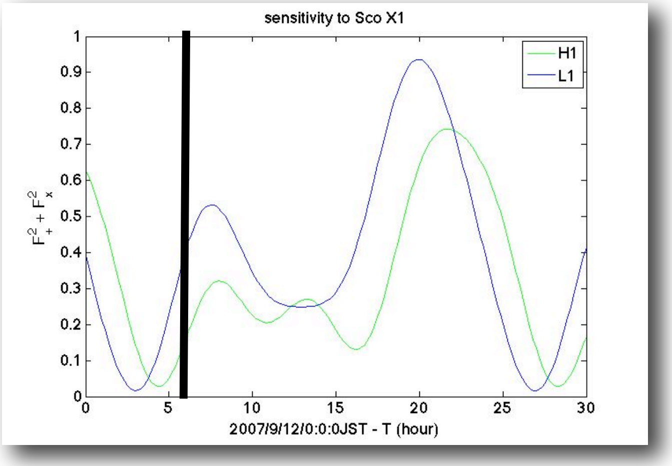
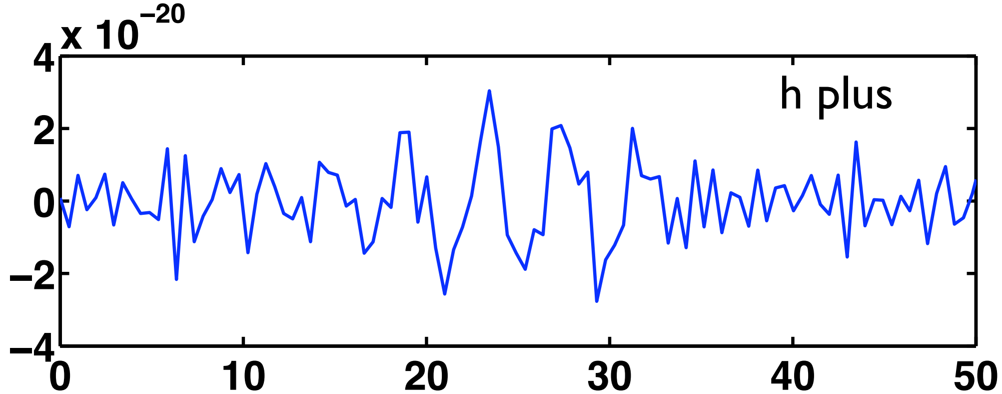
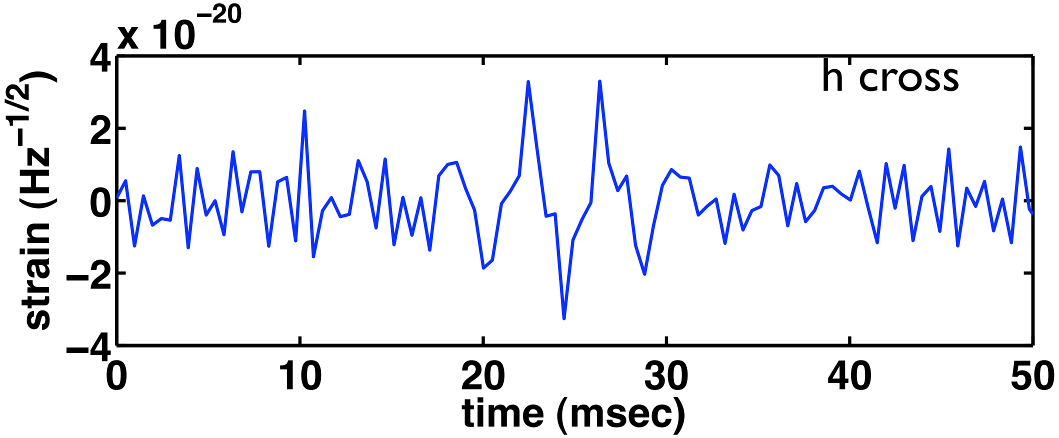
Reconstruction of G.W. waves

H1+H2+L1

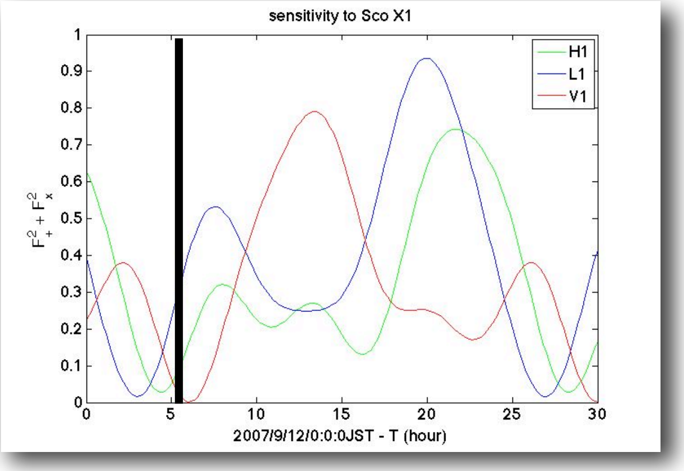


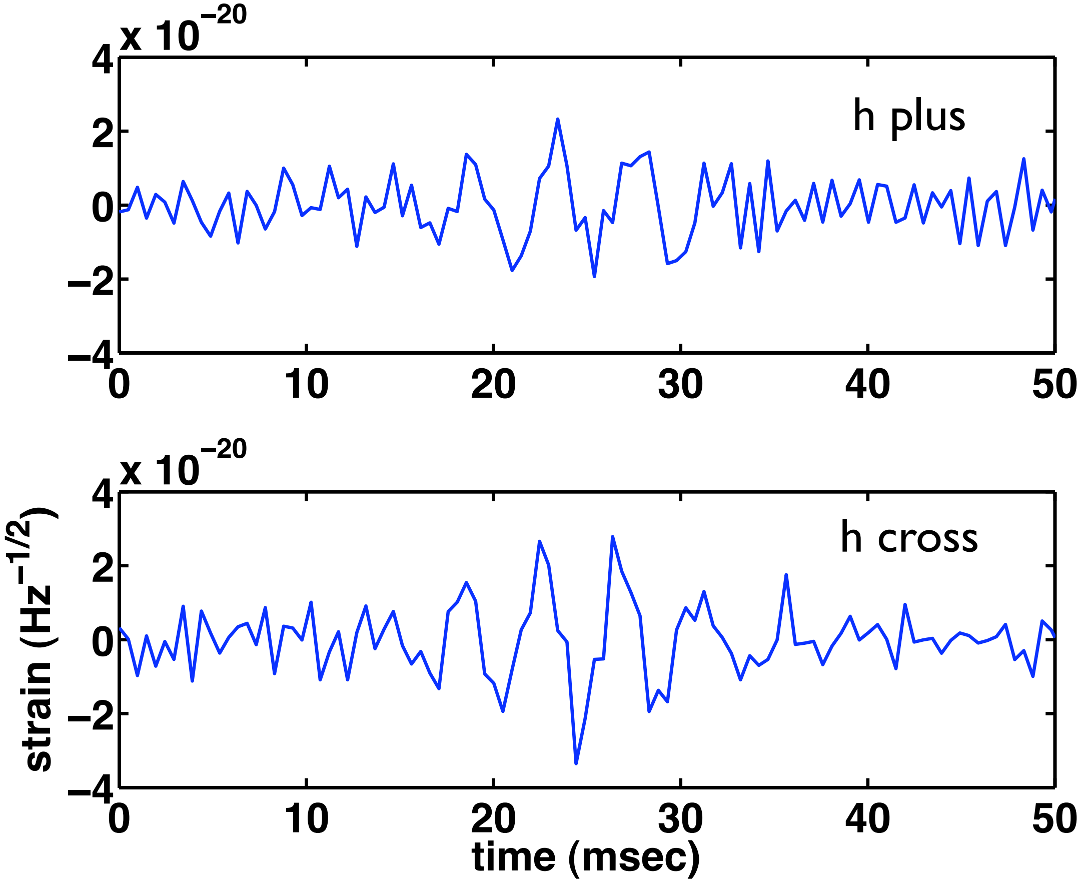




Reconstruction of G.W. waves

H1+H2+L1+V1





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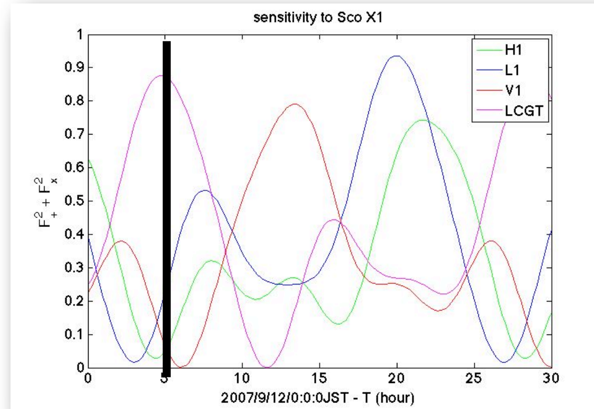
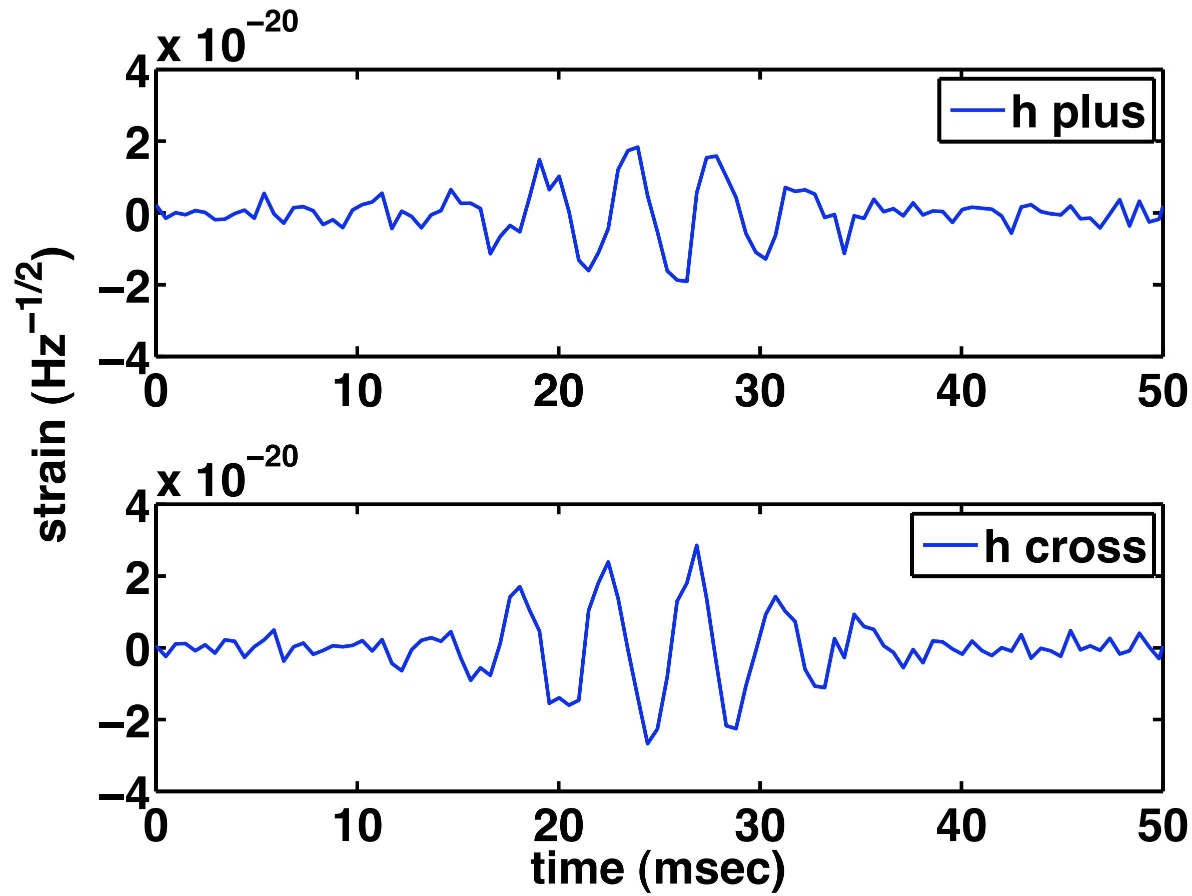
Reconstruction of G.W. waves

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

Triggered search

LIGO

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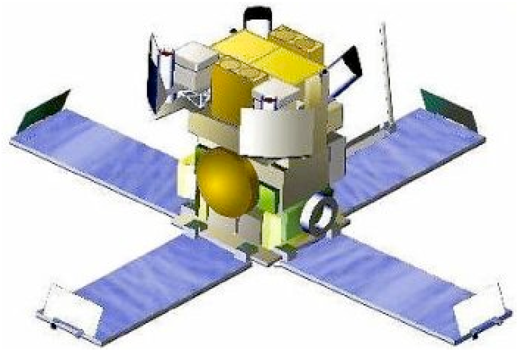

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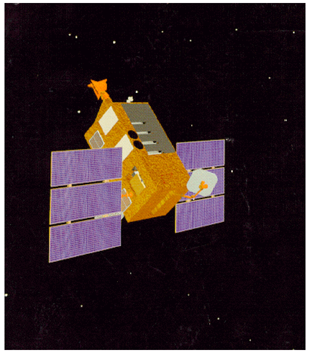

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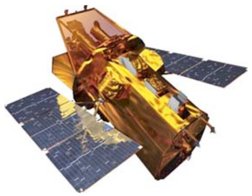
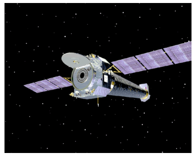


SWIFT

MXX-Newton



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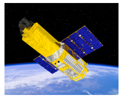
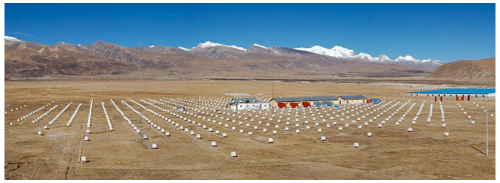
Parkes ,



AstroE2



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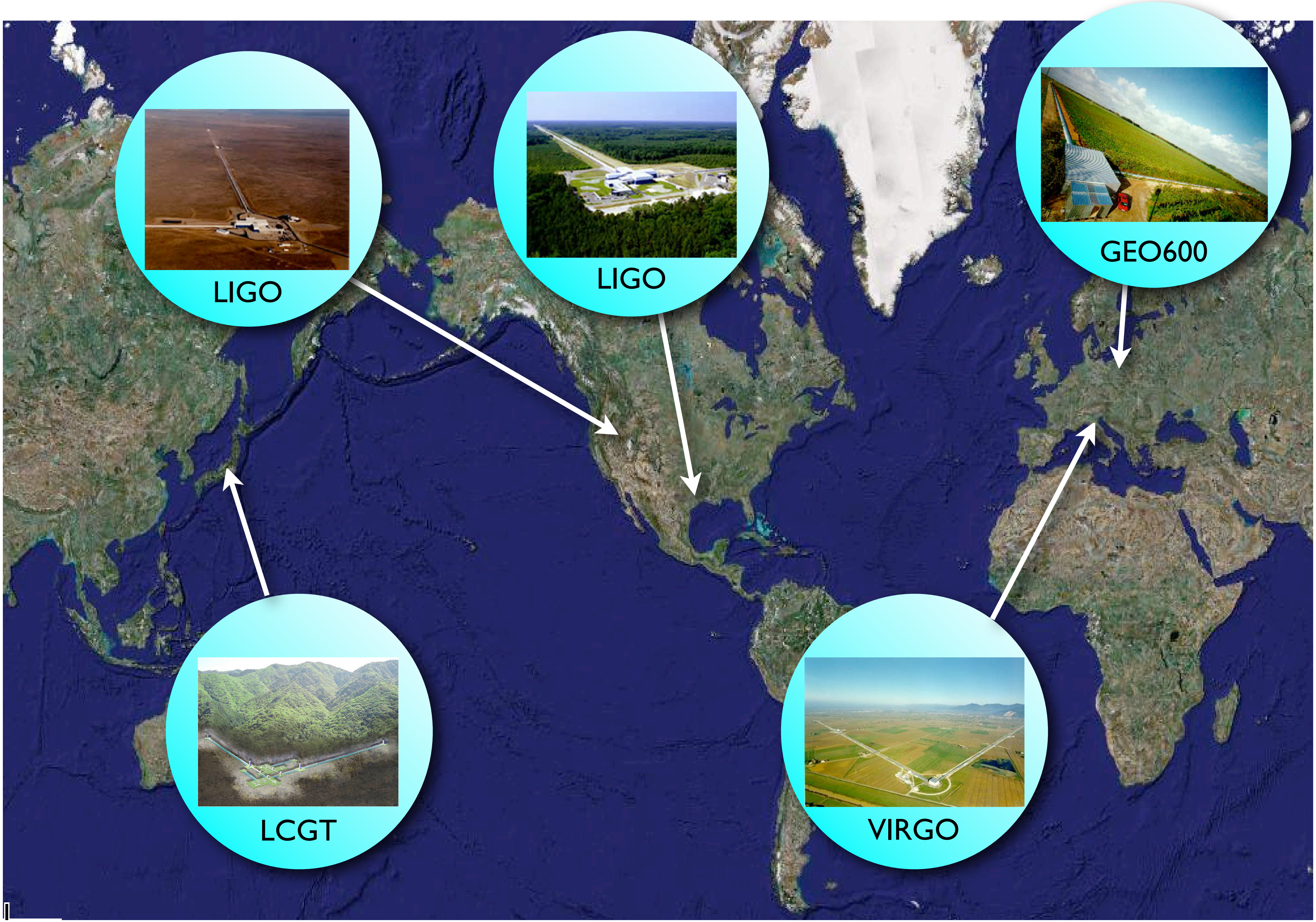
AGASA ,

SDSS

G070616-00-Z

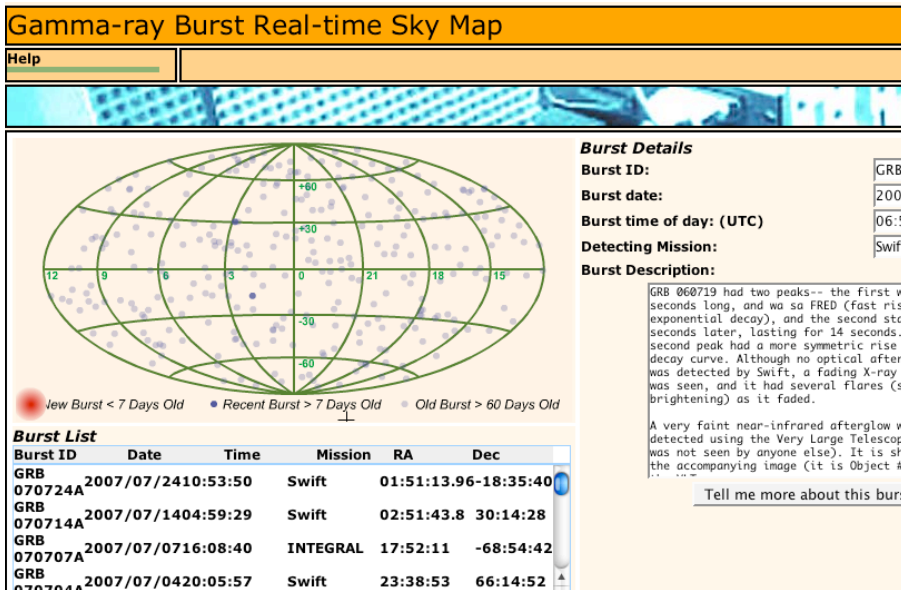
Gravitational wave detector network



Analysis procedure

-- in case of GRB --

excellent GRB alert system

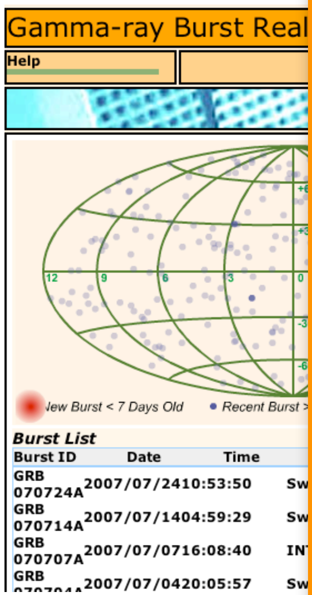


http://grb.sonoma.edu/

Analysis procedure

-- in case of GRB --

excellent G



http:/

List of astronomical information and available data

GRB Name	GPS Time	R.A.	Declination	Detectors in Science Mode
051105	815207214.000	265.289	34.921	H2
051105B	815223963.000	9.477	-40.481	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

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

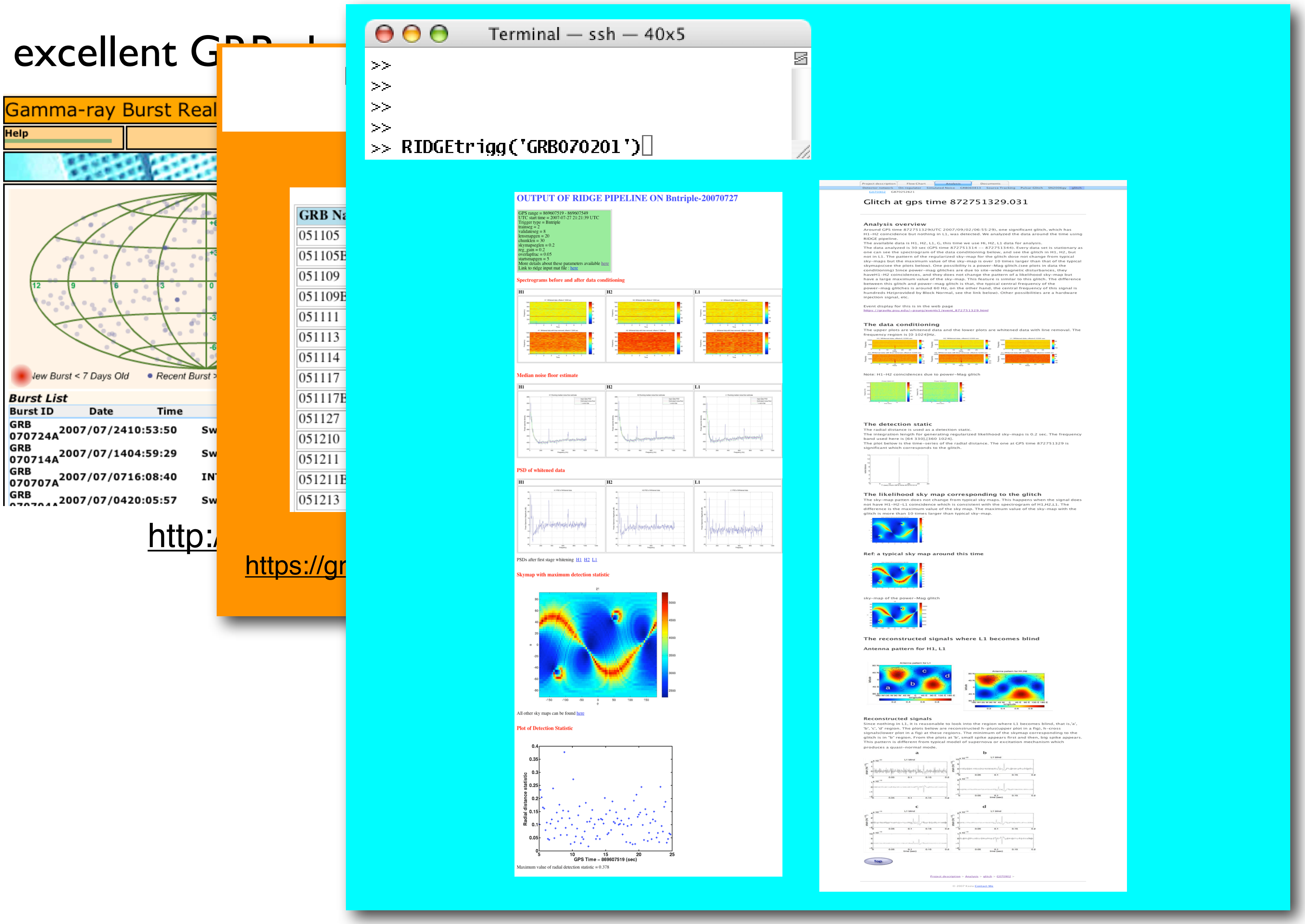
GPS time

sky position

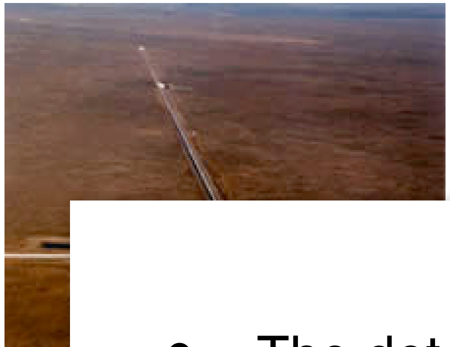
detectors
on science mode

Analysis procedure

-- in case of GRB --



Triggered search



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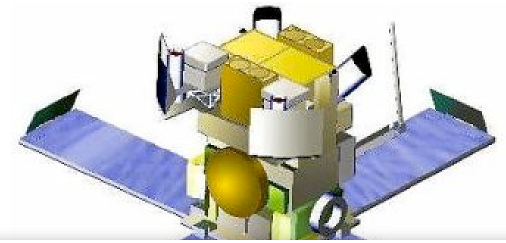

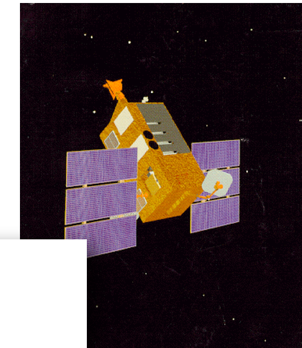

RXTE

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rkes

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- 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

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TIBET

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AGASA

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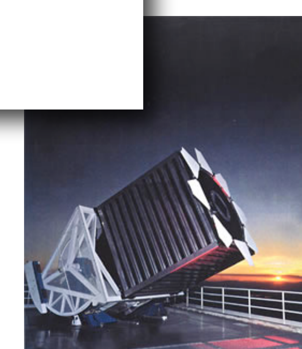
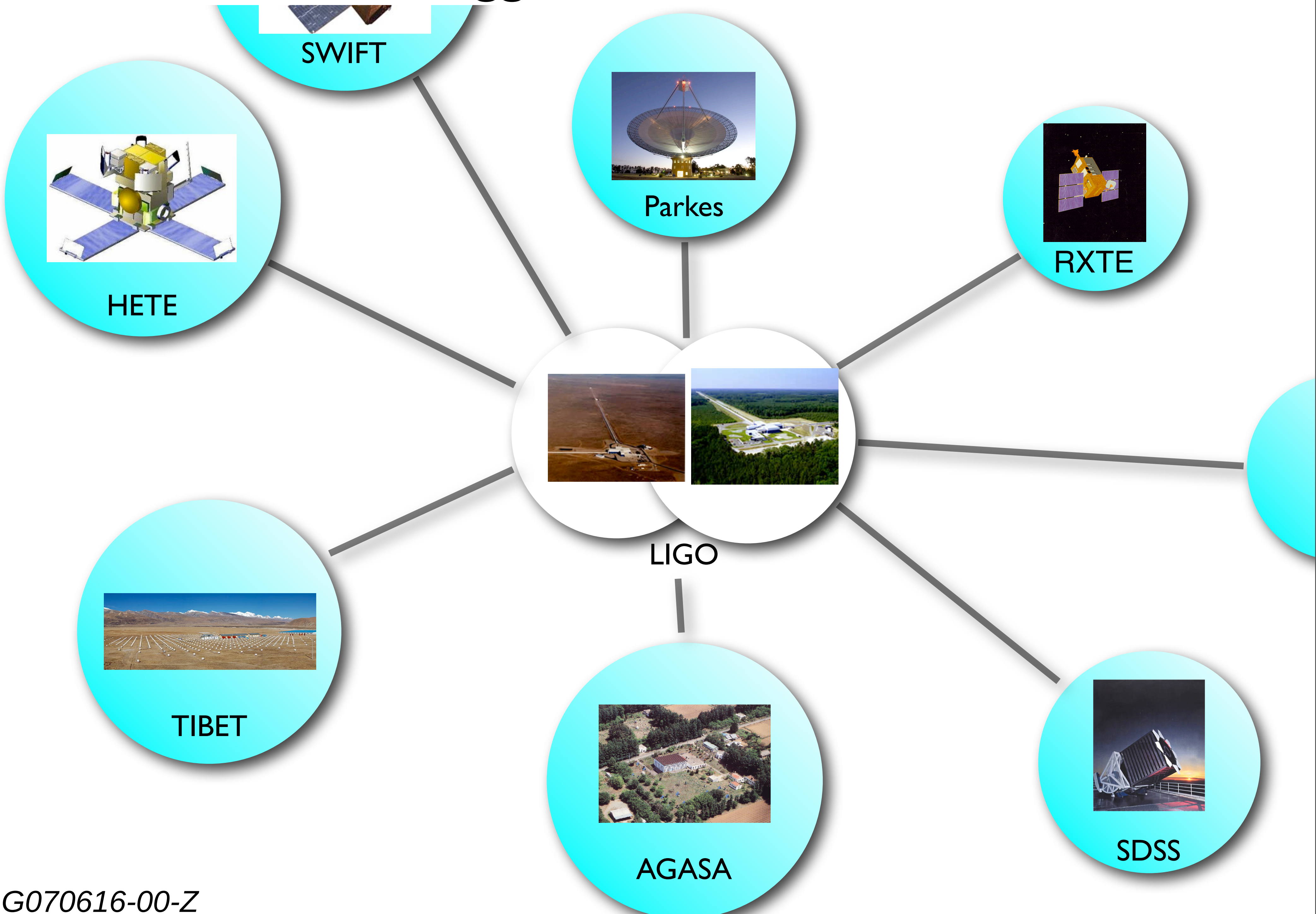


SDSS

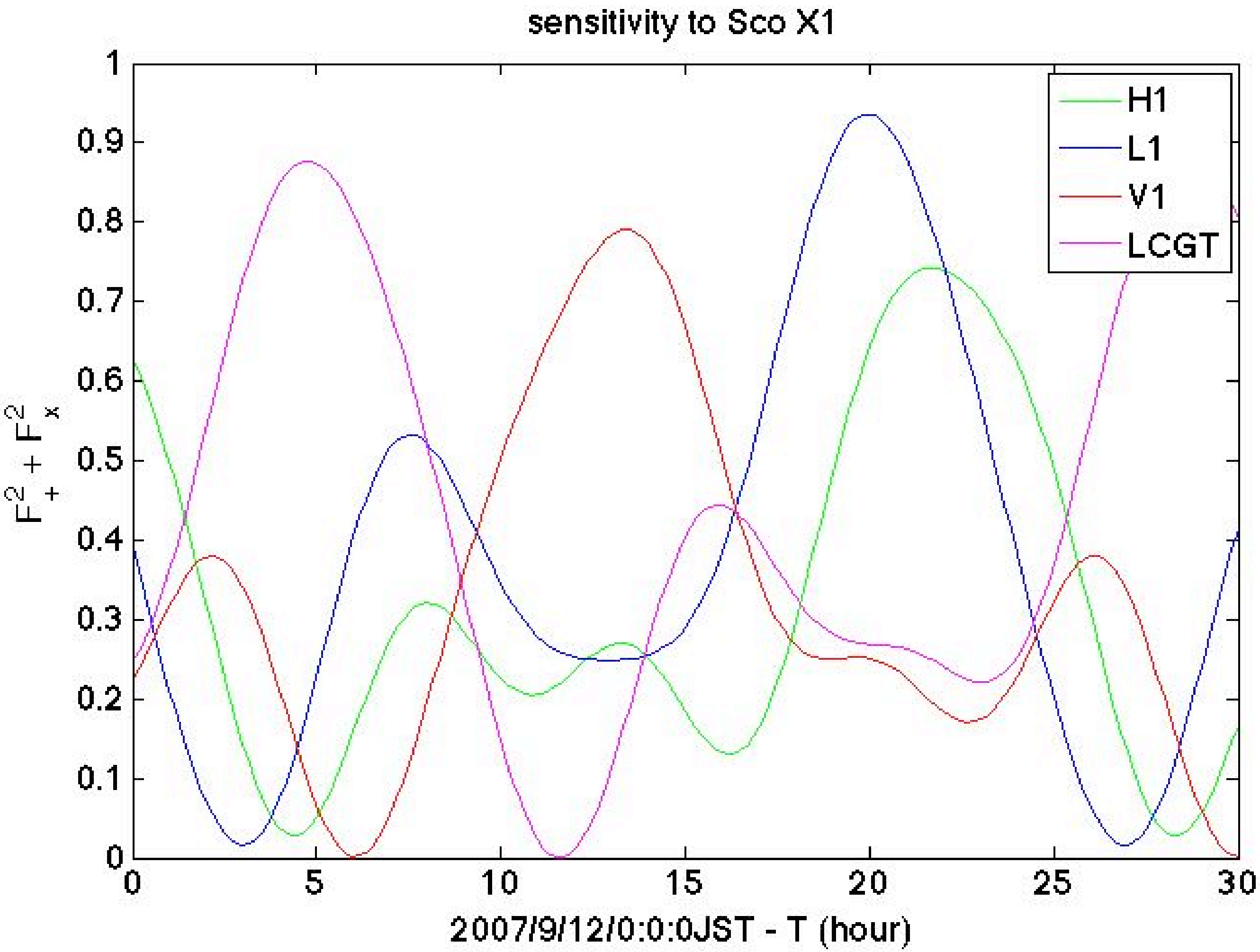
G070616-00-Z

Triggered search



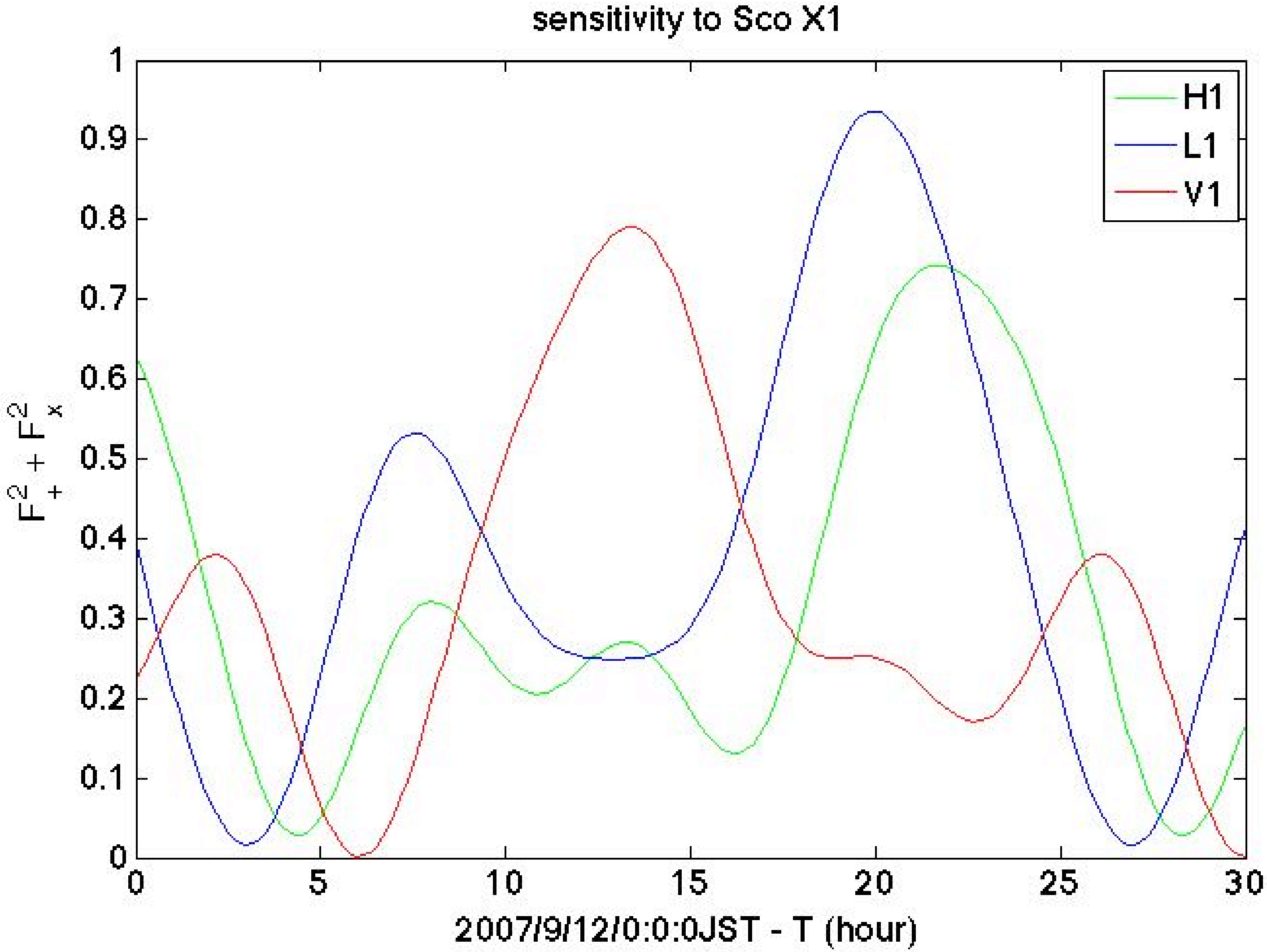
Sensitivity to Sco X-1

H1 - L1 - V1 - LCGT

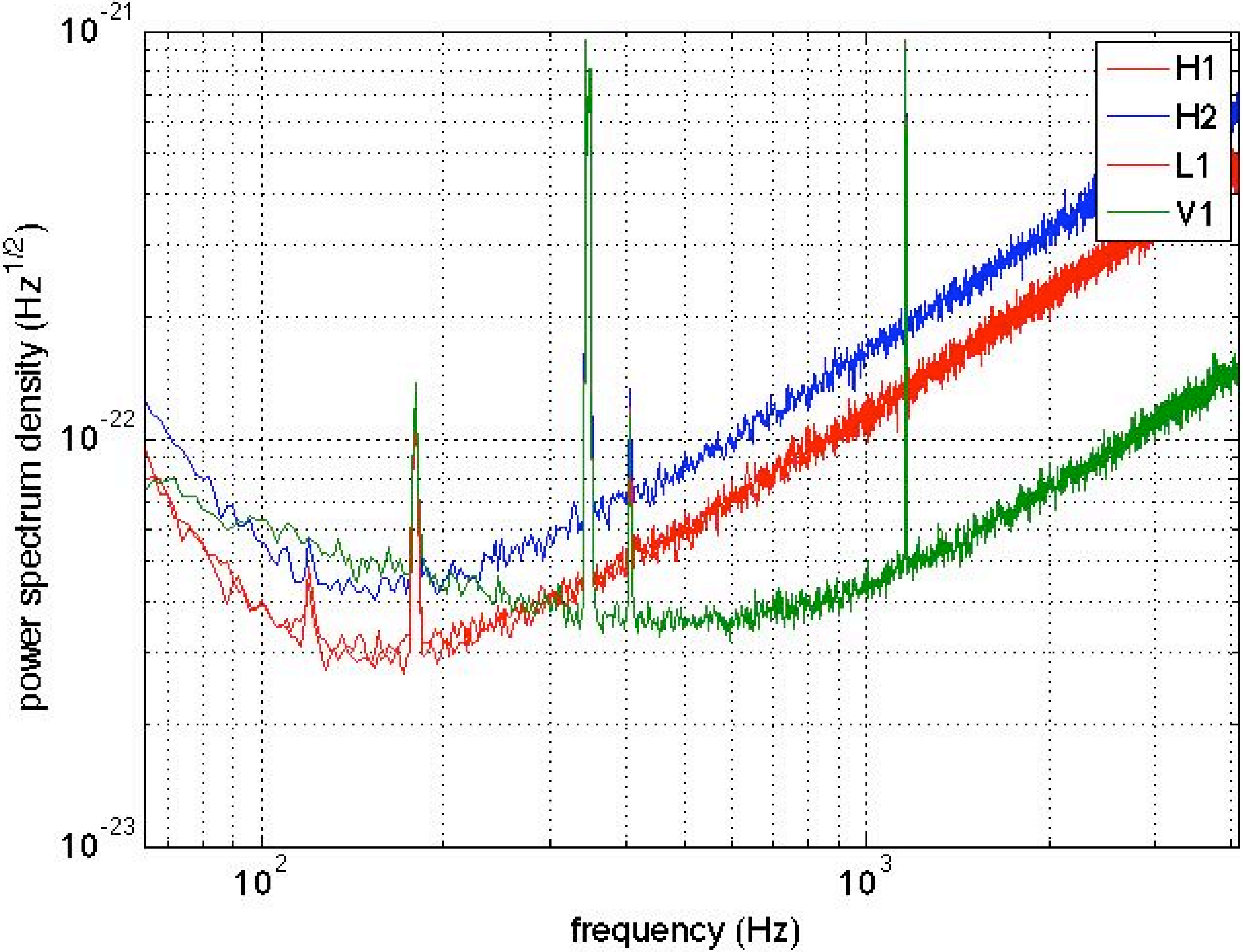


Sensitivity to Sco X-1

H1 - L1 - V1

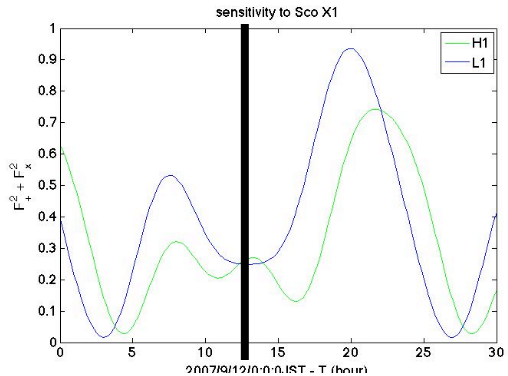


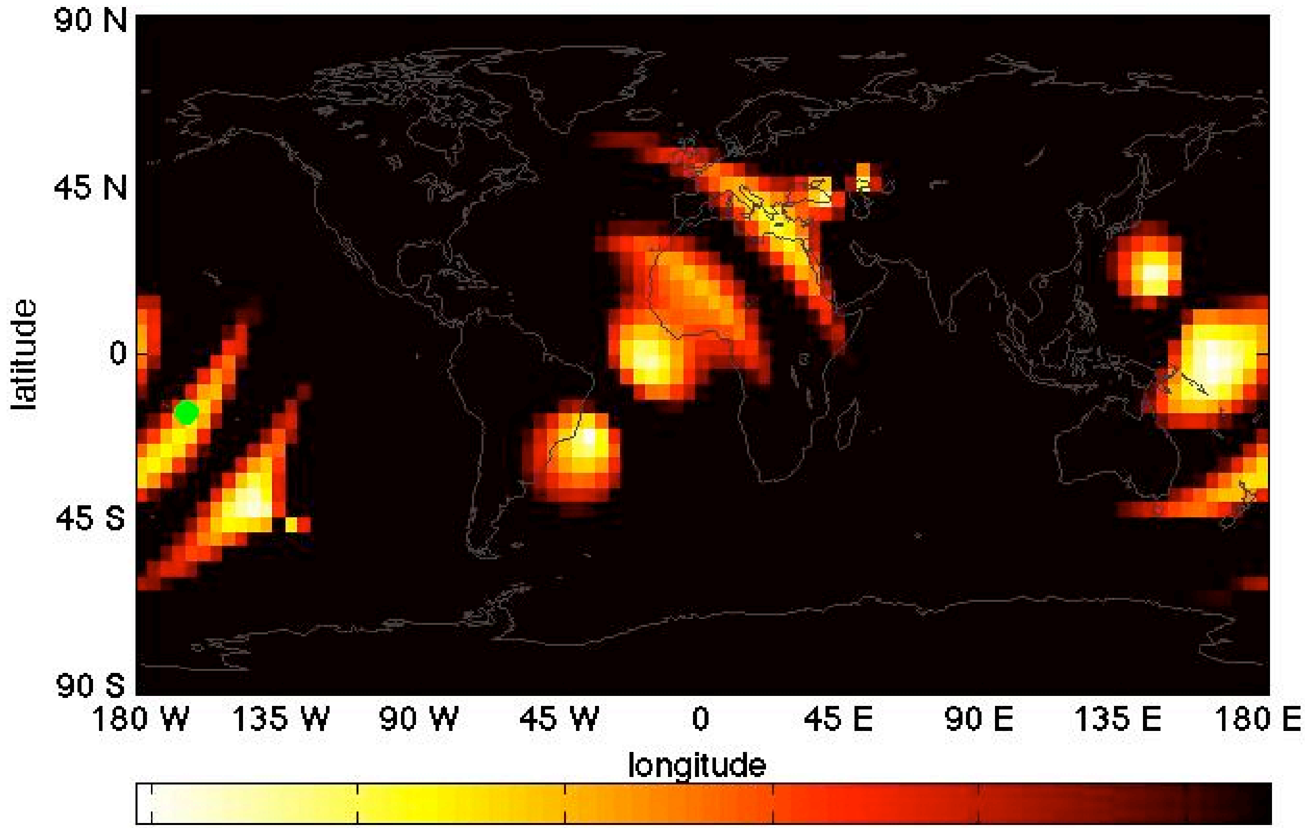
Simulated data



skymap

H1+H2+L1



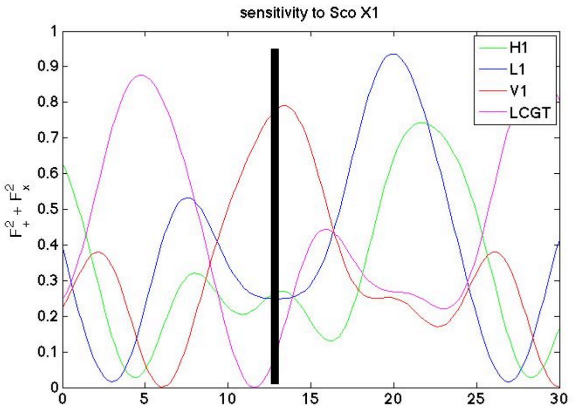


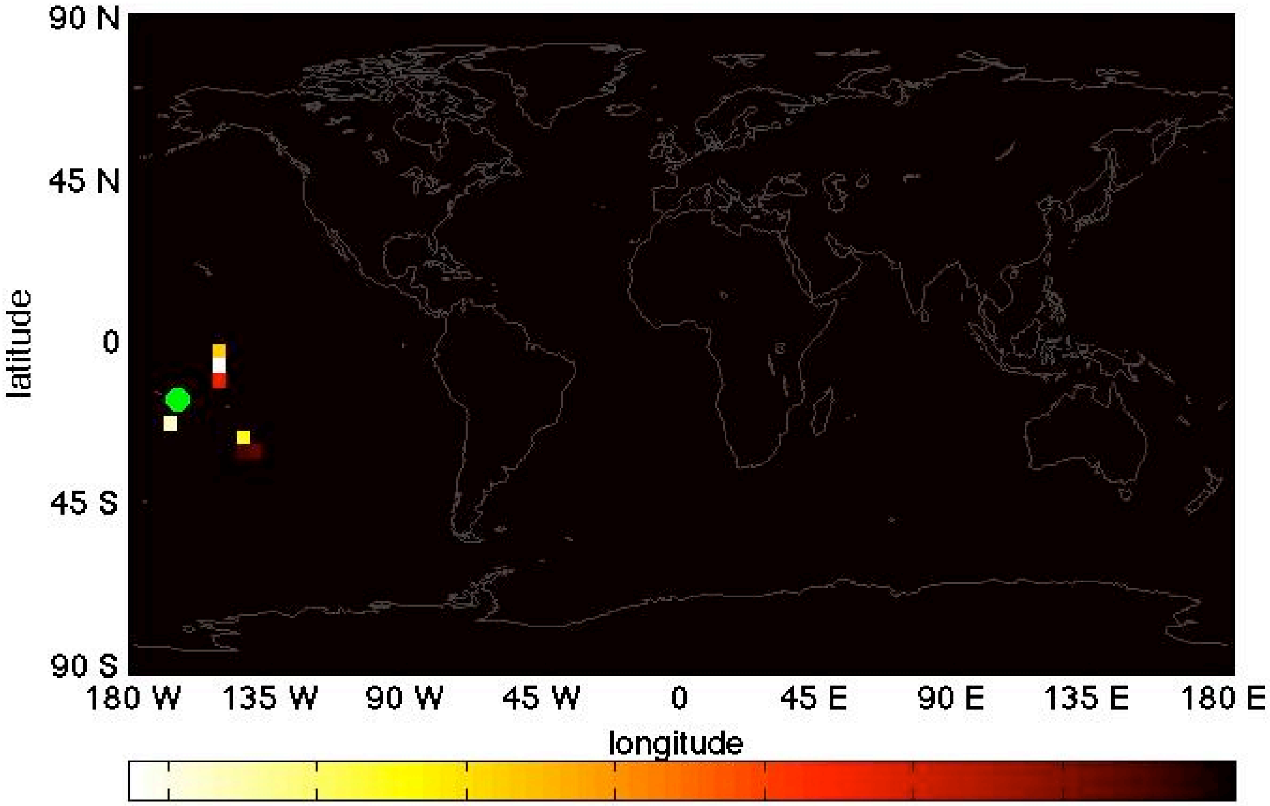
minimum of skymap

1.2 x minimum of skymap

skymap

H1+L1+V1+LCGT



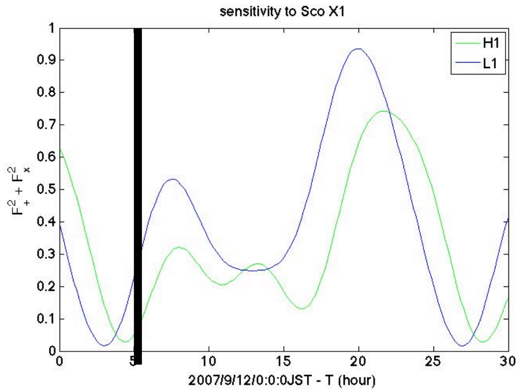


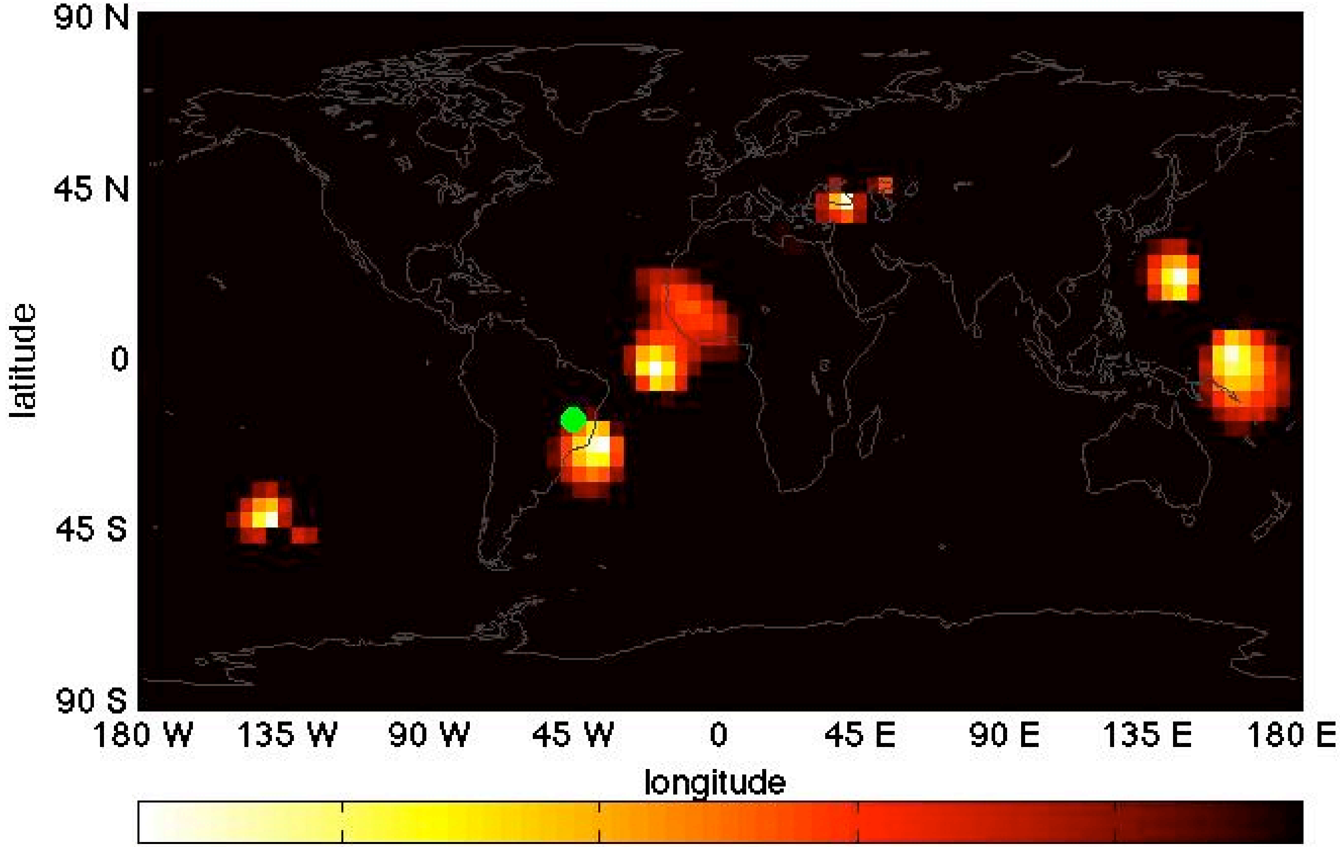
minimum of skymap

1.2 x minimum of skymap

skymap

H1+H2+L1



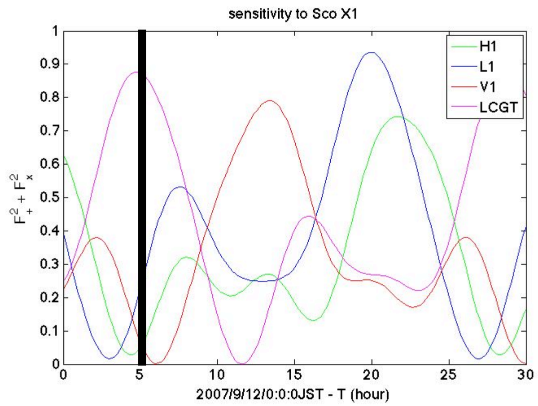


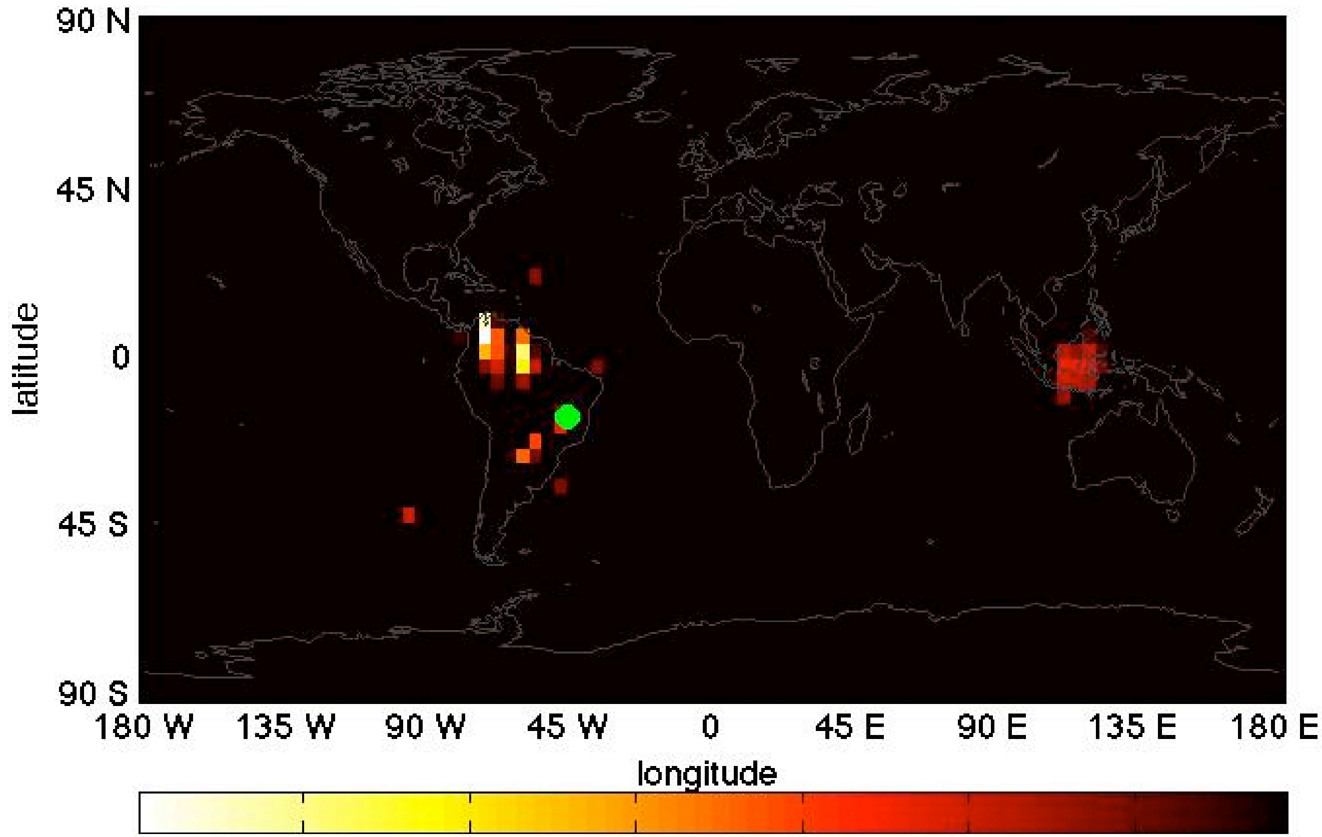
minimum of skymap

1.2 x minimum of skymap

skymap

H1+L1+V1+LCGT





minimum of skymap

1.2 x minimum of skymap