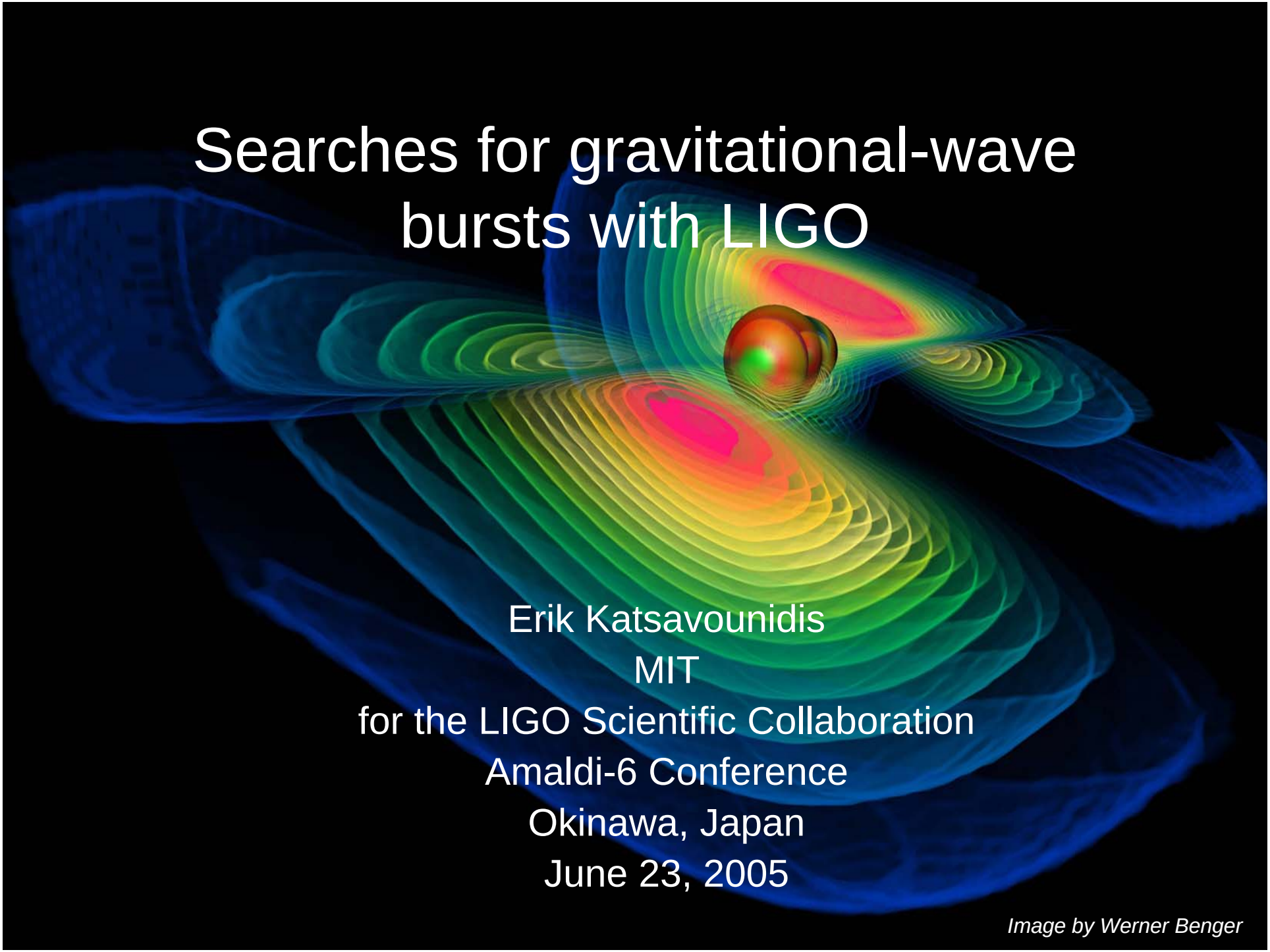
Searches for gravitational-wave bursts with LIGO



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Amaldi-6 Conference
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Image by Werner Benger

LIGO-G050313-00-D

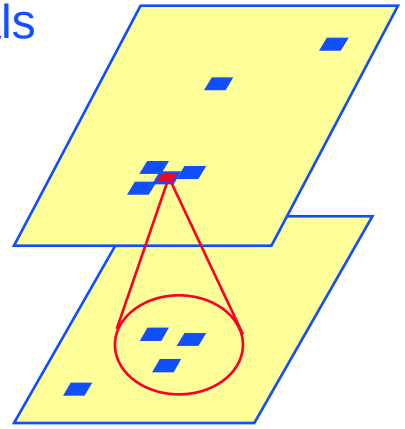
Data taking and burst searches at a glance

	S1: 408 hours Aug 23 - Sep 9, 2002		S2: 1415 hours Feb 14 - Apr 14, 2003		S3: 1680 hours Oct 31, 2003 -Jan 9, 2004	
	Lock	**Sensitivity**	**Lock**	**Sensitivity**	**Lock**	**Sensitivity**
H1 (2km)	58%	1×10^{-20} /sqrt(Hz)	74%	6×10^{-22} /sqrt(Hz)	69%	**6×10^{-23} /sqrt(Hz)**
H2 (4km)	73%	1×10^{-20} /sqrt(Hz)	58%	6×10^{-22} /sqrt(Hz)	63%	3×10^{-22} /sqrt(Hz)
L1 (4km)	42%	**3×10^{-21} /sqrt(Hz)**	37%	**3×10^{-22} /sqrt(Hz)**	22%	2×10^{-22} /sqrt(Hz)
H1&H2&L1	23%		22%		16%	
	O(100hrs) x3coincidence GEO in coincidence **Analysis complete:** Phys. Rev. D 69, 102001(2004)		O(300hrs) x3coincidence TAMA in coincidence **Analyses complete:** LIGO-GRB030329 gr-qc/0501068 LIGO-only: gr-qc/0505029 LIGO-TAMA: gr-qc ~2wks		O(300hrs) x3coincidence TAMA/GEO coincidence **Analysis complete:** LIGO-only: here, today! **In progress:** LIGO-GEO prototypical analysis S2/S3 multi-GRB	

Burst search goals

- Goal: search for signals of unknown waveform and unknown origin that have short duration (<1sec) and enough power in LIGO's sensitive band of ~50Hz to few kHz
  - » Core collapse supernovae
  - » Binary black hole mergers
  - » Coalescence of binary compact objects
  - » Black hole normal modes
  - » Cosmic string cusps and kinks
  - » The unexpected!
- Coincidence observation with other astronomical observations:
  - » Supernovae & Gamma Ray Bursts
  - » Use temporal and directional information to perform a cross-correlation search
  - » GRB030329 during S2: gr-qc/0501068 (Submitted to PRD)

Progress in Burst search methodology

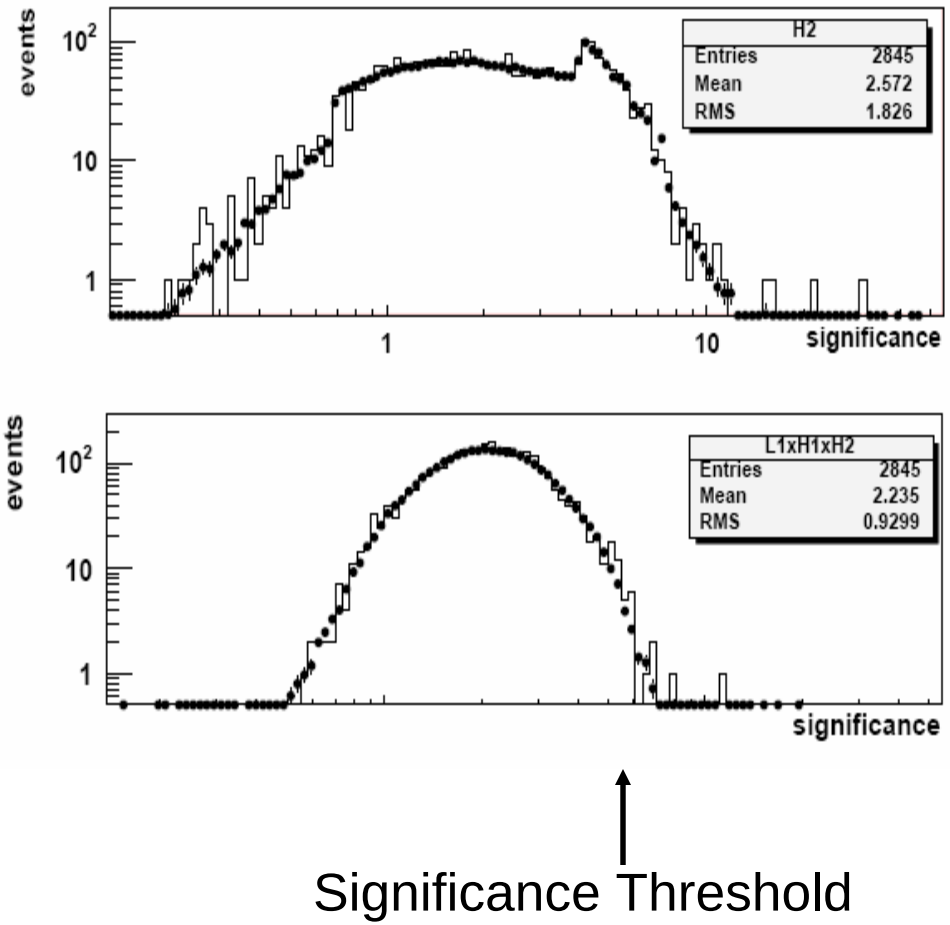


- Rely on multi-instrument coincidence for reduction of accidentals
  - » H1-H2-L1
  - » Time-frequency matching via projection onto a Fourier basis
  - » Projection to a wavelet basis
  - » Waveform consistency test for raw time series
  - » Coincidence analysis with TAMA and GEO for 700-2000Hz search
- Understanding data quality and investigating potential vetoes of paramount importance
- A "blind" search tuned on a subset of the data
  - » Playground O(10%) of full data
  - » Tune the search for a low background O(<0.1)
  - » Now using time-delayed coincidences to tune analysis parameters with effectively higher statistics
- Determine background by forming time-delayed coincidences
- Measure detector and search response via software and hardware injections
  - » Establish efficiency as function of signal strength
  - » Quantify accuracy of burst parameter estimation
  - » Use ad hoc waveforms
  - » Invoke astrophysically motivated waveforms
- Search results:
  - » establish a bound on their rate at the instruments
  - » interpret bound on a rate vs. strength exclusion diagram
  - » Scrutinize remaining events, statistical issues in setting upper limits and establishing detection

Event selection: WaveBurst pipeline

- Excess power method in the wavelet time-frequency domain
  - » Selects clusters in 64-1100Hz
- Forming triple coincidence:
  - » Mean time of clusters from the three instrument pairs to fall within 20ms
  - » Frequency bands of the three pairs to overlap
- Construct combined significance Z_G of triple coincidence events
  - » Apply threshold to control (WaveBurst) final triple coincidence rate
- Rate in playground of 15 μHz

Histogram of trigger significance

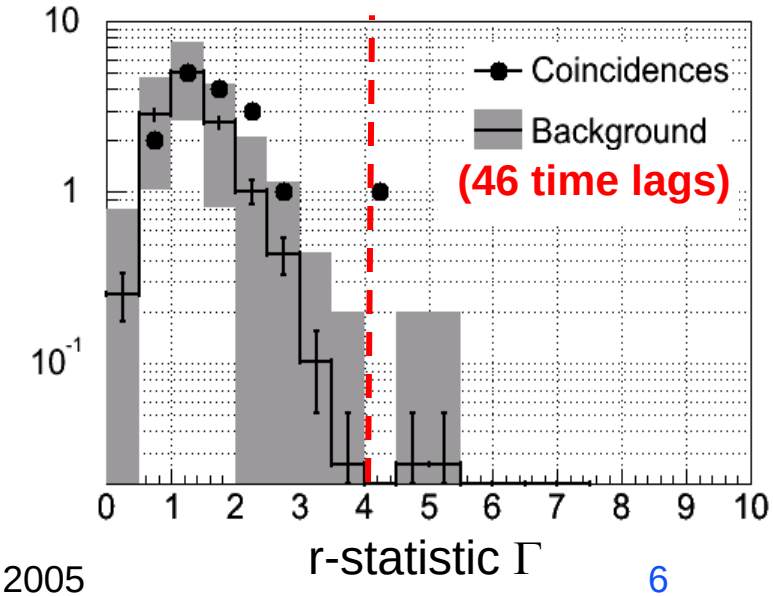


Final event cut: r-statistic test for waveform consistency

- Building block of r-statistic: linear correlation coefficient of two time series:

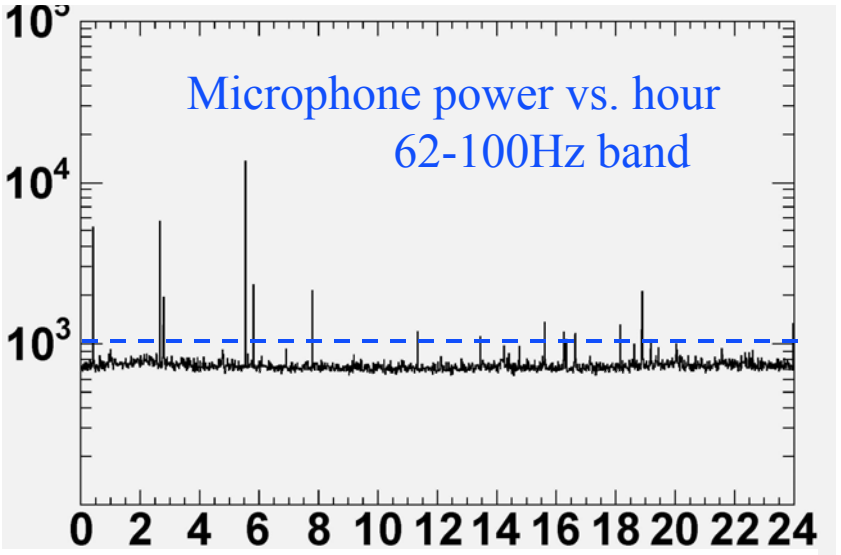
$$r_k = \frac{\sum_i (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_{i+k} - \bar{y})^2}}$$

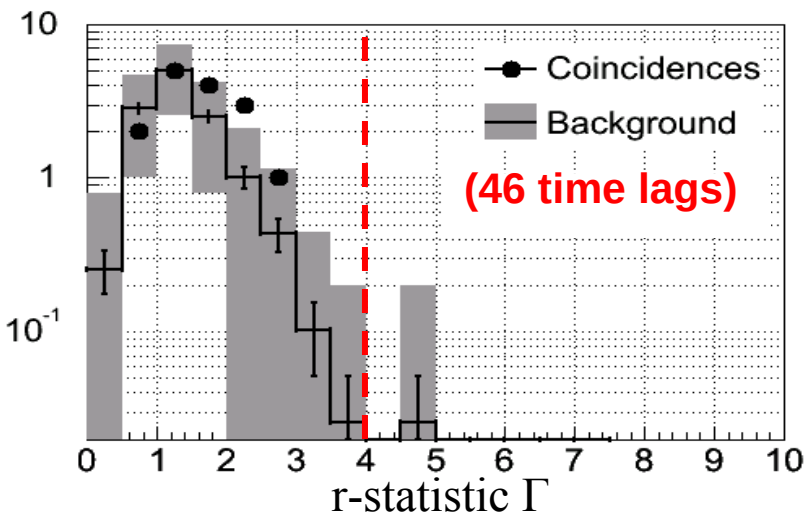
- Calculating the statistic:
  - » Examine all interferometer pairs
  - » Possible physical time-delays due to ToF (+-10ms)
  - » Integration window: 20, 50, 100ms
- Compare distribution of r-values to the null hypothesis
- Using playground, establish event logarithmic confidence to threshold at in order to yield target false alarm rate
  - » S2 tuning philosophy: target for 0.1 background event, >99% of WaveBurst need to be rejected
  - » A combined confidence of Γ>4 was selected



S2 event analysis

- For the remaining zero-lag event, auxiliary interferometric and environmental channels were examined
- H1-H2 events resulted from an acoustic disturbance: amplitude and frequency of the gravitational wave readout channel can be accounted for by the acoustic event recorded simultaneously by the microphones
- Acoustic veto based on power in 62-100Hz band in H2 PSL table microphone was introduced: it vetoes ~0.7% of live-time, one zero-lag event and one background event.
- Background estimate is 0.025 events with 0 events observed over the (239.5-1.7) hours of the S2 analysis
- 90% CL upper limit is 2.6 events
  - » Accounts for modified coverage due to introduction of post-facto veto
- Rate upper limit of 0.26 events/day



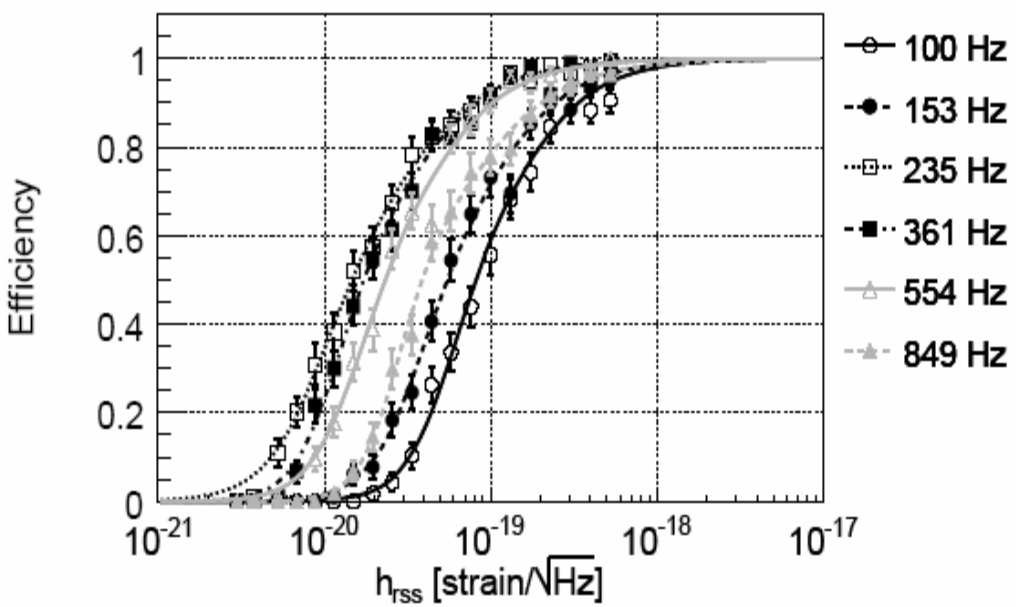


Detection Efficiency Studies

- Measure test waveform efficiencies vs. signal strength $h_{rss} = \sqrt{\int |h(t)|^2 dt}$
- Different signal morphologies exercised (ad hoc and astrophysically motivated)
  - » Sine-Gaussians, Gaussians
  - » core collapse supernovae from three models (ZM,DFM,OBLW)
  - » BBH merger (and ringdown) waveforms (Lazarus project)

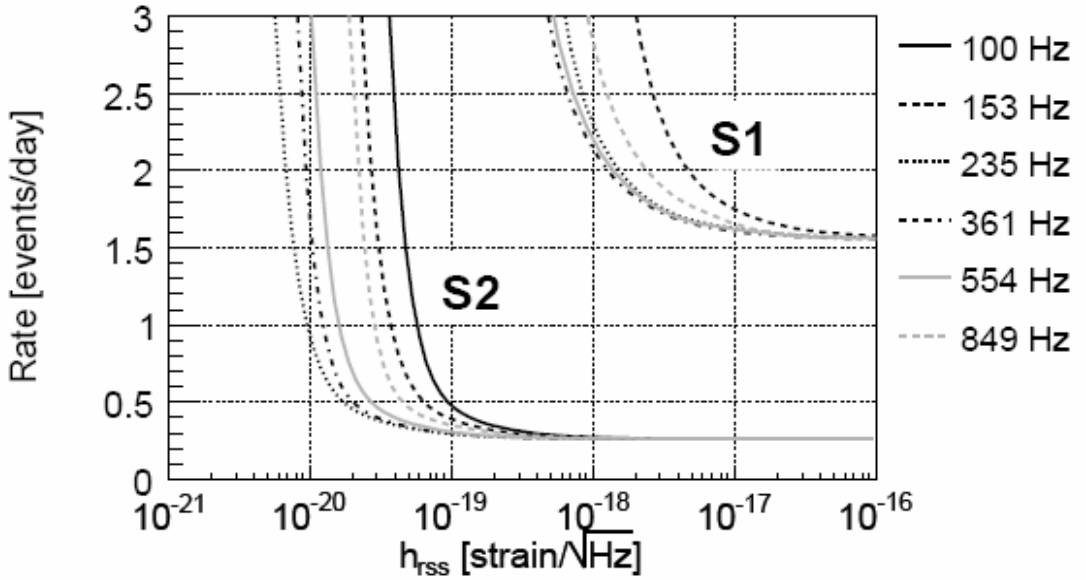
- Source sky coordinates and polarizations were taken randomly; fixed inclination taken for SN,BBH
- Software injections: signals added to digitized interferometer output
- Hardware injections: signals added to length servo signal

Q=8.9 sine-Gaussian Efficiencies

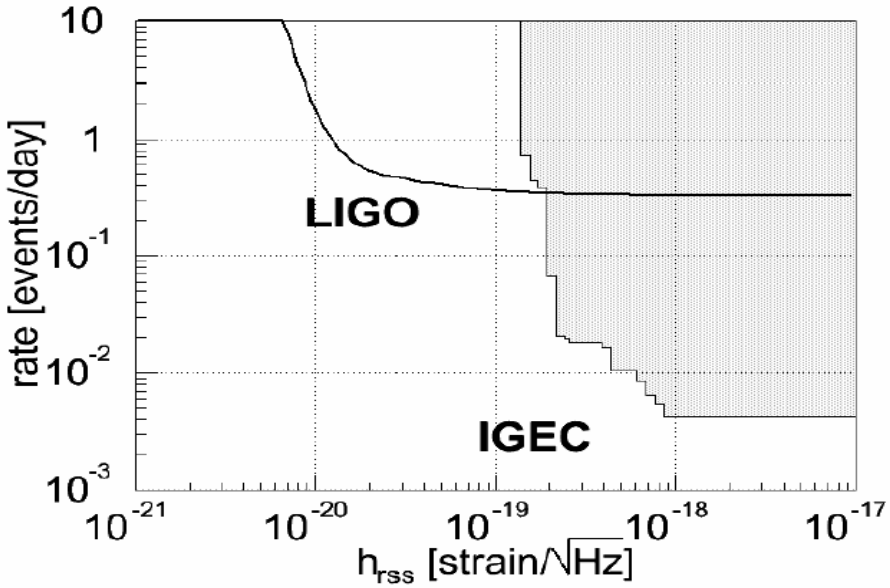


Interpreted results: rate-strength curves

- S2 search detects less than 0.26 events/day at the 90% conf. level
- Divide by the efficiency curve for a particular waveform to get rate vs strength exclusion region



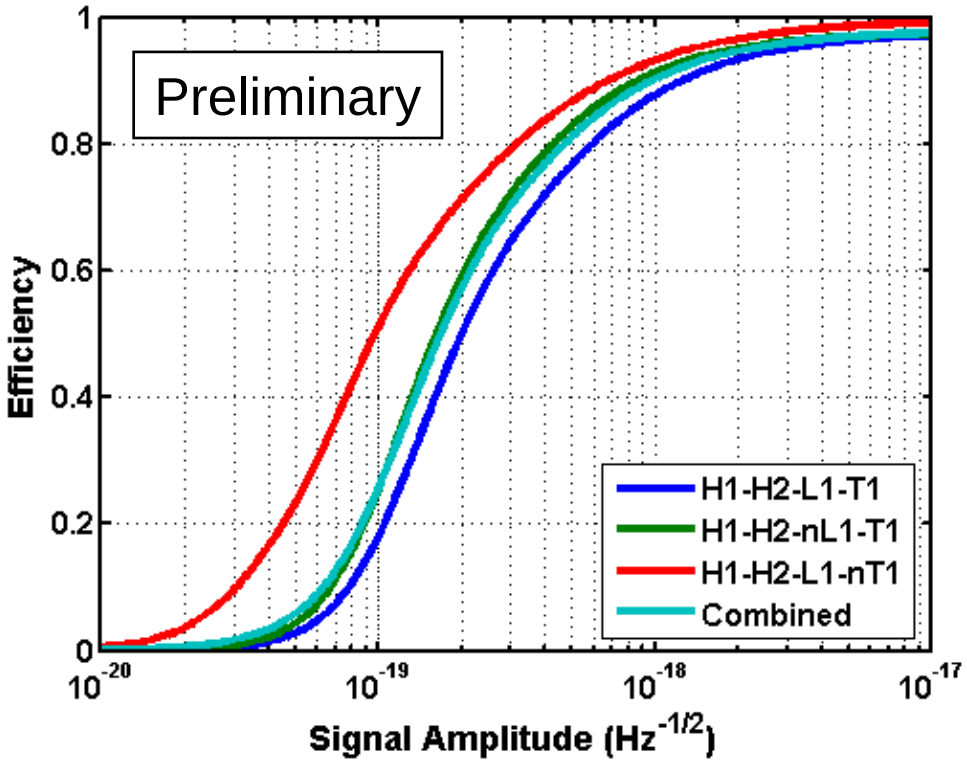
- IGEC rate at strong signals: 0.004 events/day
- Using a 0.1ms Gaussian relate h_{rss} that is relevant to signal detection for LIGO to $|h(f_b)|$
- Optimal orientation is considered for both detectors, same conf. level of upper limit (95%)



LIGO-TAMA search

- LIGO - TAMA S2/DT8 joint burst search
  - » High-frequency search uses the minimum of noise envelope: [700,2000]Hz
  - » Complementary to the LIGO-only S2 search [100,1100]Hz
  - » Uses similar overall methodology
- Maximize observation time
  - » 19.7 days of x3/x4 coincidence observation
  - » 6.9 days of x4 coincidence observation
- No gravitational wave bursts found corresponding to a 90% upper limit of 0.12 events/day
- Sine-Gaussian simulations (with sky & polarization averaging) indicate a 50% detection efficiency at 2×10^{-19} $Hz^{-1/2}$
- **Poster by Sutton and Ando for the LIGO and TAMA collabs**

Detection efficiency

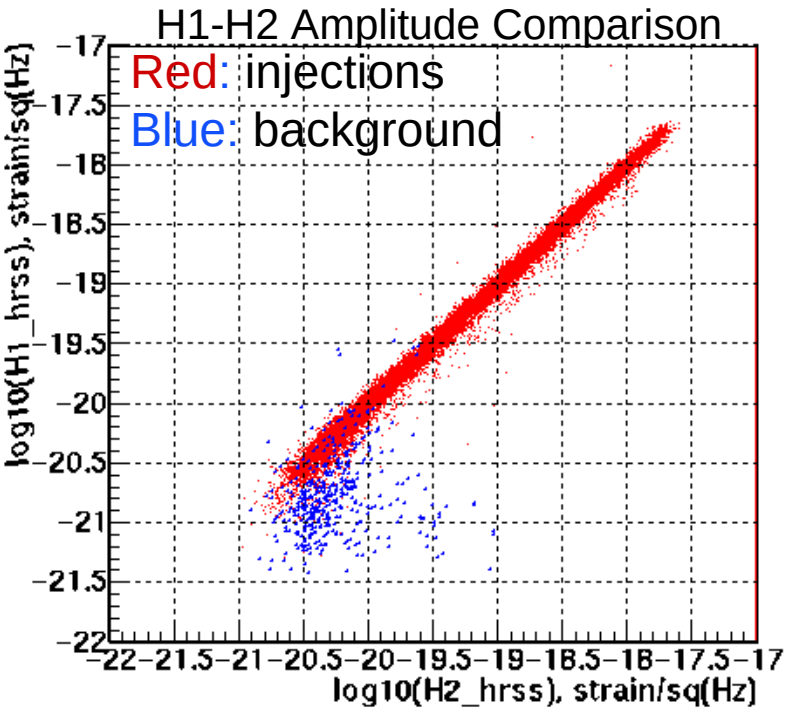


From the S2 to the S3 search

- Limitations: in the absence of any events surviving all analysis cuts, S3's livetime (~20% less than in S2) and S3's sensitivity improvement with respect to S2 not at a level to improve S2 upper limit significantly (e.g., O(10) in the livetime-strain sensitivity "product")
- Emphasis: establish the presence or not of plausible gravitational wave burst candidates during S3
- Did not set upper limit with these data
- Move the overall LIGO burst search forward: address the search challenges presented by the character of the data by introducing methodology improvements

Methodology improvements in S3

- Multi-resolution time-frequency analysis introduced (WaveBurst: 8-16-32-64-128-256 Hz)
  - » Better sensitivity, especially at low frequencies
  - » Allowed to detect longer duration signals
  - » Detection is less dependent on the waveform morphology
- Stronger coincidence requirements for the two collocated Hanford (2km/4km) detectors:
  - » Consistent strain amplitude (WaveBurst)
  - » Tighter time coincidence in checking the waveform consistency (r-stat)
  - » Waveforms 'in phase' by checking the sign of their correlation (r-stat)
- Extension of the playground to entire run's time-shifted data
- Larger variety of waveform morphologies (58 wfs) in efficiency Monte Carlos:
  - » All of the above were benchmarked

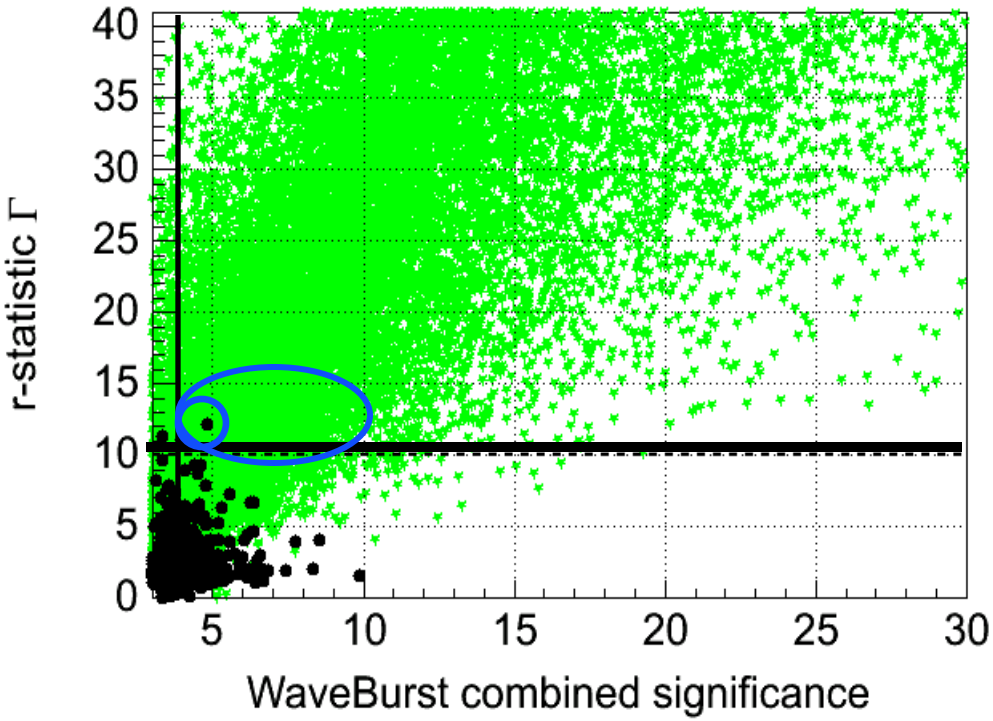


½<H1/H2<2: false dismissal~0.4%
background events ~76%

S3 Data analysis

- Simulated events imitating the signatures expected from sources uniformly positioned on the sky, with varying strength amplitude and waveform morphology
- Background events generated by 50 time-shifts of the S3 data in multiples of 4.25 seconds
- Analysis cuts established:
  - » Central frequency in the 100-1100Hz
  - » A positive H1-H2 correlation
  - » An H1-H2 amplitude consistency within a factor of two
  - » WaveBurst confidence>3.2
  - » r-statistic confidence>10

- Identified as calibration line drop-out at Hanford and decided to veto out!



- Foreground events (zero-lag)
  - » None remains
- Background events (from a new set of time-shifted data):
  - » 4 out of 5 attributed to the same calibration drop-out at Hanford

Result from the S3 burst search

- No events consistent with a gravitational wave burst were seen during LIGO's S3 run
- The search was performed over 192.2 hours of triple coincidence data. The expected background was 0.02 events
- S3 simulation Monte Carlos extend the waveform morphology adopted by the S2 search in order to investigate signals beyond the nominal minimum uncertainty ones
  - » Efficiency studies were performed in only a (randomly selected) 10% sample of the full set. Potential systematic due to this procedure is not anticipated to be large.
- Representative (and preliminary) sensitivities in units of 10^{-20} /sqrt(Hz):

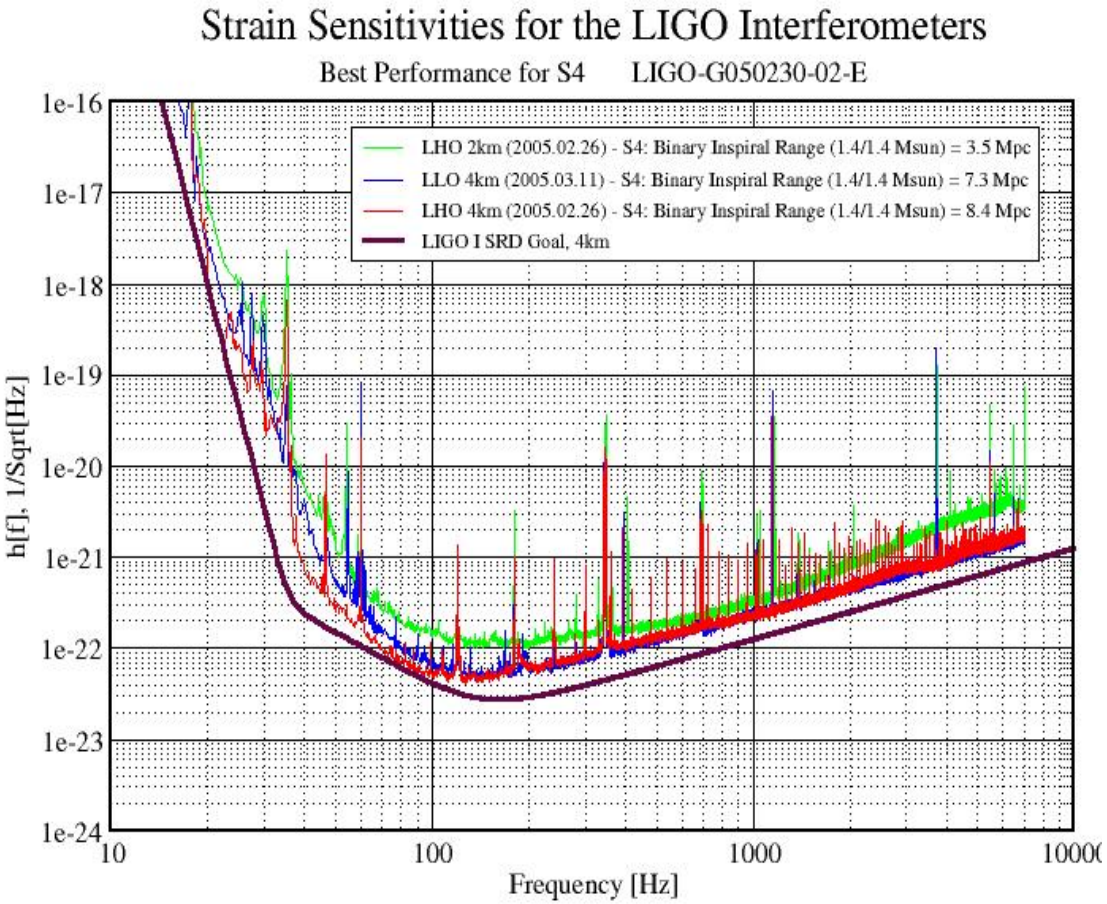
	0.1 ms Gaussian	235 Hz, Q=9 sine-Gaussian	554 Hz, Q=9 sine-Gaussian	849 Hz, Q=9 sine-Gaussian
S2	4.3	1.5	2.3	3.9
S3	1.8	0.9	1.3	2.3

LIGO-GEO

- During S4, 56 hours of L1-H1-H2-G1 coincidence, 106 hours of H1-H2-G1 coincidence
- Prototypical search for the LIGO-GEO network
  - » Focuses on high-frequency signatures: 700-2000Hz
- Builds on the LIGO-only S3 WaveBurst pipeline
- Work in progress:
  - » 10 μHz background rate
  - » Sine-Gaussian simulations (with sky & polarization averaging) indicate detection efficiency at the level of $3.4\text{-}10 \times 10^{-20}$ $Hz^{-1/2}$
- **Poster by Heng for the LIGO Scientific Collaboration**

Search for bursts in S4

- … *citius,*
- A near real-time detailed look at the data:
  - » less glitchy than previous runs
  - » an end-to-end search for strong bursts was performed
- … *altius,*
- Instruments within a factor of two of design sensitivity
- 30 days of data taking, 57% x3 coincidence (~400 hrs)
- … *fortius !*
- Off-line analysis in full-swing: expected livetime-h sensitivity "product" improvement by a factor of ~25 w/r/t S2



- Poster on S4 burst search by Igor Yakushin for the LSC

LSC burst search summary and outlook

- The LSC burst analysis working group:
  - » Conducted searches with data collected by the instruments without observing gravitational wave bursts thus far; upper limits steadily improving
  - » Continuing to improve the search methodology for untriggered and triggered searches of gravitational wave bursts
- S4 was a successful run
  - » Results from a search for bursts are expected by the end of the summer 2005
- As we are approaching design sensitivity and duty cycle …
  - » Operate as part of a global network of detectors: fully coherent follow-up for coincidences (e.g., Gürsel-Tinto-type sky localization and waveform extraction methods)
  - » Upper limits⟶ detections