Analysis of S5 data
with coherent WaveBurst pipeline

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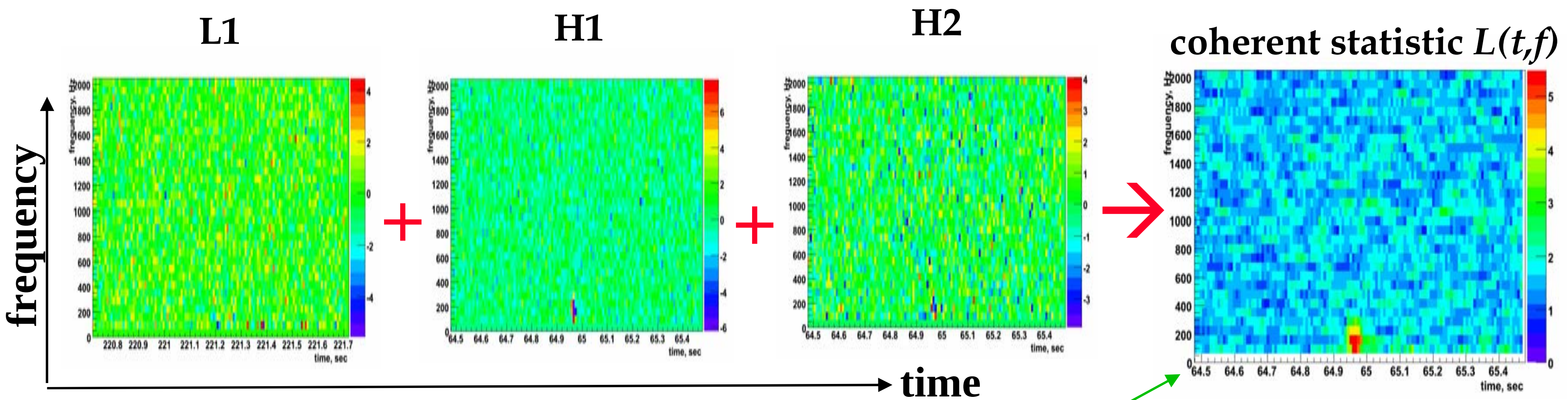
for the LSC-Virgo burst group

- **coherent WaveBurst pipeline**
- **Preliminary results from un-triggered all-sky search**
- **Study of network configurations with project 2b data**
- **Application to GRB searches**
- **Coherent Event Display**
- **Summary**

Coherent WaveBurst

End-to-end multi-detector coherent pipeline based on constrained L method

- **target detection of burst sources (inspiral mergers, supernova, GRBs,...)**
- **for confident detection combines data from several detectors**
  - **handle arbitrary number of co-aligned and misaligned detectors**
  - **reconstruction of source coordinates and GW waveforms & detector responses ξ_k**
  - **use coherent statistics for elimination of instrumental/environmental artifacts**



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

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

- **accounts for**
  - **variability of the detector responses as function of source coordinates**
  - **differences in the strain sensitivity of the GW detectors**

status of the cWB pipeline

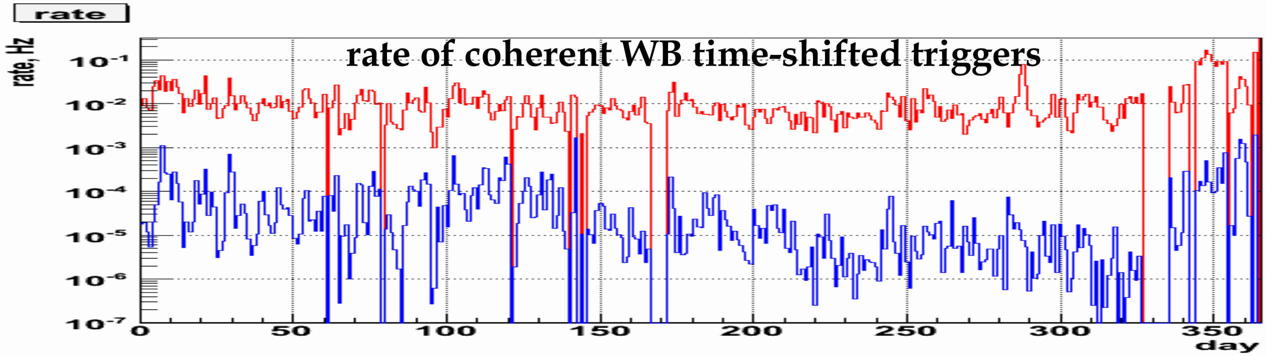
- **Development is "complete" (there is always room for improvement…)**
- **Review is complete (M.Zanolin, K.Riles, B.O'Reilly)**
  - **report draft: LIGO note** LIGO-T040155-00-Z
- **Documentation**
  http://tier2.phys.ufl.edu/~klimenko/waveburst/S5/coherent/s5allsky.html
  - **method paper PRD 72, 122002** **technical note** **project web page**
- **Performed preliminary studies for the following data sets**
  - **LIGO network**
    - **S5a, Nov 17/05 – Apr 3/06, live time 54.4 days**
    - **S5 (full year), Nov 17/05 - Nov 17/06, live time 166.6 days (x10 of S4 run)**
  - **LIGO-Geo network**
    - **S4 data, NO events observed in zero lag**
    - **S5 (full year), Jun 1/06 - Nov 17/06, live time 83.3 days**
  - **LIGO-Virgo run 2b data**

cWB Selection cuts

- **Trigger production cut**
  threshold on the likelihood of the TF pixels *L(t,f)*
- **Post-production cuts (control FA rate and sensitivity)**

$$E_{tot} = 2L + N_{ull} = E_{incoherent} + E_{coherent} + N_{ull}$$

  - **double OR coincidence** $L - L_{L1} > T \,\&\, L - L_{H1} > T \,\&\, L - L_{H2} > T \ldots$
  - **network correlation coefficient** $C_{net} = \frac{E_{coherent}}{N_{ull} + E_{coherent}}$
  - **average SNR per detector**
    ρ_k – estimated detector SNR $\rho = \frac{1}{n}\sum_{1}^{n} \rho_k$ or $\rho = \left(\prod \rho_k\right)^{1/n}$

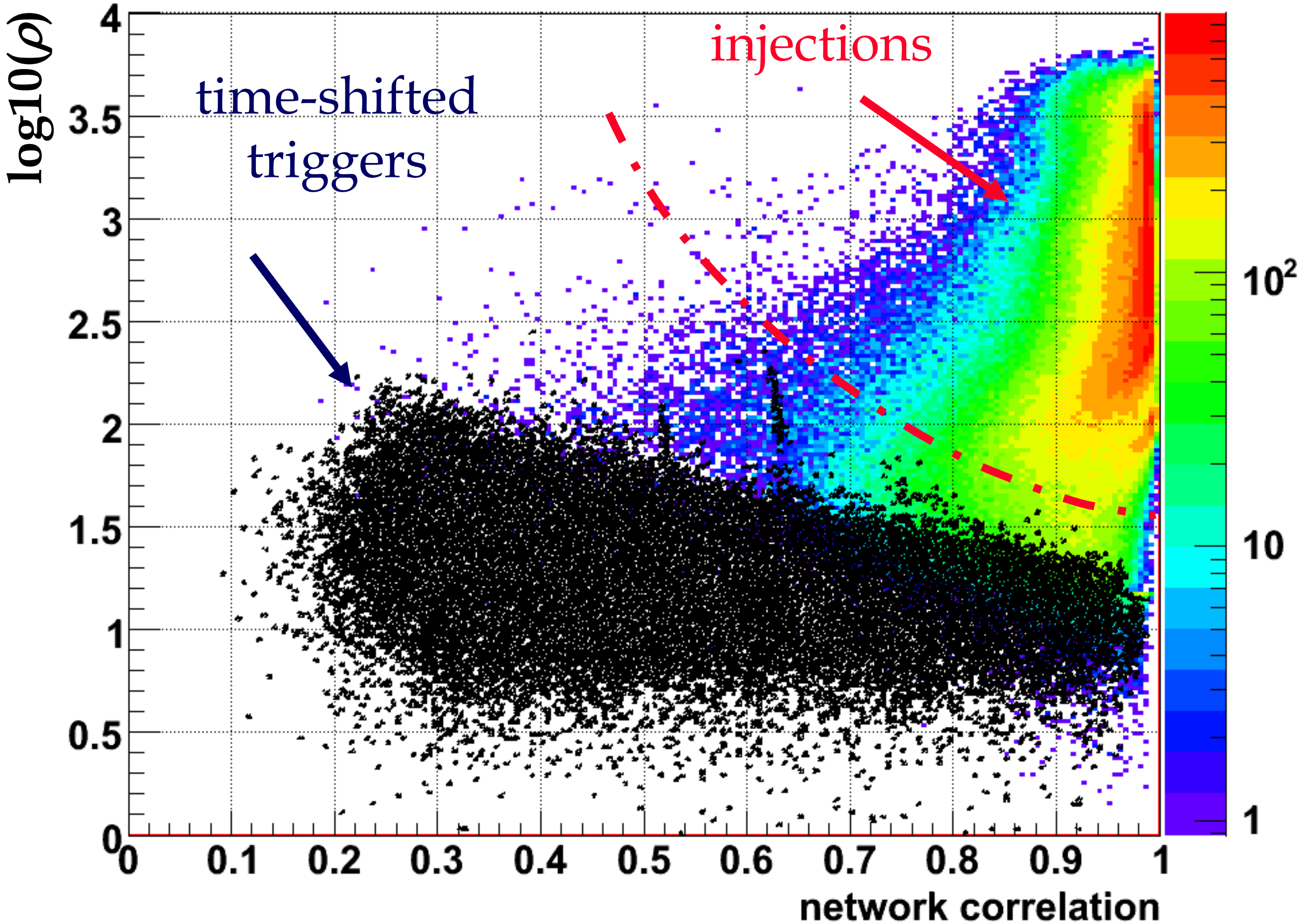


"single glitches"

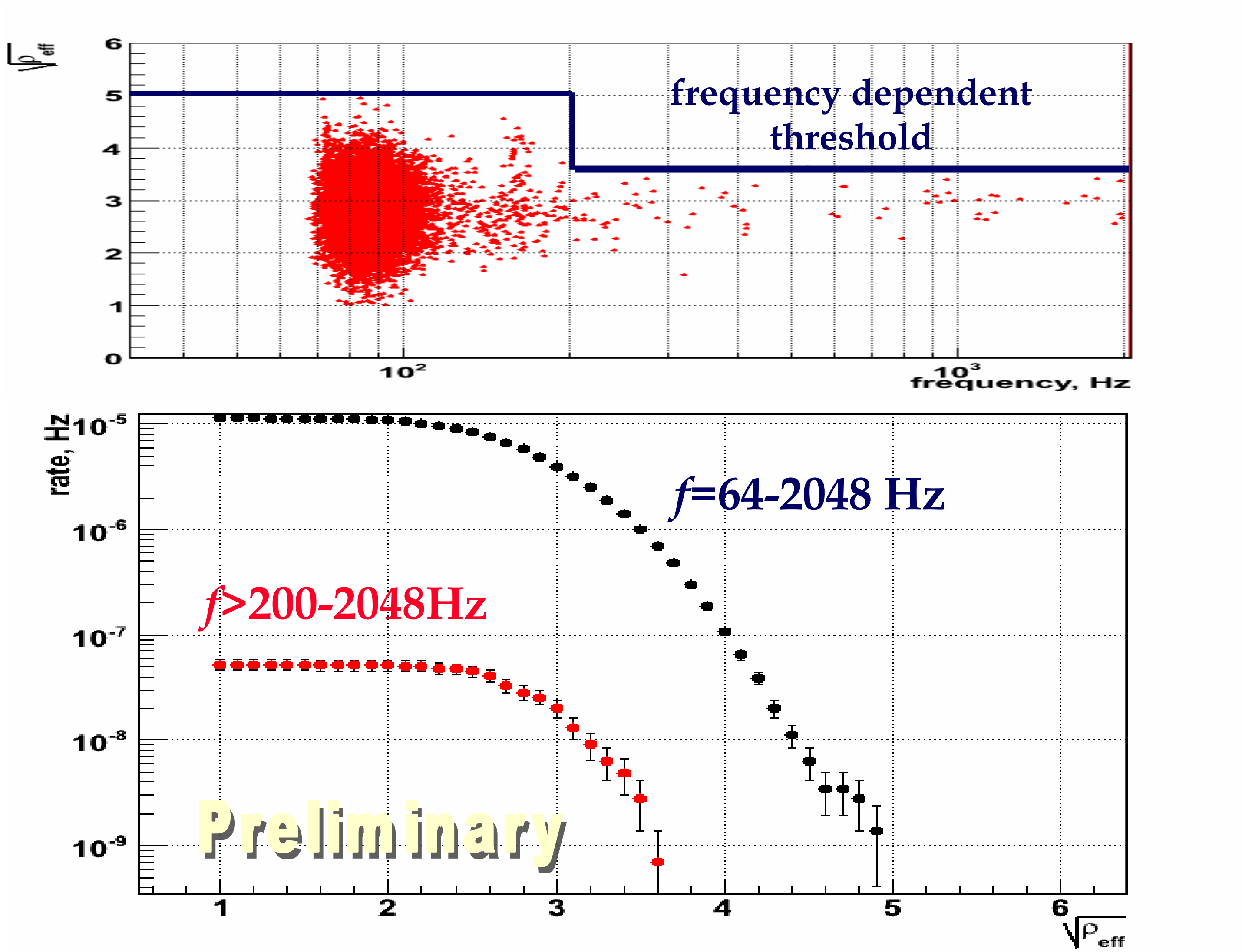
"double glitches"
T=36

Effective SNR

$$\rho_{eff} = \rho^{C_{net}}$$



S5 Rates



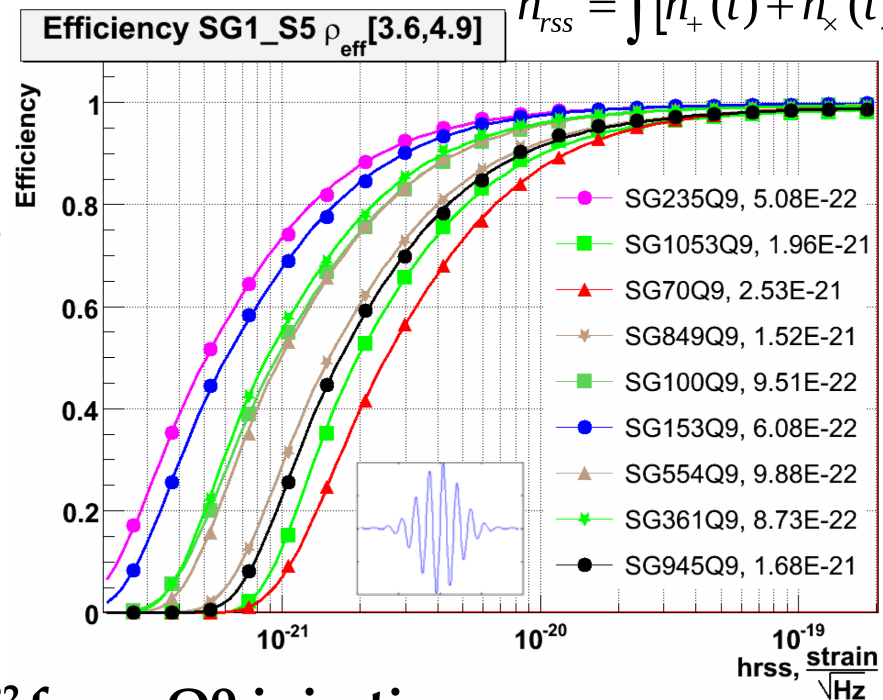
expected background rate of <1/46 year for a threshold of $\sqrt{\rho_{eff}} = [3.6, 5.0]$

Detection efficiency for bursts

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

- Use standard set of ad hoc waveforms (SG,GA,etc) to estimate pipeline sensitivity
- Coherent search has comparable or better sensitivity than the incoherent search
- Very low false alarm rate (~1/50years) is achievable

Preliminary



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

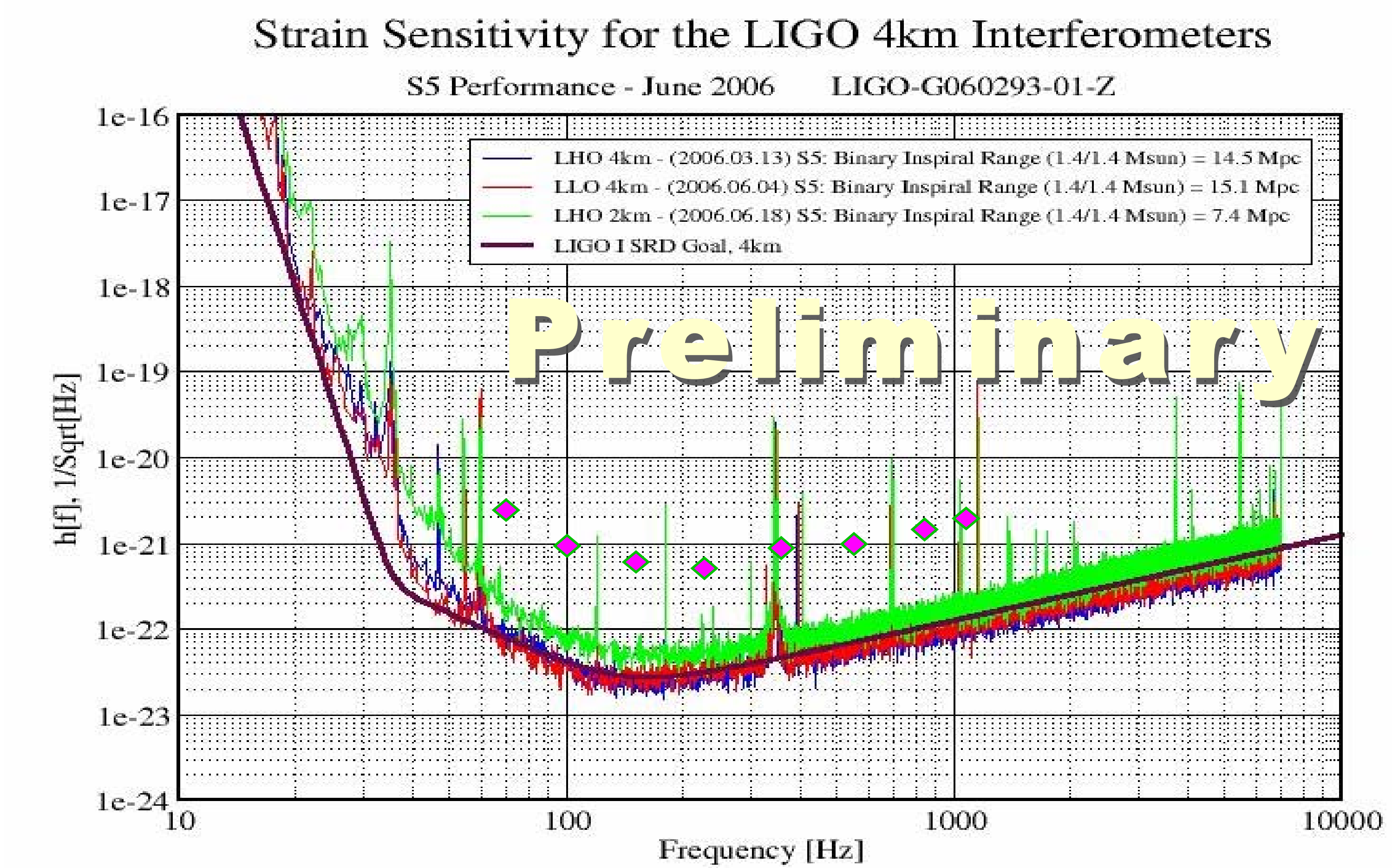
expected sensitivity for full year of S5 data for high threshold coherent search

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

High threshold coherent search

set thresholds to yield no events for 100xS5 data (rate ~1/50 years)

◆- expected S5 all-sky sensitivity to sine-gaussian scalar waves



Status of the S5 all-sky search

- **preliminary results (no zero lag) reported on GWDAW11**
- **plan APS presentation (by Igor Yakushin)**
- **wait for final calibration, DQ flags and veto. After that need few weeks to finalize search**
- **meanwhile study H1xH2, L1xH1 network configurations**

Analysis of project 2b data

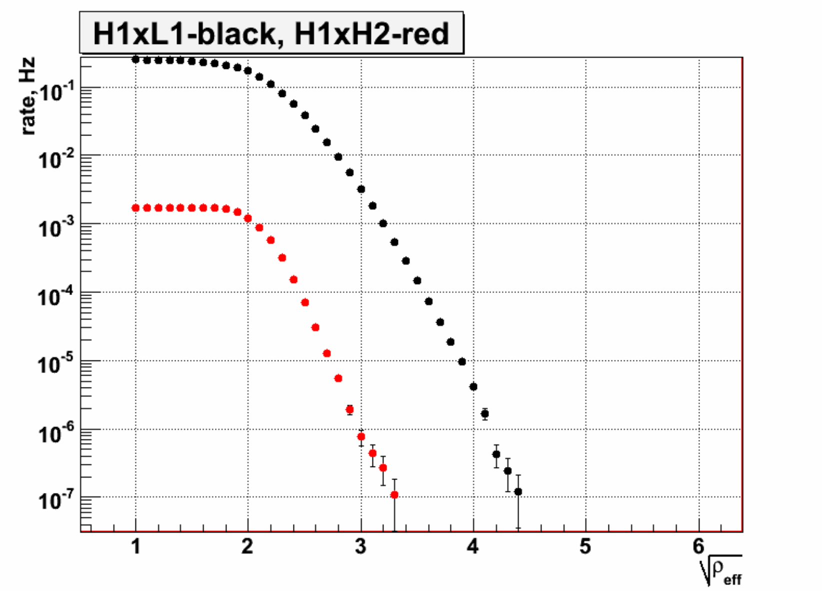
- **project 2b data (*includes LIGO-GEO and WSR1 Virgo data*)**
  - **Sep. 8, 2006 – Sep. 10, 2006**
  - **establish data exchange between LSC and Virgo**
  - **exercise data analysis algorithms**

- **studies with coherent WaveBurst**
  - **Igor run different network configurations:**
    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**

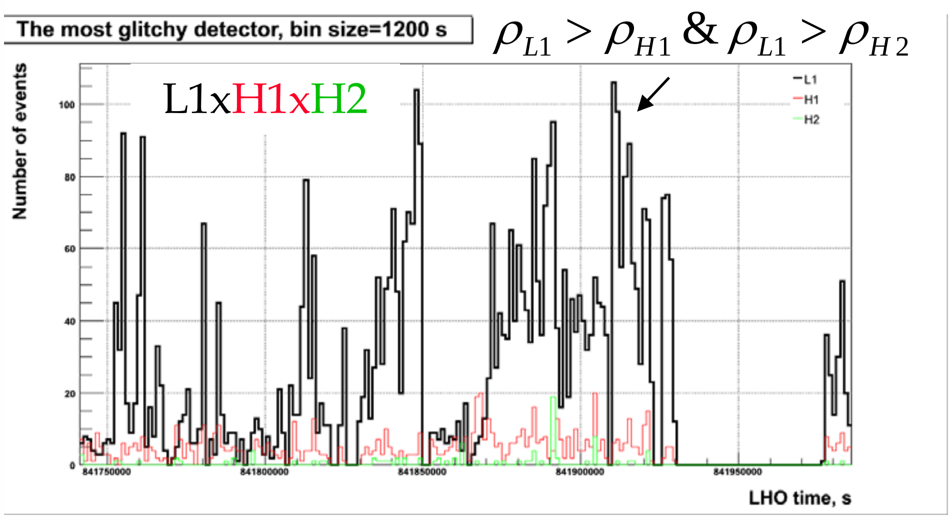
LIGO network

- **performance at FA rate of 1μHz**

network	hrss@50% sg361q9	hrss@50% sg849q9	hrss@50% sg1615q9	live time sec
H1xH2	11×10^{-22}	16×10^{-22}	31×10^{-22}	182772
L1xH1	10×10^{-22}	21×10^{-22}	46×10^{-22}	157599
L1xH1xH2	8×10^{-22}	14×10^{-22}	37×10^{-22}	157599



relative glitch rates of the detectors



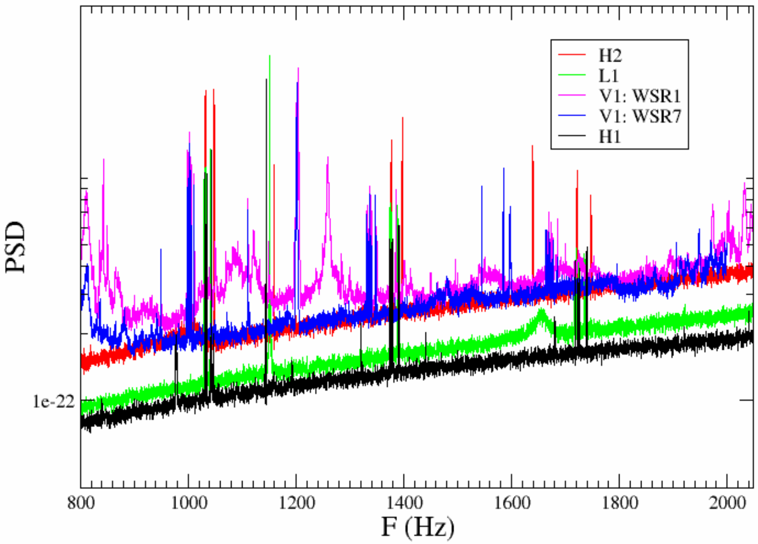
LIGO-Virgo-GEO network

- **performance at FA rate of 1μHz**

h_{rss} errors ~15%

network	hrss@50% sg361q9	hrss@50% sg849q9	hrss@50% sg1615q9	live time sec
H1xH2	11×10^{-22}	16×10^{-22}	31×10^{-22}	182772
L1xH1xH2	8×10^{-22}	14×10^{-22}	37×10^{-22}	157599
L1xH1xH2xV1	9×10^{-22}	17×10^{-22}	40×10^{-22}	104062
L1xH1xH2xG1	9×10^{-22}	16×10^{-22}	41×10^{-22}	140351
L1xH1xH2xV1xG1	9×10^{-22}	16×10^{-22}	42×10^{-22}	102907

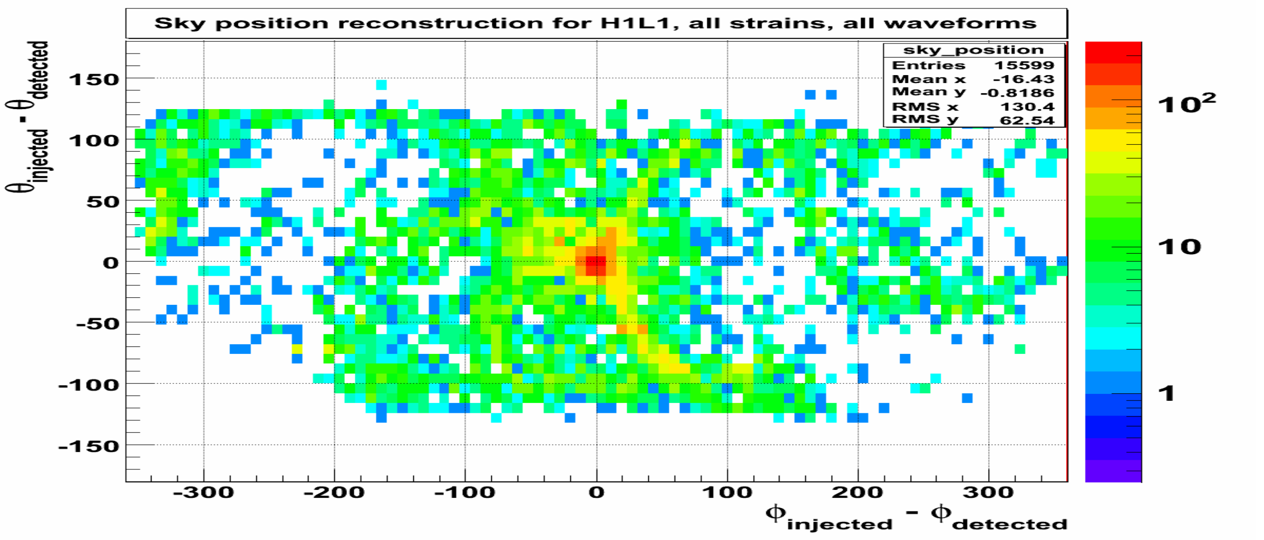
both sensitivity and stationarity of the noise are critical for a detector to be useful in the network



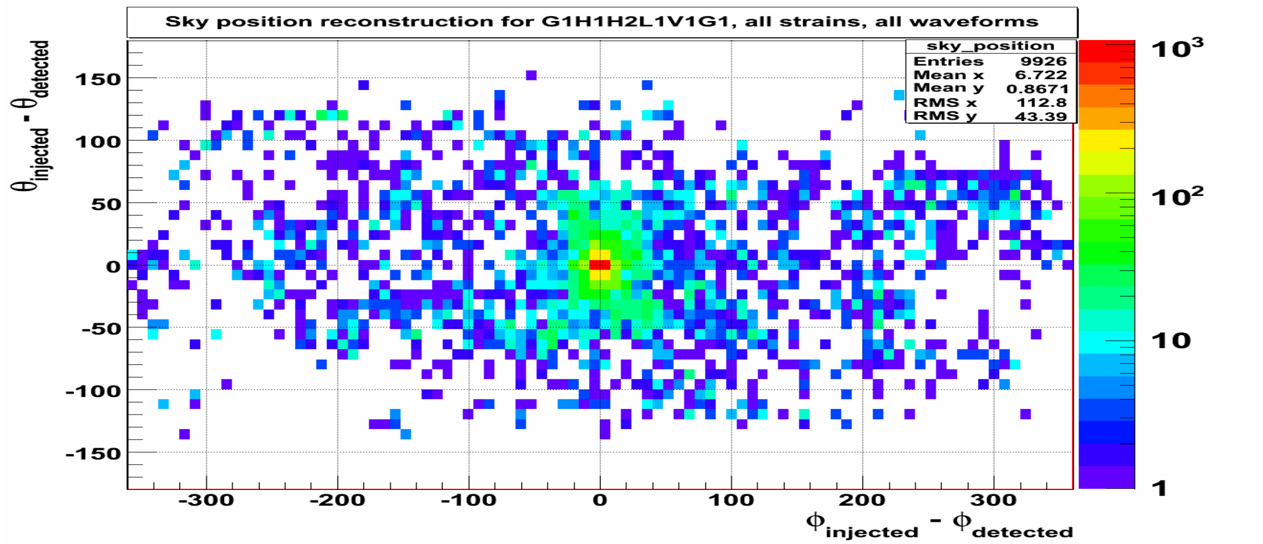
Coordinate reconstruction

H1xL1

coordinate reconstruct is possible for loud events due to a time delay between detectors and different antenna patterns



L1xH1xH2x V1xG1



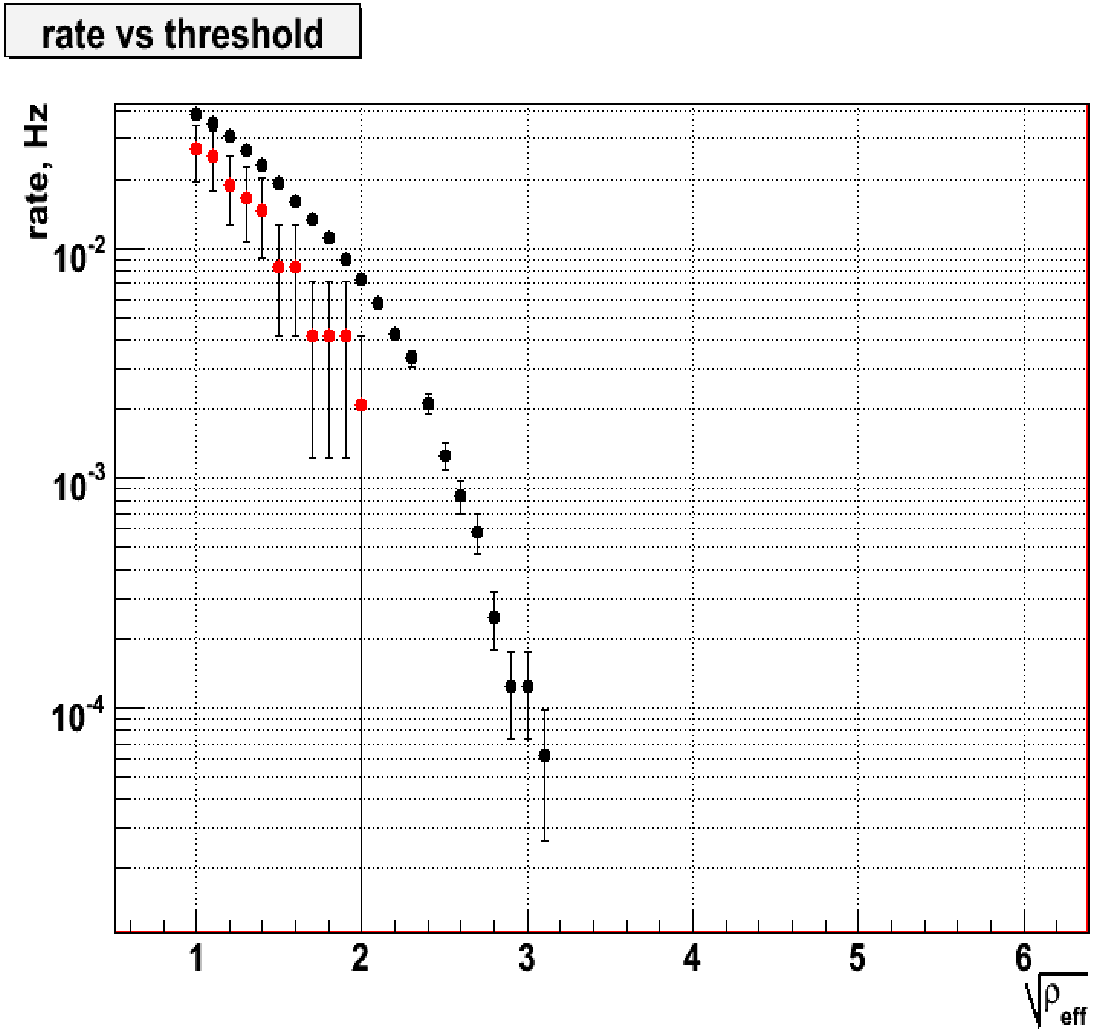
Triggered searches with cWB

- cWB can be used to search for GW-GRB association by analyzing data around GRB triggers in a small patch on the sky at GRB location.
  - run analysis at lower threshold than for the un-triggered search.
- How cWB can complement current triggered searches?
  - ability to handle arbitrary number of co-aligned and misaligned detectors
  - conceptually different method – no need to specify a priori a duration (integration time) and bandwidth of anticipated GW event
- Peter Kalmus run a demo analysis on GRB 051213 with 3 LIGO detectors using 480 sec of data around the GRB time.

rates

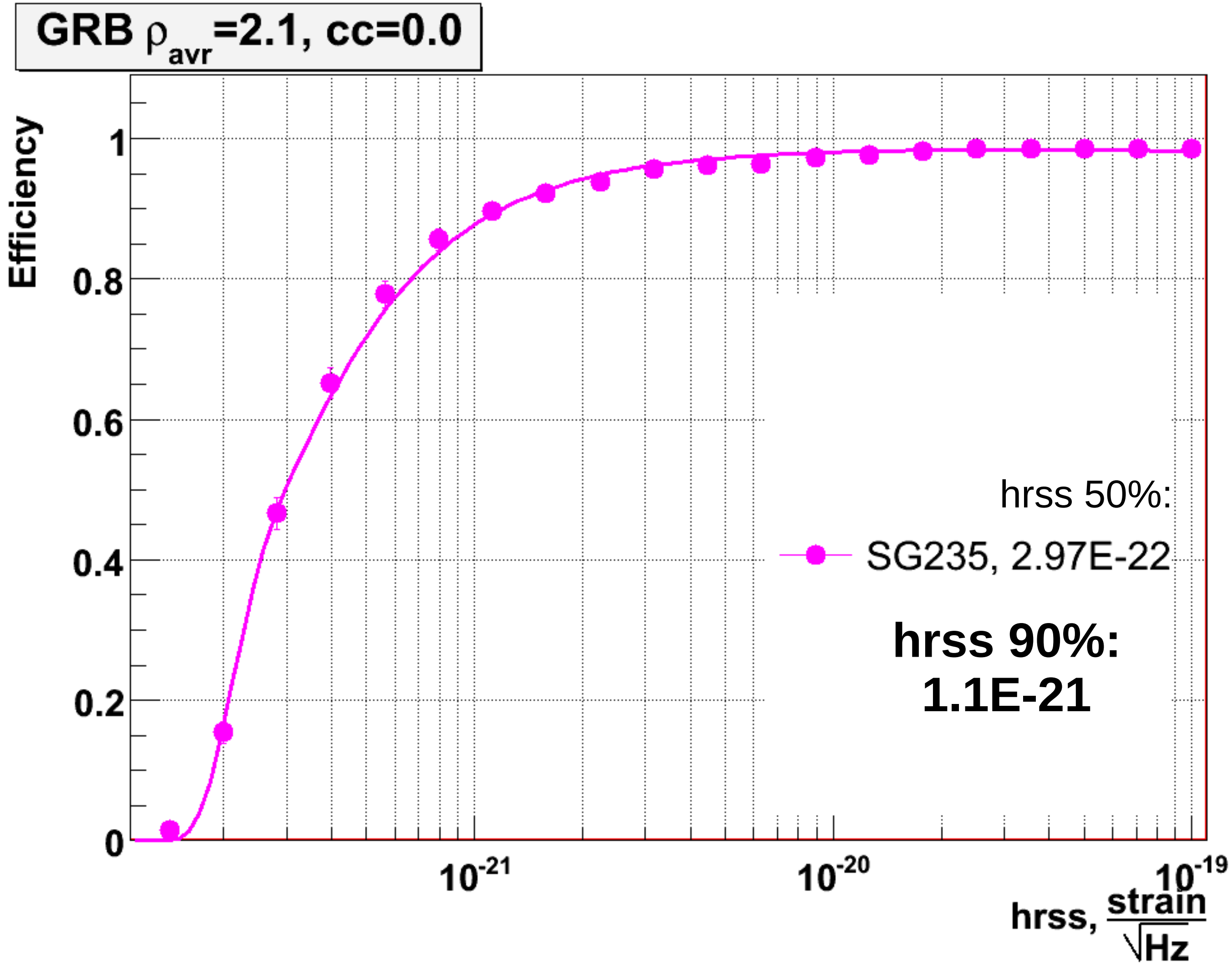
FA rate is estimated from time-shifted data (100 lags)

The effective SNR $\sqrt{\rho_{eff}}$ of the loudest event observed in zero lag is used as threshold to construct efficiency curves



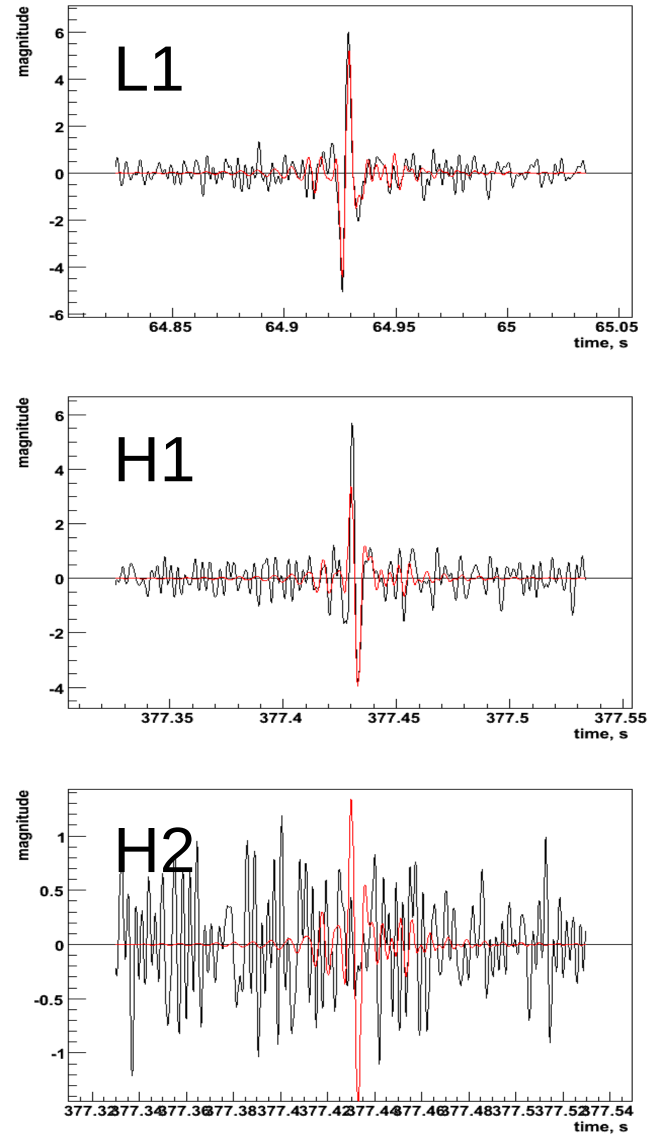
upper limit on hrss

for sine-Gaussian wave at 235Hz and Q=9



Coherent Event Display

- **Tool developed by Adam Mercer for**
  - **visualisation of the GW burst candidates**
  - **coherent follow up analysis of burst triggers**
- **Uses Coherent WaveBurst algorithm**
- **Generates a web page containing**
  - **Full set of the coherent event parameters**
  - **Time-Frequency Maps**
  - **Reconstructed Detector Responses**
  - **Likelihood, Correlation, Alignment and Sensitivity Skymaps**
  - **Likelihood Time-Frequency Maps**



http://tier2.phys.ufl.edu/~ram/private/event_display/

Summary & Plans

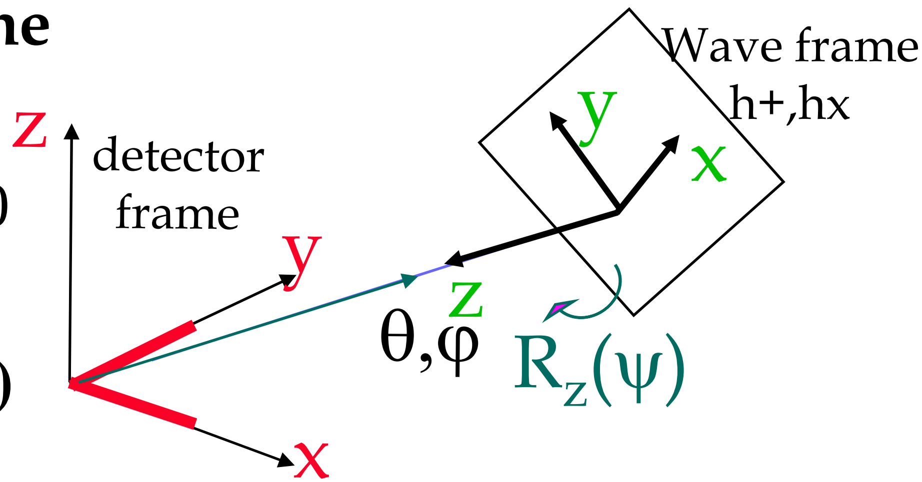
- **coherent WaveBurst pipeline**
  - performed analysis of S5a set (no zero lag analysis)
  - study of rates and sensitivity for one year of S5 data
  - robust discrimination of glitches
  - excellent computational performance
    trigger production for one year of S5 data (101 time lags) takes 1-2 day.
- **prospects for the S5 all-sky coherent search**
  - trigger production & simulation with final S5 calibration
    in a time scale of few weeks after the v3 h(t) data is available
  - analyze outliers and apply DQ and veto cuts
  - final estimation of the detection efficiency and rates
  - analyze zero lag triggers → produce final result
  - expect 20-30% better sensitivitycompare to S5a in-coherent search

Network response matrix

- **Dominant Polarization Frame**

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

(all observables are $R_Z(\Psi)$ 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

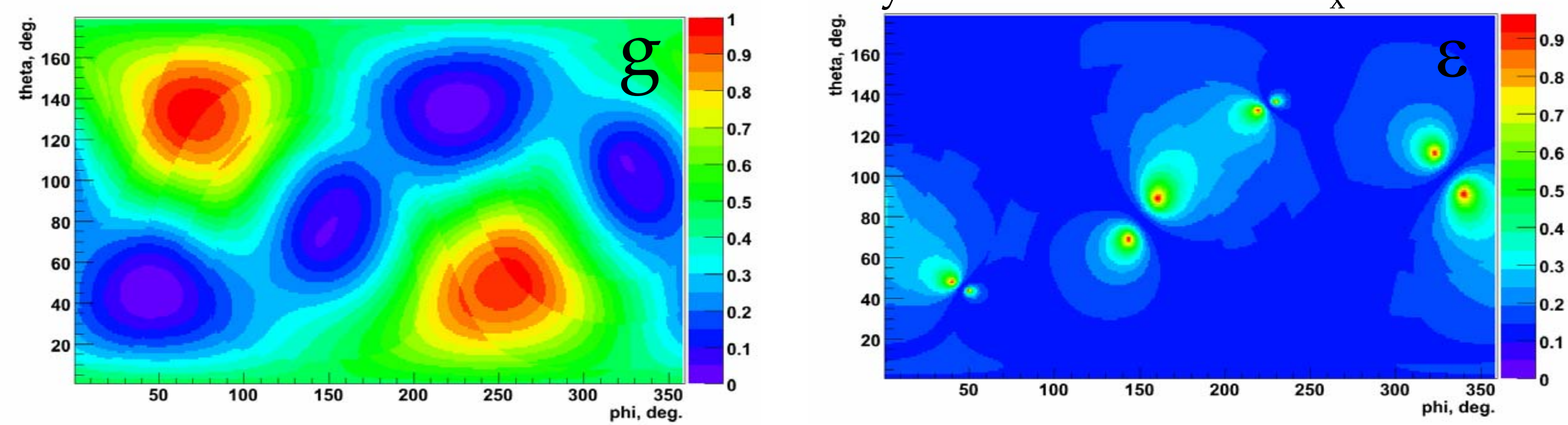
(PRD 72, 122002, 2005)

Virtual Detectors & Constraint

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

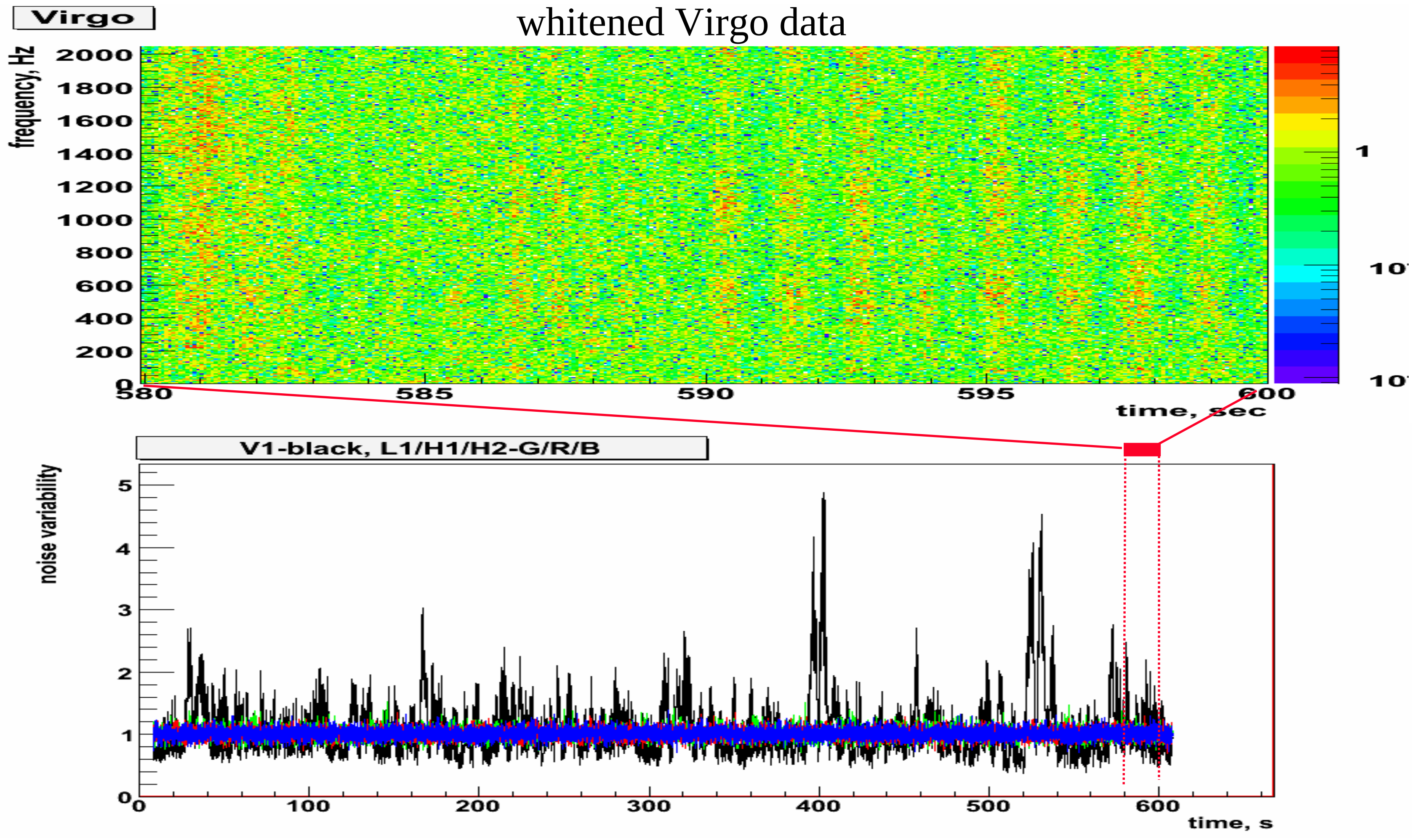
detector	output	noise var.	likelihood	SNR
plus	X_+	g	$L_+ = X_+^2/g$	$g\int h_+^2 dt$
cross	X_x	εg	$L_x = X_x^2/\varepsilon g$	$\varepsilon g\int h_\times^2 dt$

L1xH1xH2 network essentially is not sensitive to h_x



- **constrain 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**
  - **several different constraints are implemented in cWB**

variability of Virgo noise



- **Significant variability of Virgo noise due to angular motion of mirrors induced by seismic noise.**