Searching for gravitational wave bursts with the new global detector network

Shourov K. Chatterji
INFN Sezioni di Roma / Caltech LIGO Laboratory
for the LIGO Scientific and Virgo Collaborations

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Overview

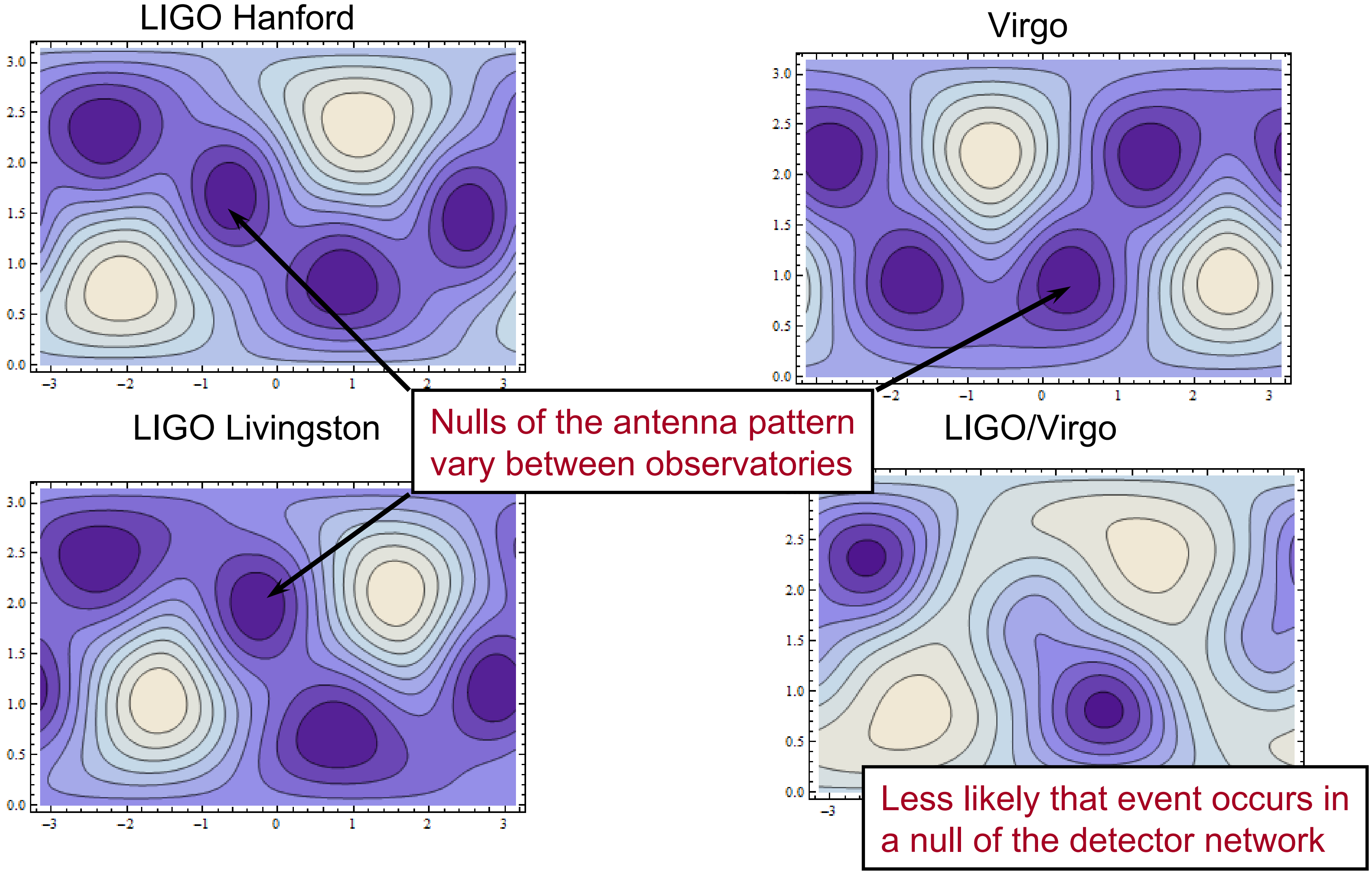
- Outline
  - Benefits of joint data analysis
  - Agreement on joint data analysis
  - Trial analysis using real data
  - Coherent analysis methods
  - Sky position and signal recovery
  - Summary and outlook

- This talk focuses on the search for gravitational-wave bursts with unknown waveform
- See the talk by G. Guidi “First LSC-Virgo joint GW search for binary neutron stars” later this afternoon for information on another joint data analysis effort.

Benefits of joint data analysis

Benefits of a global network

- Improved sky coverage



LIGO Hanford

Virgo

LIGO Livingston

LIGO/Virgo

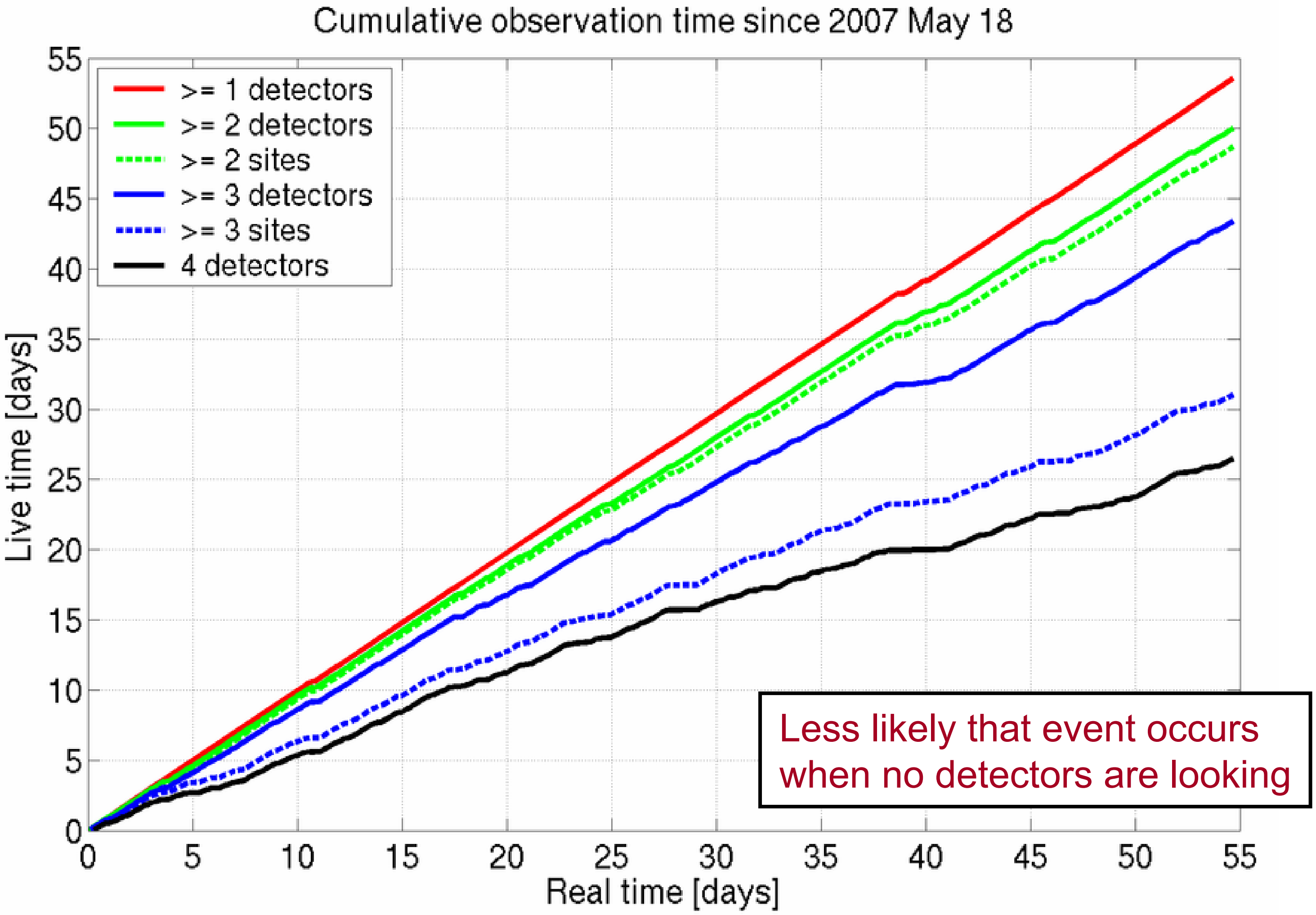
Nulls of the antenna pattern vary between observatories

Less likely that event occurs in a null of the detector network

Average response to signals with random linear polarization in Earth fixed coordinates

Benefits of a global network

- Improved duty cycle



Less likely that event occurs when no detectors are looking

Cumulative observation time of the LIGO/Virgo network since 2007 May 18

Benefits of a global network

- Increased signal to noise ratio
  - Coherently sum signals from multiple detectors
- Improved detection confidence
  - Multi-detector coincidence greatly reduces false rate
  - Coherent consistency tests can differentiate between gravitational-wave signals and instrumental anomalies
- Permits improved directional searches
  - Gamma ray burst progenitors
  - Supernovae
- Improved source reconstruction
  - “Inverse problem” requires **3** non-aligned detectors
  - Provides sky position and both polarizations of waveform
  - Permits comparison with theory
  - This is where the science is!
- Shared best practices
  - Learn from each other’s approaches

Agreement on joint data analysis

Agreement on joint data analysis

- Recognizing the benefits of joint data analysis, the LIGO Scientific and Virgo collaborations have entered into an agreement to jointly analyze data from the GEO, LIGO, and Virgo detectors
- Sharing of data started in May 2007 when Virgo commenced its first long science run in coordination with LIGO’s fifth science run
- A joint run plan committee is coordinating detector operation and commissioning schedules to improve the prospects for detection

- Initial joint data analysis working group meeting since June 2004
- Performed joint data analysis exercises with simulated and small amounts of real data to demonstrate benefits and understand technical issues

- Full joint data analysis meetings are now taking place
- Performed trial end-to-end analysis of a small set of real data

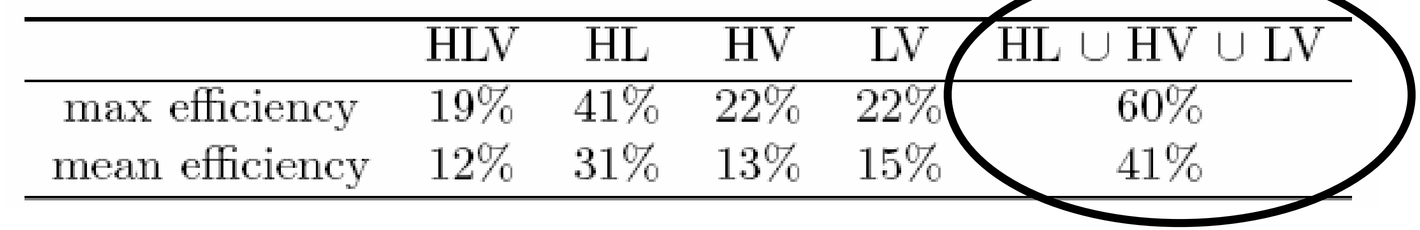
Trial analysis using real data

“Project 2b”

- “Proof of principle” analysis using real detector data
- ~68 hours of coincident data from September 2006
  - LIGO’s 5th science run (S5)
  - Virgo’s 1st weekly science run (WSR1)
- Includes data from all 5 LSC and Virgo detectors
  - GEO600 (G1)
  - Hanford 4km (H1)
  - Hanford 2km (H2)
  - Livingston (L1)
  - Virgo (V1)
- Data from each observatory shifted in time by a different secret amount
- Apply both coincident and coherent search methods
- Perform “end to end” analysis
- Examine sensitivity to a variety of simulated burst signals
- Identify options and issues for the upcoming joint analysis

Coincident Power Filter analysis

- Applied the Power Filter burst search algorithm described in *G.M. Guidi et al 2004 Class. Quantum Grav.* ***21*** *S815-S820*
- Produces whitened time-frequency spectrograms at multiple time-frequency scales
- Identifies statistically significant regions of excess signal power
- Tests for temporal coincidence of events between detectors within the expected speed of light travel time
- Considered union of all double coincident triggers as described in *F. Beauville, et al., in preparation, arXiV:gr-qc/0701026*

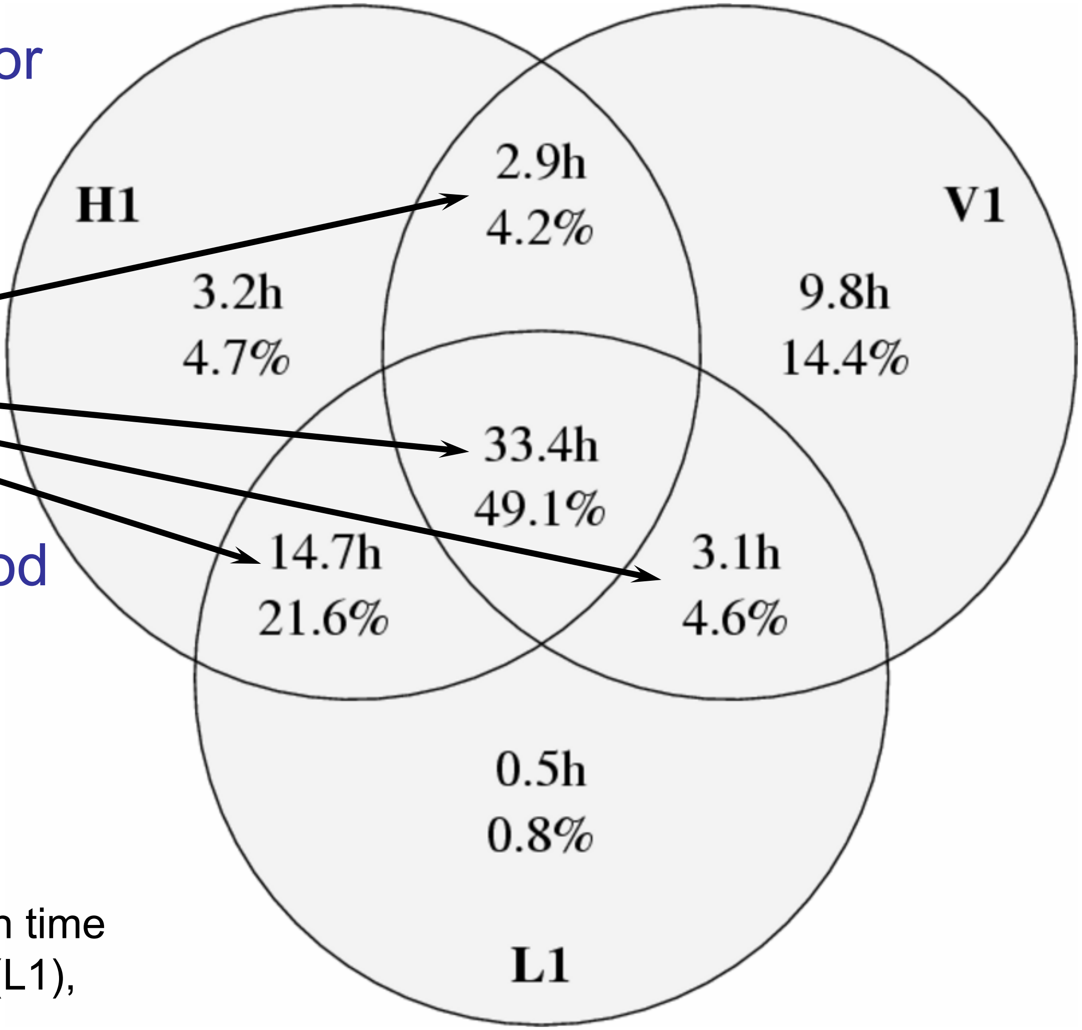


	HLV	HL	HV	LV	$HL \cup HV \cup LV$
max efficiency	19%	41%	22%	22%	60%
mean efficiency	12%	31%	13%	15%	41%

- Sensitivity of the search characterized by injecting sinusoidal Gaussians bursts with varying center frequencies and amplitudes.
- Individual detector thresholds tuned to simultaneously maximize the detection efficiency for all injected signals at a 1μHz false rate

Analyzed data

- Coincident analysis focused only on three detectors
  - Hanford 4km (H1) detector
  - Livingston (L1) detector
  - Virgo (V1) detector



≥ 2 sites
54.6 hours
80.3%

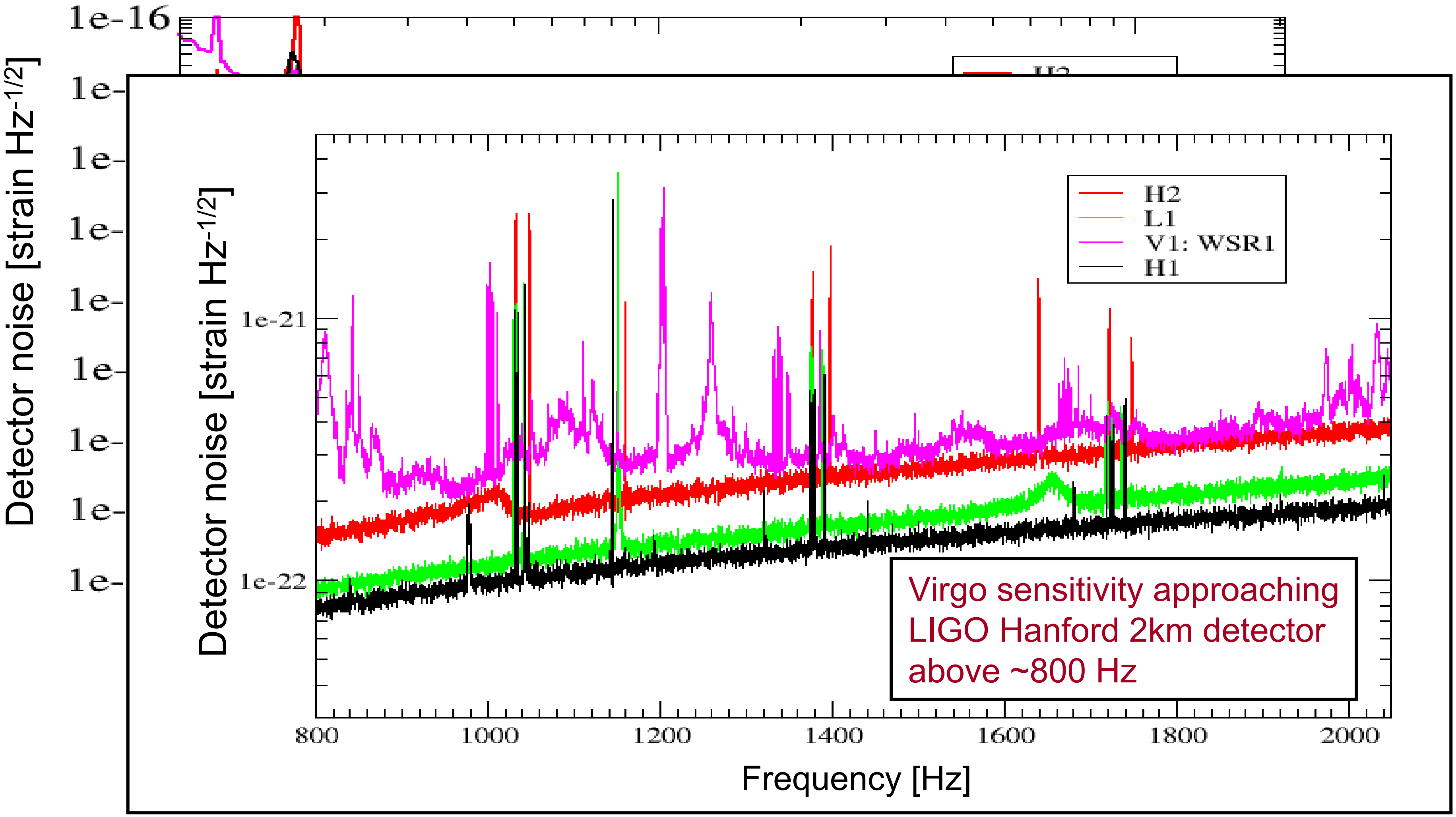
- Restricted analysis to good quality data and rejected events coincident with anomalous detector behavior.

Venn diagram of available observation time for the Hanford 4km (H1), Livingston (L1), and Virgo (V1) detectors

Analyzed frequency range

- Coincident analysis focused only on 800 to 2000 Hz.

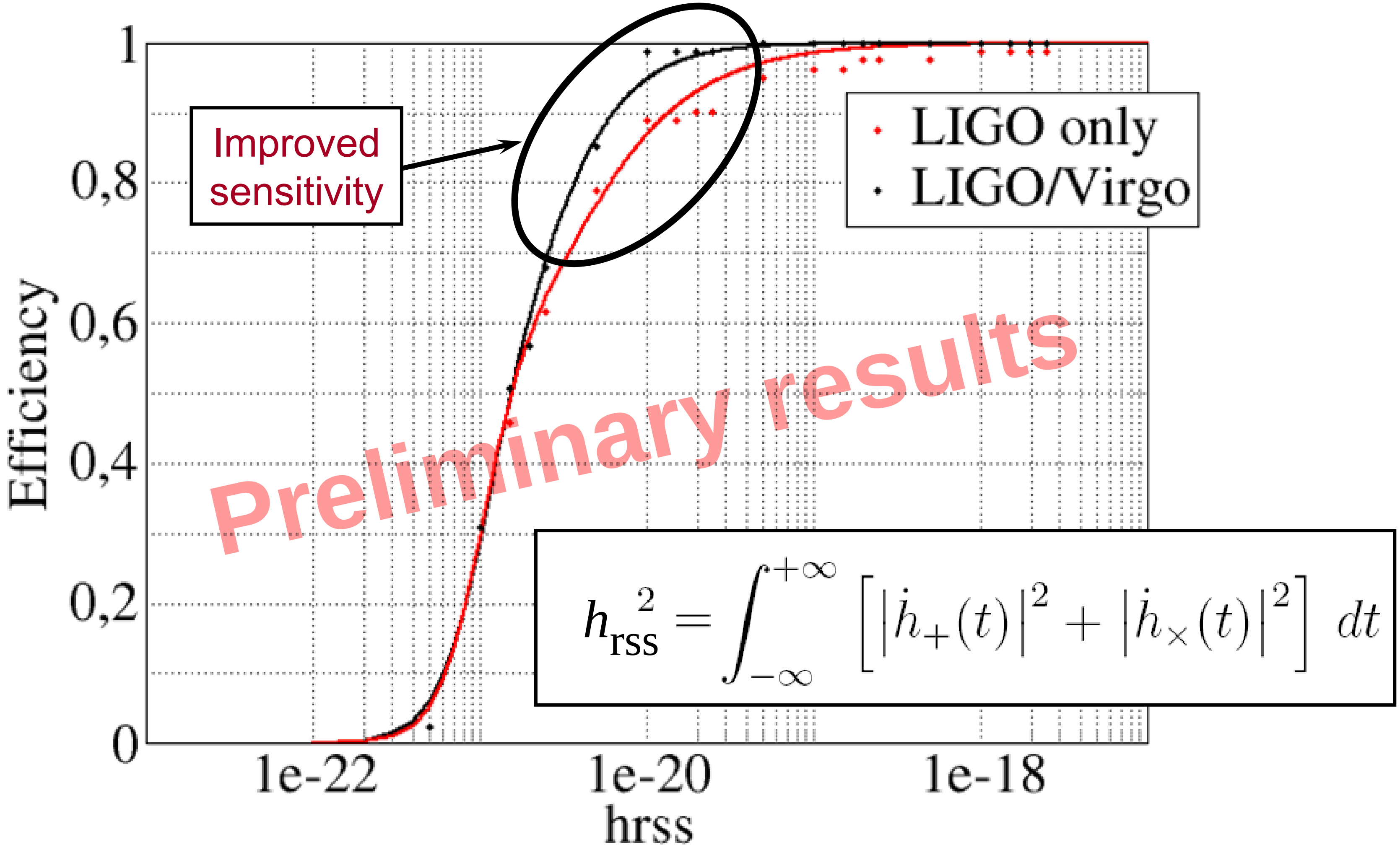
Detector sensitivities from September 2006



Virgo sensitivity approaching LIGO Hanford 2km detector above ~800 Hz

Pairwise coincident sensitivity

Sensitivity to 849 Hz Q 9 sinusoidal Gaussians at a 1 μHz false detection rate

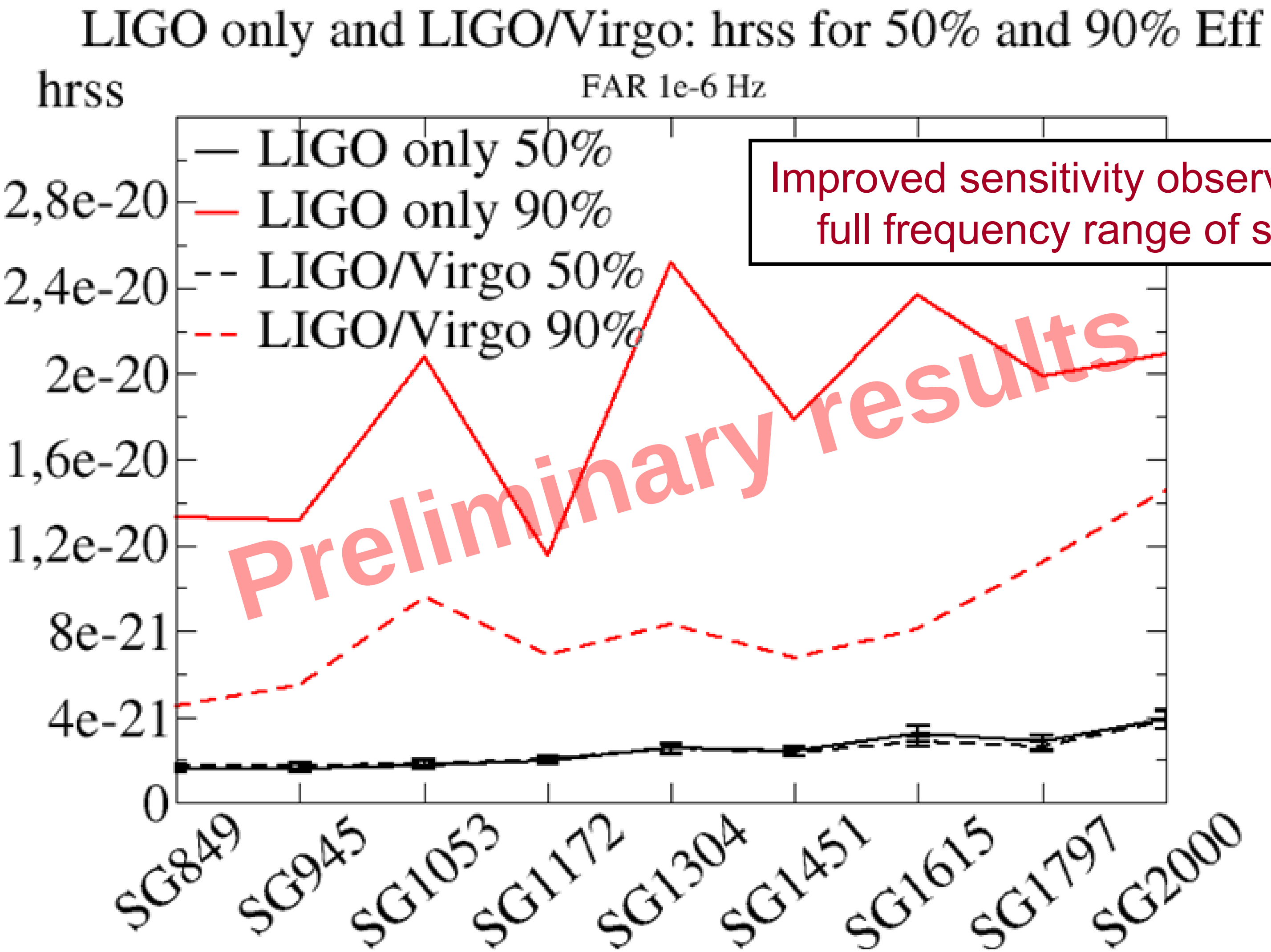


Improved sensitivity

$$h_{\text{rss}}^{2} = \int_{-\infty}^{+\infty} \left[\left| \dot{h}_{+}(t) \right|^{2} + \left| \dot{h}_{\times}(t) \right|^{2} \right] dt$$

Comparison of LIGO only (H1L1) and LIGO/Virgo (H1L1+H1V1+L1V1) sensitivities

Pairwise coincident sensitivities



Improved sensitivity observed over full frequency range of search

Comparison of LIGO only (H1L1) and LIGO/Virgo (H1L1+H1V1+L1V1) sensitivities

Coherent analysis methods

Related talks and posters at this conference:

- *Coherent waveburst algorithm for gravitational wave searches (S. Klimenko, I. Yakushin, A. Mercer, and G. Mitselmakher)*
- *Robust Bayesian detection of unmodeled bursts of gravitational waves (A. Searle, S. Chatterji, P. Sutton, M. Tinto)*

Coherent analysis methods

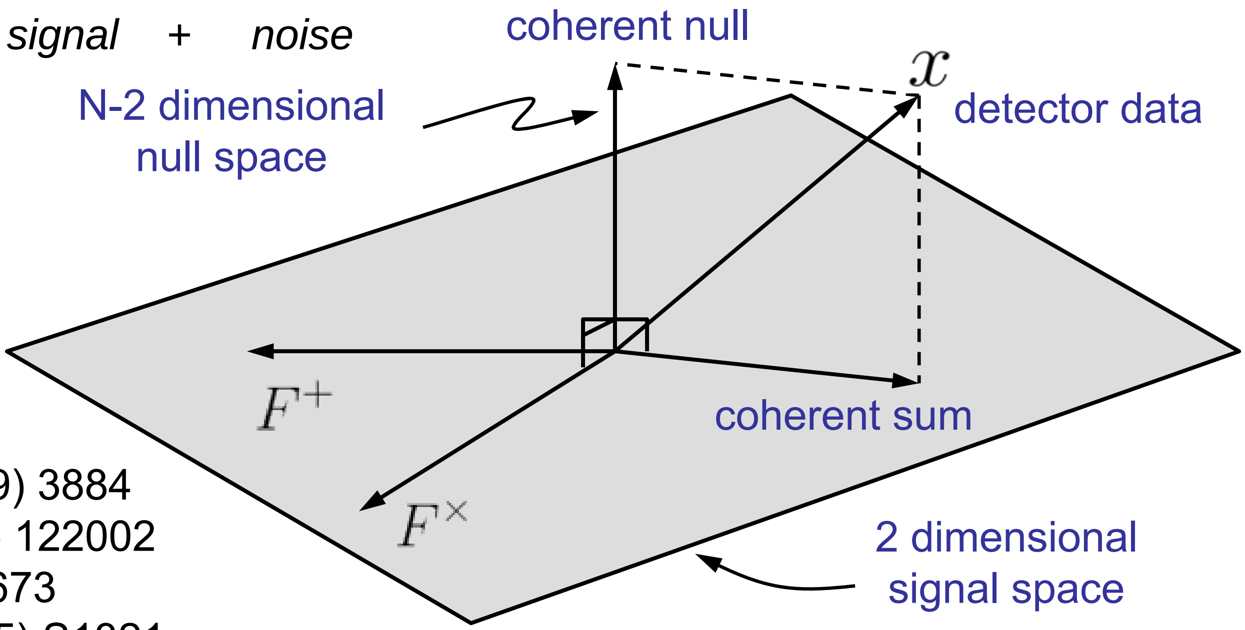
- Naturally handles arbitrary networks of detectors
- Analysis repeated as a function of frequency and sky position
- Produces significance and consistency sky maps

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

data = *response* x *signal* + *noise*

Coherent sum:
Find linear combinations of detector data that maximize signal to noise ratio

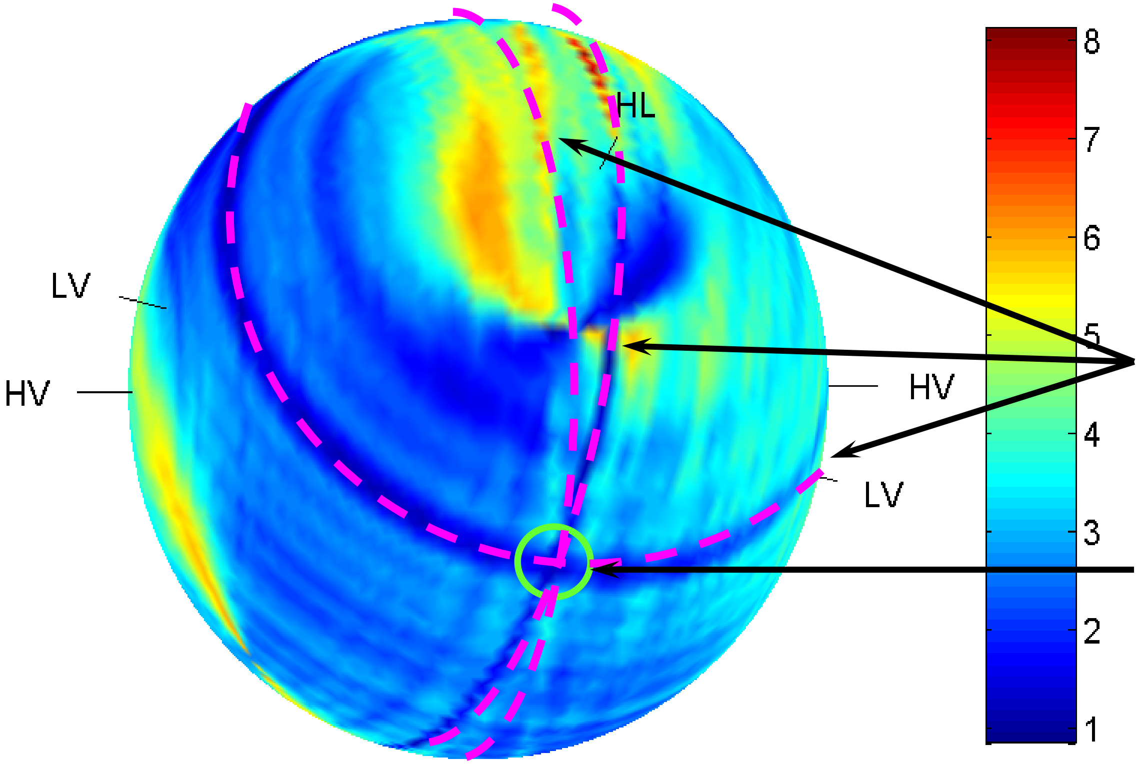
Null sum:
Linear combinations of detector data that cancel the signal provide useful consistency tests.



- Gursel and Tinto, PRD 40 (1989) 3884
- Klimenko, et al., PRD 72 (2005) 122002
- Rakhmanov, CQG 23 (2006) S673
- Wen and Schutz, CQG 22 (2005) S1321
- Chatterji, et al. PRD 74 (2006) 082005

Simulated coherent consistency test

Test the coherent null stream for consistency with detector noise as a function of sky position



Color indicates χ^2 per degree of freedom of the coherent null sum as a function of sky position

Interference fringes from combining signal in two detectors form rings along locus of constant time delay

True source location at intersection of rings has χ^2 per degree of freedom of ~1

Figure from PRD 74 (2006) 082005

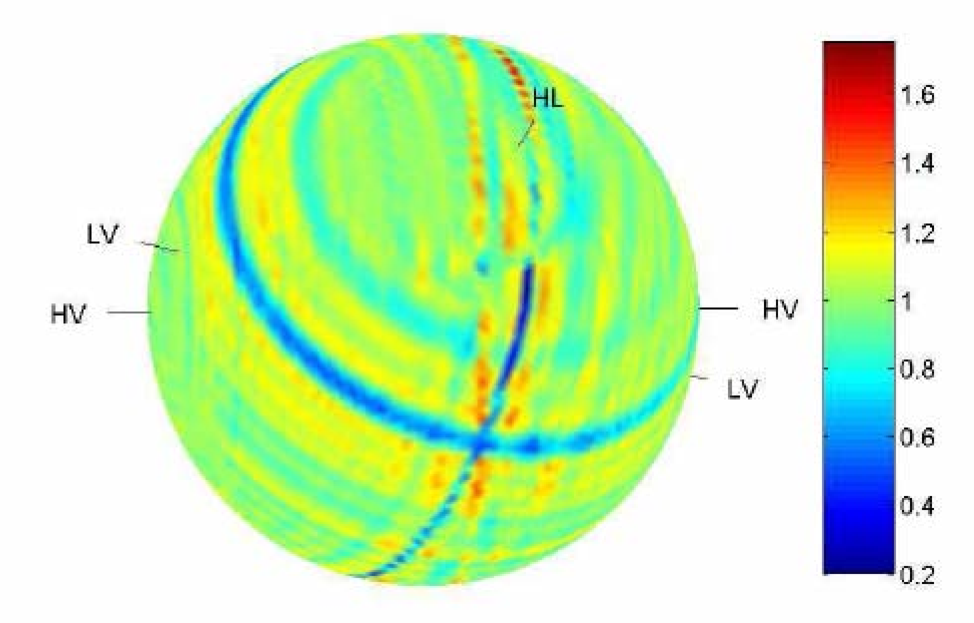
Simulated (A1B3G3) supernovae signal from Dimmelmeier *et al*. A&A 393 (2002) 523
Injected with SNR of 20 into simulated design sensitivity H1, L1, and V1 detector noise

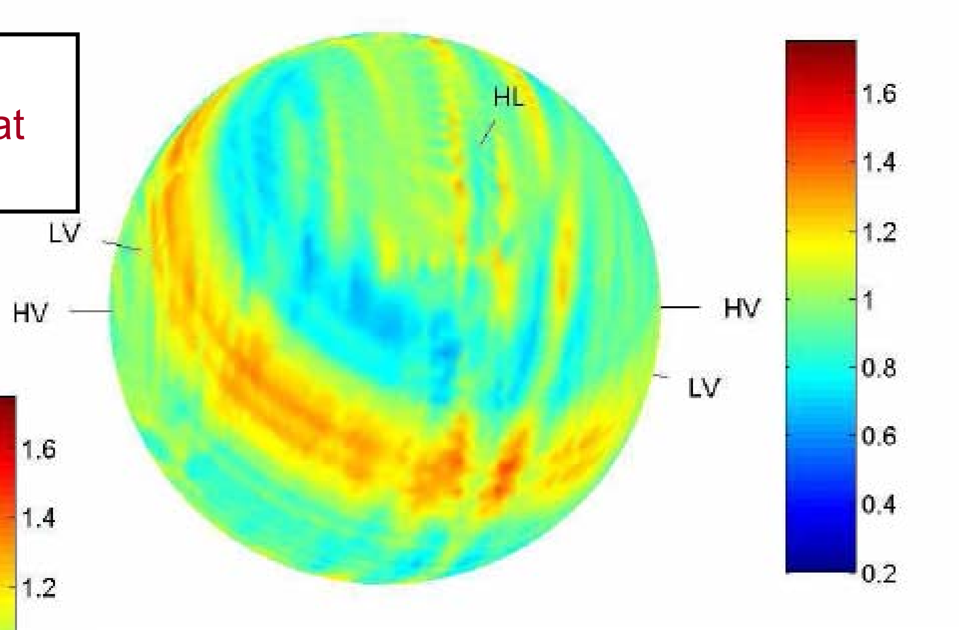
Simulated coherent consistency test

Consistency tests useful for distinguishing coincident detector glitches from real signals

Detector glitches do not exhibit the ring features with reduced null sum energy that are observed for consistent signals

Simulated gravitational-wave burst (consistent supernovae waveforms)





Simulated coincident glitch (inconsistent supernovae waveforms)

Color indicates fraction of available signal energy remaining in null stream

Figures from PRD 74 (2006) 082005

Simulated (A1B3G3) supernovae signal from Dimmelmeier *et al*. A&A 393 (2002) 523
Injected into simulated design sensitivity H1, L1, and V1 detector noise

Sky position and signal recovery

Related talks and posters at this conference:

- *Reconstruction of burst signals with networks of gravitational wave detectors (S. Klimenko, I. Yakushin, A. Mercer, S. Mohanty, and G. Mitselmakher)*

Sky position recovery

- Noise fluctuations cause coherent methods to identify sky positions along rings of constant Δt
- Timing based sky position can provide more accurate results
- Simulated timing based recovery of 1 ms Gaussian signals yields ~1 degree accuracy

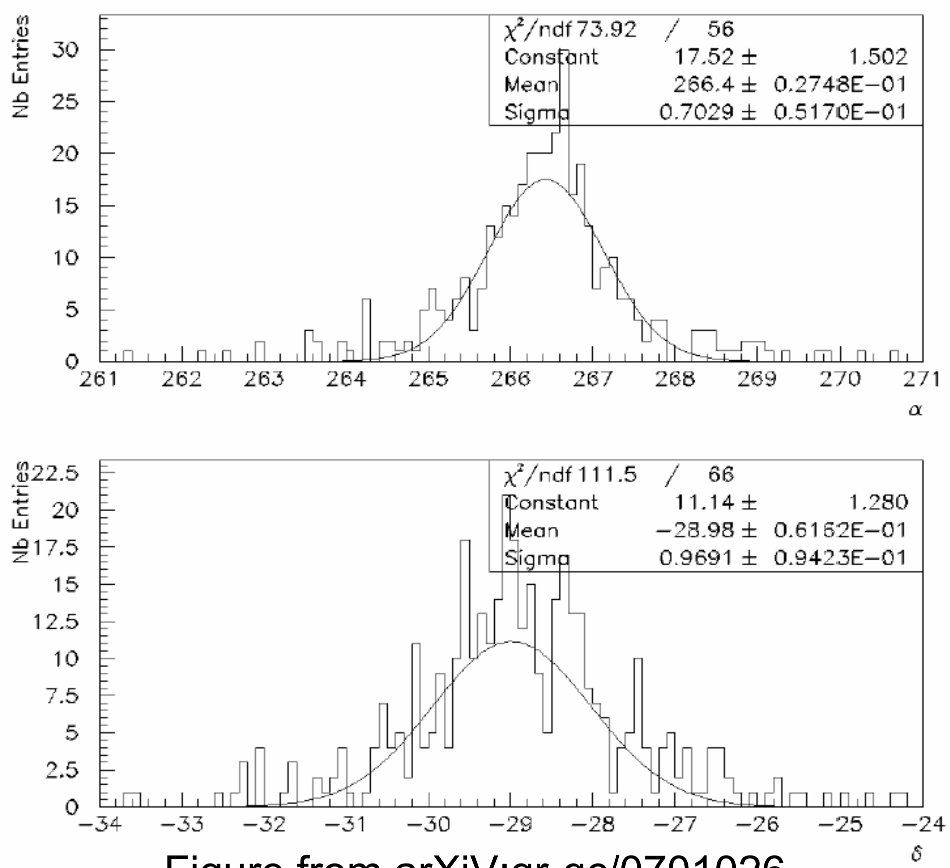
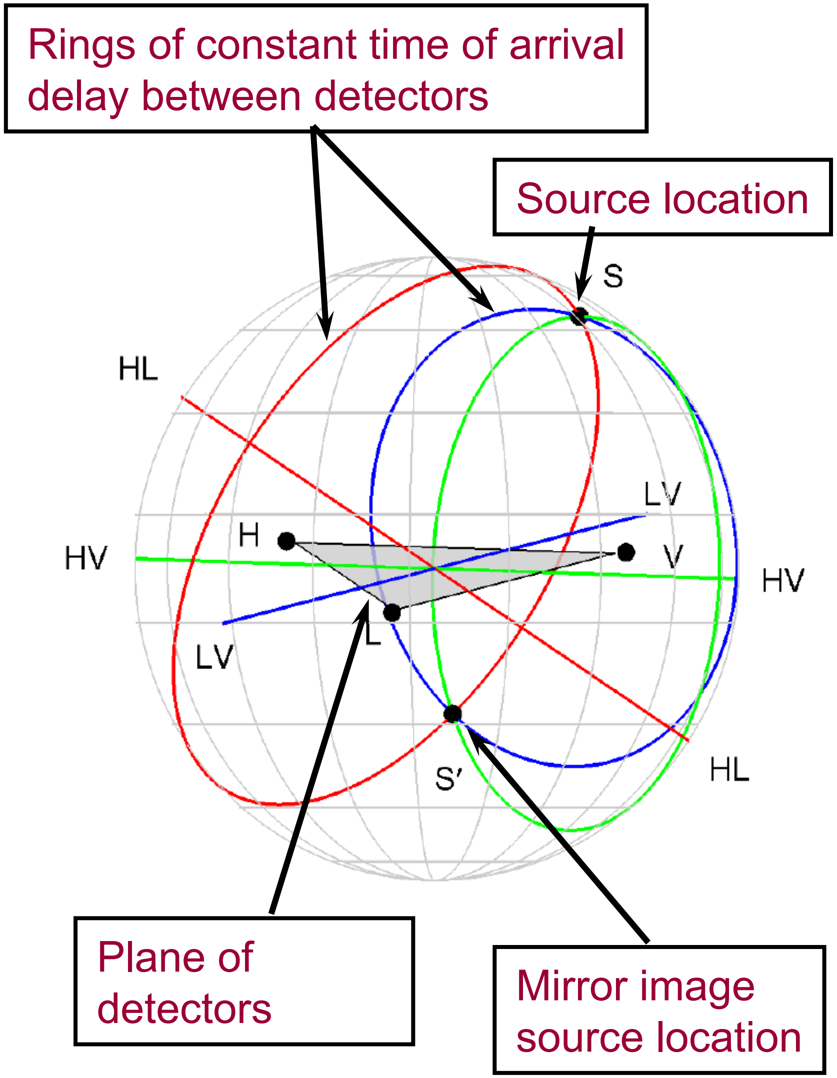


Figure from arXiV:gr-qc/0701026


Rings of constant time of arrival delay between detectors

Source location

Plane of detectors

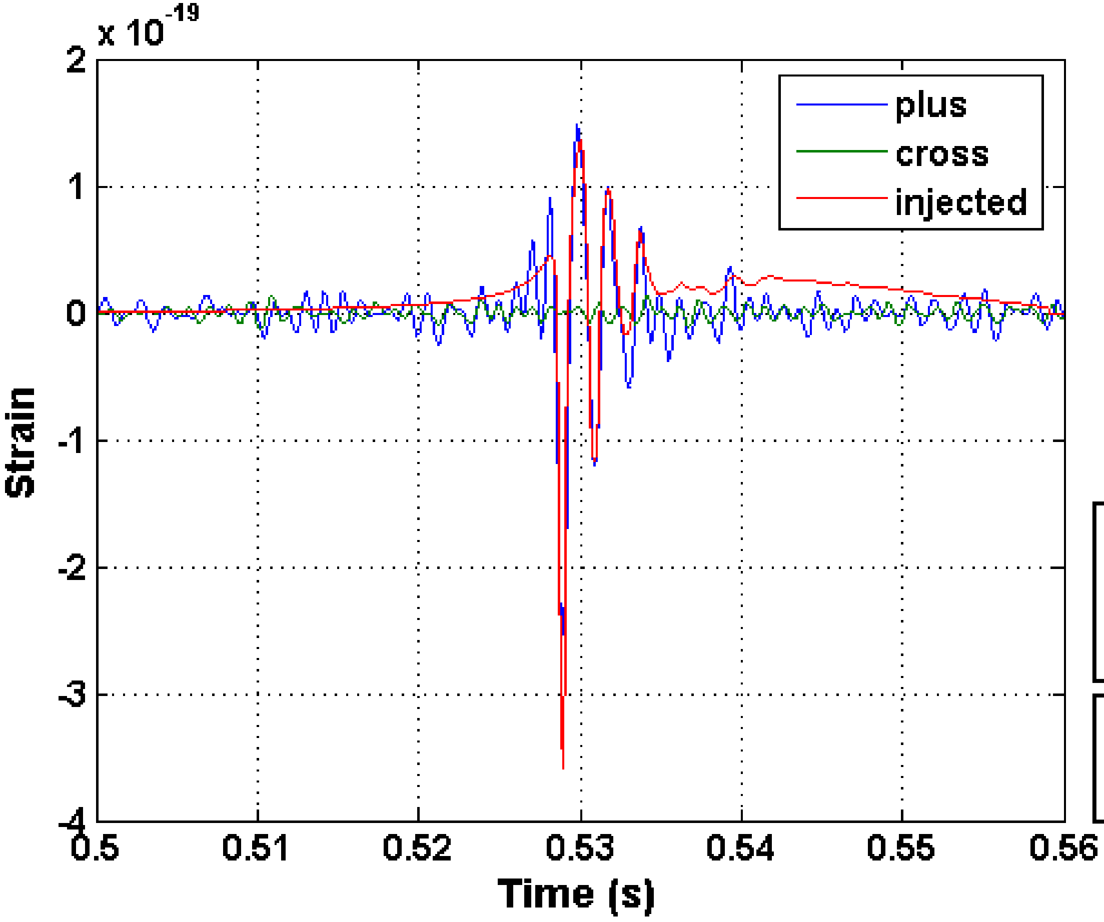
Mirror image source location

Figure from PRD 74 (2006) 082005

Simulated waveform recovery

Given a best guess sky position, estimate the signal **h** from **x** = **Fh** + **n** by identifying the psuedo-inverse **R** such that **RF** = **I**.

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$



Simulated (A4B1G4) supernovae from Dimmelmeier *et al*. A&A 320 (1997) 209

Injected with SNR 40 into simulated H1, L1, and G1 detector noise

Signal injected only into h+ polarization

Recovered h+ signal (blue) is a noisy, band-passed version of the injected signal (red)

Recovered hx signal (green) is just due to noise.

Summary and outlook

- The LIGO Scientific and Virgo collaborations are now jointly analyzing data from a network of 5 interferometric detectors
- Coincident and coherent analysis tools are now available to take advantage of data from networks of detectors
- The union of pairwise coincident triggers from the LIGO/Virgo network provides an improvement in detection efficiency and coverage over the LIGO only network
- We expect even greater benefit at the current Virgo sensitivity
- Coherent methods naturally handle arbitrary networks of detectors and provide increased detection confidence, consistency tests, and parameter estimation.
- Coherent methods applied to trial data, but not ready to present
- Coincident and coherent analysis methods complement each other and can be used as part of a hierarchical search
- We are ready to start analyzing joint GEO, LIGO, and Virgo data
- Already started joint search for gravitational waves associated with gamma ray bursts

Current sensitivities