Coherent all-sky search for gravitational wave bursts with LIGO, GEO and VIRGO detectors

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Coherent vs coincidence methods

- Coincidence methods:
  - Find excess energy trigger in each detector;
  - Select time(-frequency) coincidence triggers;
  - Do (semi)coherent follow-up of the remaining triggers (L. Cadonati, K.Thorne talks):
    - Amplitude consistency cut;
    - Correlation consistency cut, etc.
- 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 coordinate 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: $\xi_k[i] = F_{+,k}(\theta,\varphi)h_+[i] + F_{x,k}(\theta,\varphi)h_x[i]$

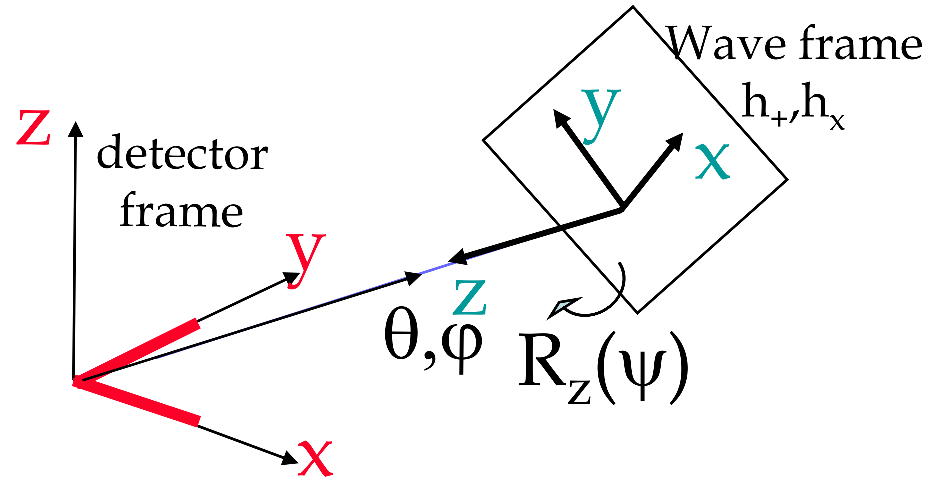
- For the given point in the sky (θ,φ) maximize L to determine h_+ and h_x.
- Maximize L (or other statistic) over (θ,φ) to determine the most probably source coordinates.
- Use L as detection statistic.
- There is a problem with this approach: for some source coordinates (depending on the network) the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

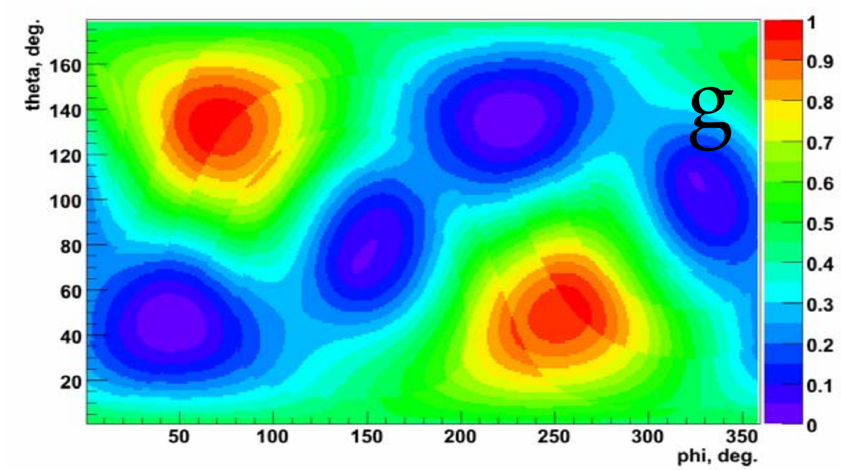
(Klimenko et al PRD 72, 122002, 2005)

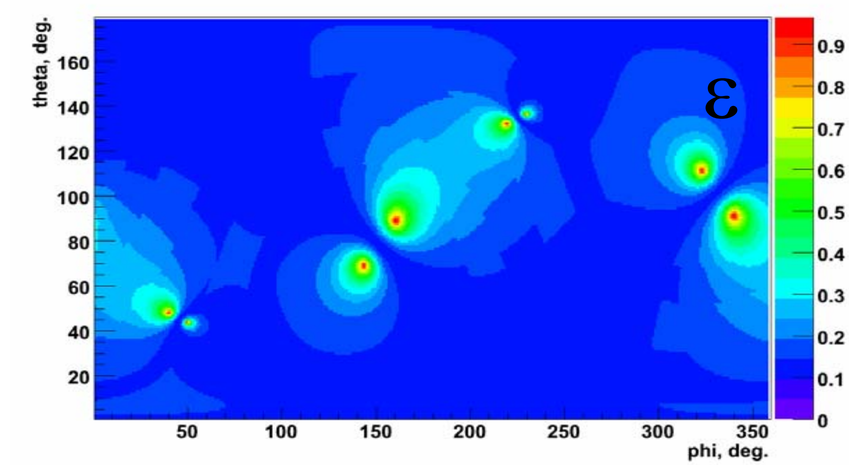
Constrained likelihood

- **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

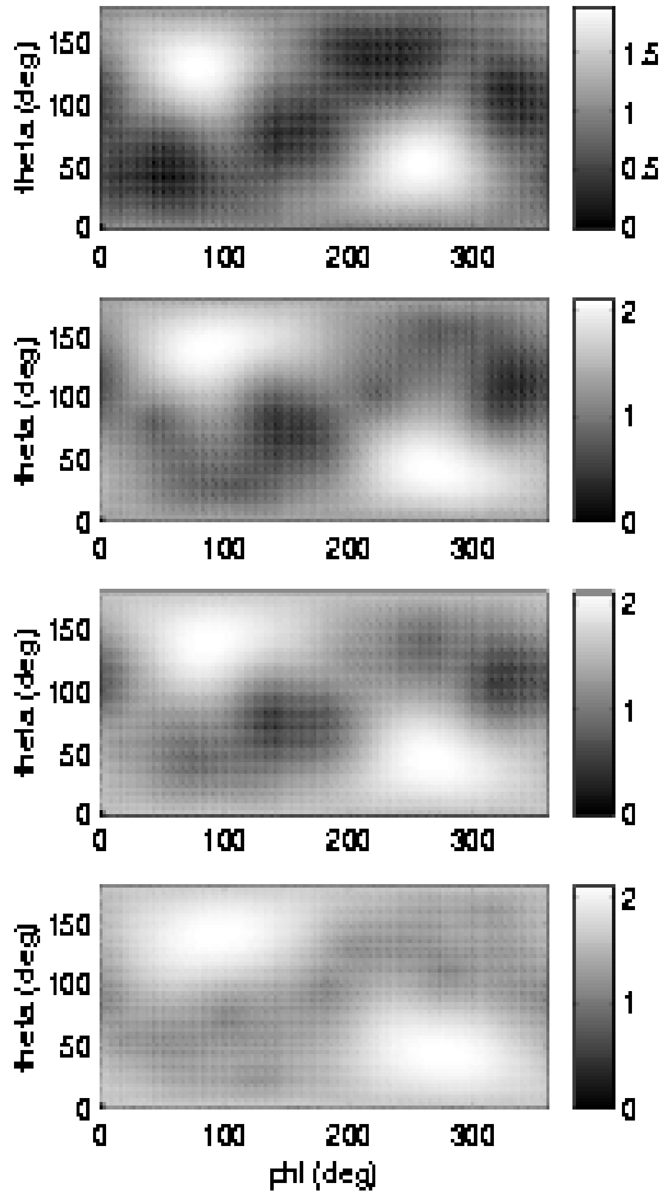
need several detectors for better sky coverage

H1-L1

+GEO

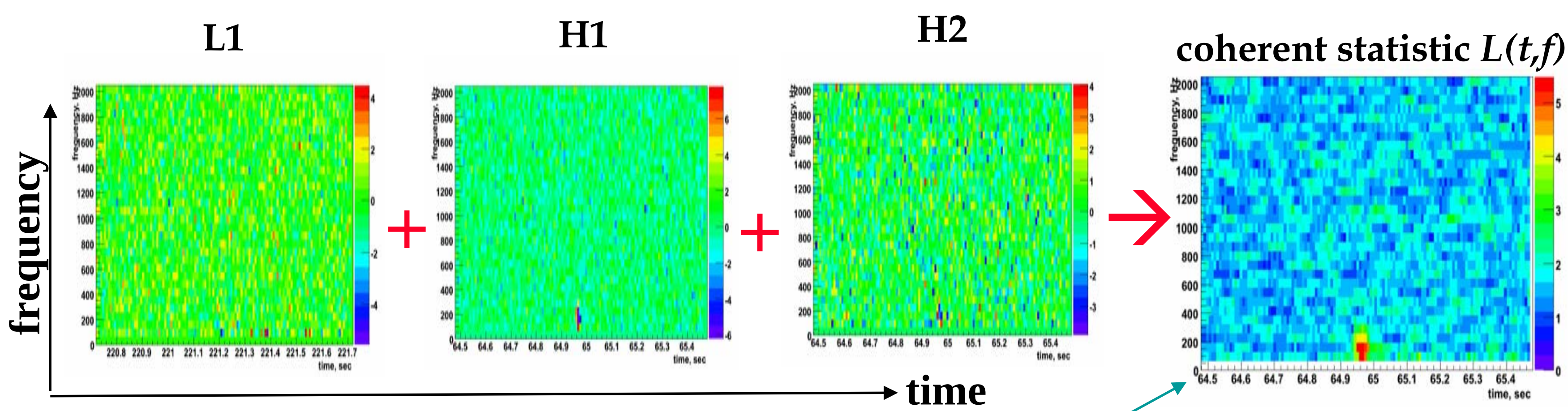
+VIRGO

+TAMA



Coherent WaveBurst

- End-to-end pipeline to search for unmodeled gravitational wave bursts (inspiral mergers, supernova, GRBs,...).
- 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 coordinates and waveforms (A.Mercer talk).



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

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

similar method is described in M. Rakhmanov's talk

Coherent WaveBurst

- Coherent WaveBurst was used for analysis of the following datasets:
  - S4 LIGO-GEO:
    - No candidate events found;
    - Comparison of coherent and incoherent methods;
    - Paper in preparation;
  - S5a LIGO:
    - Nov 17, 2005 – April 3, 2006, livetime 54.4 days (for the incoherent analysis of the same data set see L. Cadonati's talk);
  - S5 full year LIGO:
    - Nov 17, 2005 – Nov 17, 2006, livetime 166.6 days;
  - S5 LIGO-GEO:
    - Jun 1, 2006 – Nov 17, 2006, livetime 83.3 days;
  - LIGO-VIRGO-GEO project 2b:
    - Project is carried out jointly with the VIRGO collaboration;
    - Sep 8, 2006 – Sep 10, 2006;
    - S5 LIGO-GEO run;
    - WSR1 (**W**eekend **S**cientific **R**un) VIRGO run;
    - artificial time shifts between detectors.

LIGO-VIRGO-GEO Project 2b
jointly with VIRGO collaboration

- Data
  - Sep. 8, 2006 – Sep. 10, 2006
  - includes LIGO-GEO S5 data and VIRGO WSR1 data
  - sensitivity of VIRGO detector is comparable with H2 above 500Hz
- Goal
  - establish data exchange between LSC and VIRGO
  - exercise data analysis algorithms
  - do joint analysis with VIRGO collaboration
- Studies with coherent WaveBurst
  - H1H2, L1H1, L1H1H2, L1H1H2V1, L1H1H2G1, L1H1H2V1G1
  - frequency band 256-2048 Hz (limited by VIRGO & GEO)
  - false alarm rates are estimated from *time-shifted data* (100 time lags)
  - detection efficiency is estimated by using sine-Gaussian injections
  - Status
    - In progress
  - Preliminary lessons
    - Adding less sensitive detector does not degrade network sensitivity
    - Source coordinate reconstruction gets better as more detectors are added to the network

S5a LIGO:

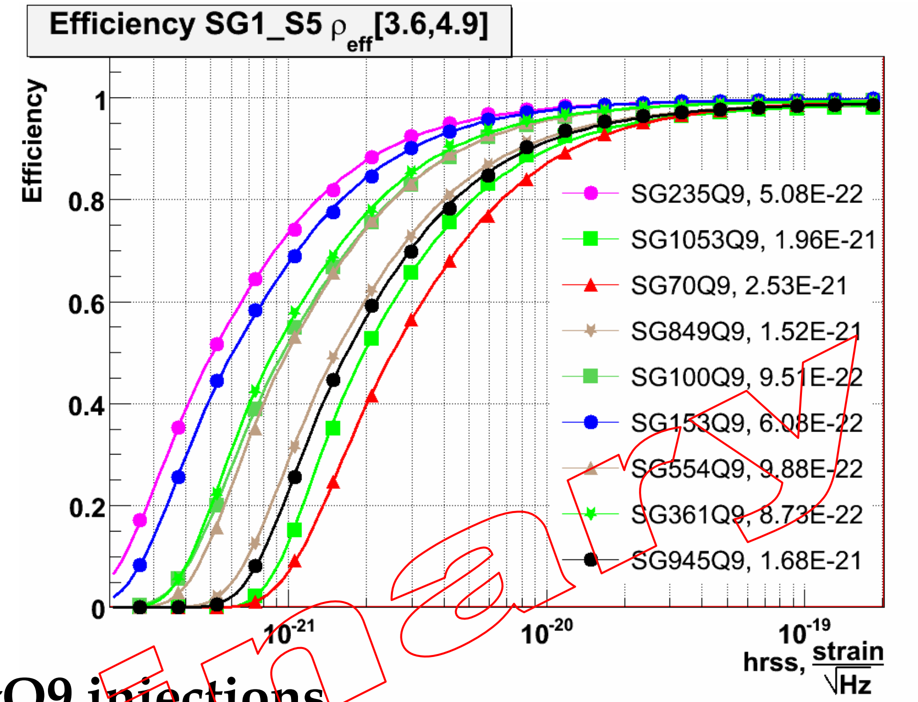
Nov 17, 2005-Apr 3, 2006

- 64-2048 Hz;
- 100 time shifts to estimate false alarm rate;
- L1H1H2;
- Short and long sine-gaussian, gaussian, band-limited white noise waveforms to estimate sensitivity;
- The results can be compared with incoherent WaveBurst + CorrPower analysis (L. Cadonati talk) and other coincidence methods (K. Thorne talk).

S5

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

- Coherent WaveBurst pipeline is more sensitive than incoherent WaveBurst + CorrPower pipeline at about the same false alarm rate.
- The difference in sensitivity is especially noticeable for 70 Hz sine-gaussian: incoherent pipeline used H1H2 amplitude consistency cut but amplitudes were not reconstructed well at this frequency.



hrss@50% in units 10^{-22} for sgQ9 injections

rate	Search	70	100	153	235	361	553	849	1053
S5a: 1/2.5y	WB+CP	40.3	11.6	6.2	6.6	10.6	12.0	18.7	24.4
S5a: 1/3y	cWB	28.5	10.3	6.0	5.6	9.6	10.7	16.9	21.9

expected sensitivity for full year of S5 data for high threshold coherent search

S5: 1/46y	cWB	25.3	9.5	6.1	5.1	8.7	9.9	15.2	20.0

Conclusion & Plans

- Coherent algorithms are now available to handle arbitrary networks of gravitational wave detectors.
- On S5a data coherent WaveBurst is more sensitive than incoherent WaveBurst + CorrPower search.
- Waiting for final data quality segments and calibration to redo the analysis of the full year of S5.
- We plan to use all the detector combinations for LIGO-only S5 analysis: L1H1H2, H1H2, H1L1, H2L1.
- When available, GEO data will also be (re)analyzed.
- In a month VIRGO plans to join S5 and exchange data with LIGO and we are ready to apply coherent WaveBurst pipeline to the joint burst search .