Data Analysis Techniques for LIGO

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Lesson Plan

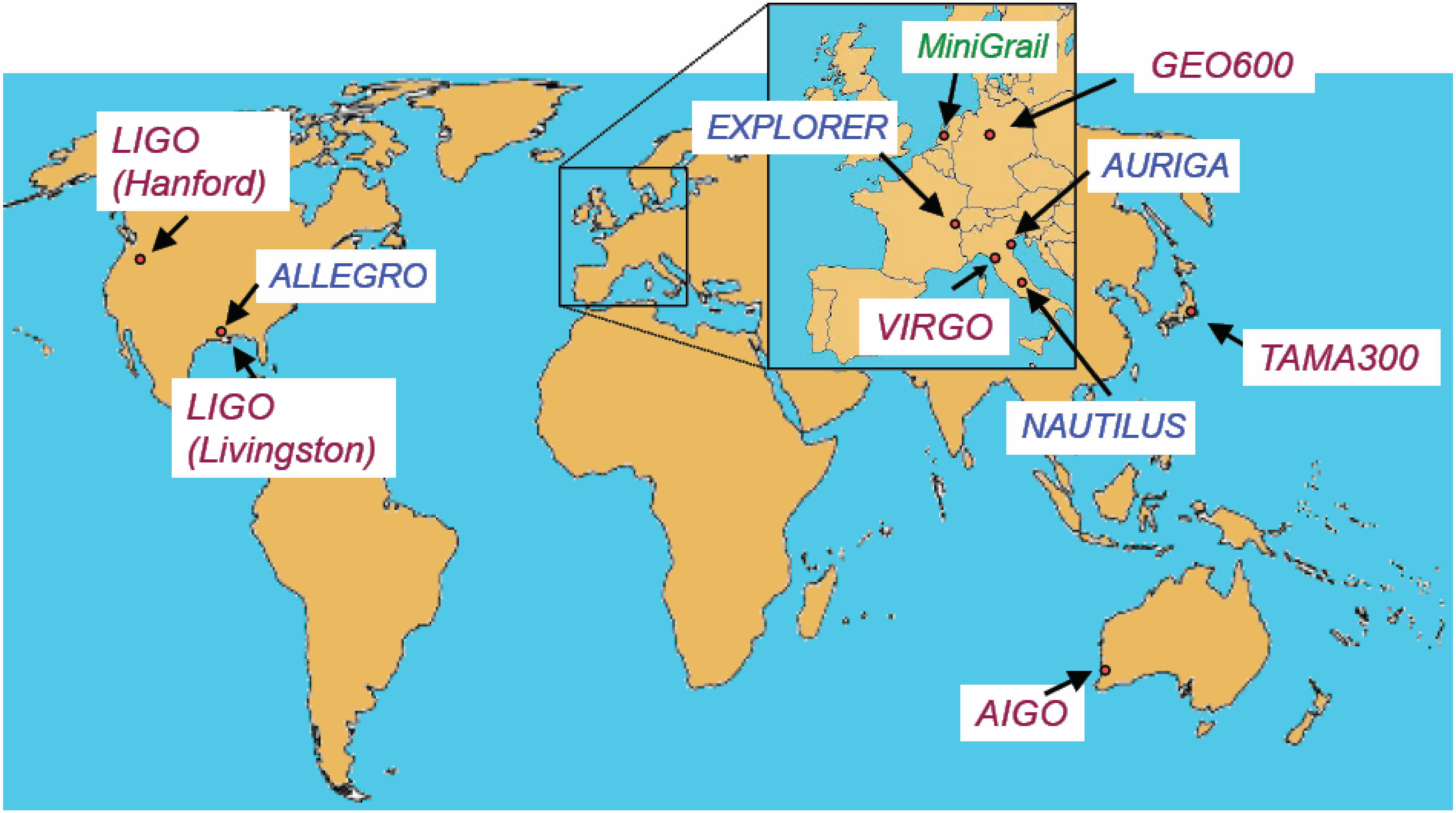
Yesterday:

1. Introducing the problem: GW and LIGO
2. Search for Continuous Waves
3. Search for Stochastic Background

Today:

4. Search for Binary Inspirals
5. Search for Bursts
6. Network Analysis

GW Detectors Worldwide



Benefits of a global network

- Improved sky coverage
  - Less likely that event occurs in null of detector network
- Improved duty cycle
  - More likely that at least one detector observes an event
- Improved search algorithms
  - Three detector sites permit fully coherent search
- Improved detection confidence
  - Multi-detector coincidence greatly reduces false rate
  - Coherent consistency tests can differentiate between gravitational-wave signals and instrumental glitches
- Improved source reconstruction
  - Inverse problem requires three detector locations
  - Sky position reconstruction, waveform reconstruction, astrophysical parameter estimation, etc.
  - This is where the science is!
- Shared best practices
  - Learn from each other's approaches

Coincidence Analysis

The "historical" approach: we demand a signal to show up in all detectors: AND strategy

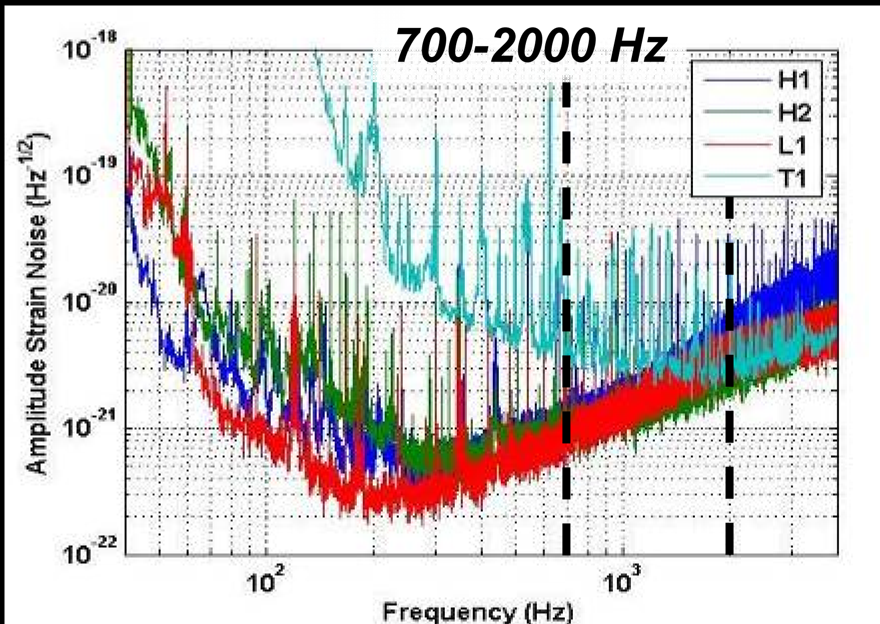
benefits and costs:

- Reduction of false alarm rate
- Increase in observation time
- Confidence in a coincident detection
- Sensitivity restricted to common band, limited by the least sensitive detector

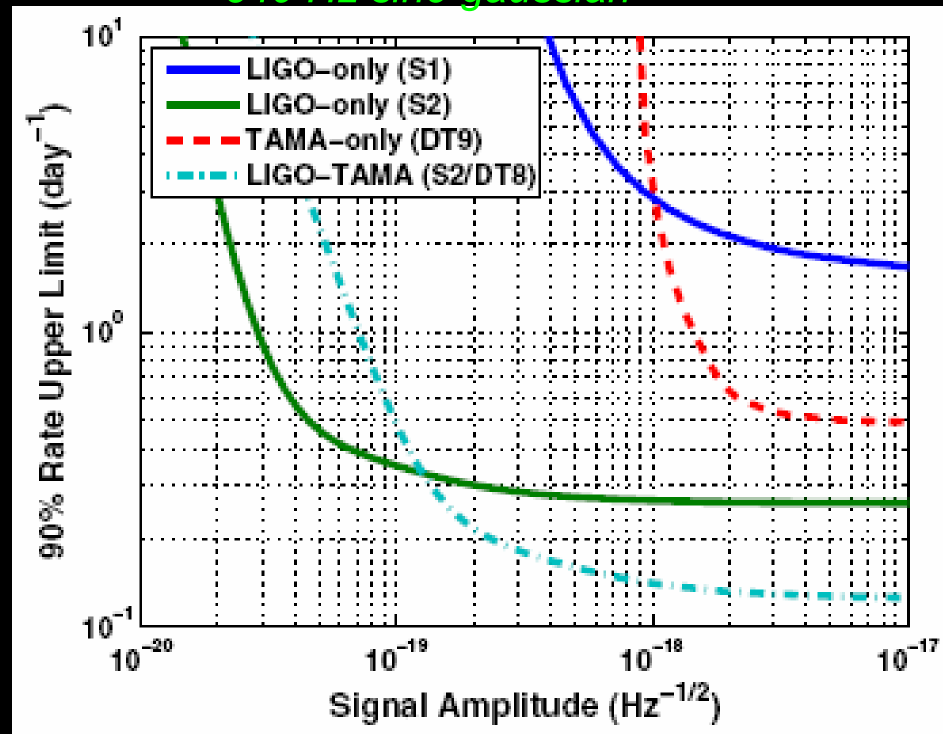
Coherent analyses will help us avoid sensitivity loss when one detector has a poor noise spectrum.

S2: LIGO-TAMA

TAMA300 Mitaka (Japan)



849 Hz sine gaussian



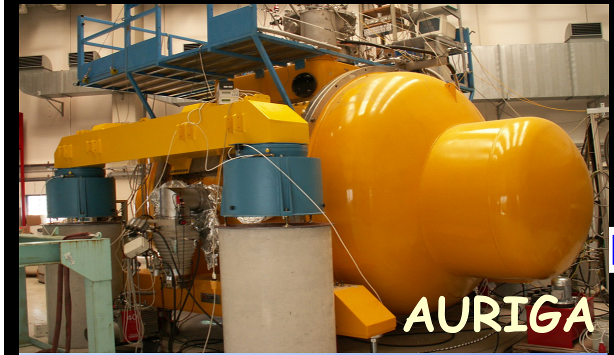
detector combination	observation time (hr)	fraction of total observation time
H1	1040	74%
H2	821	58%
L1	536	38%
T1	1158	82%
H1-H2-L1-T1	256	18%
H1-H2-nL1-T1	320	23%
H1-H2-L1-nT1	62	4%
network totals	638	45%

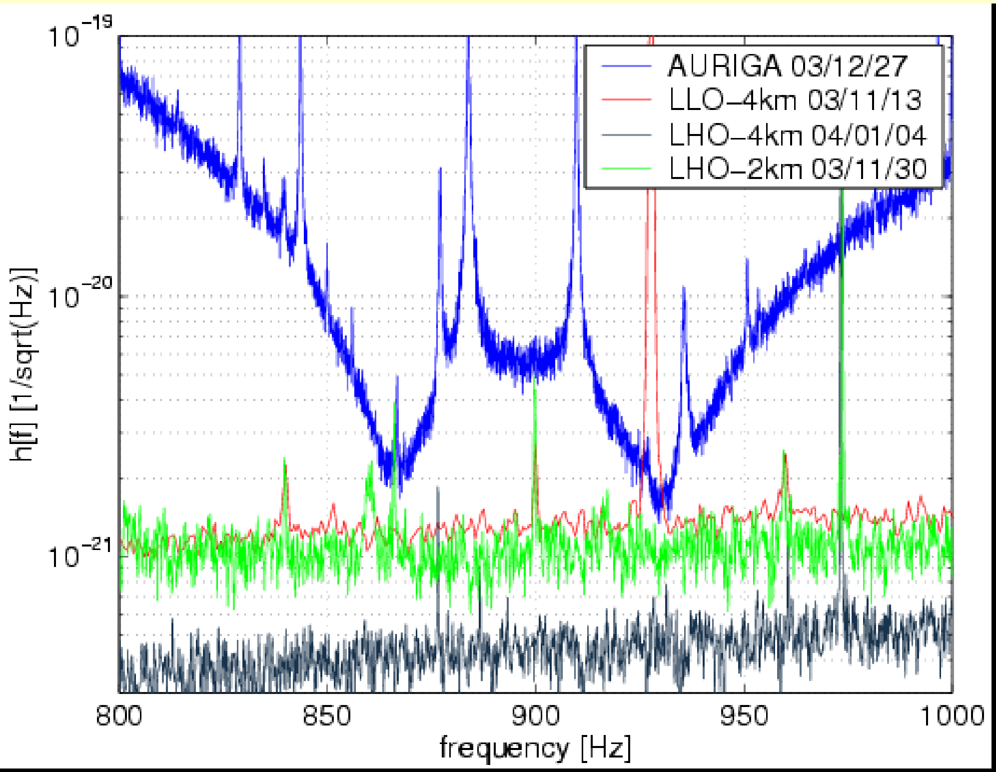
PHYSICAL REVIEW D **72,** 122004 (2005)

S3:LIGO-AURIGA

LIGO S3 run: Oct 31 2003 – Jan 9 2004

AURIGA run 331: Dec 24 2003 – Jan 14 2004





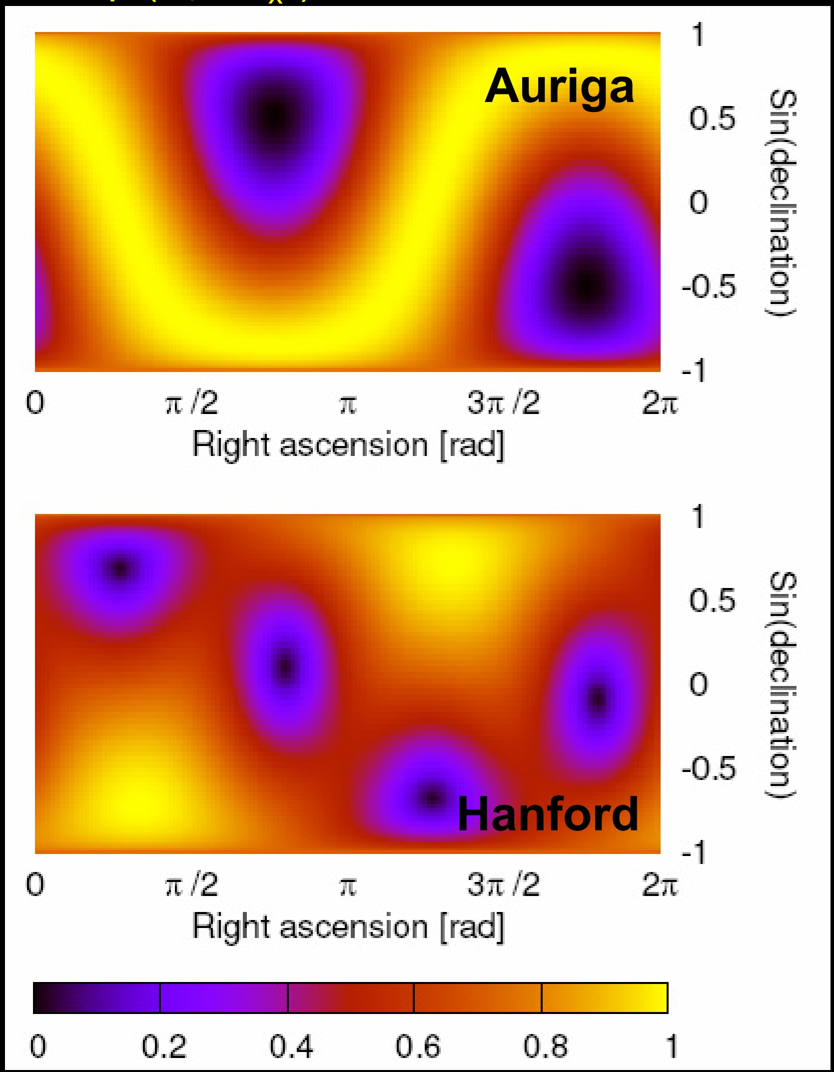
Best performance during the 331 and the S3 run

- LIGO S3: large rate of transients, noise variability
- AURIGA 331: poor data quality (un-modeled excess noise)

Ref: Class. Quant. Grav. ***22*** *(2005) S1337-S1347*

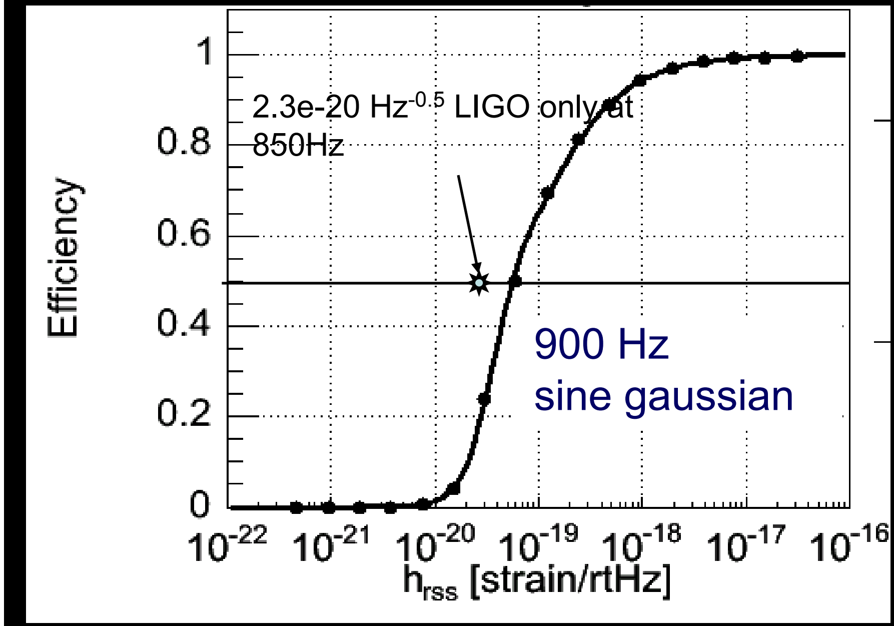
S3:LIGO-AURIGA

sqrt($F_+^2+F_x^2$)



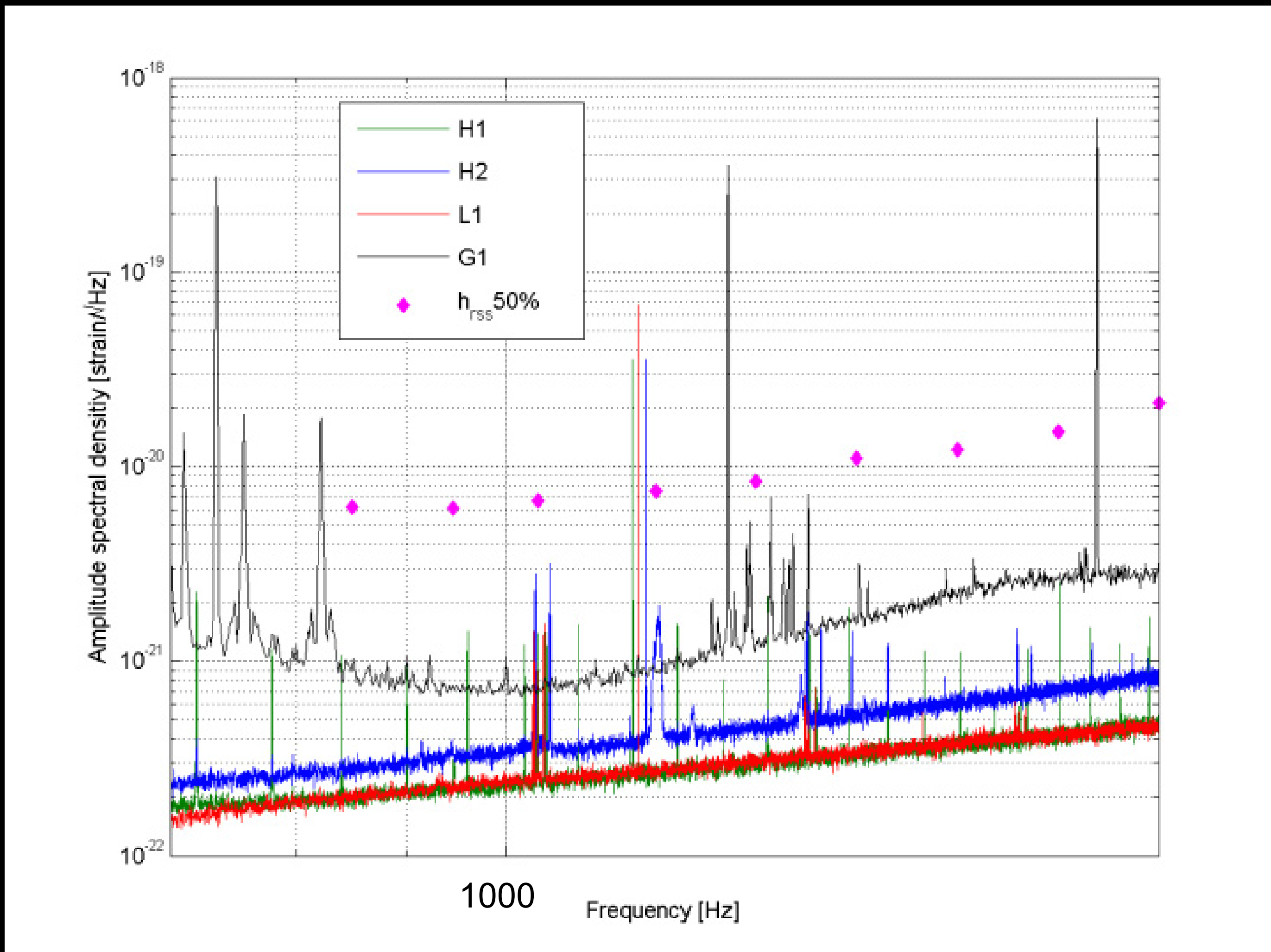
Ref: Class. Quant. Grav. ***22*** *(2005) S1337-S1347*

Method: r-statistic test (LIGO cross-correlation) around the time of the AURIGA triggers.



Ref: J. Phys.: Conf. Ser. 32 32 (2006) 198-205

S4: LIGO-GEO

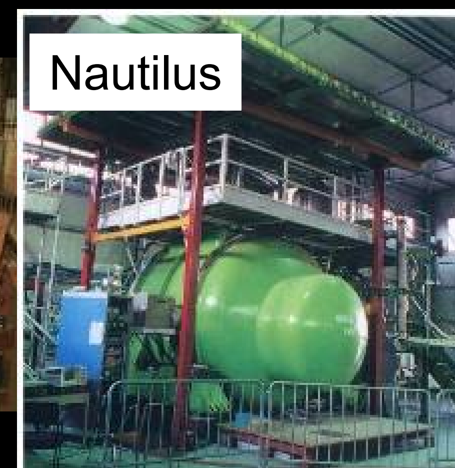


Method: 4-detector waveburst and r-statistic test. (direct extension of LIGO pipeline). Larger frequency.

GEO600 (British-German) Hanover, Germany

S5+: LIGO-IGEC2

Exploring methods for
- detection validation (no joint upper limit);
- coverage for times when only one interferometer is functioning
- communication protocols,
  early warning alert



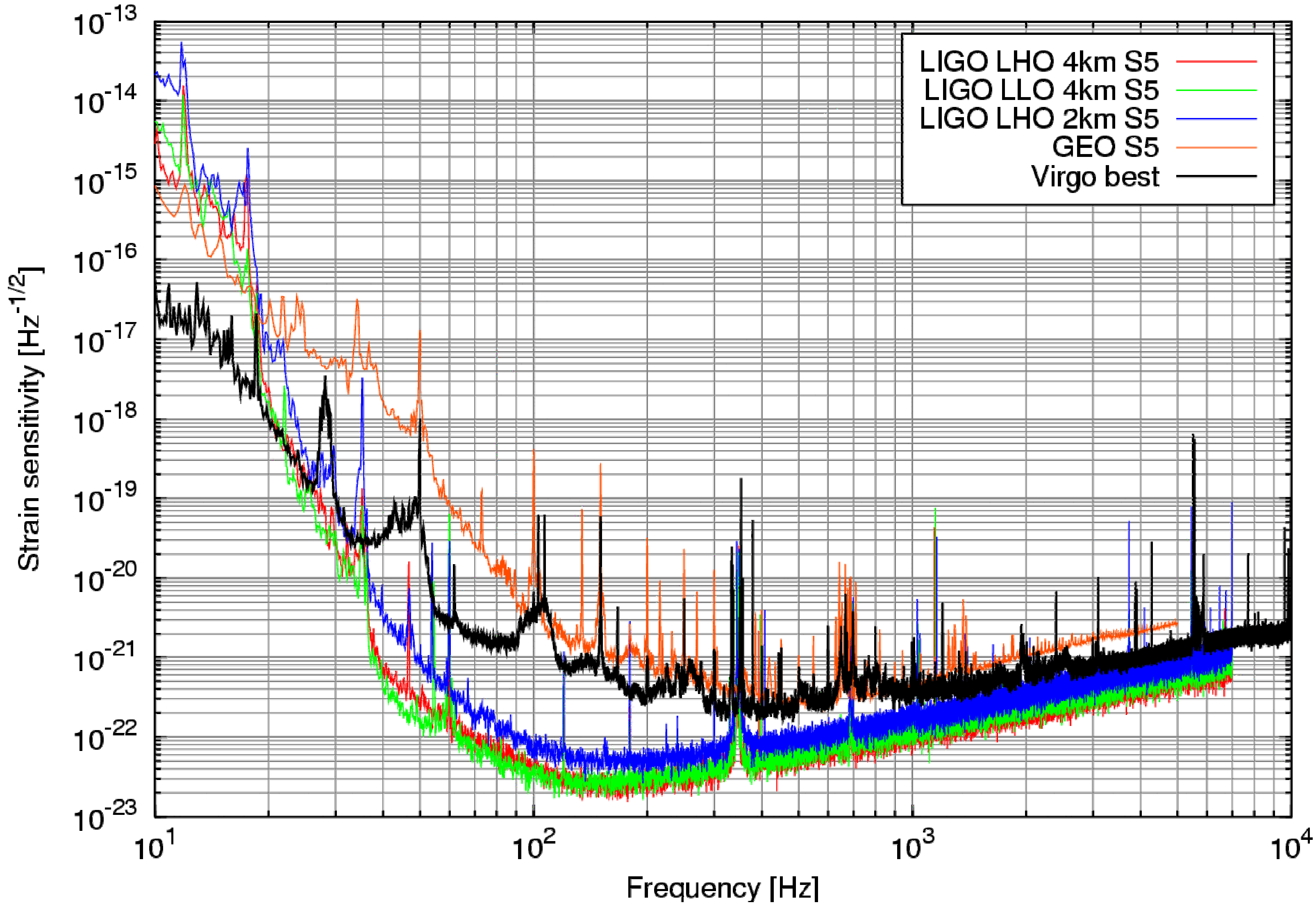
LIGO-Virgo

- The LIGO Scientific Collaboration (LSC) and the Virgo collaboration have entered into an agreement for joint analysis of data
- The Virgo detector is currently in commissioning and focusing on a high frequency sensitivity comparable to the LIGO detectors

VIRGO Cascina, Italy

- Joint data analysis will begin when Virgo reaches roughly comparable sensitivity over a scientifically interesting frequency region.
- Joint data analysis exercises with simulated data have already been performed for the inspiral, burst, and stochastic analysis
- A prototype burst analysis of ~48 hours of real data is in progress

LIGO-Virgo



Source: Gabriele Vajente, December 2006

OR Coincidence Strategies

- For coincident searches, union of double coincident detector networks provides improved performance
- Burst results for simulated supernovae in the direction of the galactic center at a 1 μHz false rate:

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

- Inspiral results for simulated signals from M87 and NGC 6744 at SNR threshold of 6:

	HLV	HL	HV	LV	HL ∪ HV ∪ LV
NGC 6744 efficiency	48%	65%	54%	49%	72%
M87 efficiency	24%	42%	32%	30%	56%

From LIGO-Virgo simulated data

Coherent Analysis: "the next big thing"

Merge data from multiple detectors while taking into account the different noise level and directional sensitivities of each detector

- improve efficiency of the network
- reduce false alarms

coherent methods can tell us:

- Where the signal came from (sky location of the source)
- What it actually looks like (waveform reconstruction)

based on work by Gursel and Tinto PRD 40, 3884 (1989)

The Basic Problem & Solution

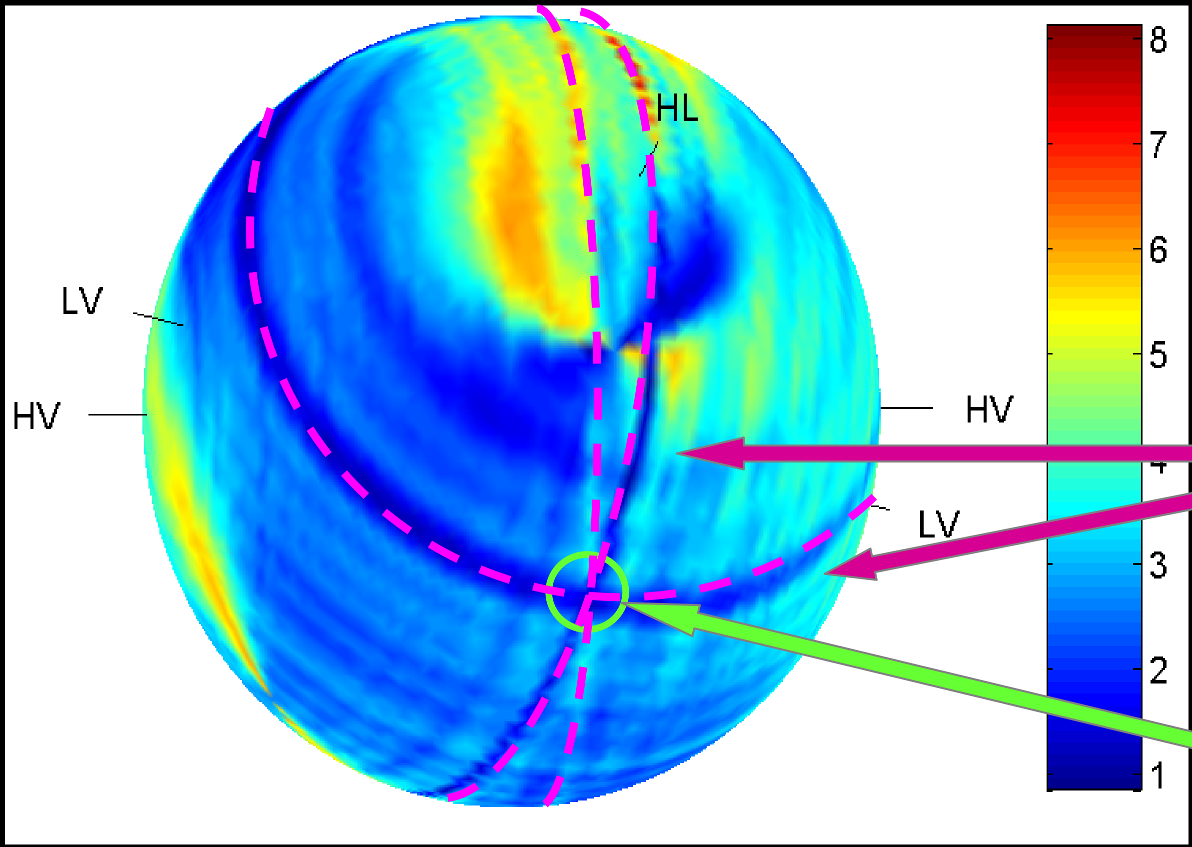
- Output of D detectors:
  - Waveforms $h_+(t)$, $h_x(t)$, source direction Ω all unknown.
  - How do we find them?

data — detector antenna responses — GWB (unknown) — noise (unknown)

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_D \end{bmatrix} = \begin{bmatrix} F_1^+(\Omega) & F_1^\times(\Omega) \\ F_2^+(\Omega) & F_2^\times(\Omega) \\ \vdots & \vdots \\ F_D^+(\Omega) & F_D^\times(\Omega) \end{bmatrix} \begin{bmatrix} h^+ \\ h^\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_D \end{bmatrix}$$

- Approach: Treat Ω, h_+ & h_x at each instant of time as independent parameters to be fit by the data.
  - Scan over the sky (Ω).
  - At each sky position construct the least-squares fit to h_+, h_x from the data ("noisy templates").
  - Amplitude of the template and the quality of fit determine if a GWB is detected.

Example: Supernova GWB



χ^2 / DOF consistency with a GWB as a function of direction for a simulated supernova (~1 kpc)

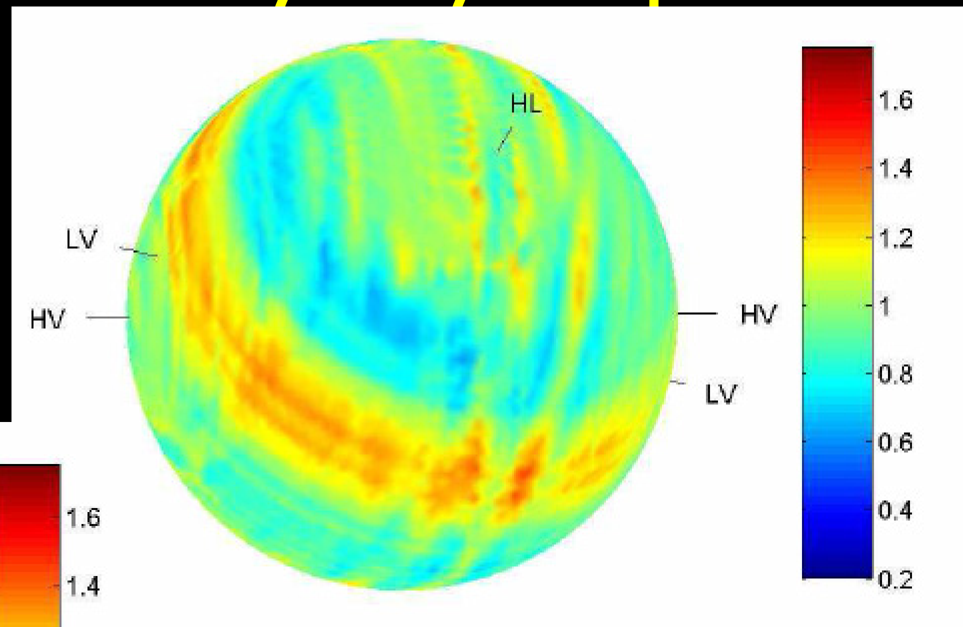
Interference fringes from combining signal in two detectors.

True source location:
– intersection of fringes
– χ^2 / DOF ~ 1

GWB: Dimmelmeier et al. A1B3G3 waveform, Astron. Astrophys. 393 523 (2002) , SNR = 20
Network: H1-L1-Virgo, design sensitivity

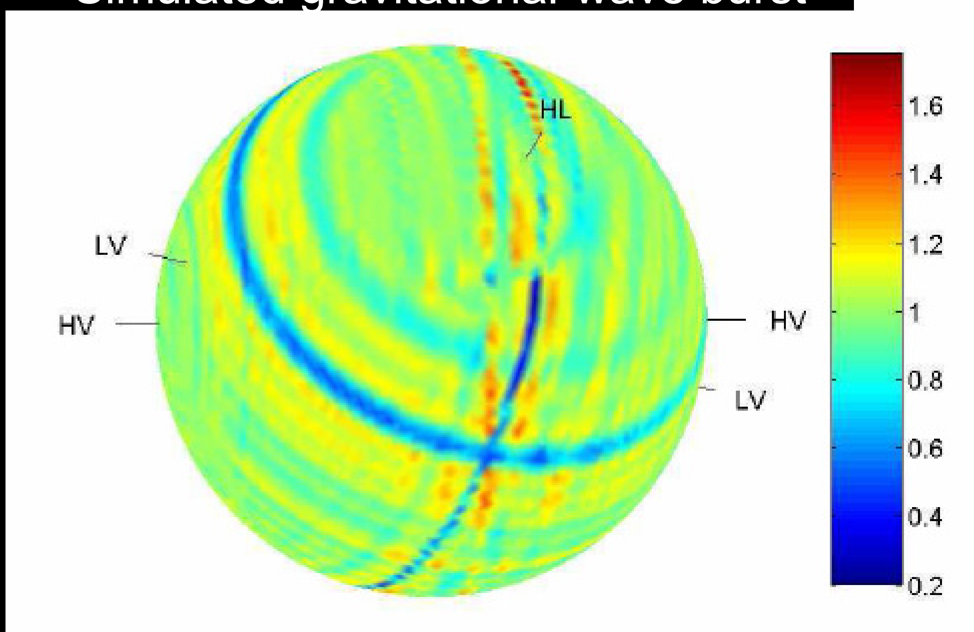
Ref: LIGO-G060228-00

Example consistency sky maps



Simulated coincident glitch

Simulated gravitational-wave burst

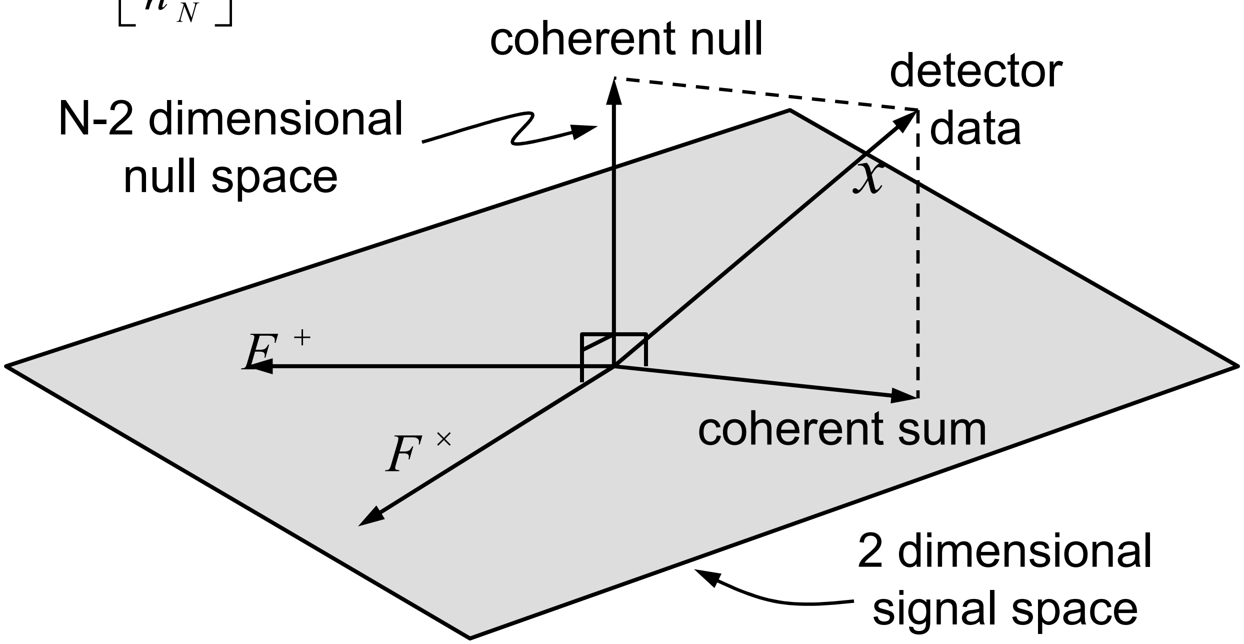


Fully coherent search methods

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

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.

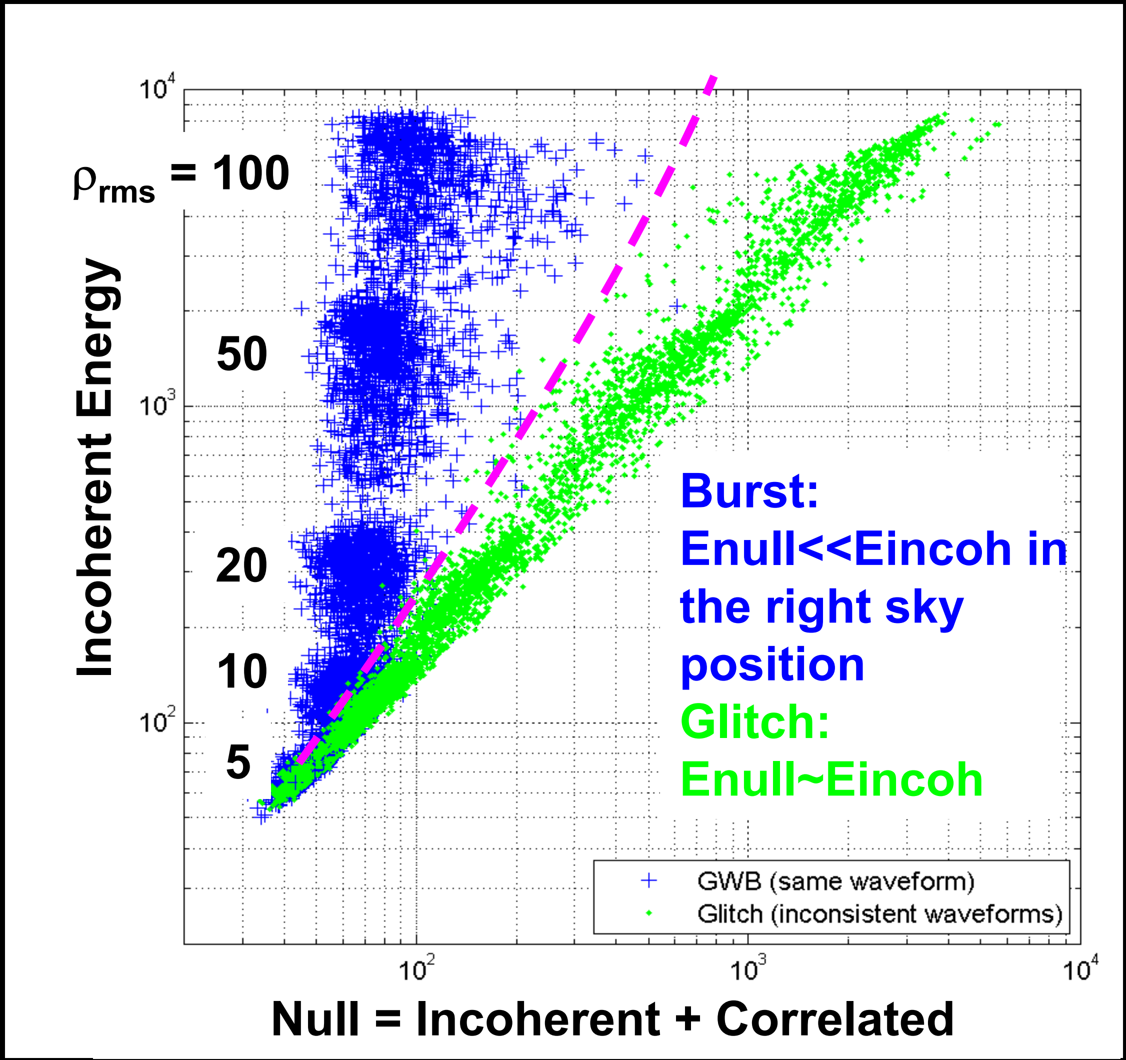


Phys.Rev. D74 (2006) 082005

$$\text{cancellation measure} \equiv \frac{\text{null energy } \mathbf{E}_{\mathbf{null}}}{\text{incoherent energy } \mathbf{E}_{\mathbf{inc}}} = \begin{cases} \ll \mathbf{1} & \text{GWB} \\ \sim \mathbf{1} & \text{glitch} \end{cases}$$

Example: 5000 bursts vs. 5000 glitches

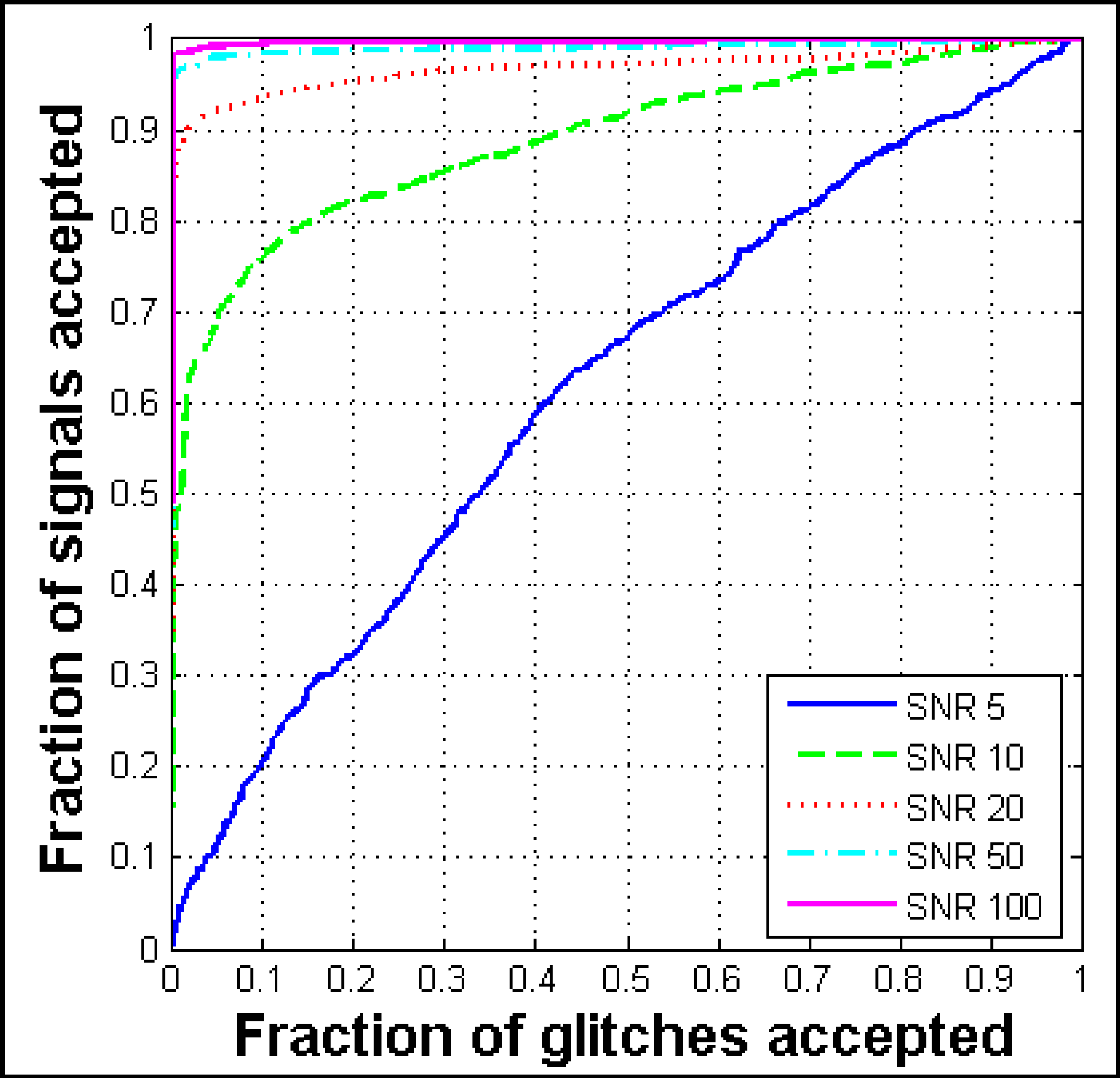
- One point from each simulation.
  - The sky position giving strongest cancellation, i.e. the lowest Enull/Eincoh
- GWB and glitch populations clearly distinguished for SNR > 10-20.
- Similar to detection threshold in LIGO.



Ref: LIGO-G060228-00

LIGO-G070051-00

Distinguishing signals from artifacts



Ref: LIGO-G060228-00

Simple example: collocated detectors

- The two LIGO Hanford detectors (H1H2) can be combined to form two new detector data streams

H+ The optimal linear combination that maximizes the signal to noise ratio of potential signals.

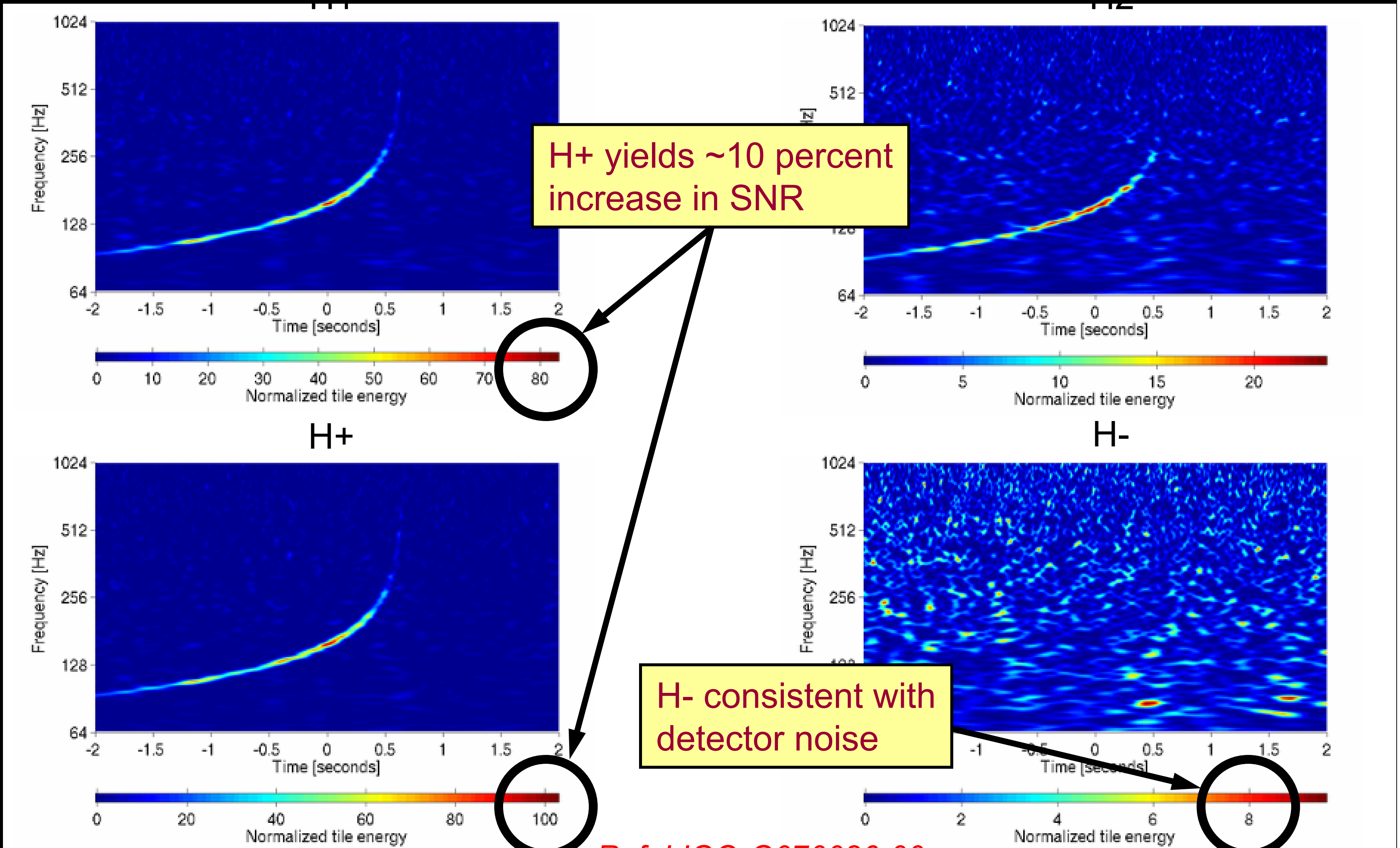
$$H_{+} = \left(\frac{1}{S_1} + \frac{1}{S_2} \right)^{-1} \left(\frac{H_1}{S_1} + \frac{H_2}{S_2} \right)$$

- – Weighting is inversely proportional to detector noise S
- – Resulting SNR is the quadrature sum of SNRs

H- The null stream, which should be consistent with noise in the case of a true gravitational-wave

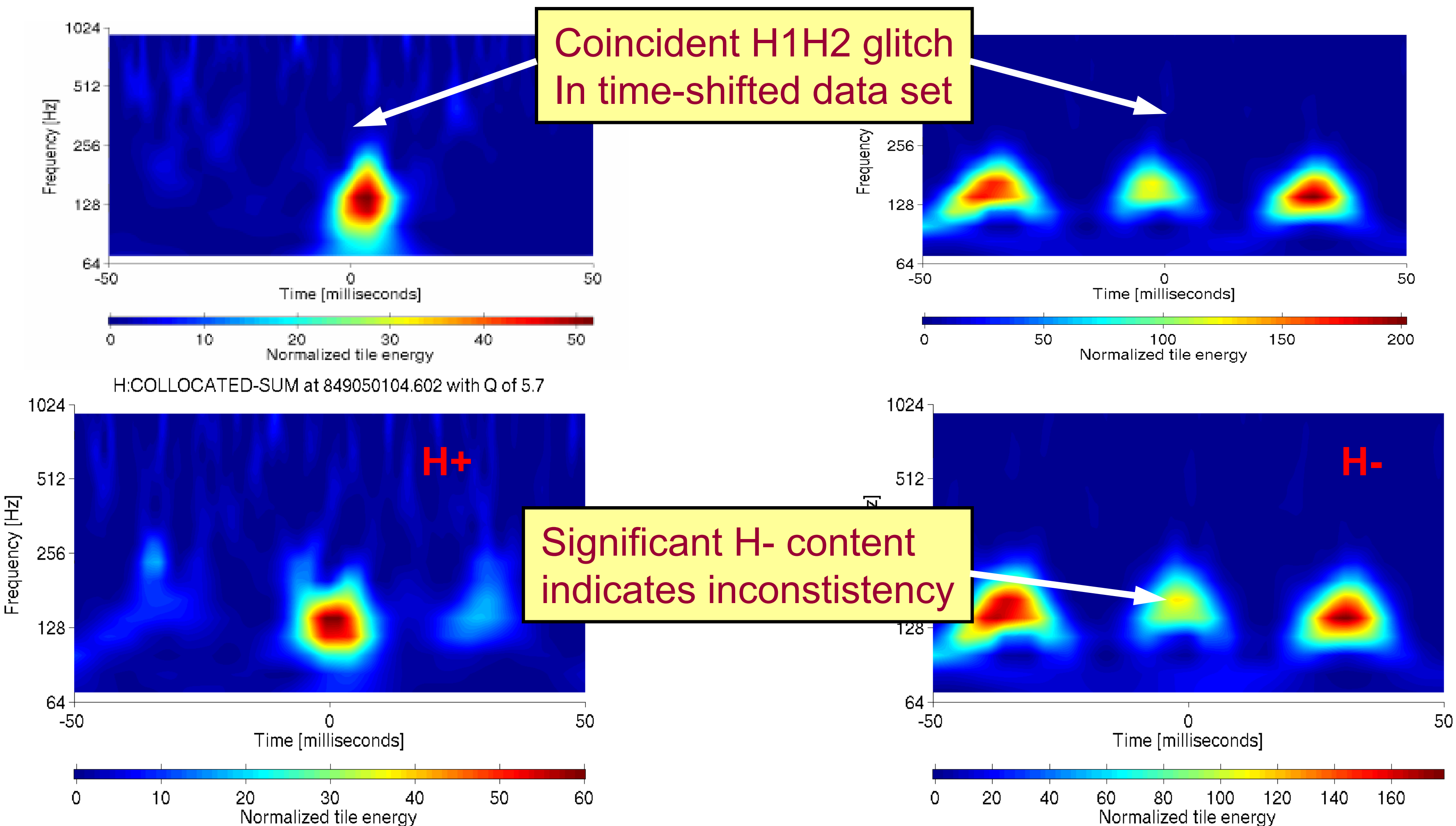
$$H_{-} = H_1 - H_2$$

H1H2 example: Inspiral at 5 Mpc



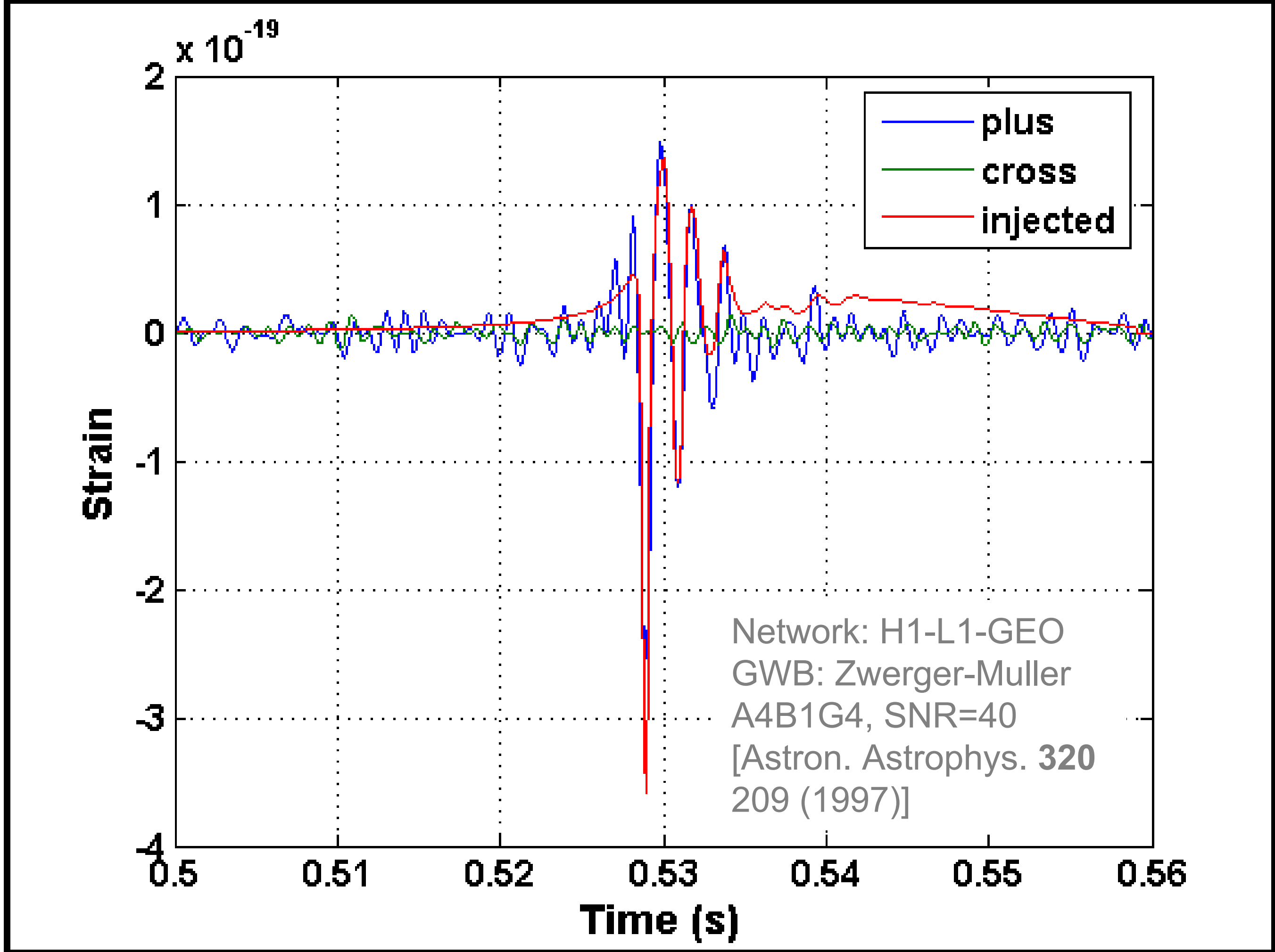
Ref: LIGO-G070026-00

H1H2 example: time shifted glitch



Ref: LIGO-G070026-00

Waveform Recovery



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

Injected GWB signal has $h_x = 0$.

Recovered h_x (green) is just noise.

Ref: LIGO-G060228-00

Remaining slides:

a talk by Patrick Sutton with an overview of coherent methods for GWB detection

LIGO-G060276-00