All-Sky Search for Gravitational Wave Bursts during the fifth LSC Science Run

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7th Edoardo Amaldi Conference on Gravitational Waves, Sydney, Australia, July 8-14, 2007

LIGO-G070404-06-Z

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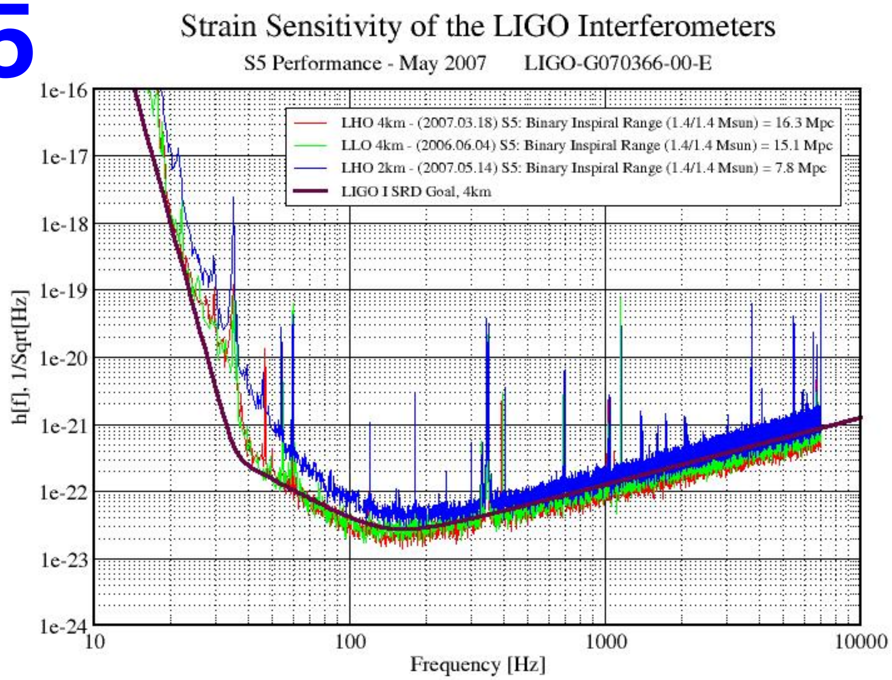
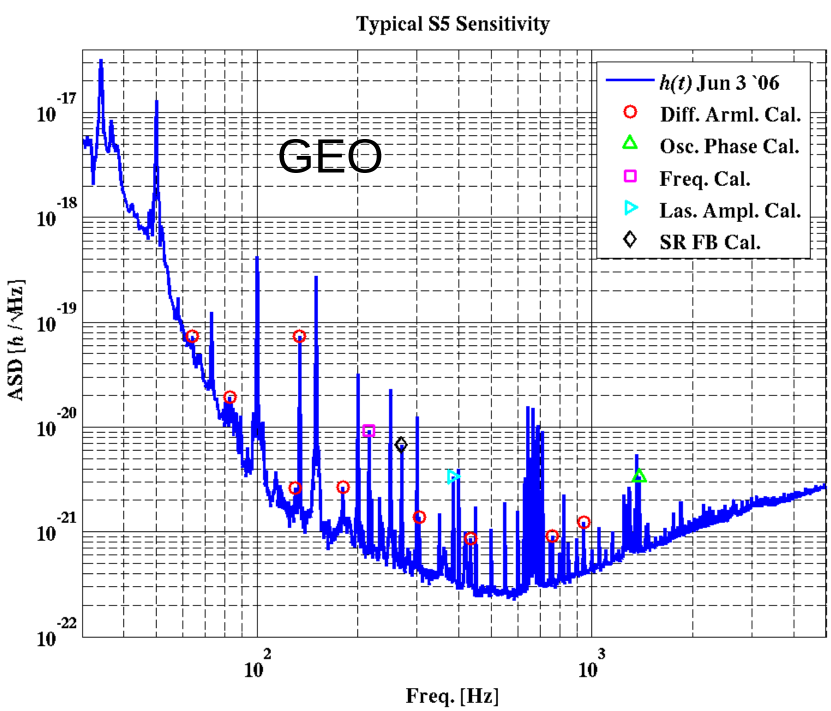
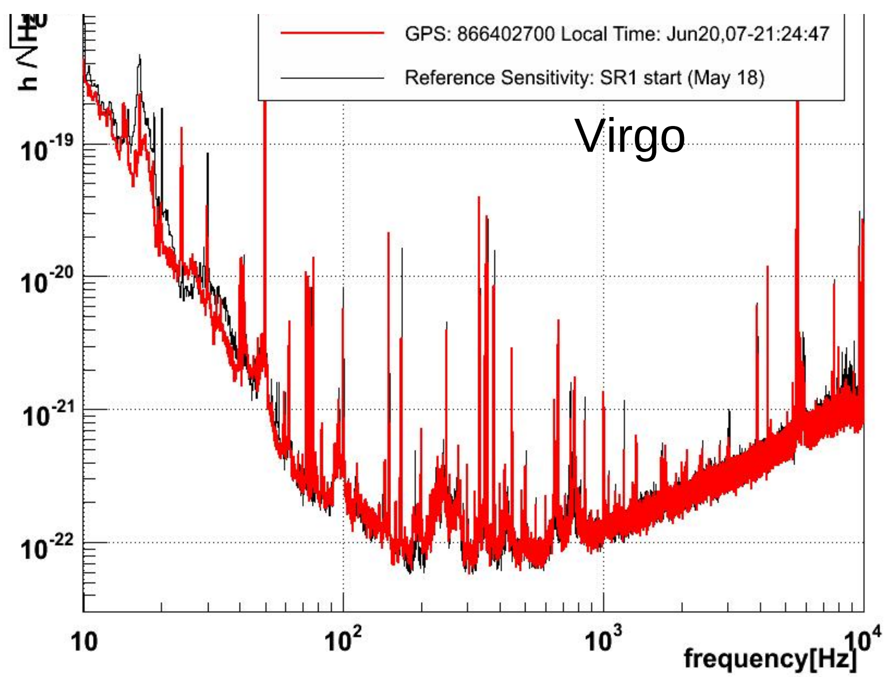
S5

- LIGO 5th Science Run (S5) started in Nov 2005 and will continue till ~Oct 2007 until 1 year of coincidence data is collected. As of 06/26/07 we have collected ~83% of that.
- During S5 GEO was running part time.
- In May 2007 Virgo started its first Science Run. Virgo detector will run till the end of S5.







Coherent and coincidence methods

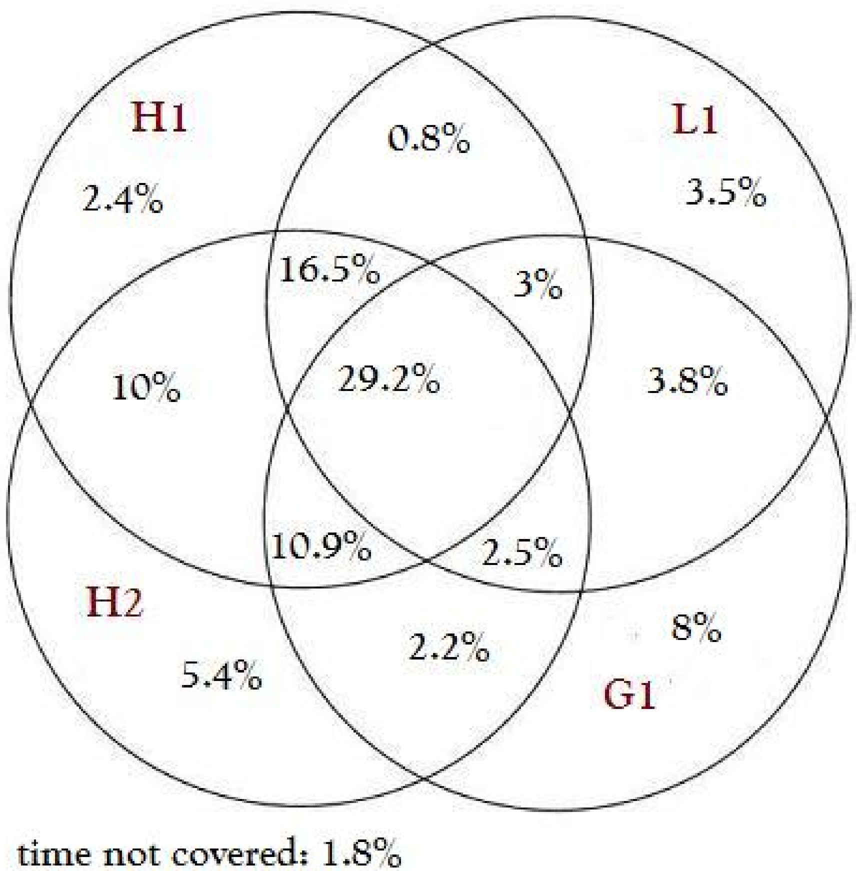
- Coincidence methods:
  - Find excess energy trigger in each detector
  - Select time(-frequency) coincidence triggers
  - Do coherent follow-up of the remaining triggers:
    - Amplitude consistency cut
    - Correlation consistency cut
- Coherent methods:
  - Use a statistic that combines from the beginning in a coherent way data streams from all the detectors
  - Can be used with arbitrary number of aligned or misaligned detectors
  - Waveform and source position reconstruction

Utilizing different networks of detectors

- The more detectors are in the network
  - the more sensitive search can be made
    - less sensitive detectors do not decrease the network sensitivity for coherent search
    - but glitchy detectors might
  - the better we can reconstruct gravitational wave signal and its coordinates
- The fewer detectors are in the network:
  - the more livetime can be analyzed
- For S5 analysis of the first year, we would like to use H1H2L1-, H1H2-, H1L1-, H2L1- networks; also some combinations with G1 (when available)
- Possible problem with H1H2-network: correlated glitches
- Now when Virgo is running, we would like to use it as well

Utilizing different networks of detectors

- Venn's diagrams of livetime for different networks during the first year of S5



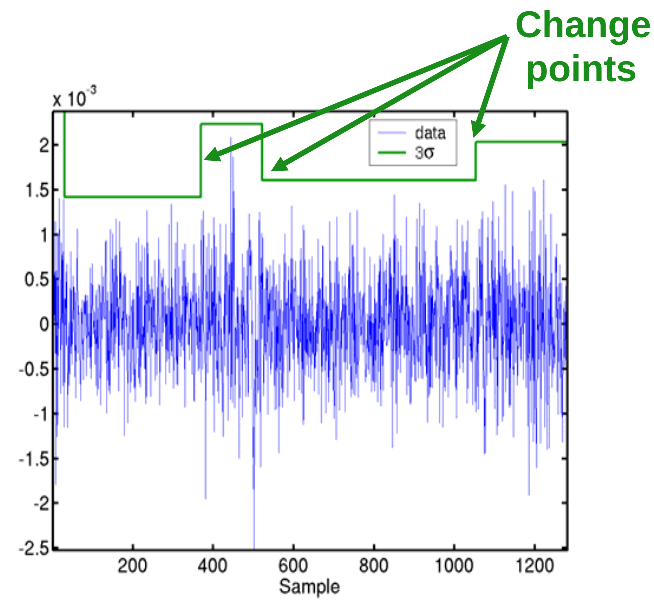
- 100% corresponds to the first year of S5
- During 1.8% of this period no IFO was in Science mode
- Only one detector – 19.3% (not analyzed by burst searches)
- H1H2L1 – 45.7%
- H1H2 – 66.6%
- H1L1 – 49.5%
- H2L1 – 48.2%
- G1H1H2 – 40.1%
- G1H1L1 – 32.2%
- G1H1H2L1 – 29.2%

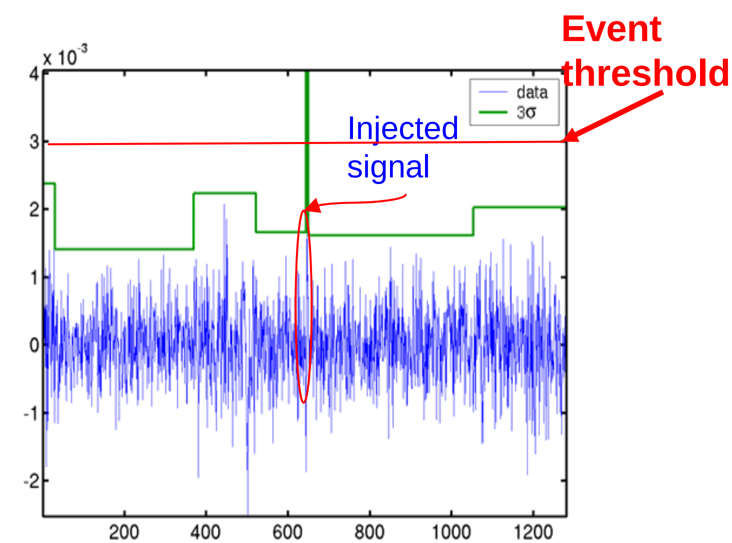
Untriggered all-sky burst searches in S5

- BlockNormal is an example of coincidence pipeline:
  - Coincidence of single detector triggers
  - Coherent follow-up of the resulting triggers using CorrPower
- Coherent WaveBurst is an example of purely coherent method in which coherent statistic is used from the beginning both for detection and reconstruction of signals
- QPipeline is in between coherent and coincidence pipelines:
  - Coherent statistic is applied to the network of co-located H1H2 detectors
  - Coincidence of single detector L1 triggers with H1H2 coherent triggers is taken
  - Coherent follow-up of the resulting triggers using XPipeline

BlockNormal

- Identify change-points in mean, variance of time-series data in each detector
- Threshold on excess power in blocks between change-points
- Use multiple frequency bands to provide coarse frequency resolution
- Select coincident triggers with timing, combined power criteria on H1,H2,L1
- Waveform consistency test (CorrPower) then applied to all coincident triggers





QPipeline

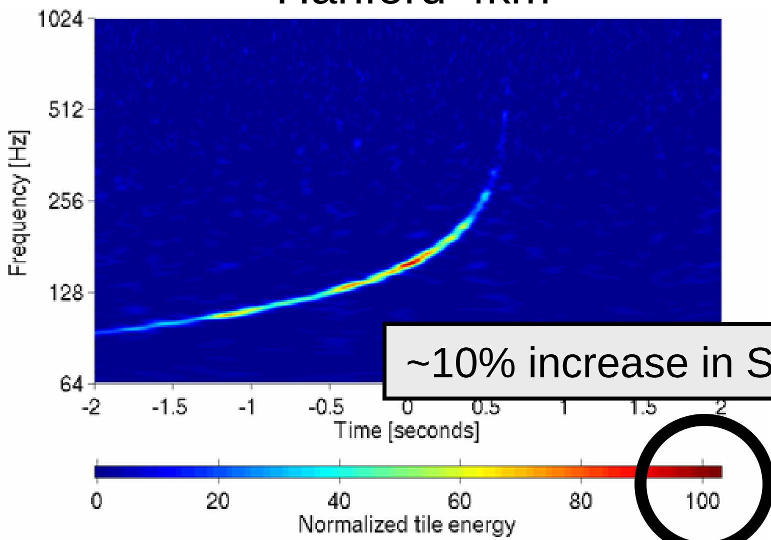
- Multiresolution time-frequency search for gravitational-wave bursts
- Equivalent to templated matched filter search for waveforms that are sinusoidal Gaussians after whitening
- Uses the two co-aligned Hanford detectors to improve sensitivity to bursts and reject instrumental artifacts
  - H+ coherent sum maximizes the signal to noise ratio of bursts
  - H– null stream should be consistent with detector noise
- First step in hierarchical coherent search of LIGO, GEO, Virgo data

$$H_+ = \frac{\frac{H_1}{S_1} + \frac{H_2}{S_2}}{\frac{1}{S_1} + \frac{1}{S_2}}$$

Simulated 1.4/1.4 Msun inspiral injected at 5Mpc

H+ coherent sum

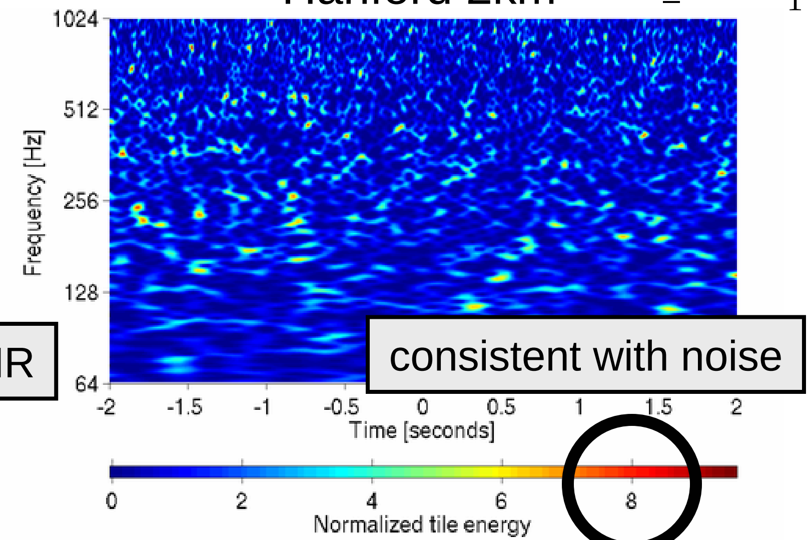
Hanford 4km



H– null stream

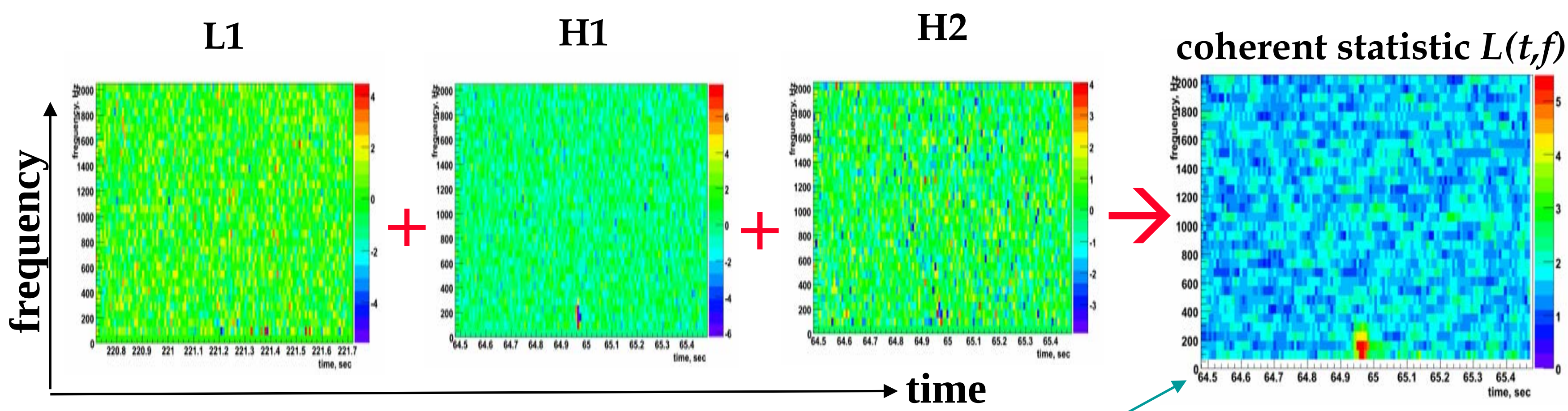
Hanford 2km

$$H_- = H_1 - H_2$$



Coherent WaveBurst

- End-to-end pipeline to search for unmodeled gravitational wave bursts (inspiral mergers, supernova ...)
- Coherent statistic – constrained likelihood - is used both for detection and signal reconstruction
- Time-frequency analysis is done using wavelets
- Analysis of multiple TF resolutions: Δf=8,16,32,64,128,256 Hz, $\Delta f \Delta T = 1/2$
- Reconstruction of source position and waveforms
- Can be applied to any number of (mis)aligned detectors; so far used to analyze the following networks: H1H2L1, H1H2, H1L1, H2L1, G1H1H2L1, H1H2L1V1, G1H1H2L1V1



$$L(t,f) = \max_{h_+ h_\times \theta\varphi} \sum_k \frac{1}{2\sigma_k^2(f)} \left[x_k^2[t,f] - \left(x_k[t,f] - \xi_k[t,f] \right)^2 \right]$$

$$\xi_k = h_+ F_{+k} + h_x F_{xk}$$

Coherent WaveBurst on the first year of S5

- Nov 14 2005 – Nov 14 2006
- 64-2048 Hz
- 100 time shifts to estimate false alarm rate
- L1H1H2, H1H2, H1L1, H2L1, G1-LIGO
- Cut on effective SNR in the network (~average SNR).
- Sensitivity is estimated on sine-gaussian signals of three different durations (Q=3,9,100), gaussians, band-limited white noise software injections
- Triple coincidence livetime in the whole S5 is > 20 times larger than that in S4
- Preliminary estimates of sensitivity suggest ~2 times better sensitivity in S5 for L1H1H2 network search than in S4

Coherent WaveBurst on the first year of S5

- **Preliminary estimate of sensitivity for full year of S5 data:**
  - **not final version of calibration**
  - **not final set of data quality flags**
  - **no vetoes used**
  - **high threshold analysis: 1 event in 46 years**

frequency, Hz	70	100	153	235	361	554	849	1053
Hrss50/1.e-22, strain/sqrt(Hz)	25.3	9.5	6.1	5.1	8.7	9.9	15.2	20

Preliminary

- The sensitivity is given as hrss of a signal at which 50% of injections are detected. hrss is defined as:

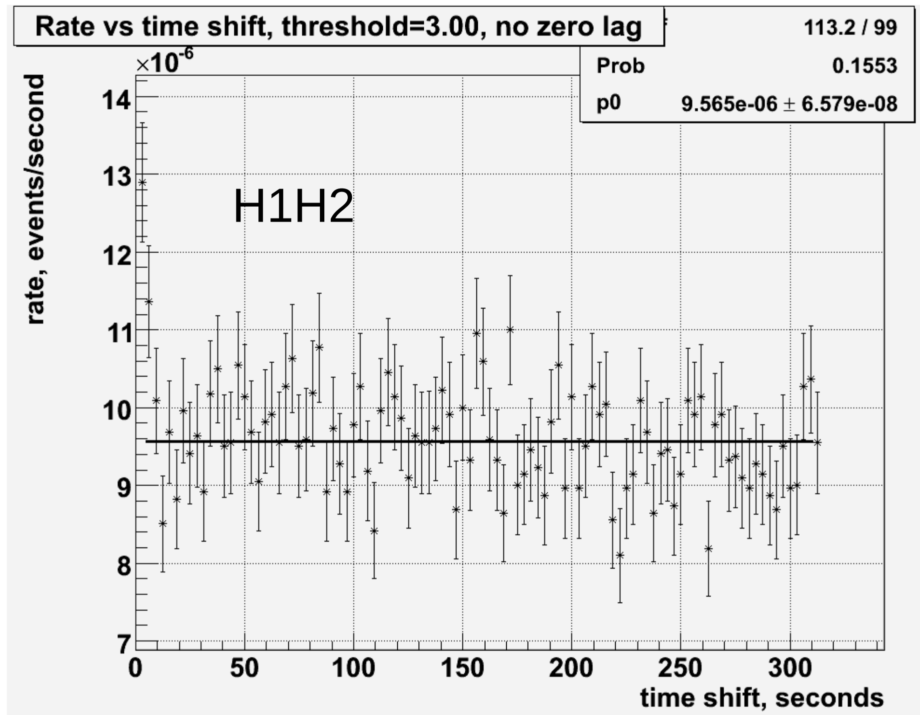
$$h_{rss}^2 = \int \left[h_+^2(t) + h_\times^2(t) \right] dt$$

- The above sensitivities are for sine-gaussian signals with Q=9 and different frequencies

$$h(t + t_0) = h_0 \sin(2\pi f_0 t) \exp\left(-\frac{(2\pi f_0 t)^2}{2Q^2} \right)$$

Coherent WaveBurst on the first year of S5

- Livetime for H1H2 network is about 44% larger:
  - H1H2L1 ~ 179 days
  - H1H2 ~ 258 days
- Other 2-detector networks add just a few percent of livetime in comparison with H1H2L1
- On sine-gaussian software injections, sensitivity of the search for H1H2L1 network is almost twice better than sensitivity for H1H2 network



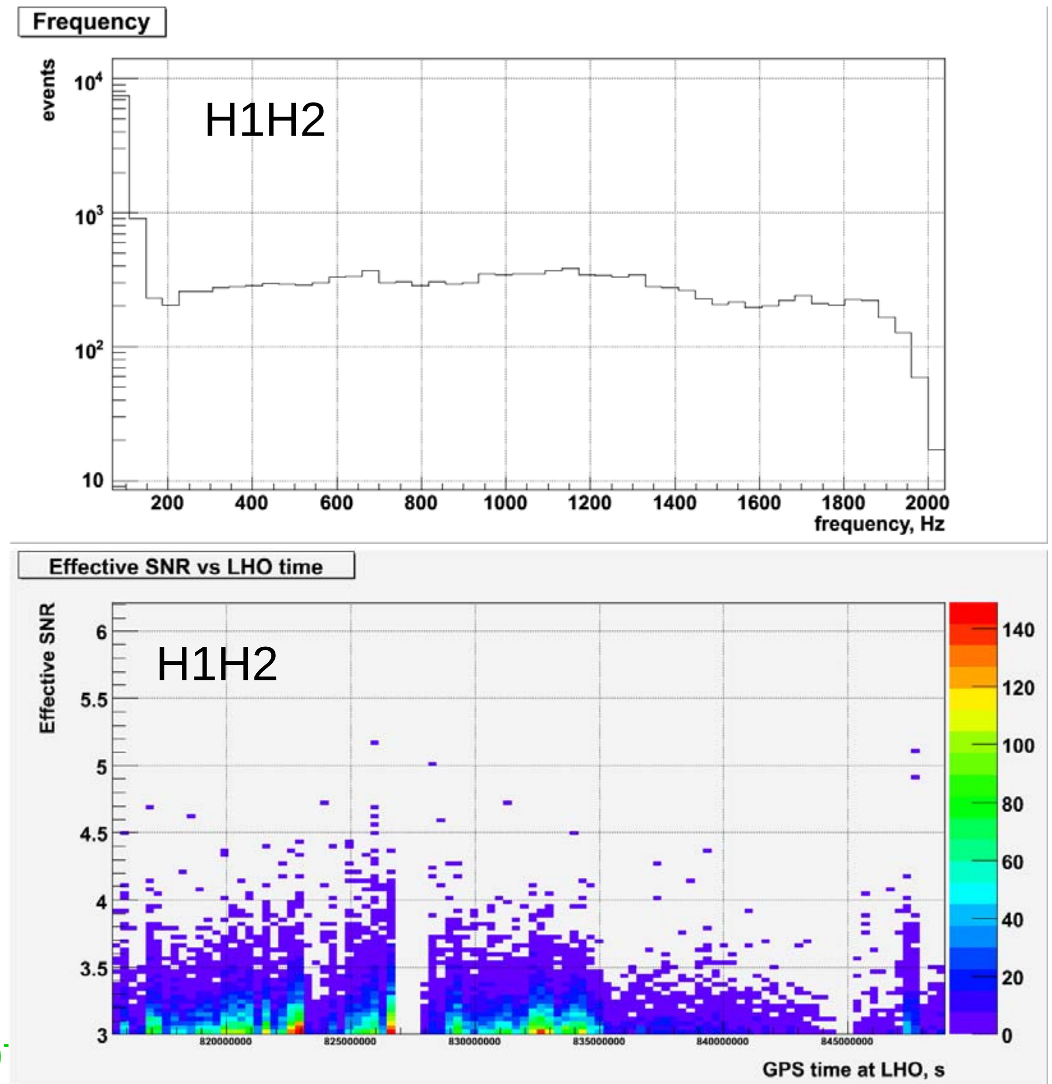
- For H1H2 network we also have to worry about correlated glitches: for small non-zero time shifts the rate increases!

Need good vetoes!

Coherent WaveBurst on the first year of S5

- Distribution of time-shifted triggers over frequency shows that most of the triggers are at low frequency and demonstrates the need for frequency-dependent cut
- Effective SNR vs time plot on time-shifted triggers shows that there are several epochs in the data and suggests to use time-dependent threshold on effective SNR
- Both statements are true for all LIGO detector networks

On time-shifted H1H2 triggers:



Conclusion & plans

- We are using both coherent and coincidence methods to analyze S5 data. The final upper limit result will be given for the most sensitive method to be determined.
- We are using all possible LIGO 2- and 3-detector combinations to maximize sensitivity and livetime of the search. It is still an open question how to combine these searches.
- We plan also to use GEO when available in some combinations with LIGO detectors.
- In May 2007 Virgo started its first science run which will continue till the end of S5 (~Oct 2007). We plan to do joint LIGO-GEO-Virgo search for gravitational wave bursts. As an exercise we have done it on one Sep 2006 weekend of data

  (project 2b, see S. Chatterji presentation) using different methods developed both at LIGO and Virgo.

Abstract

- Title: All-Sky Search for Gravitational Wave Bursts during the fifth LSC Science Run
- Speaker: Igor Yakushin for the LIGO Scientific Collaboration
- The fifth science run of LSC instruments, S5, started in November 2005, is still in progress and is expected to collect one year of coincidence data. We report on the status of searches for unmodeled gravitational wave bursts in the first year of S5 (Nov 2005 - Nov 2006). We employ both coherent and coincidence methods. All the two- and three-detector networks were studied to maximize the analyzed livetime, sensitivity and improve signal reconstruction.

Maximum Likelihood Ratio method for GW detection

Flanagan, Hughes, PRD57 4577 (1998)

Likelihood ratio: $L(x\,|\,H_i) = \ln\left(\frac{P(x\,|\,H_i)}{P(x\,|\,0)}\right)$, $P(x\,|\,H_i)$ - probability to measure x given hypothesis H_i

Maximum Likelihood Ratio: $L_{MLR}(x) = \max_{H_i}\left(L(x\,|\,H_i)\right)$

In case of stationary gaussian detector noise: $$L(x\,|\,h_+, h_x) = \sum_{k=1}^{K}\sum_{i=1}^{N}\frac{1}{\sigma_k^2}\left(x_k[i]\xi_k[i] - \frac{1}{2}\xi_k^{\,2}[i]\right)$$

k – detector index, i – sample index

Detector response: $\xi_k[i] = F_{+,k}(\theta,\varphi)h_+[i] + F_{x,k}(\theta,\varphi)h_x[i]$

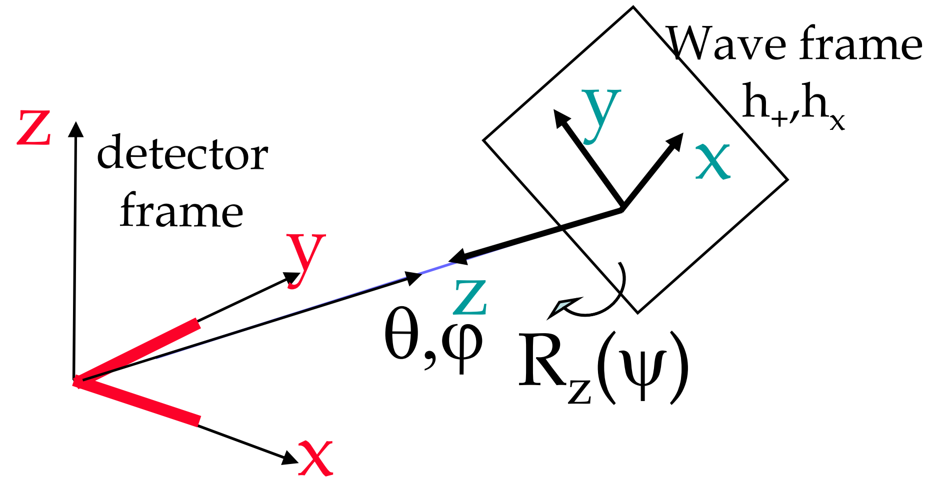
- For the given point in the sky (θ,φ) maximize L to determine h_+ and h_x.
- Maximize L (or other statistic) over (θ,φ) to determine the most probably source coordinates.
- Use L as detection statistic.
- There is a problem with this approach: for some source coordinates (depending on the network) the solution might be ill-defined.

Network Response Matrix

- **Dominant Polarization Frame**

$$\sum_k \frac{F_{+k}(\Psi_{DPF})F_{\times k}(\Psi_{DPF})}{\sigma_k^2} = 0$$

all observables are *RZ(Y)* invariant



- **DPF solution for GW waveforms satisfies the equation**

$$\begin{bmatrix} \sum_k \frac{x_k[i]}{\sigma_k^2} F_{+k} \\ \sum_k \frac{x_k[i]}{\sigma_k^2} F_{\times k} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \sum_k \frac{F_{+k}^2}{\sigma_k^2} & 0 \\ 0 & \sum_k \frac{F_{\times k}^2}{\sigma_k^2} \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} \rightarrow \begin{bmatrix} X_+ \\ X_\times \end{bmatrix} = g \begin{bmatrix} 1 & 0 \\ 0 & \varepsilon \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix}$$

g **– network sensitivity factor**

ε **– network alignment factor**

network response matrix

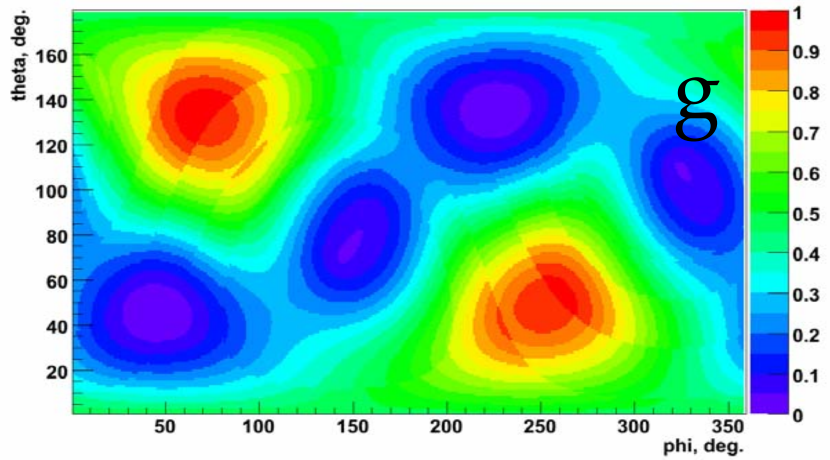
(Klimenko et al PRD 72, 122002, 2005)

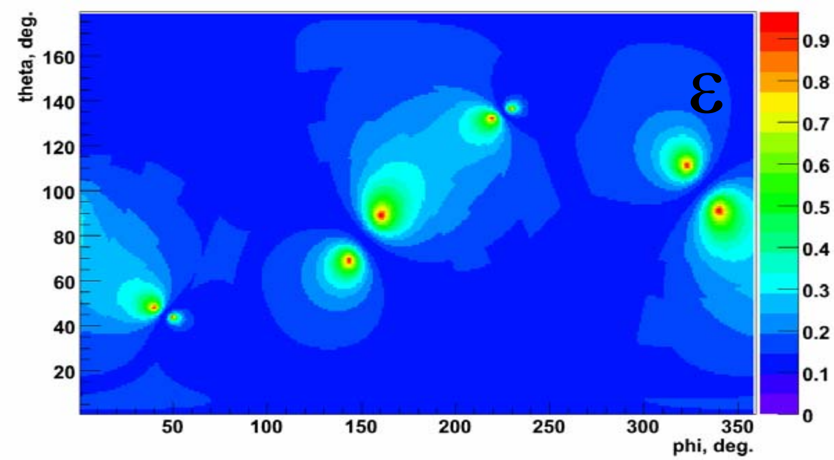
Constrained likelihood

- **Any network can be described as two virtual detectors**

detector	output	noise var.	likelihood	SNR
plus	X_+	g	$L_+ = X_+^2/g$	$g\int h_+^2 dt$
cross	X_x	εg	$L_x = X_x^2/\varepsilon g$	$\varepsilon g \int h_\times^2 dt$

L1xH1xH2 network not sensitive to h_x for most of the sky





- **Use constraint on the solutions for the h_x waveform.**
  - **remove un-physical solutions produced by noise**
  - **may sacrifice small fraction of GW signals but**
  - **enhance detection efficiency for the rest of sources**

Network sensitivity

$$SNR_{tot} = g\left[\left\langle h_1^2 \right\rangle + \varepsilon \left\langle h_2^2 \right\rangle\right]$$

Assumption: all the detectors have the same sensitivity

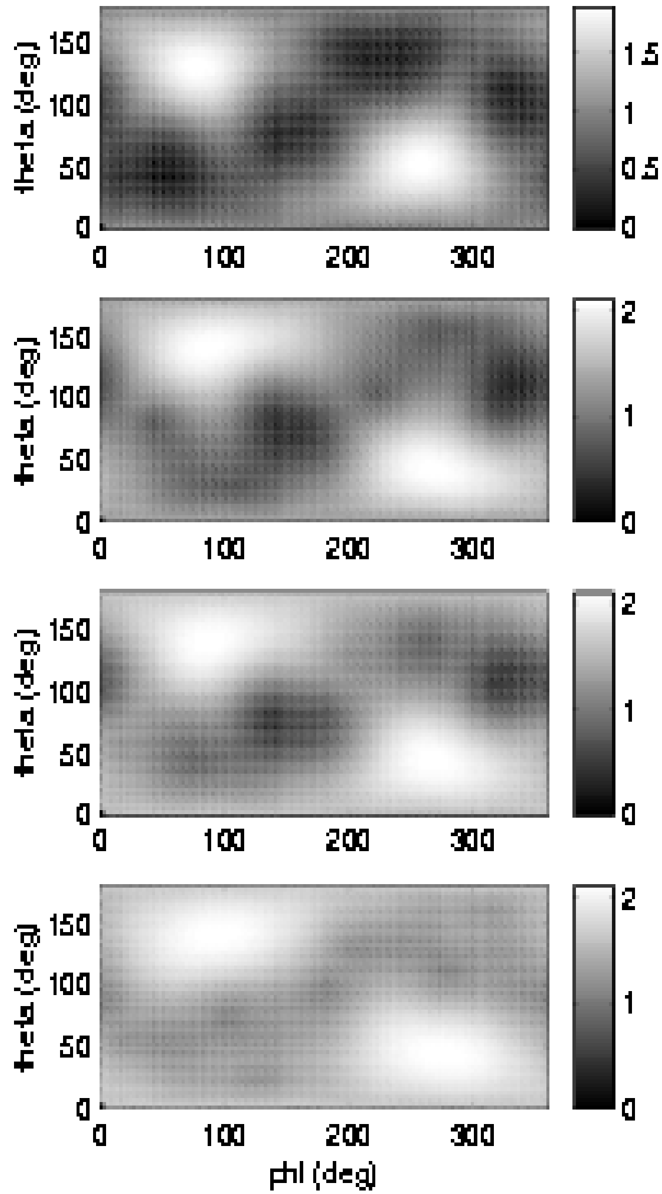
need several detectors for better sky coverage

H1-L1

+GEO

+VIRGO

+TAMA



Sensitivity of all-sky burst search in S4

- For an estimated average background of 0.04 triggers over S4 observation time [http://arxiv.org/abs/0704.0943v1]: