Coherent detection and reconstruction of burst events in S5 data

S.Klimenko, University of Florida
for the LIGO scientific collaboration

11th Gravitational Wave Data Analysis Workshop

- **coherent network analysis**
- **coherent WaveBurst pipeline**
- **S5 data**
- **S5 results (all results are preliminary)**
- **Summary**

Coherent Network Analysis for bursts

- Target detection of burst sources (inspiral mergers, supernova, GRBs,...)
  - use robust model-independent detection algorithms
- For confident detection combine measurements from several detectors
  - handle arbitrary number of co-aligned and misaligned detectors
  - confident detection, elimination of instrumental/environmental artifacts
  - reconstruction of source coordinates
  - reconstruction of GW waveforms
- Detection methods should account for
  - variability of the detector responses as function of source coordinates
  - differences in the strain sensitivity of the GW detectors
- Extraction of source parameters
  - confront measured waveforms with source models

Coherent network analysis

Combine data, not triggers; solve inverse problem of GW detection

- **Guersel,Tinto, PRD 40 v12,1989**
  - **reconstruction of GW signal for a network of three misaligned detectors**
- **Likelihood analysis: Flanagan, Hughes, PRD57 4577 (1998)**
  - **likelihood analysis for a network of misaligned detectors**
- **Two detector paradox: Mohanty et al, CQG 21 S1831 (2004)**
  - **state a problem within likelihood analysis**
- **Constraint likelihood: Klimenko et al, PRD 72, 122002 (2005)**
  - **address problem of ill-conditioned network response matrix**
  - **first introduction of likelihood constraints/regulators**
- **Penalized likelihood: Mohanty et al, CQG 23 4799 (2006).**
  - **likelihood regulator based on signal variability**
- **Maximum entropy: Summerscales at al, to be published**
  - **likelihood regulator based on maximum entropy**
- **Rank deficiency of network matrix: Rakhmanov, CQG 23 S673 (2006)**
  - **likelihood based in Tickhonov regularization**
- **Redundancy veto: Schutz et al, CQG 22 S1321 (2005)**
- **GW signal consistency: Chatterji et al, PRD 74 082005(2006)**
  - **address problem of discrimination of instrumental/environmental bursts**

Likelihood

- **Likelihood for Gaussian noise with variance $s^2{}_k$ and GW waveforms h_+, h_x : $x_k[i]$ – detector output, F_k – antenna patterns**

$$L = \sum_i \sum_k \frac{1}{2s_k^2}\left[x_k^2[i] - \left(x_k[i] - x_k[i]\right)^2\right]$$

detector response - $x_k = h_+ F_{+k} + h_x F_{xk}$

- **Find solutions by variation of *L* over un-known functions h_+, h_x**
  (Flanagan & Hughes, PRD 57 4577 (1998))

- **Split energy between signal and noise**

$$2L = E - N$$

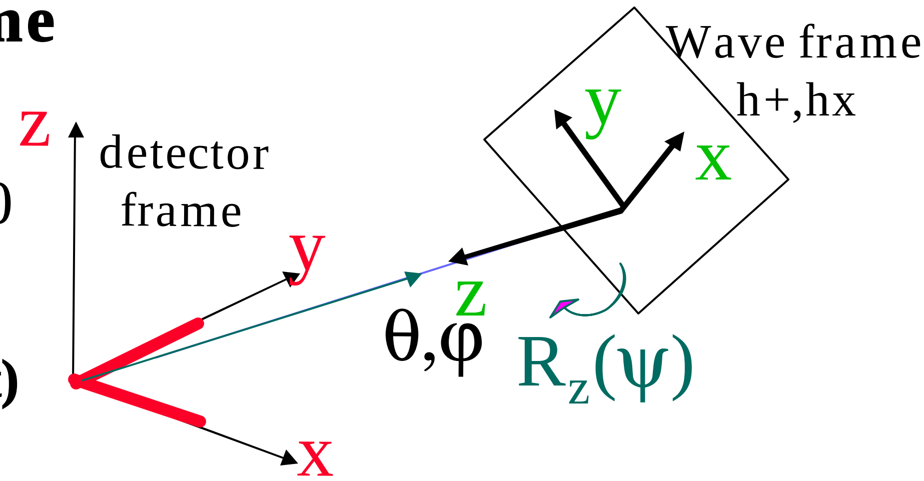
detected (signal) energy | **total energy** | **noise (null) energy**

Network response matrix

- **Dominant Polarization Frame**

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

(all observables are $R_z(Y)$ invariant)



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

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

- ***g* – network sensitivity factor**
- ***e* – network alignment factor**

network response matrix

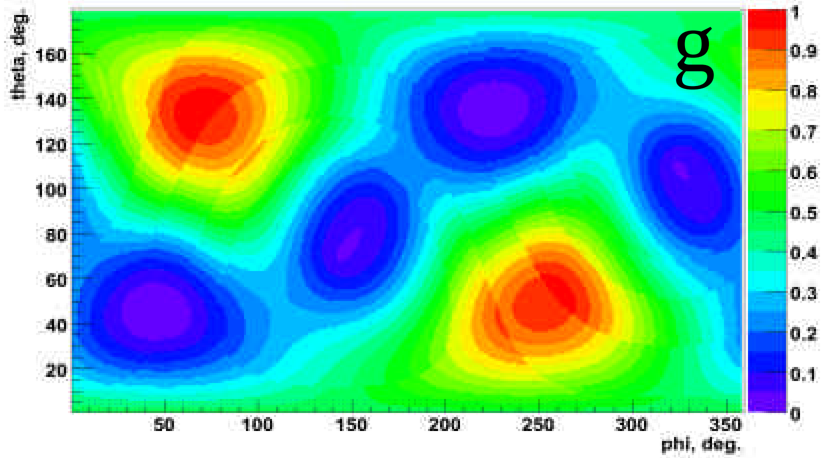
(PRD 72, 122002, 2005)

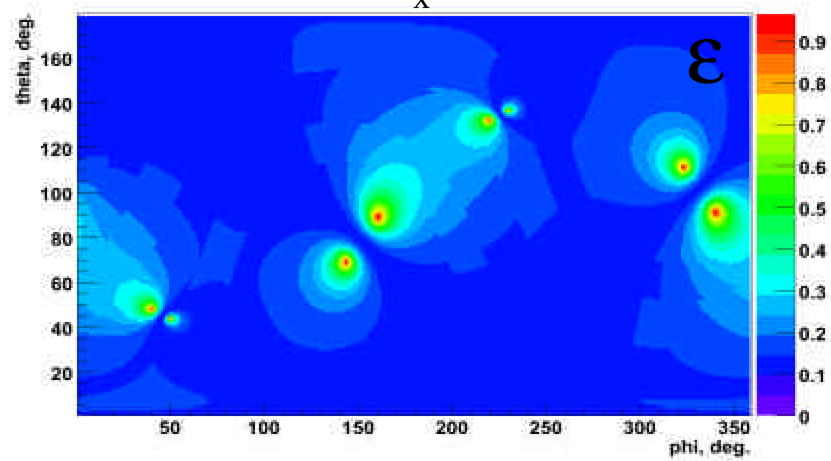
Virtual Detectors & Constraint

- **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	eg	$L_x = X_x^2/eg$	$eg\int h_\times^2 dt$

L1xH1xH2 network not sensitive to h_x



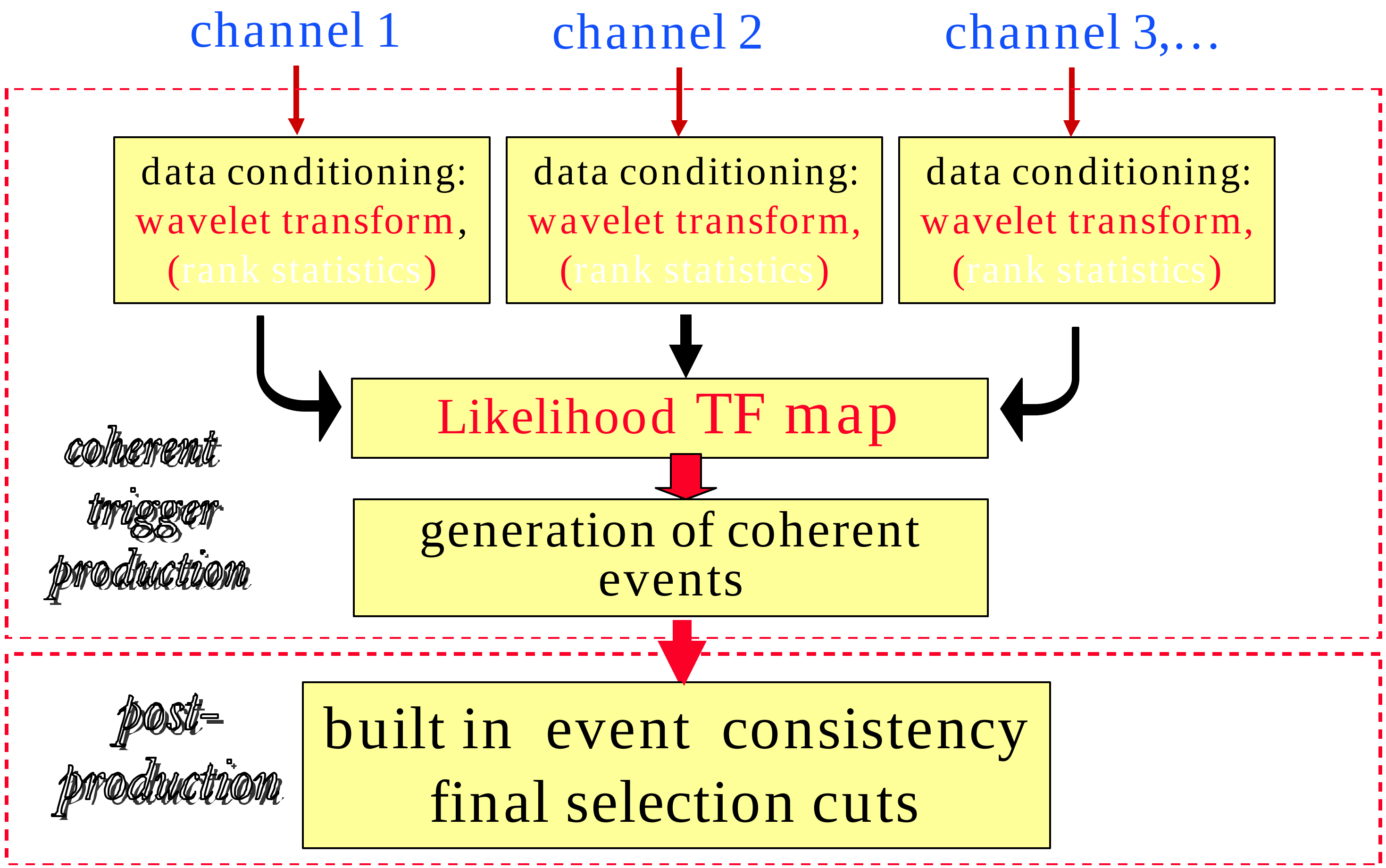


- **Use "soft constraint" on the solutions for the h_x waveform.**
  - **remove un-physical solutions produced by noise**
  - **may sacrifice small fraction of GW signals but**
  - **enhance detection efficiency for the rest of sources**

$$L = L_+ + L_\times$$

$$L_{soft} = L_+ + eL_\times$$

Coherent WaveBurst



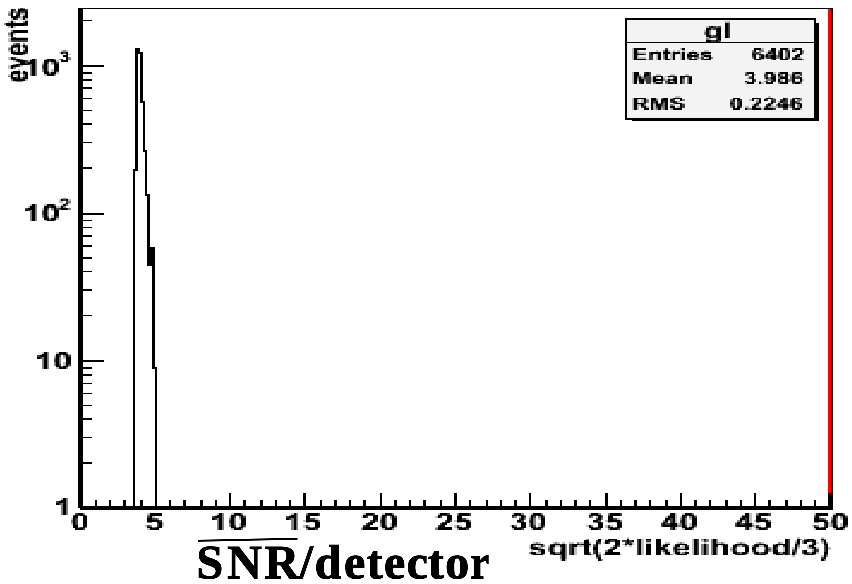
- **Similar concept as for the incoherent WaveBurst, but use coherent detection statistic**
- **Uses most of existing WaveBurst functionality**

S5 data

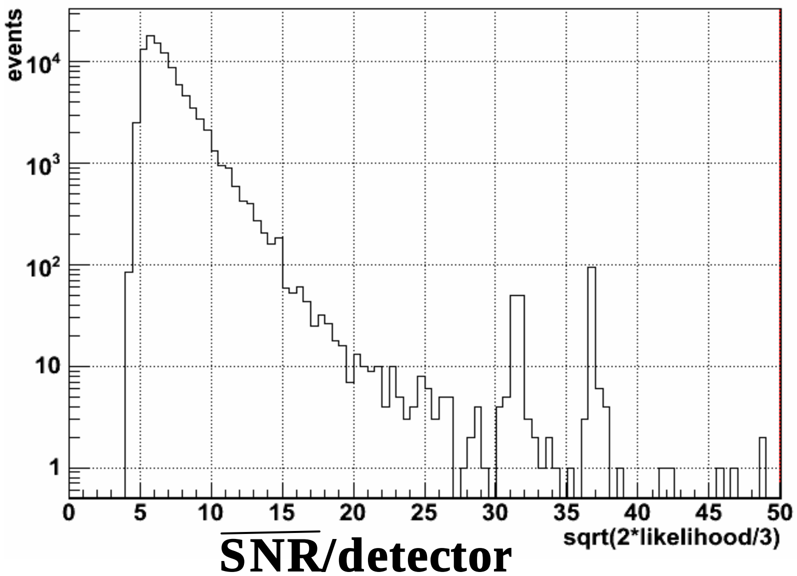
- **LIGO network**
  - **S5a, Nov 17, 2005 – Apr 3, 2006**
    - **live time 54.4 days, preliminary DQ is applied**
  - **S5 (first year), Nov 17, 2005 - Nov 17, 2006**
    - **live time 166.6 days (x10 of S4 run)**
    - **duty cycle 45.6% (after data quality cuts)**
- **LIGO-Geo network**
  - **S5 (first year), Jun 1, 2006 - Nov 17, 2006**
    - **live time 83.3 days**
- **run fully coherent analysis with LIGO and LIGO-Geo networks**
  - **frequency band 64-2048 Hz**
  - **results are presented for *time-shifted data*:**
    100 artificial data samples where L1 detector is shifted in time with respect to the other detectors

Likelihood of coherent WaveBurst triggers

simulated Gaussian-noise



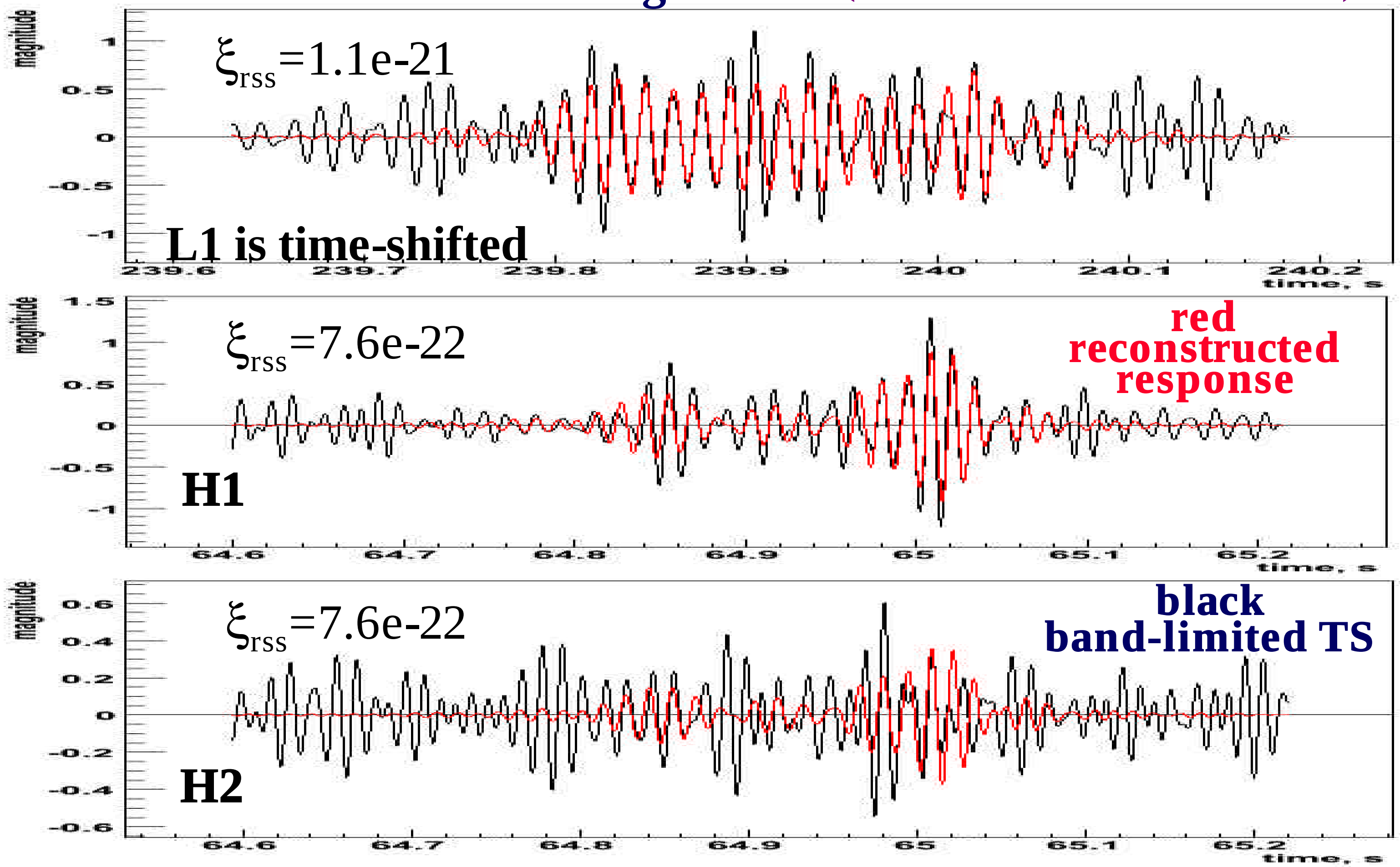
S5 time-shifted triggers



- For Gaussian stationary detector noise any event with significant likelihood is a "GW signal"
- For real data the pipeline output is dominated by glitches
- Glitch's responses are "typically inconsistent in the detectors"
- Coincidence, correlation, "similarity of waveforms" – what is the meaning of this in the coherent analysis?

Waveform Consistency

L1/H1 coincident glitch (network correlation = 0.3)



- **How to quantify consistency?**
  - select a coincidence strategy
  - use network correlation coefficient

$$x_{rss} = \sqrt{\int x^2(t)dt}$$

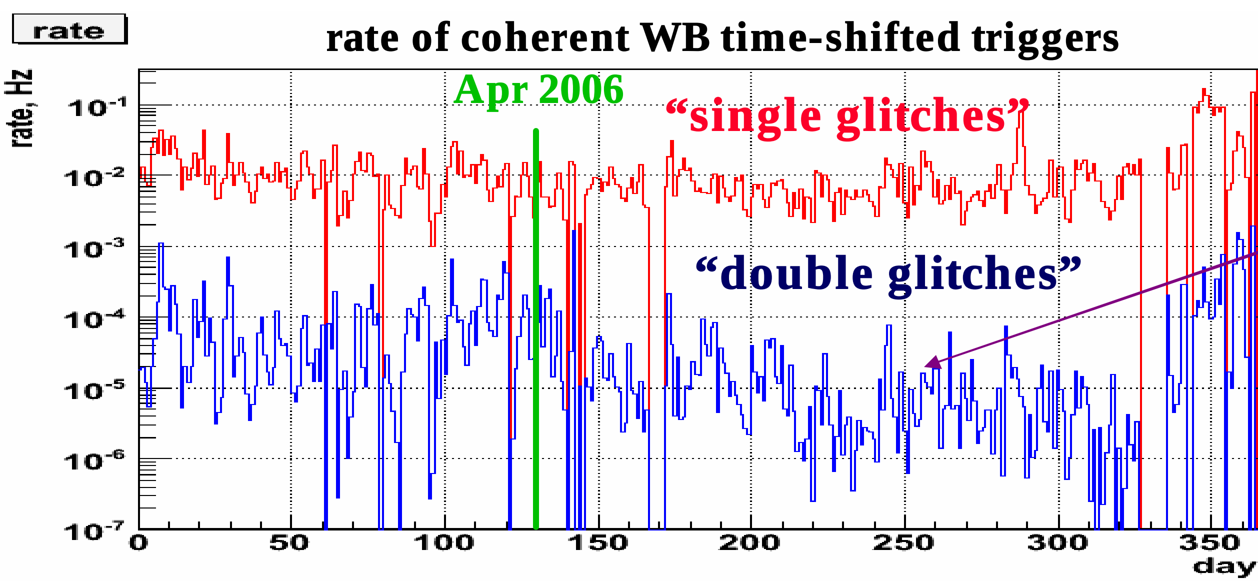
Coincidence strategies

- **Coherent triggers are coincident in time by construction**
  - **Definition of a coincidence between detectors depends on selection cuts on energy reconstructed in the detectors**

$$E_i = \langle x_i^2 \rangle - N_i$$

$\langle x_i^2 \rangle$ - total energy
N_i – null (noise) energy

  - **Optimal coincidence strategies are selected after trigger production**
    - **loose:** $E_{H1}+E_{H2}+E_{L1}>E_T$ **(same as likelihood → "sum of detected SNRs")**
    - **double OR:** $E_{H1}+E_{H2}>E_T$ && $E_{H1}+E_{L1}>E_T$ && $E_{H2}+E_{L1}>E_T$
    - **triple:** $E_{H1}>E_T$ && $E_{H2}>E_T$ && $E_{L1}>E_T$



use coincidence cut: double OR (E_T=36)

reduce rate by 2-3 orders of magnitude

coherent energy & correlation

- **detected energy:** **in-coherent** **coherent**

$$2L = \sum_{i,j} \langle x_i x_j \rangle C_{ij} = E_{i=j} + E_{i \neq j}$$

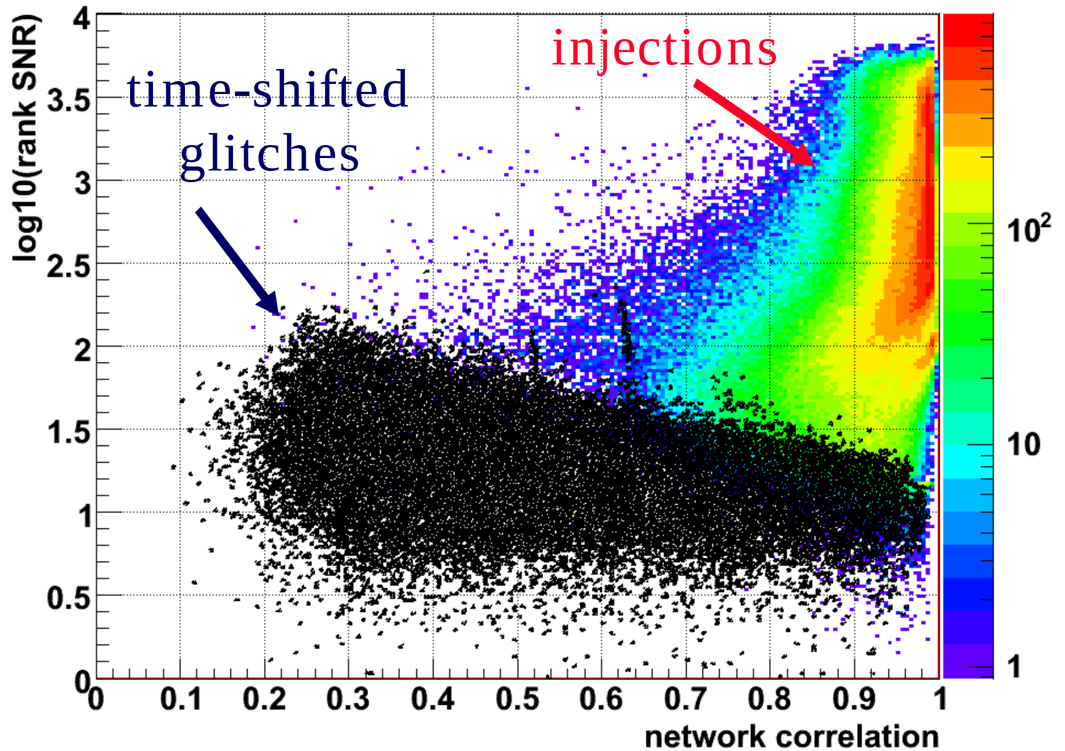
C_{ij} - depend on antenna patterns and variance of the detector noise

x_i , x_j – detector output

- **network correlation**

$$C_{net} = \frac{E_{coherent}}{N_{ull} + E_{coherent}}$$

require $C_{net} > 0.65$



Effective SNR

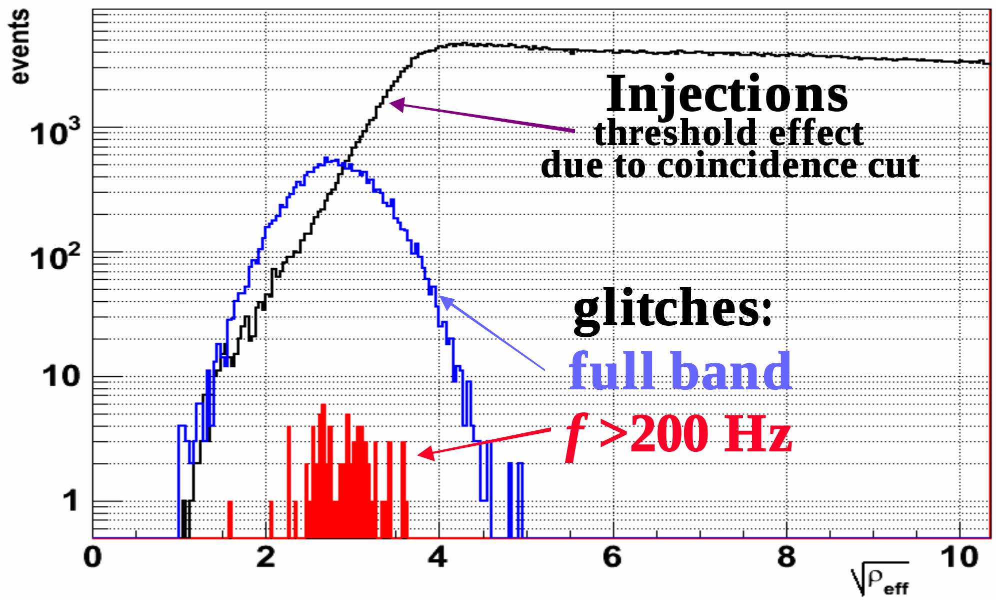
- **average SNR**

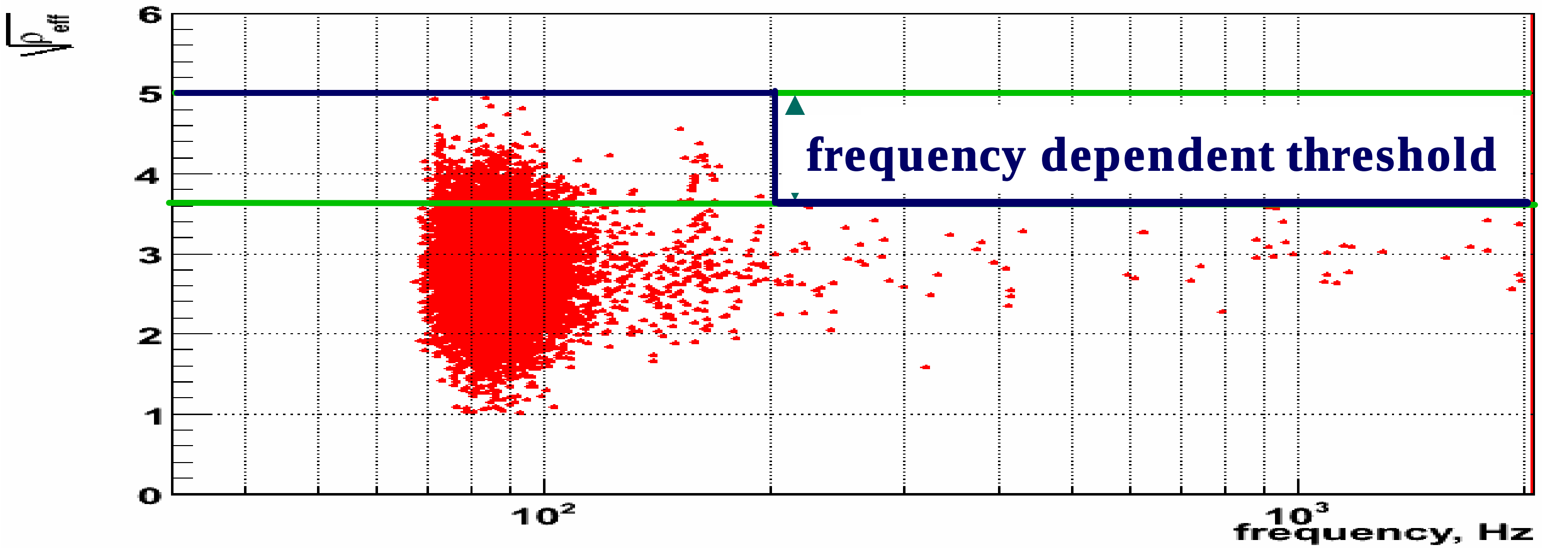
$$r = \left(r_{L1} r_{H1} r_{H2}\right)^{1/3}$$

- **effective SNR**

$$r_{eff} = r^{C_{net}}$$

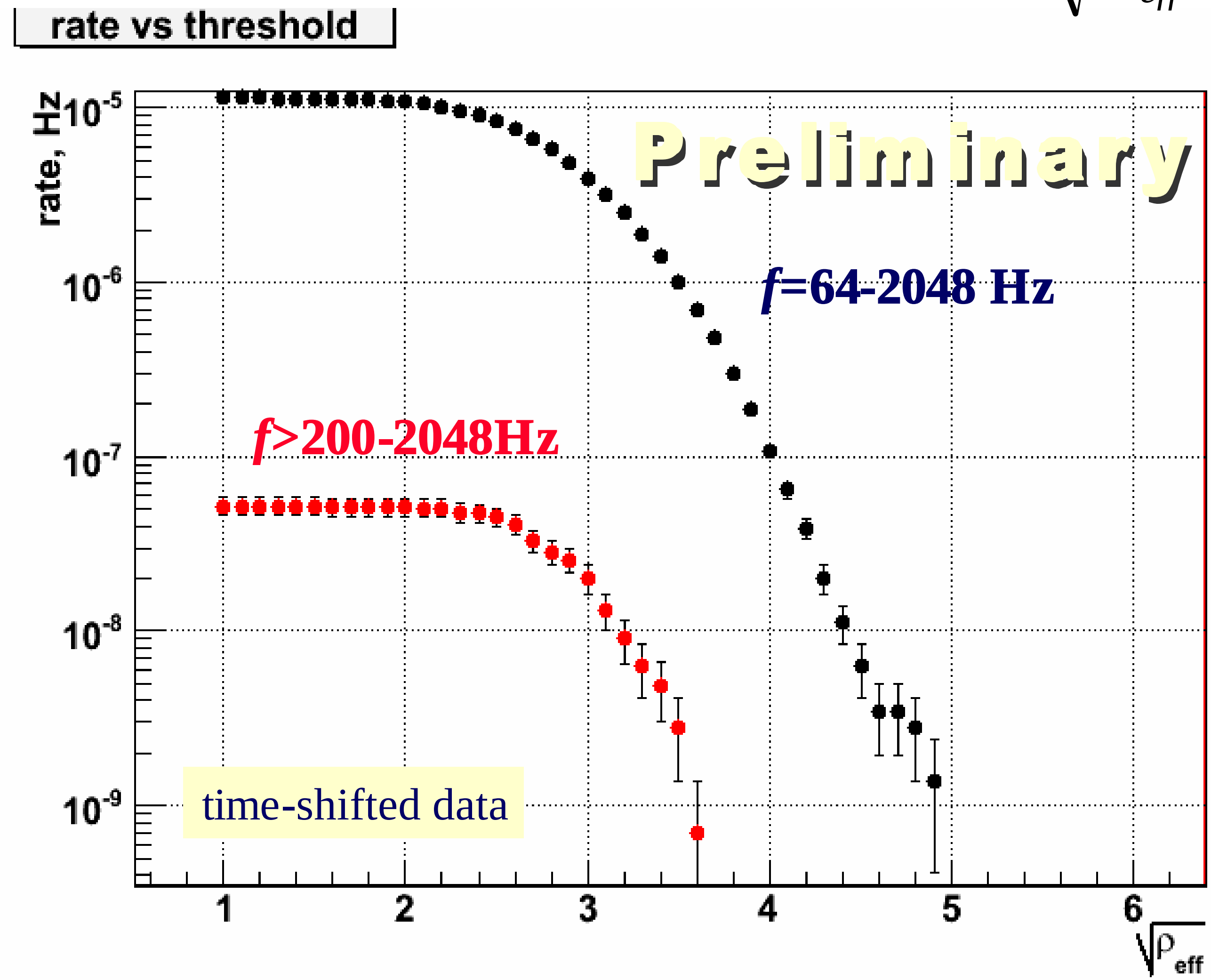
time-shifted data





S5 Rates

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

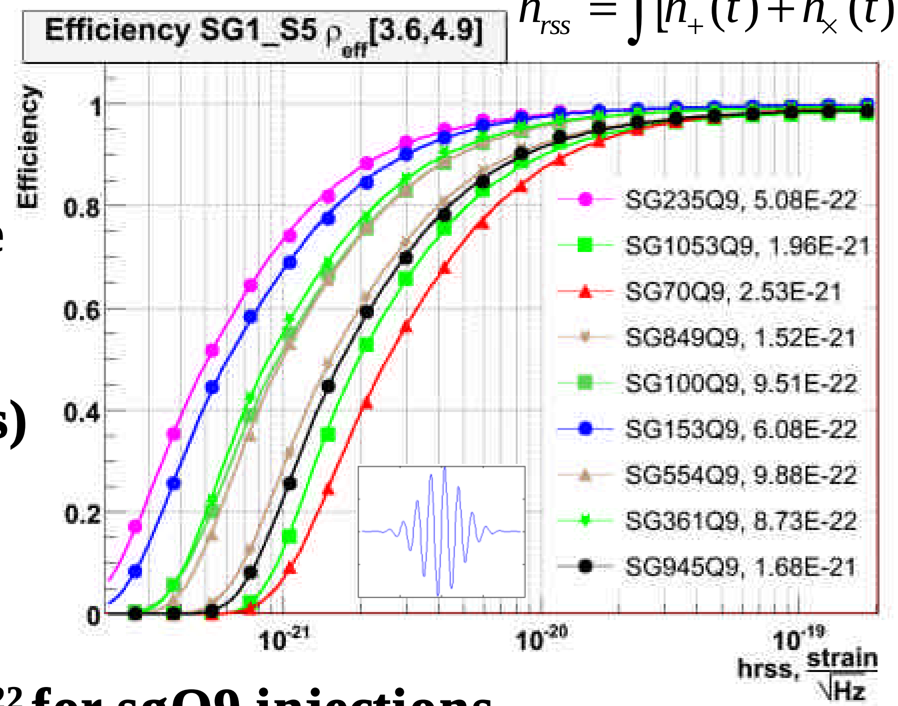


Detection efficiency for bursts

- 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 (~1/50years) is achievable

Preliminary

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



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

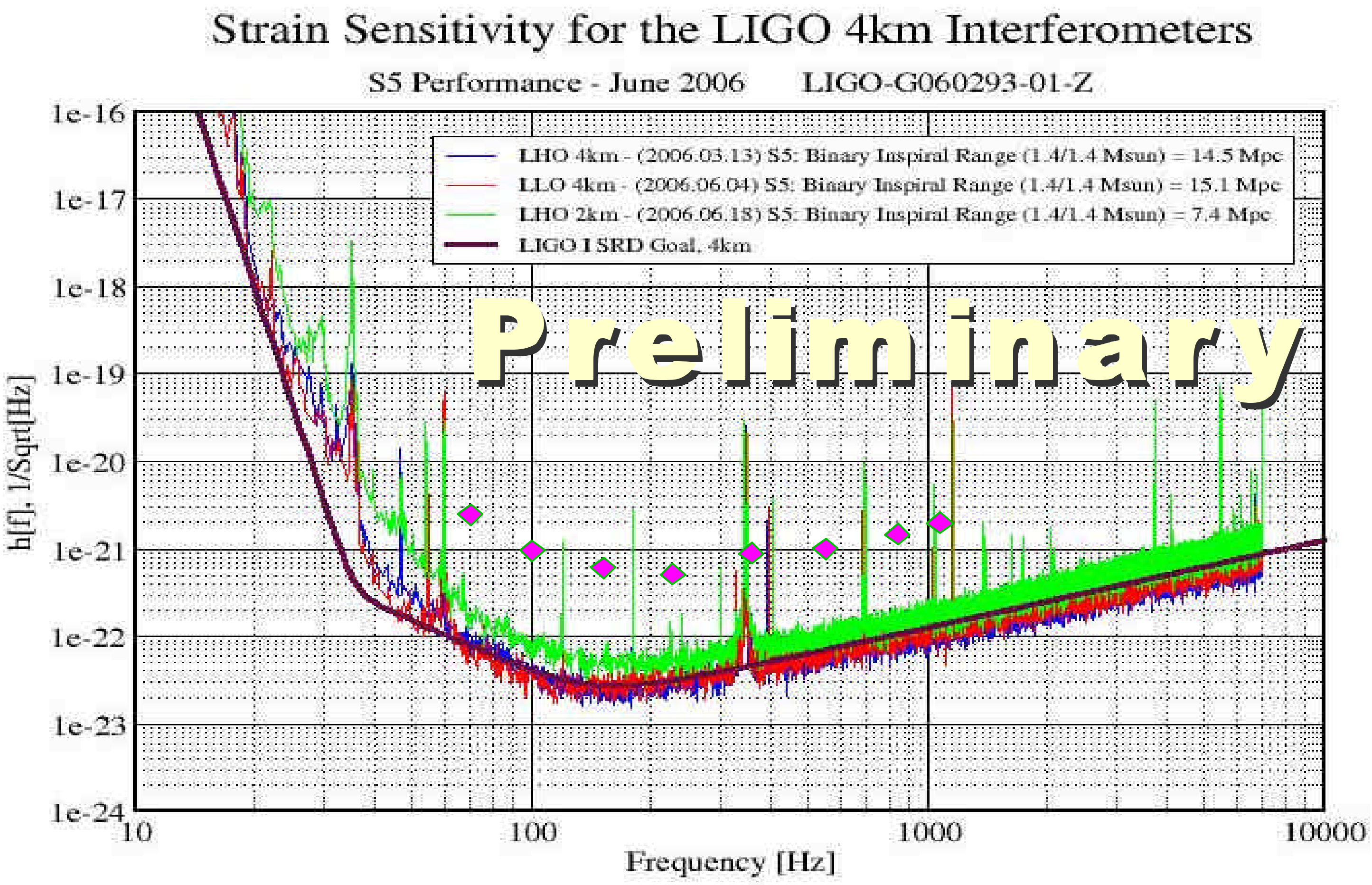
S5: 1/46y	cWB	25.3	9.5	6.1	5.1	8.7	9.9	15.2	20.0

High threshold coherent search

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

◆- expected S5 sensitivity to sine-gaussian injections

see Brian's talk for comparison with the incoherent high threshold search



Adding GEO to the network

- **GEO should not reduce network sensitivity, but help for sky locations unfortunate for LIGO, if GEO noise is fairly stationary (see Siong's talk)**

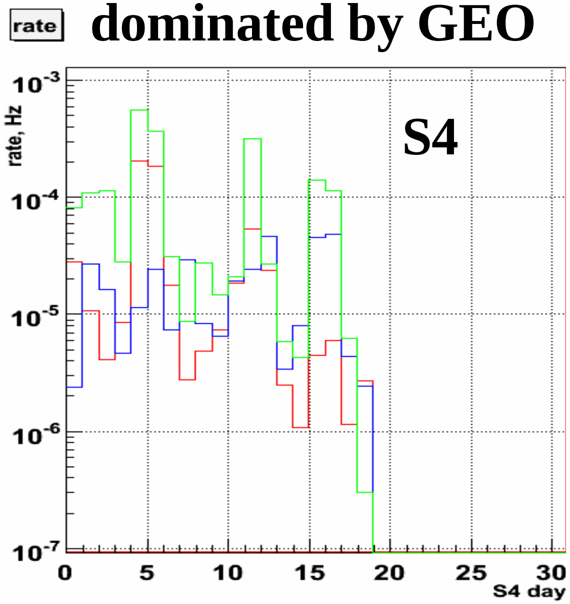
$$\text{network sensitivity } g \propto \sum_k \frac{F_{+k}^2 + F_{\times k}^2}{s_k^2}, \quad \text{detected } SNR \propto g h_{rss}^2$$

- **Determine relative "glitcheness" of detectors by sorting coherent triggers on the value of SNR (r_k) in the detectors**
  - **for example, call a trigger to be the L1 glitch if**

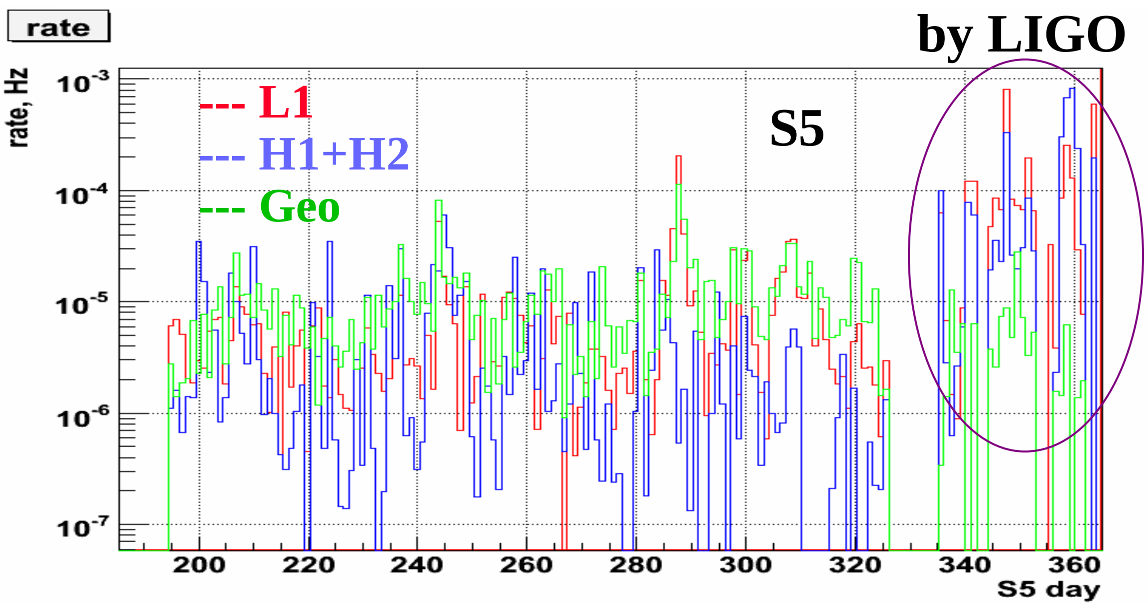
time-shifted data

$$r_{L1} > r_{H1} \; \& \; r_{L1} > r_{H2} \; \& \; r_{L1} > r_{G1}$$

dominated by GEO



dominated by LIGO



S.Klimenko, G060621-00-Z , December 21, 2006, GWDAW11

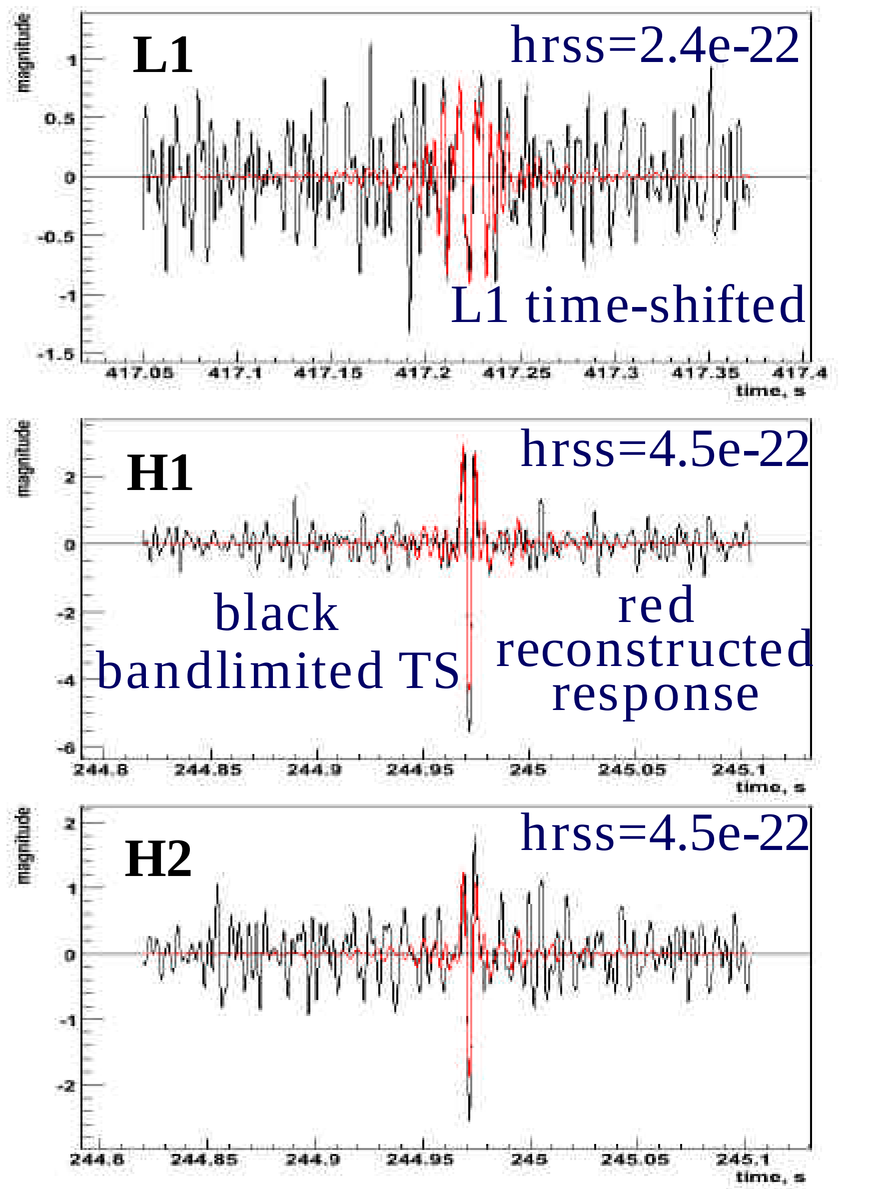
Reconstruction of burst waveforms

- **If GW signal is detected, two polarizations and detector responses can be reconstructed and confronted with source models for extraction of the source parameters**

- **Figures show an example of LIGO magnetic glitch reconstructed with the coherent WaveBurst event display (A.Mercer et al.)**
  - **Environment may produce glitches consistent in the LIGO network!**

- **Additional information from environmental channels and other detectors is very important for confident detection of GW signals**
  (see Erik's & Laura's talks on veto)

H1 / H2 coincident magnetic glitch



Summary & Plans

- coherent WaveBurst pipeline
  - generated coherent triggers for one year of S5 data
  - robust discrimination of glitches → extra-low false alarm rate at excellent sensitivity
  - excellent computational performance:
    S5 trigger production for 101 time lags takes 1 day.
- Environment may produce consistent glitches
  - GEO and Virgo are essential for confident detection
  - need detail data quality and veto analysis
- prospects for S5 un-triggered coherent search
  - analyze outliers and apply DQ and veto cuts
  - final estimation of the detection efficiency and rates
  - analyze zero lag triggers → produce final result