Searching for GW Bursts with LIGO

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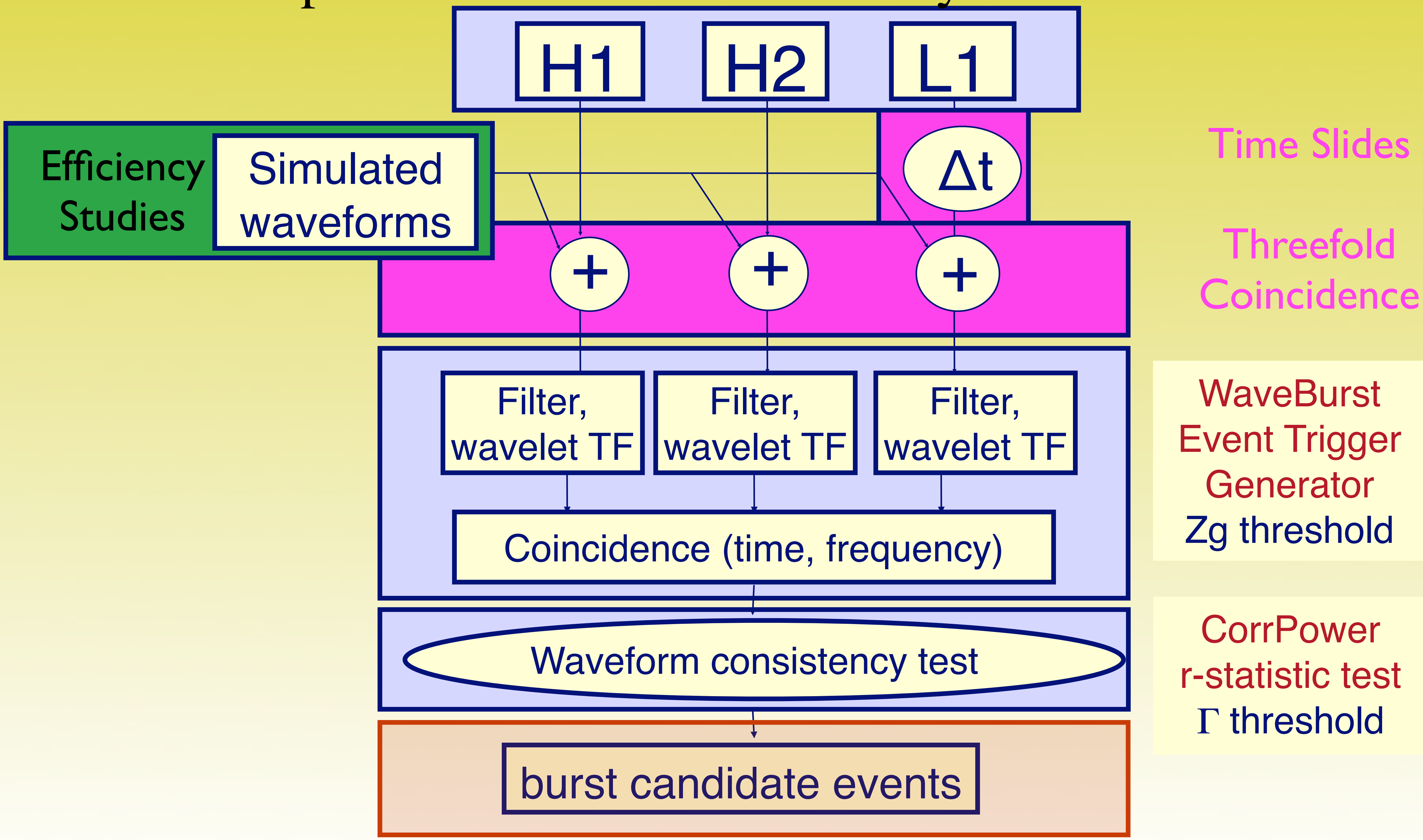
LIGO GW Burst Searches

- Current Results From LIGO
  - Un-triggered all-sky searches
  - Triggered searches for bursts from GRBs, SGRs
- The Road Ahead
  - Analysis with a Network of Detectors
  - Waveform Extraction
  - Astrophysical Interpretation
- Concluding Remarks

GW Burst All-Sky Pipeline

- Search for un-modeled short-durations bursts
- Build three-fold LIGO coincidence from pair-wise triggers
- Follow up with waveform consistency test

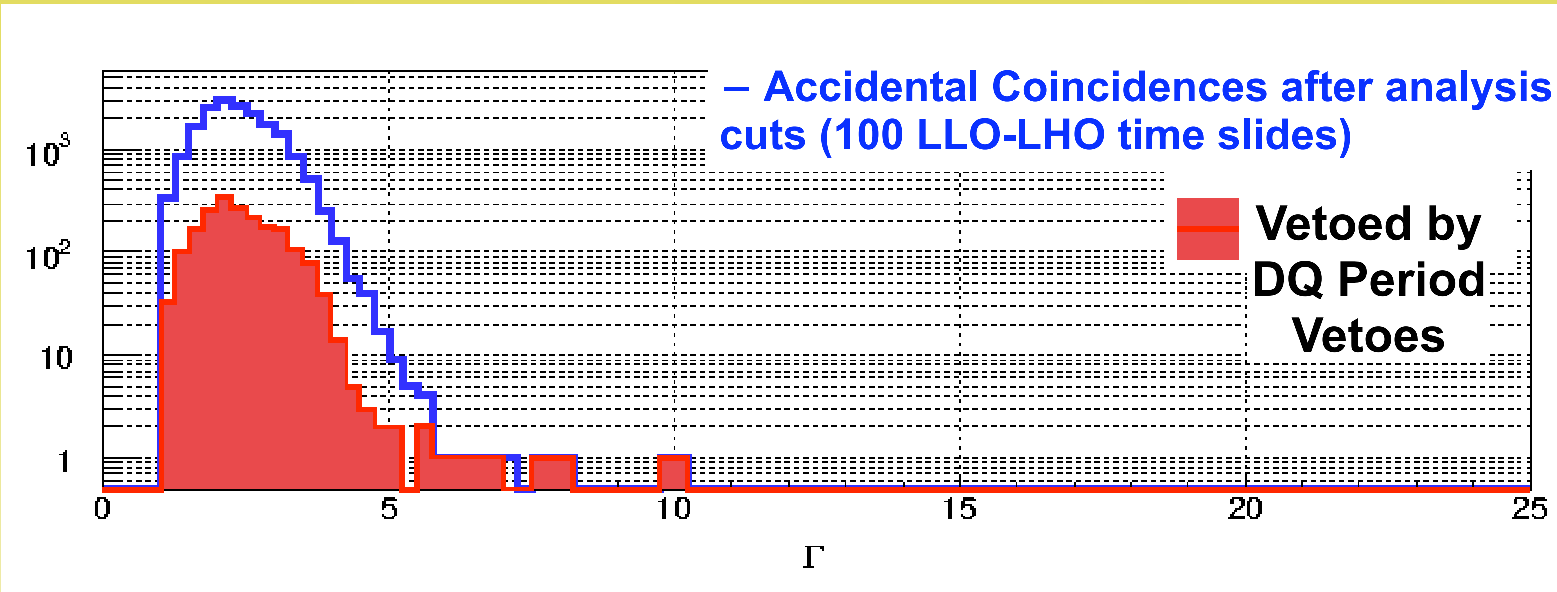


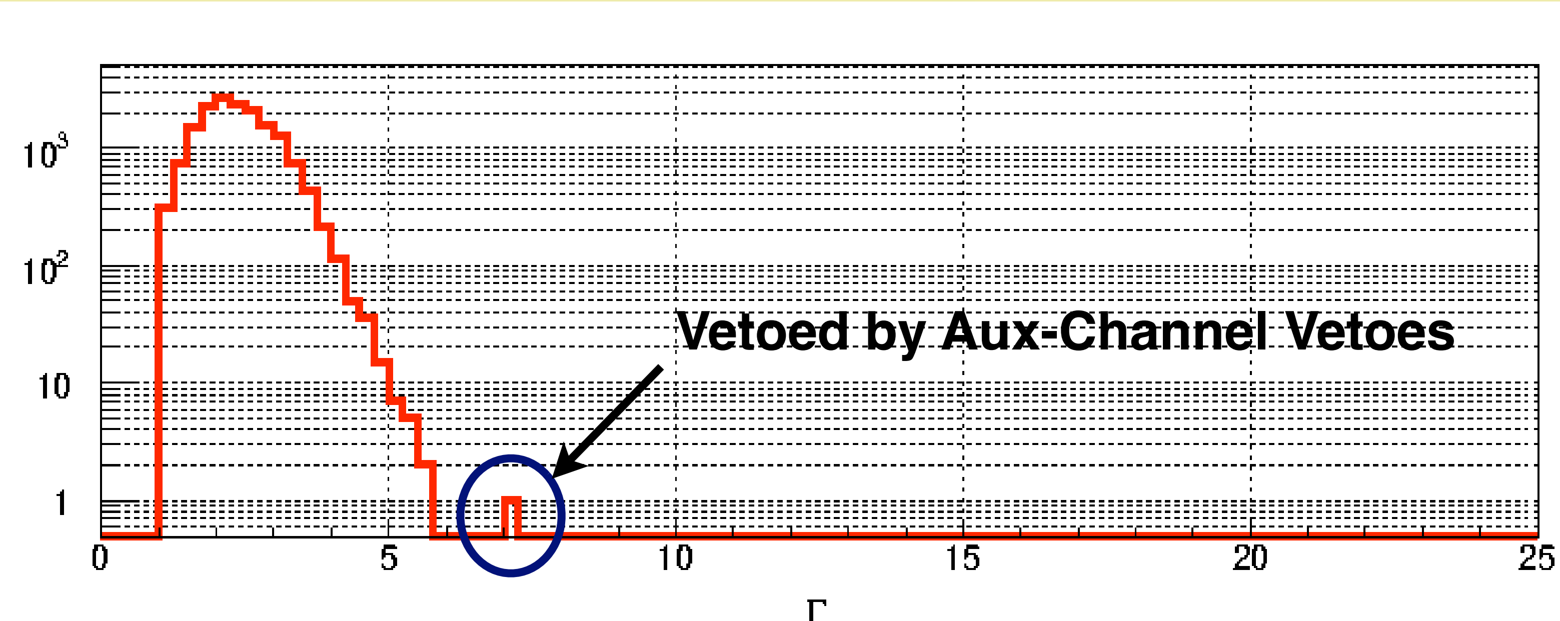
From G060634-00
(O'Reilly)

Data-Quality Period and Auxiliary-Channel Vetoes

- LIGO-only Burst GW analysis has significant background from non-Gaussian transients
- Transients at co-located LIGO detectors (H1,H2) a concern
- Periods with known artifacts, unreliable data are flagged as <u>Data Quality (DQ) period vetoes</u>
- Transient events in auxiliary channels (environmental, interferometer) that are coherent with GW channel are flagged as <u>Aux-Channel vetoes</u>
- These vetoes clean up the final trigger samples

Effect of Vetoes on early S5 result





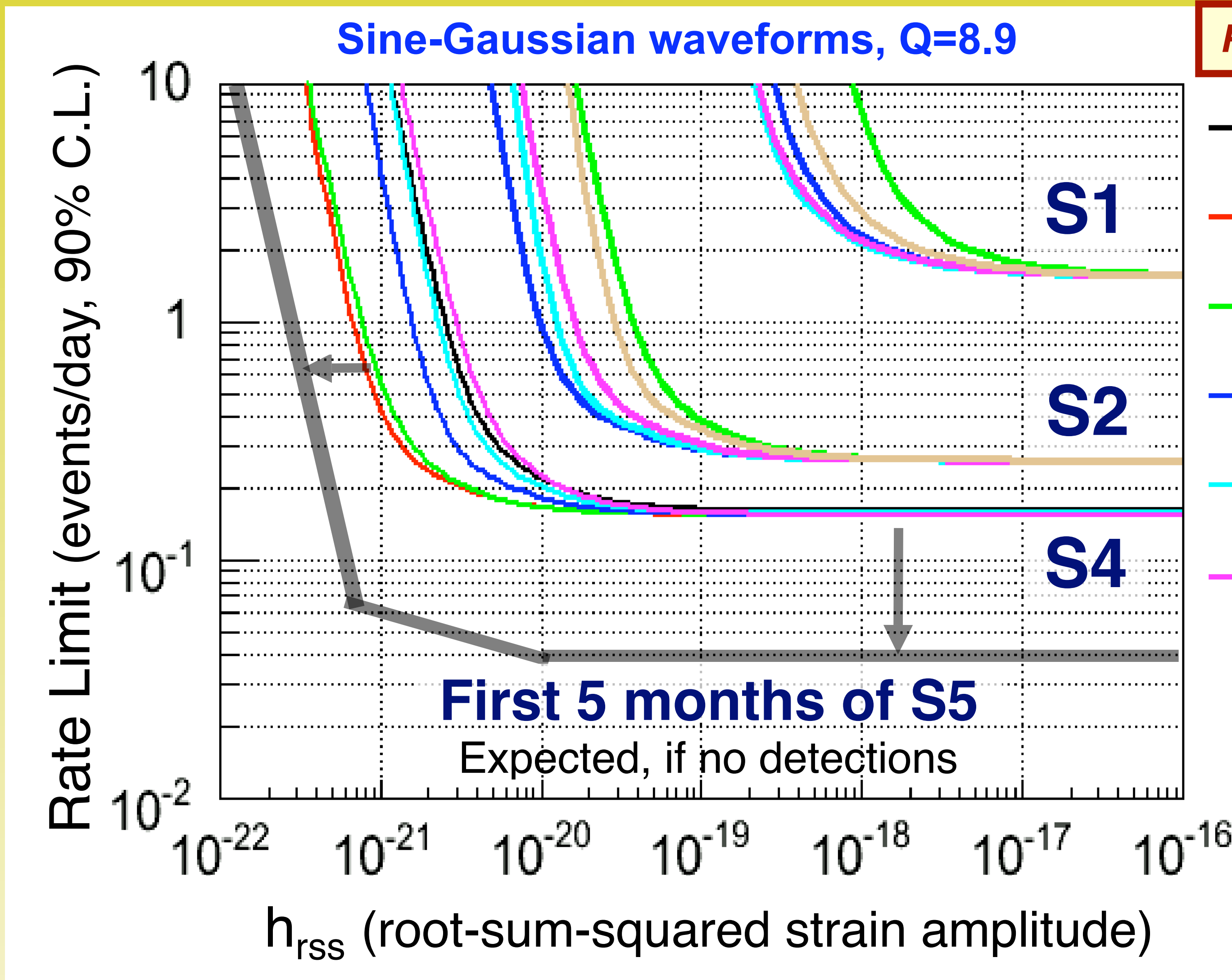
Γ= combined measure of the linear correlation of detector pairs

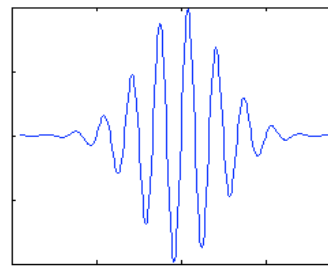
$\Gamma = (\Gamma_{H1H2} + \Gamma_{H1L1} + \Gamma_{H2L1})/3$

Plots taken from Slide 13 of G060628-00-Z (Cadonati) and Slide 8 of G060634-00-Z (O'Reilly)

All-Sky Search from S1 to S5

- Tuned for 64–1600 Hz, duration «1 sec
- No GW bursts signals seen in S1/S2/S3/S4
- Ad-hoc waveforms (Sine-Gaussian, Gaussian, etc.) used to determine detection sensitivity





- Convert to corresponding energy emission sensitivity (assuming isotropic, h_+ only polarization)

$$E_{GW} = (2.1 M_\odot c^2) \left(\frac{R}{100\mathrm{Mpc}}\right)^2 \left(\frac{f}{100\mathrm{Hz}}\right)^2 \left(\frac{h_{rss}}{10^{-21}\mathrm{Hz}^{-1/2}}\right)^2$$

$$h_{\mathrm{rss}} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt}$$

We are sensitive to $E_{GW} \sim 0.1\ M_\odot c^2$ at 20 Mpc @153 Hz

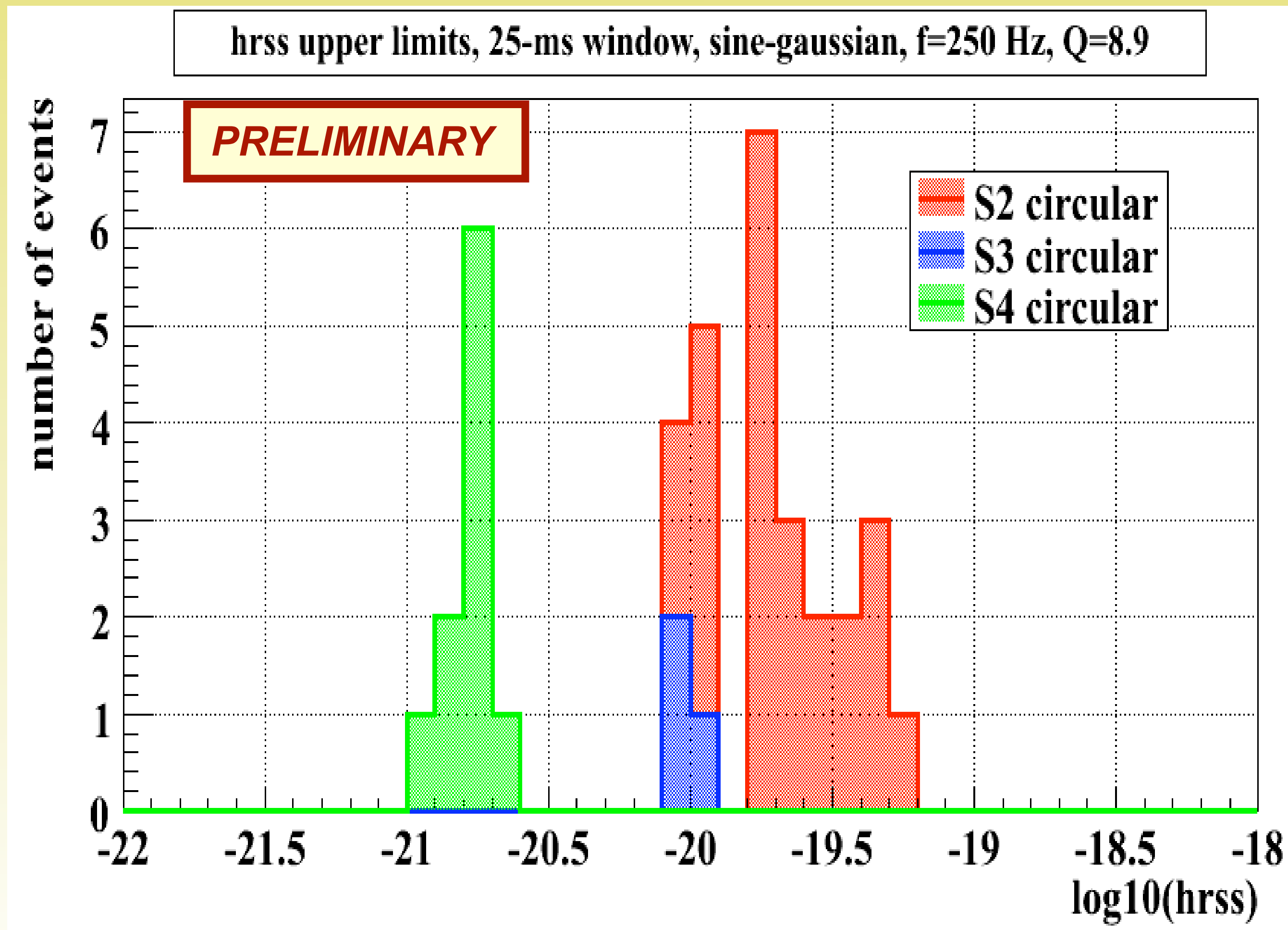
Plot taken from slide 15 of G060634-00-Z (O'Reilly).

GRB Search Results

- Search for short-duration gravitational-wave bursts (GWBs) coincident with GRBs using S2, S3 and S4 data from LIGO
- Analysis based on pair-wise cross-correlation of two interferometers
  - Increased observation time over triple-coincidence
- Target GWB durations: ~1 ms to ~100 ms; Bandwidth: 40-2000 Hz

- No GW signal found associated with 39 GRBs in S2,S3,S4 runs

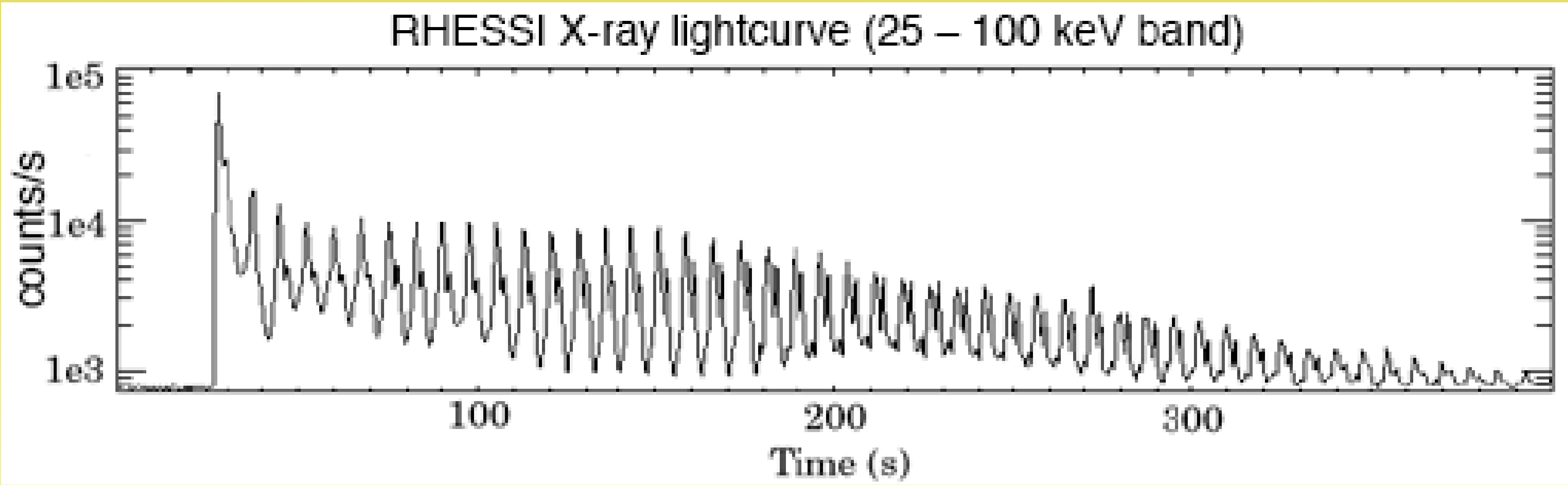
  (Sensitivity similar to untriggered search)
- About 10 GRBs/month during current S5 run



Based on G060652-00 (Mohanty). Plot is from page 10 of that talk. E_GW limit is not included to avoid confusion with untriggered result

SGR 1806-20 Result

- Record flare from Soft Gamma-Ray Repeater SGR 1806-20 on December 27, 2004
  - Quasi-periodic oscillations (QPO) in RHESSE, RXTE x-ray data



- Only one LIGO detector (H1) was observing
- Band-limited excess-power search for quasi-periodic GW signal
- No evidence for GW signal found
- Sensitivity for 92.5Hz QPO **$E_{GW} \sim 10^{-7}$ to 10^{-8} $M_{\odot}$ at 5-10 kpc** (this is comparable to electro-magnetic energy in flare)

Taken from G060631-00 (Matone). Plot is from Page 3. Result is from Page 24 in G060597-00 (Marx)

The Road Ahead

- Existing all-sky and GRB search pipelines operating in S5
- There is near-online analysis of all LIGO data for prompt chance of observation, identification of transients

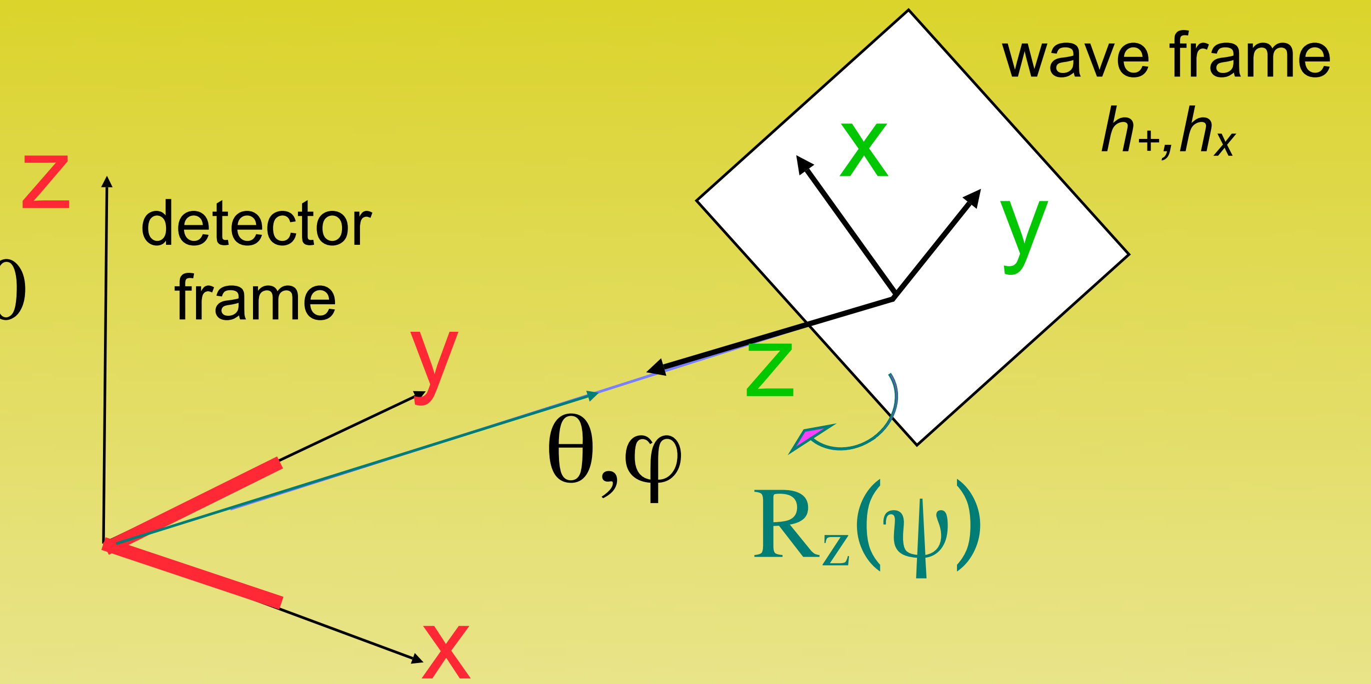
- But for GW Bursts, the Network is the Observatory
  - LIGO-only searches require intense “transient” investigations
  - Previous analyses did not make full use of network constraints
  - We need to prepare for the addition of Virgo to networks
- We are also moving from Upper Limits to Detection
  - Need to extract Waveforms when GW Bursts detected
  - Move on to Astrophysical Interpretation of Results

Network Response for All-Sky Search

- 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)



- Solution for GW waveforms satisfies the equation

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

network response matrix

- g – network sensitivity factor
- ε – network alignment factor

(PRD 72, 122002, 2005)

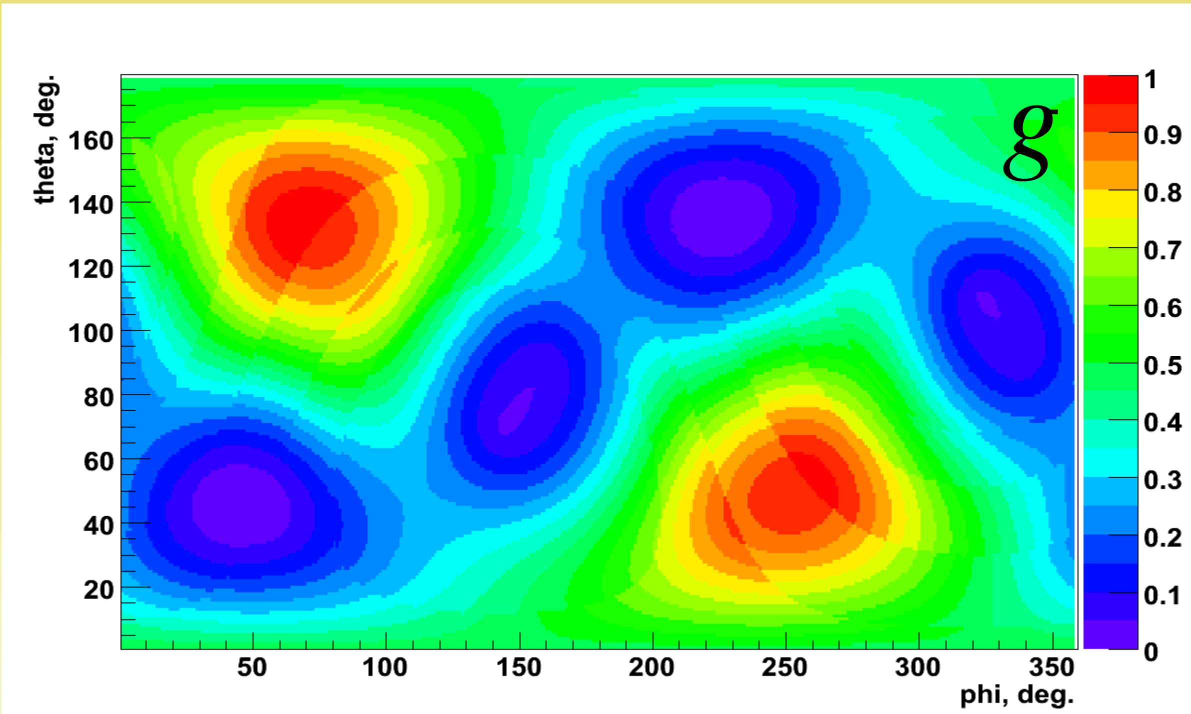
Taken from Page 4 of G060621-00 (Klimenko)

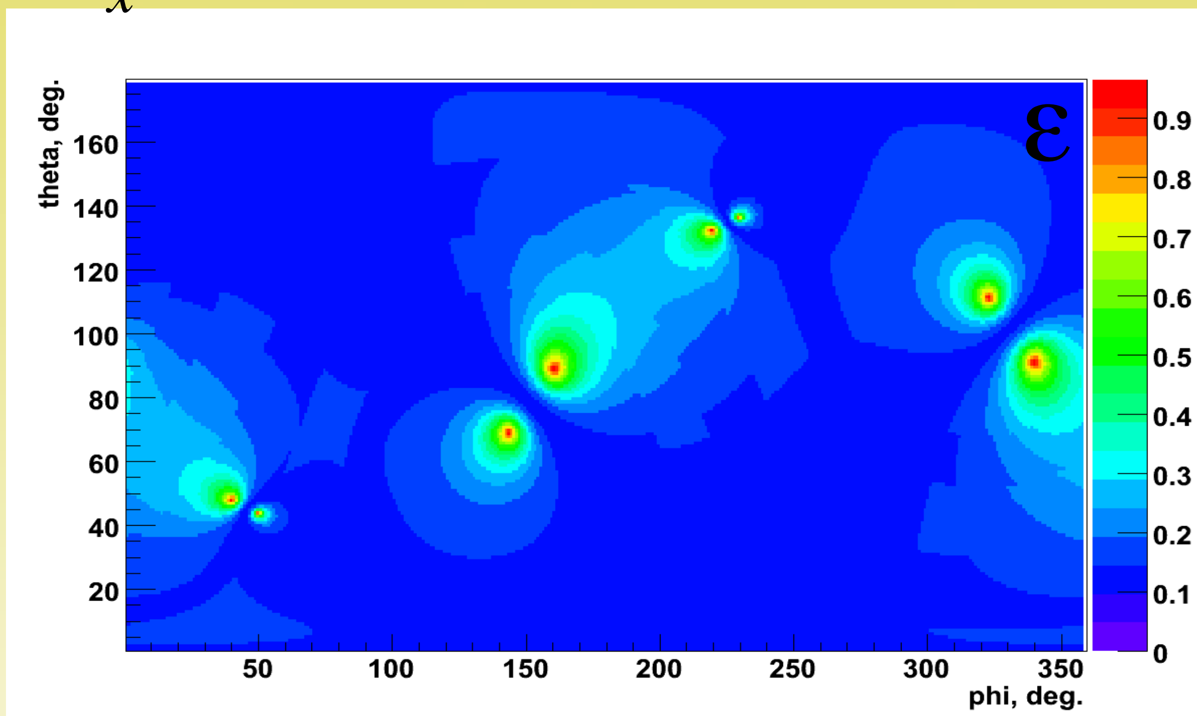
Virtual Detectors & Constraint

- Any network can be described as two virtual detectors

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

- L1×H1×H2 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

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

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

Taken from Page 5 of G060621-00 (Klimenko)

Coherent Energy & Correlation

- detected energy: in-coherent coherent

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

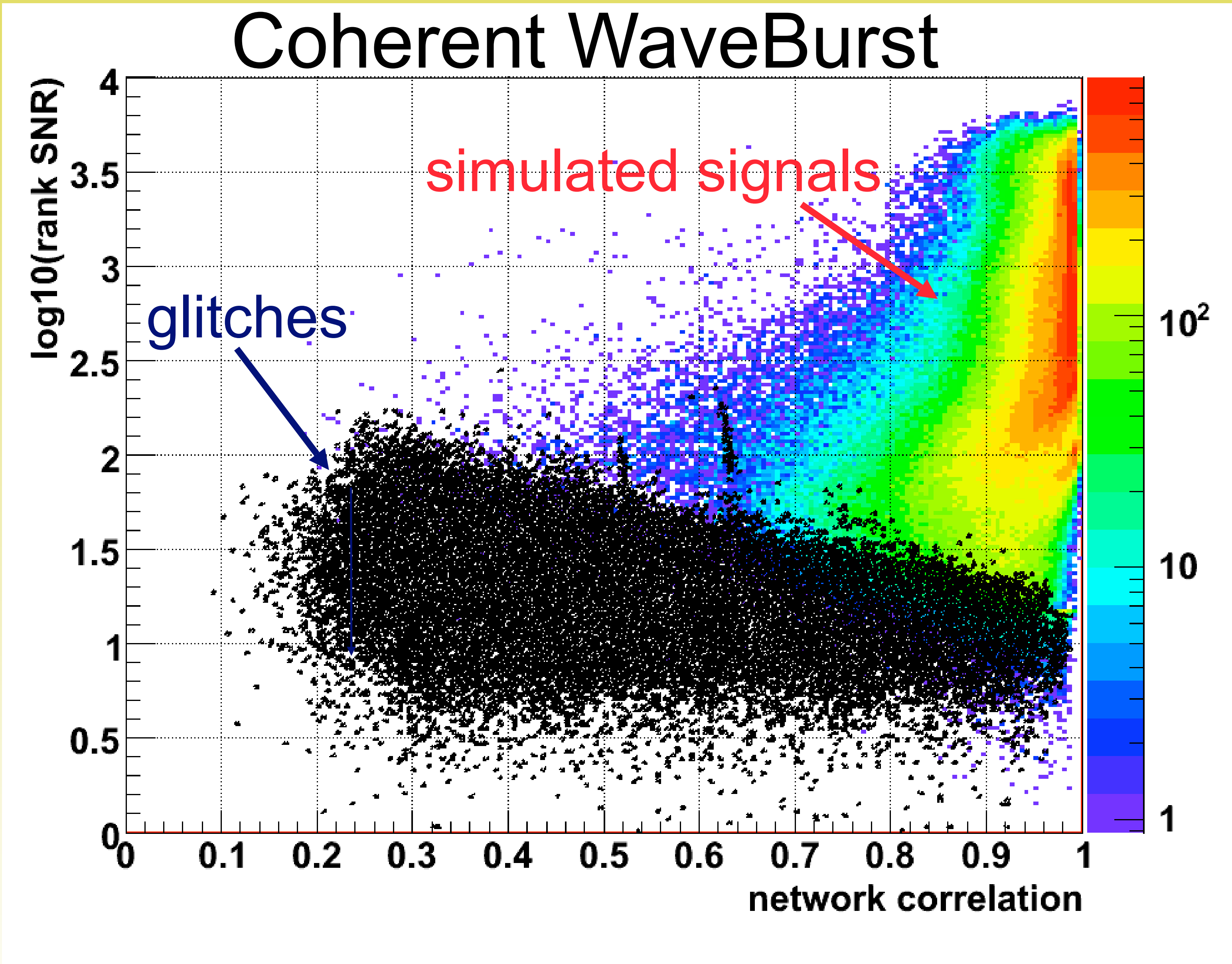
C_{ij} - depend on antenna patterns and variance of the detector noise

x_i , x_j – detector output

- Network correlation

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

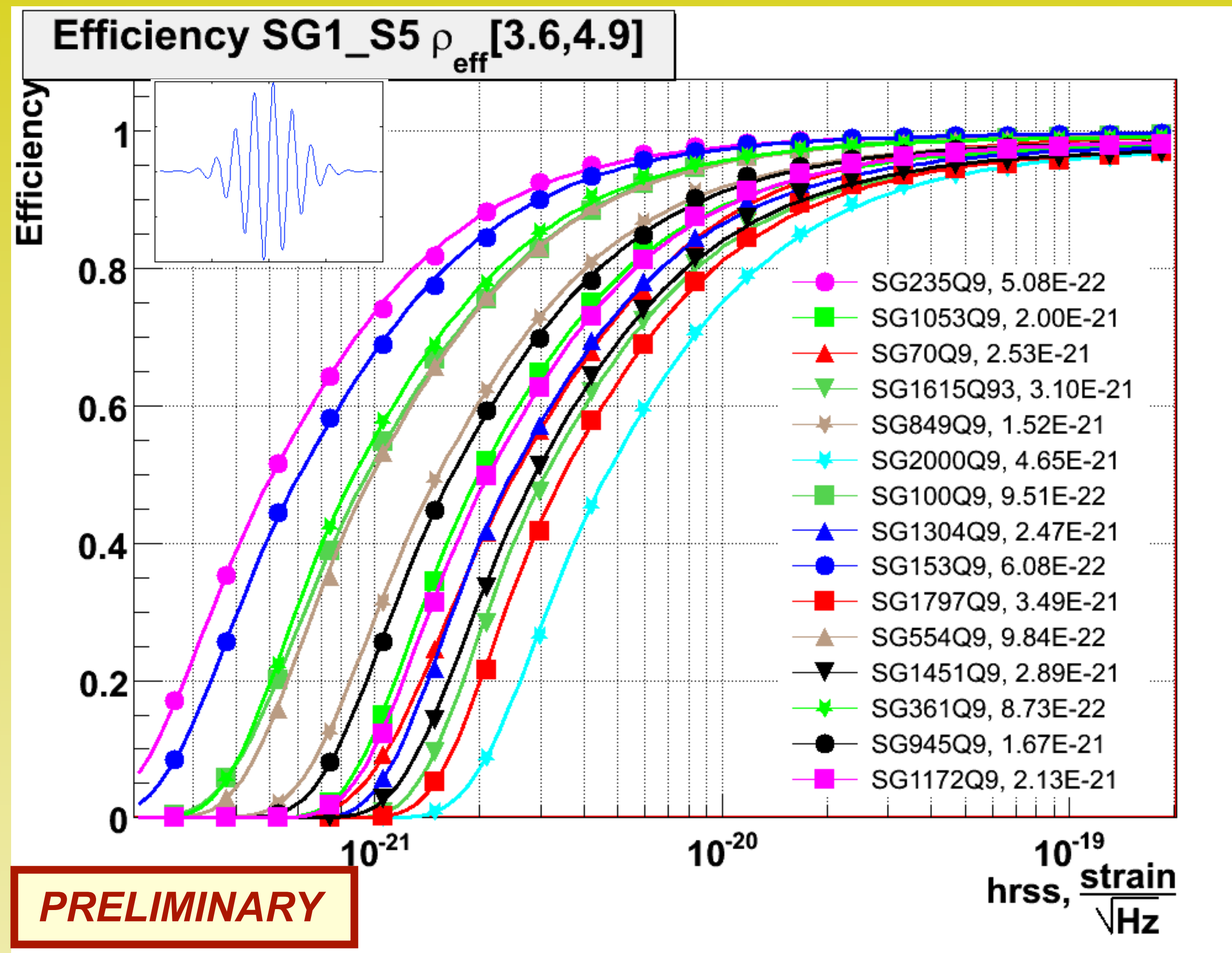
Require $C_{net} > 0.65$



From Page 11 of G060621-00 (Klimenko)

Coherent WaveBurst Performance

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



PRELIMINARY

h_{rss}@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	9.8	15.2	20.0

From Page 14 of G060621 (Klimenko)

Coherent Network for GRB Search

- Analyze triggered events for network, add regularization

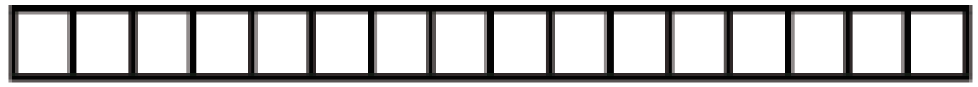
Detector output

$$\begin{bmatrix} x_1(t) \\ \vdots \\ x_k(t) \end{bmatrix} = \begin{bmatrix} F_{+,1}(\theta,\phi) & F_{\times,1}(\theta,\phi) \\ \vdots & \vdots \\ F_{+,k}(\theta,\phi) & F_{\times,k}(\theta,\phi) \end{bmatrix} \begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} + \begin{bmatrix} \eta_1(t) \\ \vdots \\ \eta_k(t) \end{bmatrix}$$

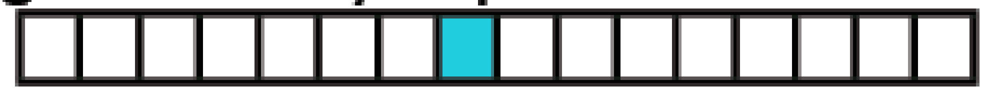
rank defficiency

Ill-posed problem

1. Data is divided into chunks



2. generate skymap at each chunk



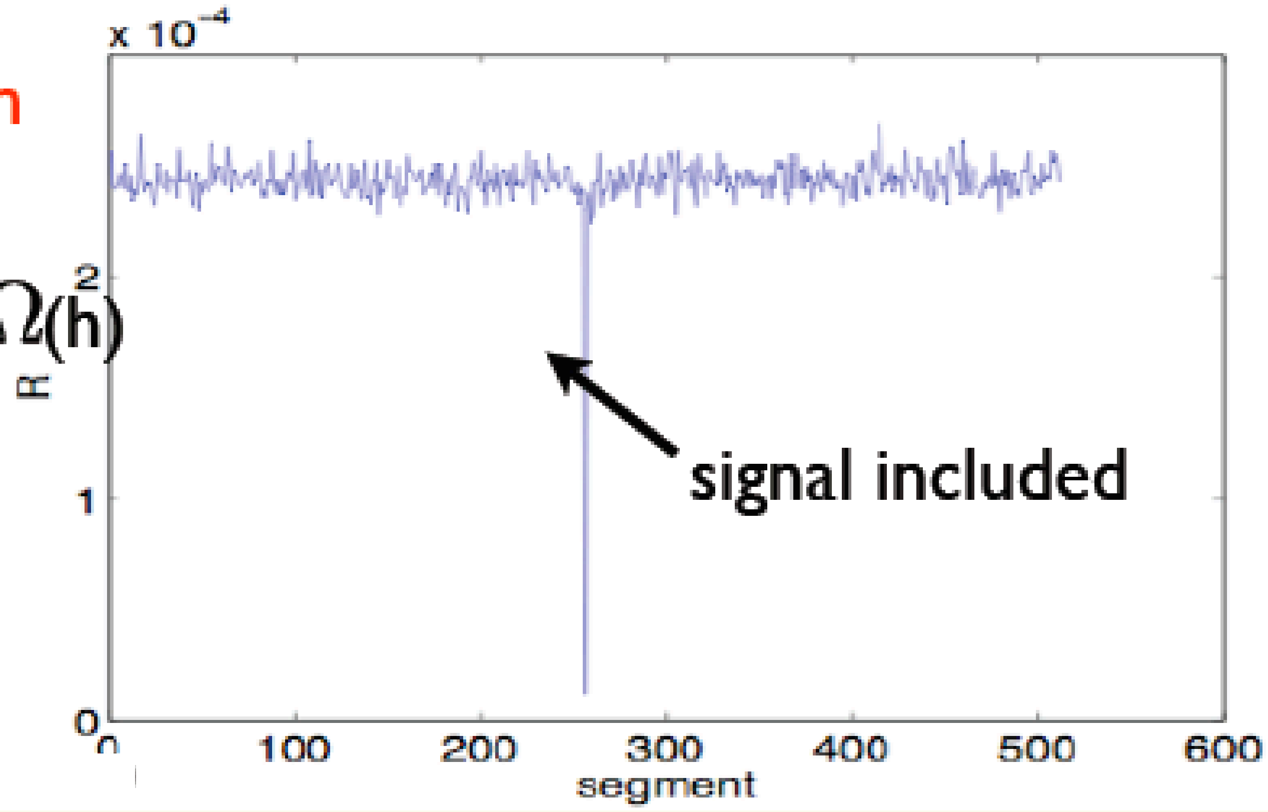
One Solution-- Tikhonov regularization

M. Rakhmanov CQG 23 (2006) S673

$$L_g = ||\mathbf{x}(t) - \mathcal{F}(\theta,\phi)\mathbf{h}(t)||^2 + g\Omega(\mathbf{h})$$

$$R = x^T Q x$$

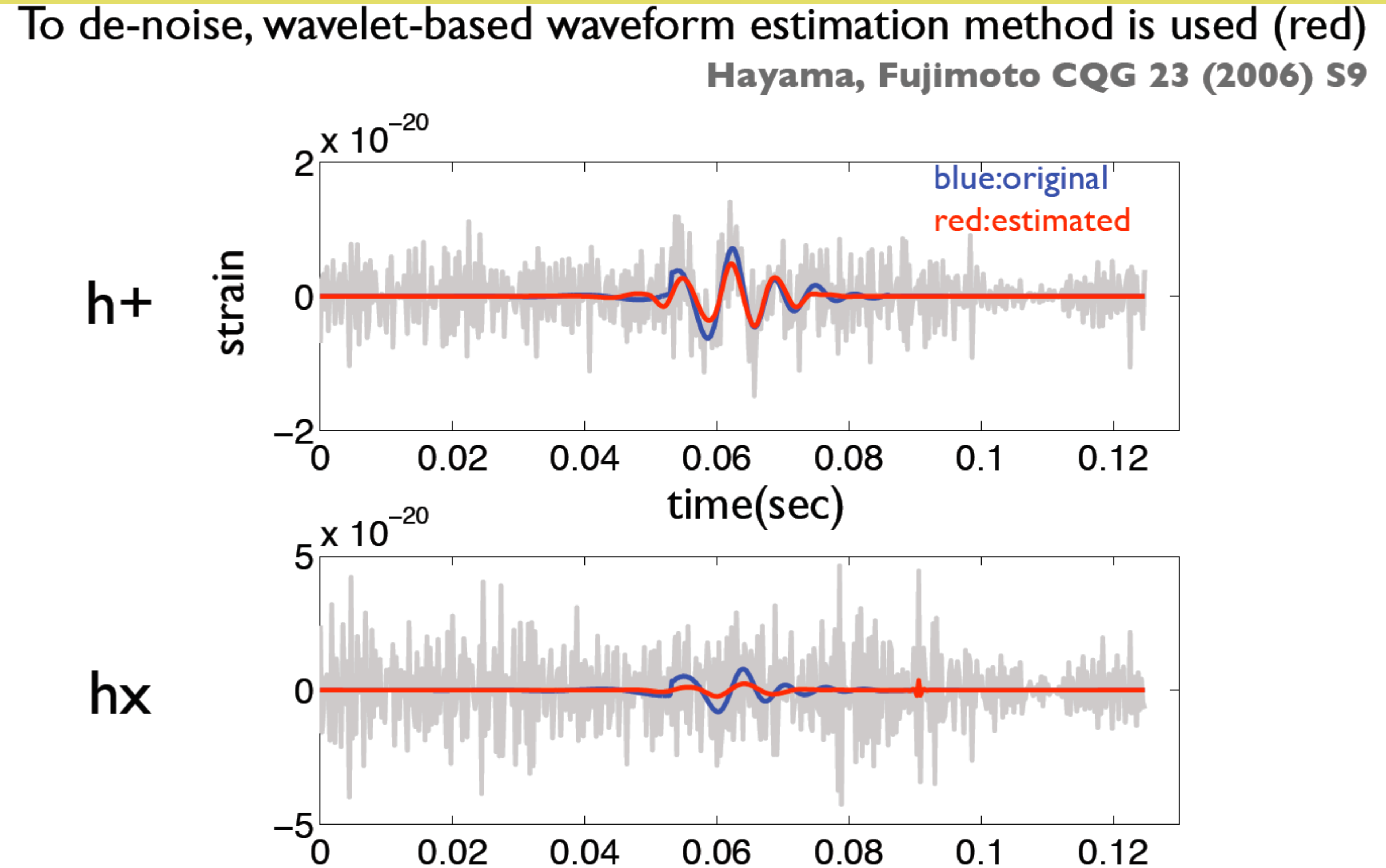
R@source location



From Page 6 of G060653-00 (Hayama)

Waveform Extraction

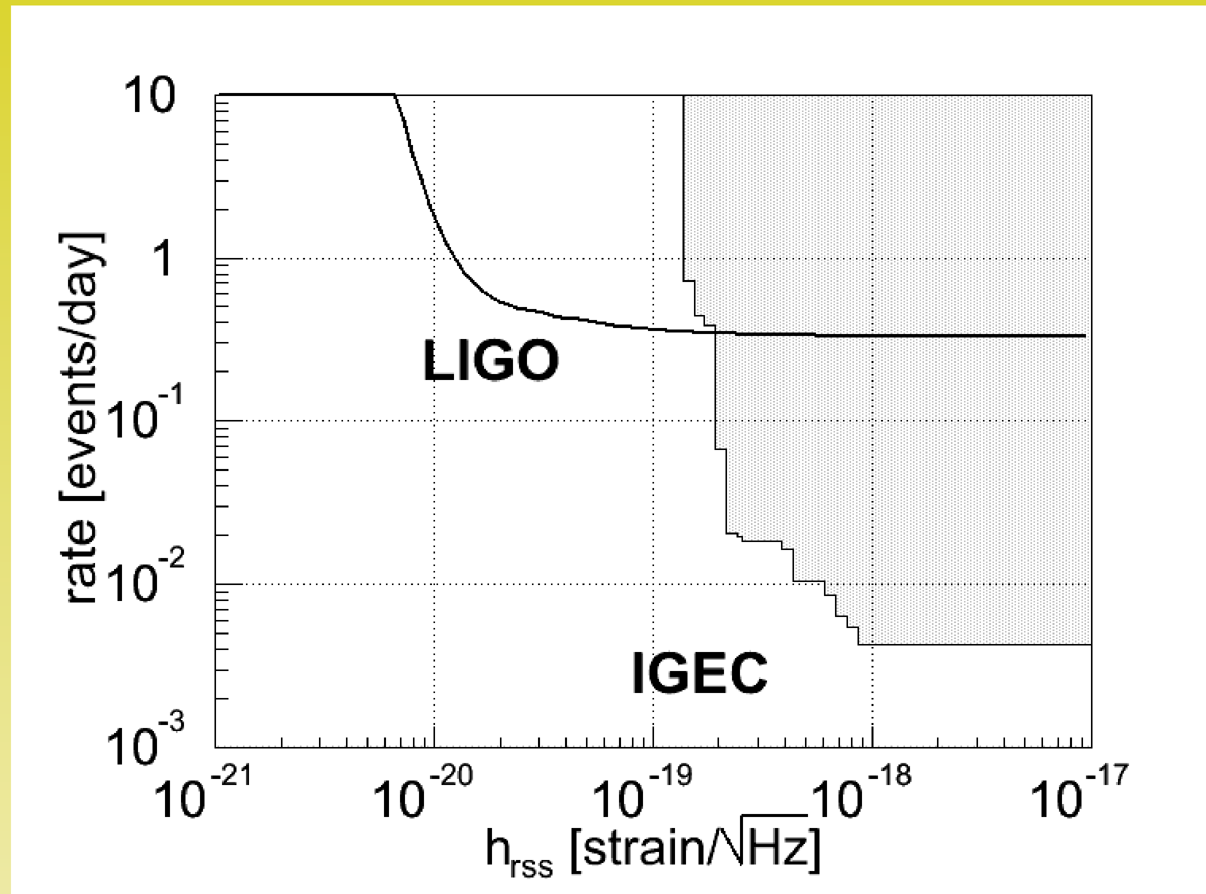
- If GW bursts are detected, we need to extract the waveforms
  - This is built into Coherent WaveBurst for all-sky search
  - Wavelet de-noising being developed for GRB search



From Page 10 of G060653 (Hayama)

Reporting GW Burst Results

- Detector-centric "Rate vs. Strength" says nothing about sources or rate of source events
  - Rate? Event rate in/at detector
  - Strength? Measure of wave amplitude in/at detector
  - "Strength" reveals nothing about, e.g., absolute luminosity

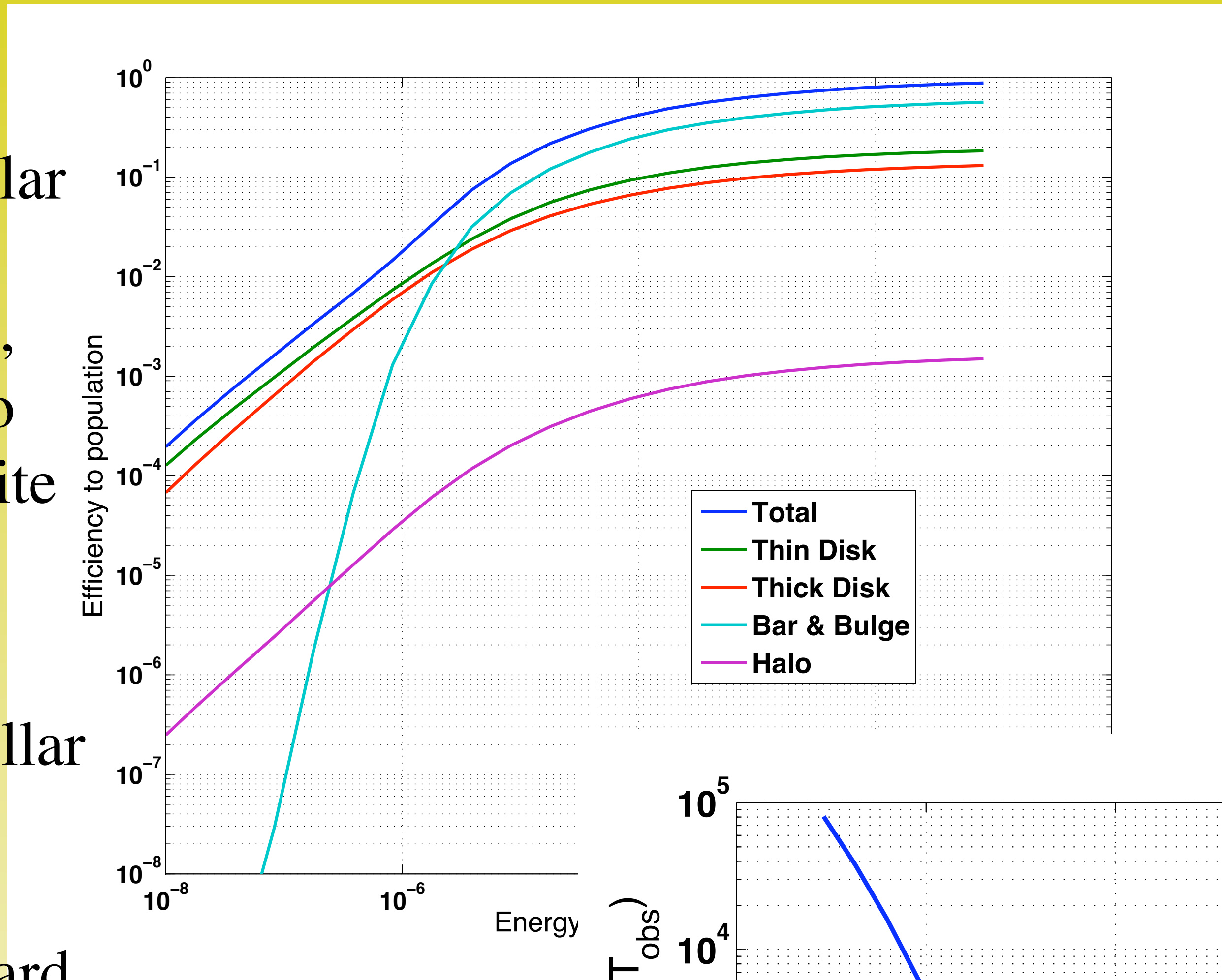


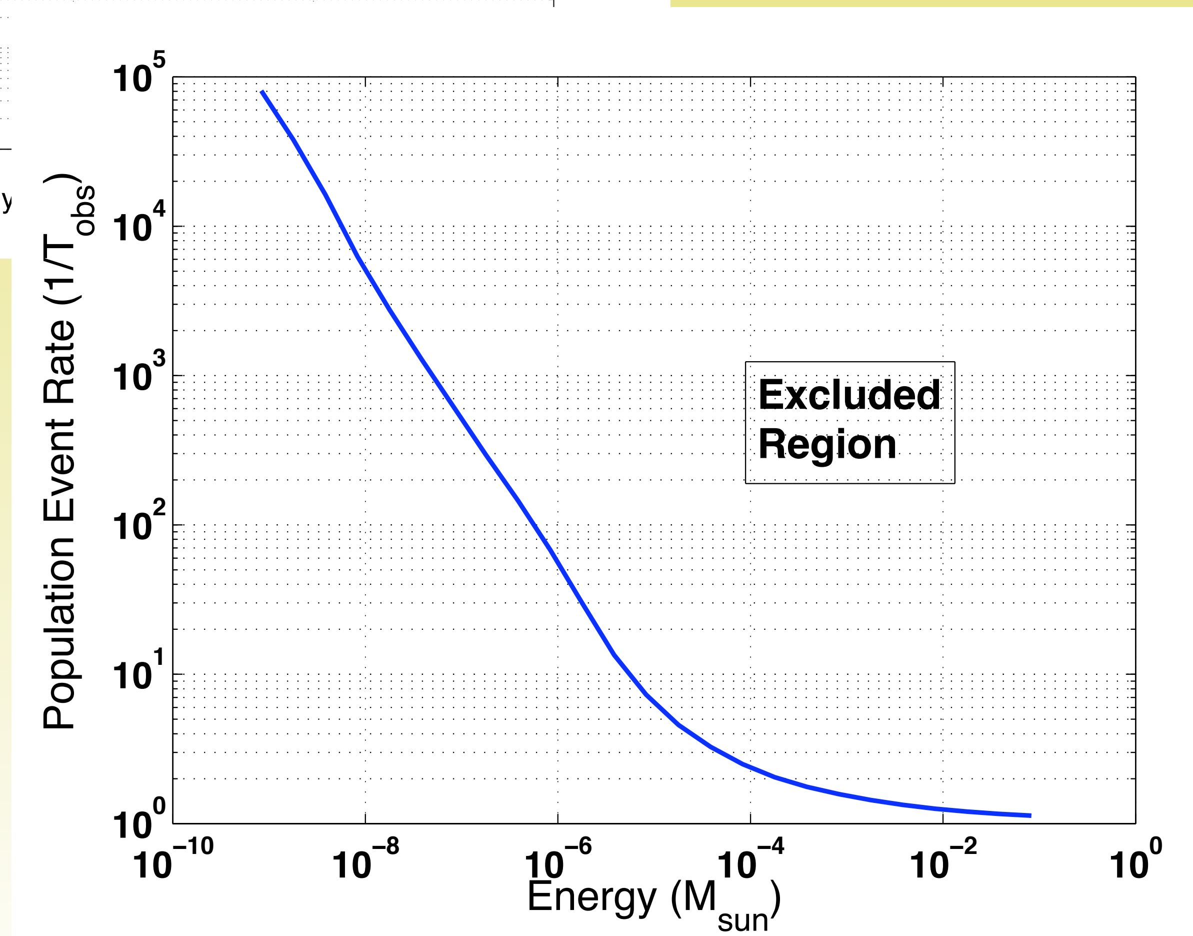
- Better: report rate in population vs. intrinsic energy radiated
- Interpretation - astrophysical or otherwise - is always in terms of a model
- Model components: population (e.g., galactic), source strain energy spectrum (appropriate for burst searches)
- New observational element: observation schedule (sidereal time associated with data being analyzed: gives "pointing" relative to source population)

From G060672-00 (Finn)

Astrophysical Interpretation

- Source population
  - Assume sources trace old stellar population
  - Galactic model with thin disk, thick disk, bulge, bar and halo characteristic of observed white dwarf population
- Source model
  - Impulsive event involving stellar mass compact object (e.g., supernovae, AIC, etc); axisymmetric source & standard candle amplitude
  - Flat spectral density to 1KHz, 10ms duration
- Detector, etc.
  - Virgo, LIGO H1, H2(2Km), L1 with sharp sigmoid efficiency (h_{50} ~10^{-20} $Hz^{-1/2}$)
  - 100% observation schedule





From G060672-00 (Finn)

Concluding Remarks

- The larger the network, the better the chances for burst detection
  - Better immunity to local transients
  - Use full waveform constraints on searches
- Fully-coherent network analyses will be used in S5 results
- LIGO burst searches look forward to our joint work with Virgo
- Even more, we look forward to GW Burst “detection” and the development of Gravitational-Wave Astronomy