LSC Data Analysis

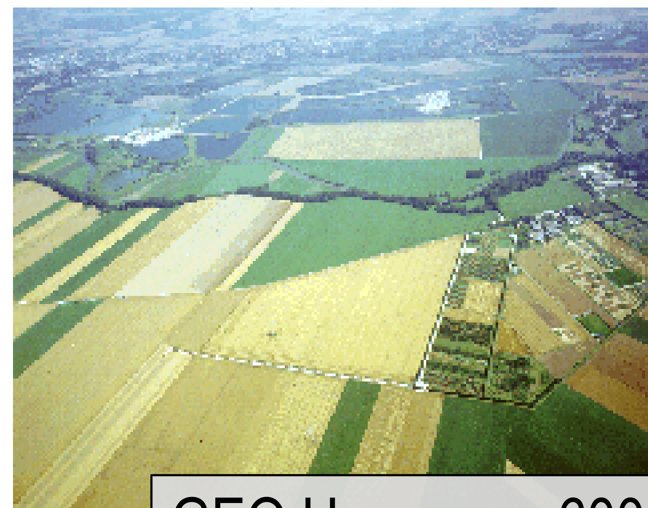
Patrick Brady
University of Wisconsin-Milwaukee
for the
LIGO Scientific Collaboration

G040390-00-Z

LSC Interferometers

LIGO Hanford: 4km & 2km interferometers in same vacuum envelope

LIGO Livingston: one interferometer (4km)

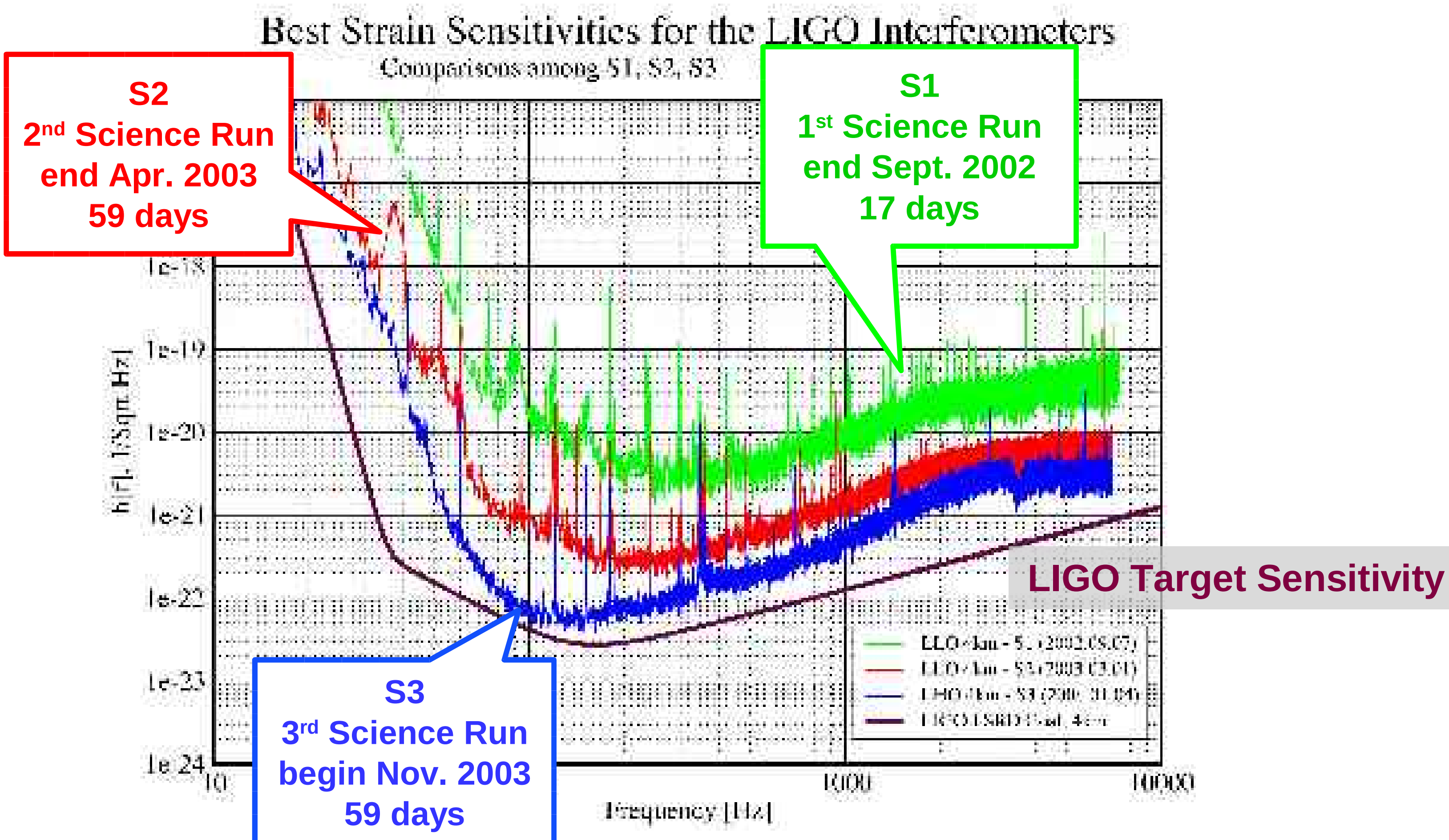


GEO Hannover: 600m interferometer

The LIGO Scientific Collaboration

G040390-00-Z

Experience with Data Taking



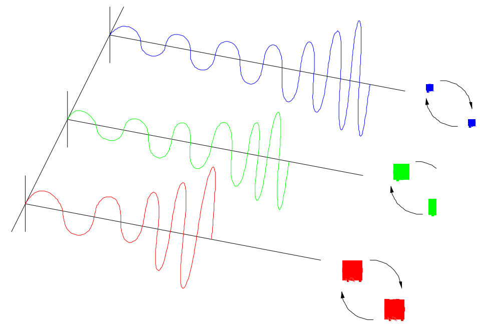
G040390-00-Z

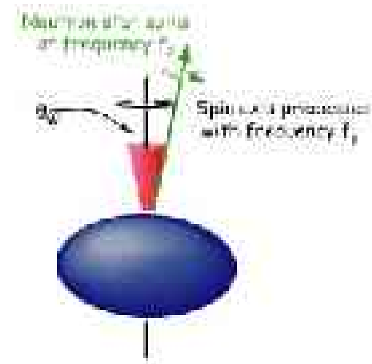
Details of Science Runs

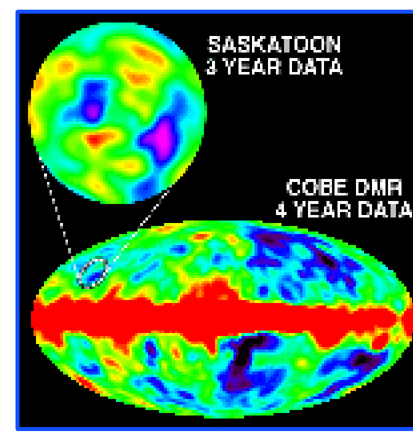
- S1 – 17 days in August / September 2002
  - » Four detectors operating: LIGO (L1, H1, H2) and GEO600
  - » Triple-LIGO-coincidence (96 hours)
  - » Four S1 astrophysical searches published (*Phys. Rev. D* *69*, 2004):
    - – Binary neutron stars (122001)
    - – Bursts (102001)
    - – Known pulsar (J1939+2134) with GEO (082004)
    - – Stochastic background (122004)
- S2 – 59 days in February-April 2003
  - » Four interferometers operating: LIGO (L1, H1, H2) and TAMA300 plus Allegro bar detector at LSU
  - » Triple-LIGO-coincidence (318 hours)
  - » Searches under way (some preliminary results)
- S3 – 70 days in October 2003-January 2004
  - » Analysis ramping up…

Target Sources for LSC Data Analysis

- Compact binary systems
  - » Black holes and neutron stars
  - » Inspiral and merger
  - » Probe internal structure, populations, and spacetime geometry
- Spinning neutron stars
  - » LMXBs, known & unknown pulsars
  - » Probe internal structure and populations
- Bursts
  - » Supernova explosions
  - » Tumbling or convection in NS birth
  - » Correlations with EM observations
- Stochastic background
  - » Big bang & other early universe
  - » Background of GW bursts





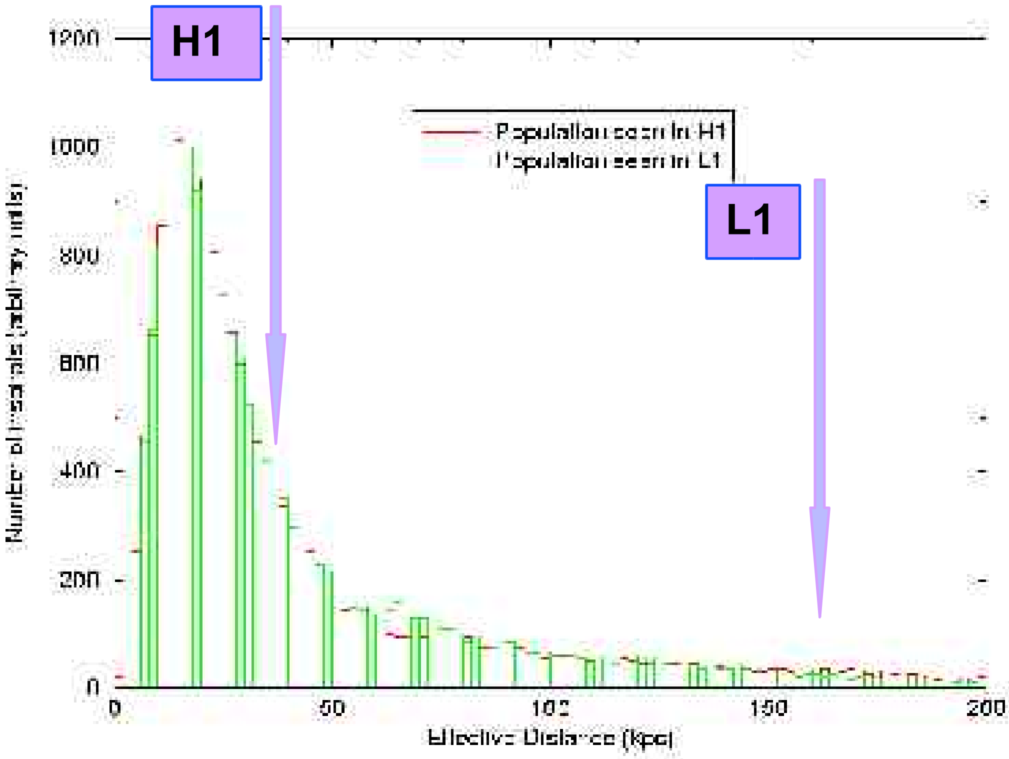


G040390-00-Z

Inspiral Group Activities

- Binary Neutron Star Search
  - » Unbiased search; upper limit on rate in absence of detection
  - » Initial LIGO may see them, AdLIGO should have many
- Black hole MACHO binary search (0.5<m1,m2<1.0)
  - » Speculative source
  - » MACHO search uses same pipeline as BNS
  - » Unbiased search; upper limit will follow neutron star result
- Binary black hole search (m1,m2 > 3.0 Msun)
  - » May be most promising source
  - » Inaccurate theoretical predictions lead to complications in analysis
  - » Detector characterization of great importance

S1 Binary Neutron Star Inspiral Search



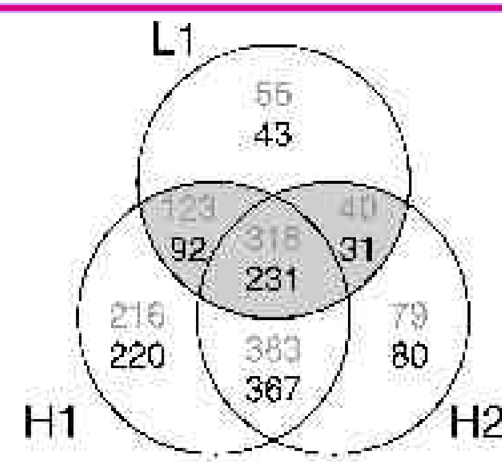
- Population included Milky Way, LMC and SMC
- Floating signal-to-noise (S/N) threshold
  - » 90% confidence limit on rate
  - » = 2.3/ (N_G * time)

- Results: max S/N=15.9
  - » Time = 236 hrs
  - » Efficiency = 0.5
  - » R < 1.7 x 10^2 / yr / MWEG

- Published: "Analysis of LIGO data for gravitational waves from binary neutron stars", PRD 69, 2004.

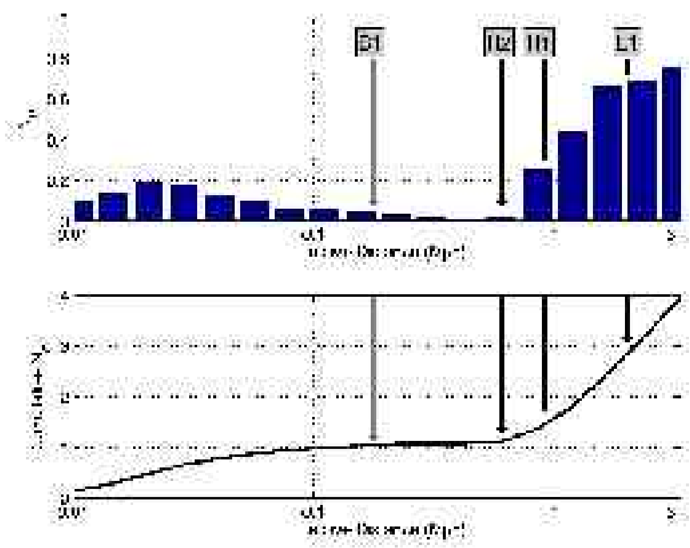
S2 Binary Neutron Star Inspiral Search

- Recorded over 1200 hours of data
  - » Did not use single IFO or H1/H2 only data
  - » Applied “data quality” cuts
  - » Applied auxiliary channel “vetoes”
- Used 355 hours of data in search
  - » Other data will be used in coincidence with TAMA

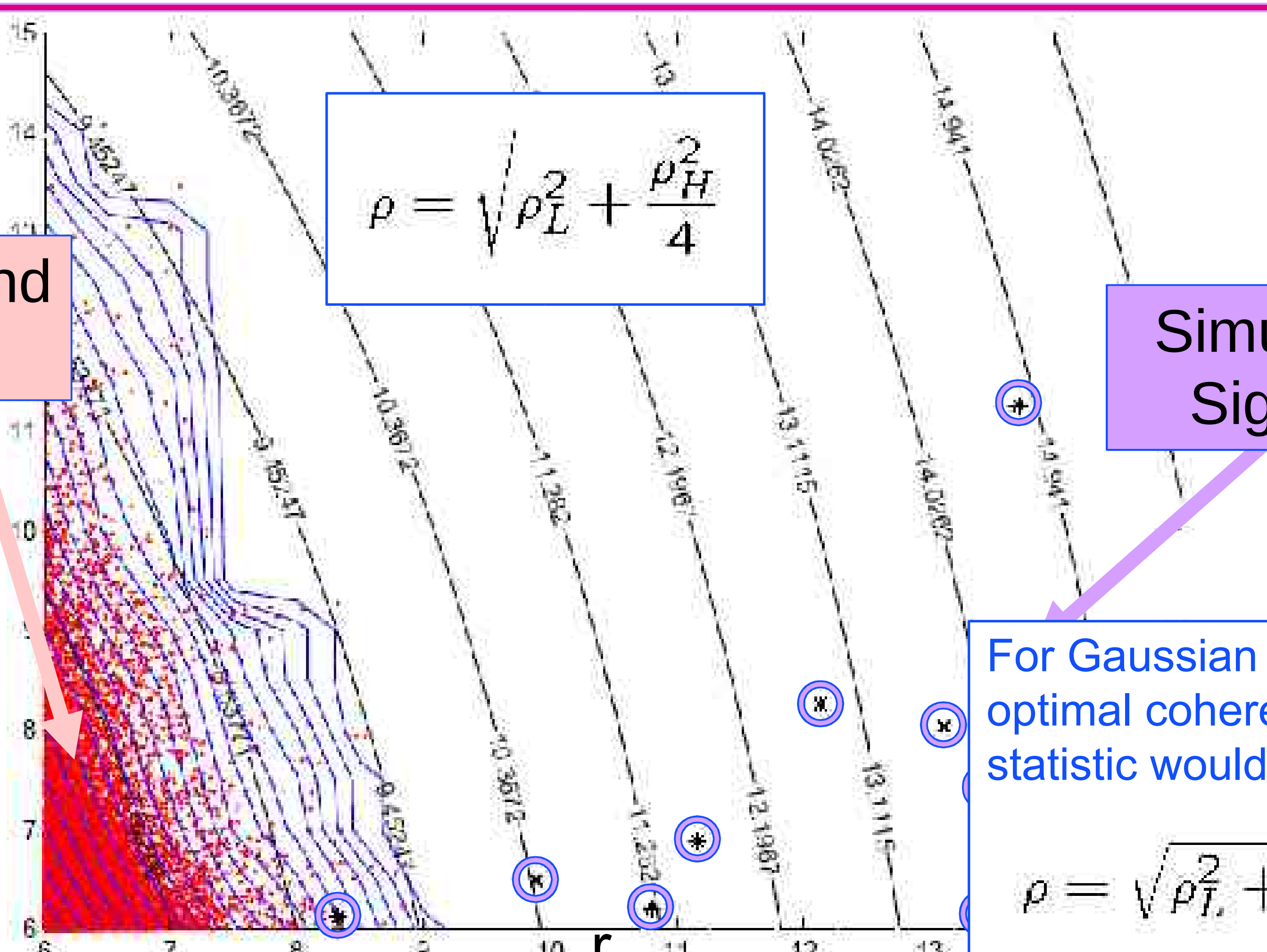


- Required triggers to be coincident in time and mass from at least two detectors

- Population includes
  - » MW, MC’s, M31-M33
  - » LLO 4k: 1.8 Mpc
  - » LHO 4k: 0.9 Mpc
  - » LHO 2k: 0.6 Mpc



S2 Background Estimation and Empirical Coherent Statistic



Background Triggers

Simulated Signals

$$\rho = \sqrt{\rho_L^2 + \frac{\rho_H^2}{4}}$$

r_H

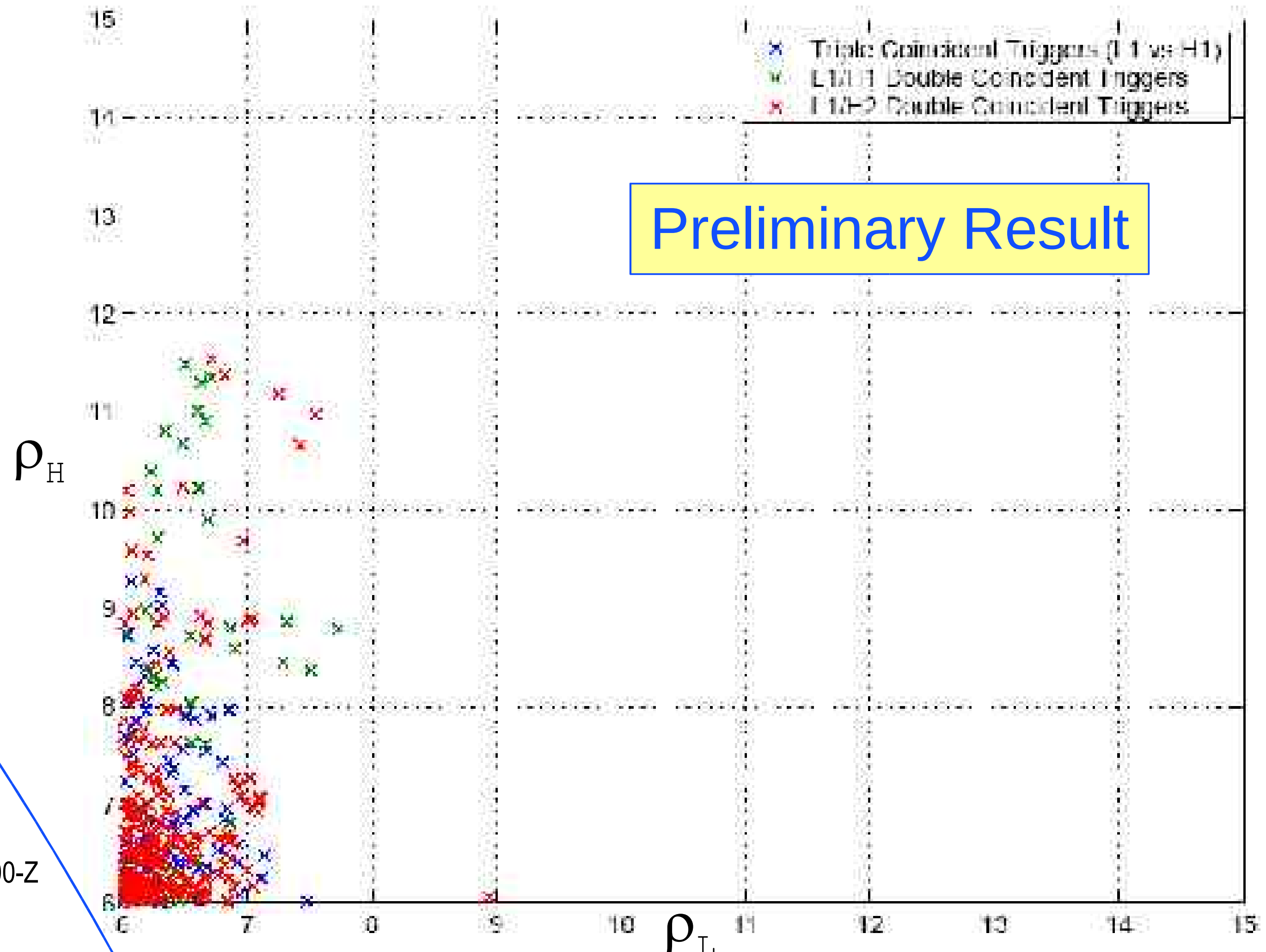
r_L

For Gaussian noise, optimal coherent statistic would be

$$\rho = \sqrt{\rho_L^2 + \rho_H^2}$$

G040390-00-Z

Preliminary S2 Triggers Observed



S2 Rate Upper Limit

- Use loudest event to determine rate
  - » No event candidates (real or background) were observed with $\rho > \rho_{max}$
- Observation time (T_{obs}) : 355 hours
- Measure detection efficiency at ρ_{max} using Monte Carlo simulation
  - » N_G = Number of Milky Way Equivalent Galaxies accessible at $\rho > \rho_{max}$
  - » Conservative lower bound on N_G = 1.14 ("worst case" for all systematic uncertainties to obtain this value)
- Obtain a one-sided frequentist confidence interval on rate:

$$R_{90\%} < 50 \text{ / yr / MWEG}$$

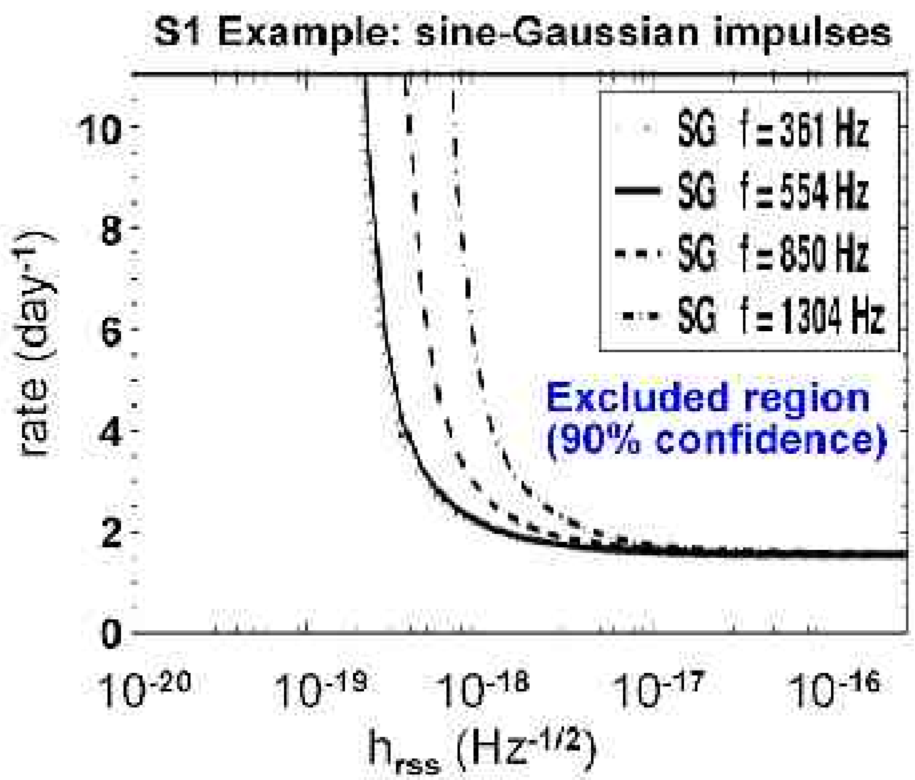
G040390-00-Z

Burst Group Activities

- Search for bursts of unknown origin/waveform
  - » Generate event triggers using variety of methods
    - – TFCLUSTERS, POWER, WAVEBURST: time-frequency methods
    - – BLOCKNORMAL: time-domain change point analysis
  - » Veto triggers due to instrumental artifacts
  - » Uninterpreted result is limit on rate of GW bursts
  - » Interpreted result uses Monte Carlo injections of astrophysical motivated signals (Zwerger et al) and other burst waveforms
- Search for bursts associated with GRB's.
  - » Triggered analysis of on-source times
  - » Result by comparison of on-source versus off-source distributions
  - » First EM triggered search with LIGO
- Other searches to come
  - » Ringdowns (overlap with inspiral); cosmic string cusps/kinks

G040390-00-Z

Burst Search of S1 Data



- Raw results
  - » sensitive to wide variety of waveform morphologies & broad frequency features
- Interpreted result:
  - » Limit on rate as function of h_{rss}
  - » Result is waveform dependent

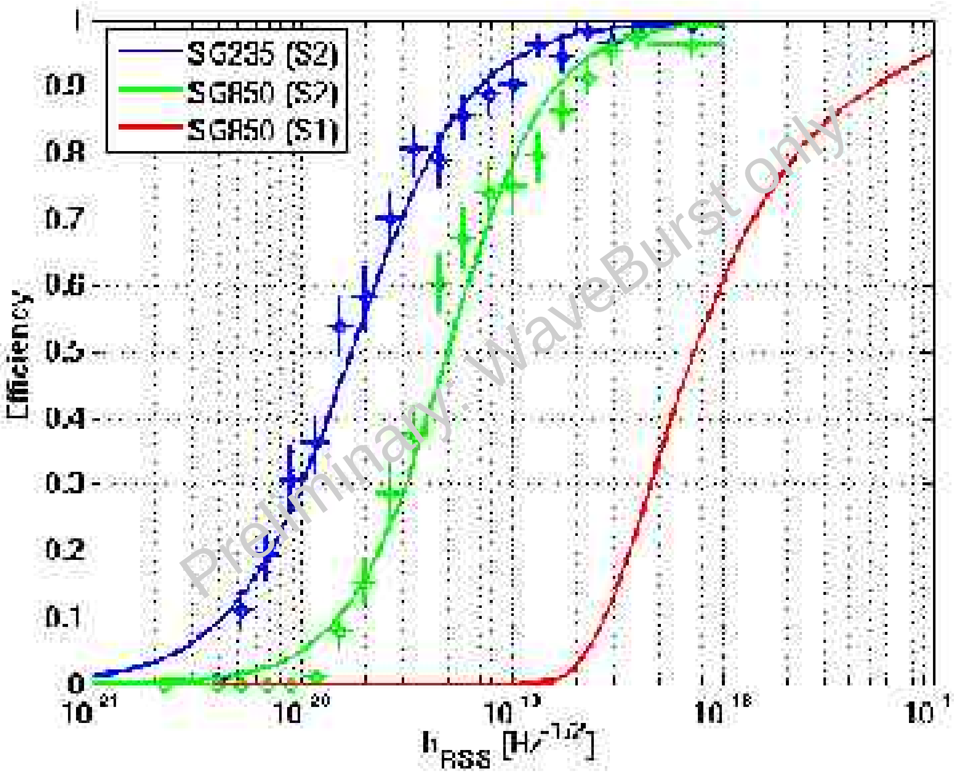
- Results:
  - » R < 1.6 per day
  - » $h_{50\%}$ ~ 4 x 10^{-19} $Hz^{-1/2}$

- Published: "First upper limits from LIGO on gravitational wave bursts", PRD _69_, 2004.

G040390-00-Z

S2 Search for Bursts

- Search for burst shorter than about 1 sec
  - » Require strict triple coincidence between two Hanford and one Livingston interferometer
  - » Generate triggers from each instrument using 4 different search techniques
  - » Follow up coincident triggers with a coherent analysis of data
- Search provides about factor of 15 improvement over S1
  - » x10 for instrumental sensitivity / stability
  - » x1.5 for more sophisticated analysis



G040390-00-Z

Gravitational Waves associated with γ-Ray Bursts

- Methodology:
  - » Cross-correlate data from multiple instruments near GRB trigger time
  - » Use times away from GRB to estimate false alarm rates
  - » Similarly, use times away from GRB to estimate false dismissal rates for signal models
  - » Method was exercised in S1 but no results appeared
- GRB 030329
  - » Detected by HETE-2, Konus-Wind, Helicon/KoronasF
  - » Especially close: z = 0.1685; dL=880Mpc
  - » Strong evidence for supernova origin of long GRBs.
  - » H1, H2 operating during, preceding burst
  - » Paper will appear soon; preliminary results at GR 17

G040390-00-Z

Continuous Wave Group Analysis

- Known pulsar searches ($f = 2 f_{rot}$)
  - » Catalog of known pulsars with accurate ephemerides
  - » Heterodyne narrow BW folding data
  - » Coherent frequency domain search using Hough transform
- Coherent frequency domain method
  - » Targetted searches (e.g. galactic core)
  - » LMXB search (e.g. ScoX-1)
  - » All sky, broadband search
- Incoherent searches
  - » Account for frequency modulation of source by appropriate averages of short-time power spectra
- In the future
  - » will implement a *hierarchical* incoherent/coherent analysis approach

G040390-00-Z

S1 Pulsar Search Results

- Detection algorithms remove:
  - » frequency modulation of signal due to Earth's motion relative to the Solar System Barycenter, intrinsic frequency changes.
  - » amplitude modulation due to the detector's antenna pattern
- Search for waves from PSR J1939+2134
  - » **No evidence** of continuous wave emission.

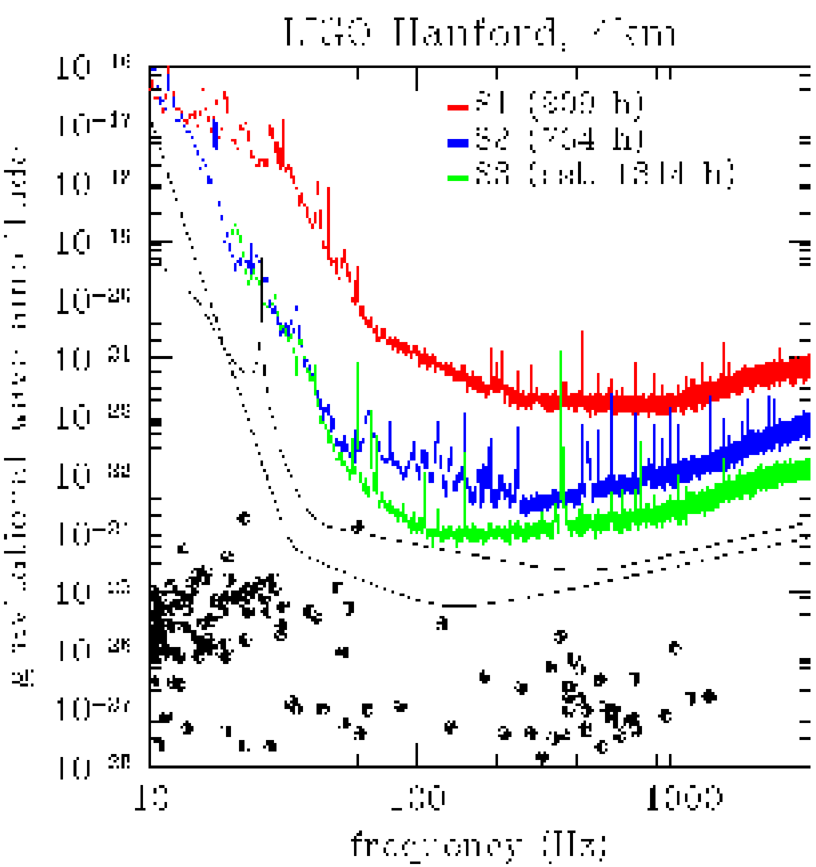
- $h_o < 1.0 \times 10^{-22}$
  - » constrains **ellipticity < 7.5x10^{-5}**
  - » (M=1.4Msun, r=10km, R=3.6kpc)

- Published: "Setting upper limits on the strength of periodic GW using first science data from GEO600 and LIGO", PRD *69*, 2004.

- Previous observational limits
  - » **$h_o < 10^{-20}$** (Glasgow, Hough et al., 1983),
  - » **$h_o < 3.1(1.5) \times 10^{-17}$** (Caltech, Hereld, 1983).

G040390-00-Z

S2 Search for Gravitational Waves from Known Pulsars



G040390-00-Z

- Target 28 pulsars:
  - » with known ephemerides
  - » gravitational wave freq > 50 Hz
- Figure shows limits on strength of gravitational waves from known pulsars **assuming gravitational waves are responsible for all observed spindown**

28 Pulsars Targeted for S2

B0021-72C	B0531+21 (Crab)	J0711-6830	J1910-5959B
B0021-72D	B1516+02A	J1024-0719	J1910-5959C
B0021-72F	B1820-30A	J1629-6902	J1910-5959D
B0021-72G	B1821-24	J1721-2457	J1910-5959E
B0021-72L	B1937+21 (S1)	J1730-2304	J1913+1011
B0021-72M	B1951+32	J1744-1134	J2124-3358
B0021-72N	B0030+0451	J1748-2446C	J2322+2057

- There are 38 known isolated radio pulsars with f_{GW} > 50 Hz
  - » includes PSR J1939+2134 (S1 target) and the Crab pulsar
- Timing information for 28 pulsars:
  - » Radio observations collected over S2/S3 for 18 by Kramer, Jodrell Bank
  - » ATNF catalogue used for 10 others
- Remaining 10 pulsars not included in the analysis because outdated spin parameters would require more that one template

G040390-00-Z

S2 Targeted Pulsar Search Results

- Assume waves from non-precessing, triaxial source with known position, spindown, and frequency
- Bayesian analysis with the following unknowns
  - » h_0 amplitude (uniform prior)
  - ≈ ψ polarization angle (uniform prior)
  - ≈ ι angle between rotation axis and line-of-sight [uniform in cos(*i*)]
  - ≈ ϕ_0 initial phase of pulsar
- Time-domain analysis of 28 known pulsars complete
- Best upper limit
  - » PSR J1910-5959D: $h_0 = 1.7 \times 10^{-24}$
  - » PSR J2124-3358: $\varepsilon = 4.5 \times 10^{-6}$
- Upper limit on Crab pulsar is about a factor of 30 from spin-down limit
- Detailed results will be presented at GR 17

G040390-00-Z

Stochastic Analysis Group

- Cross-correlate output from multiple interferometers to detect correlated gravitational wave background of cosmological or other astrophysical origin
  - » Flat spectrum for gravitational waves

- Use the Livingston-Allegro data to perform a narrow band search exploiting the ability of Allegro to modulate signal by rotating
- Explore alternative spectral characteristics for gravitational wave background

G040390-00-Z

S1 Stochastic Search Results

- Final analysis obtained best limit from H2-L1 data
- H1-H2 was dominated by instrumental correlations at SNR ~10

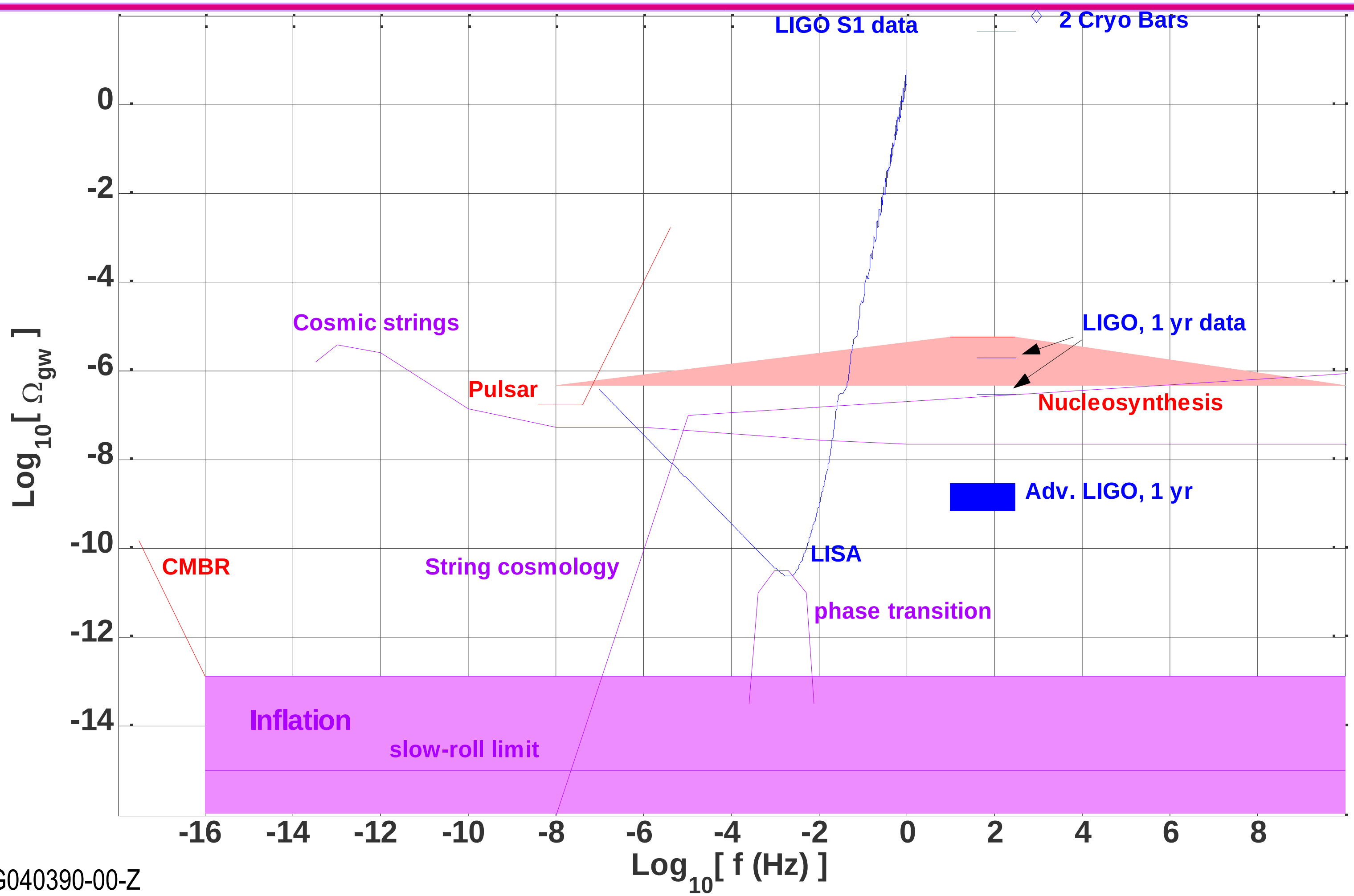
At 90% confidence

$$\Omega_0 h^2_{100} < 23$$

- Published: "Analysis of First LIGO Data for Stochastic Gravitational Waves", PRD *69*, 2004.

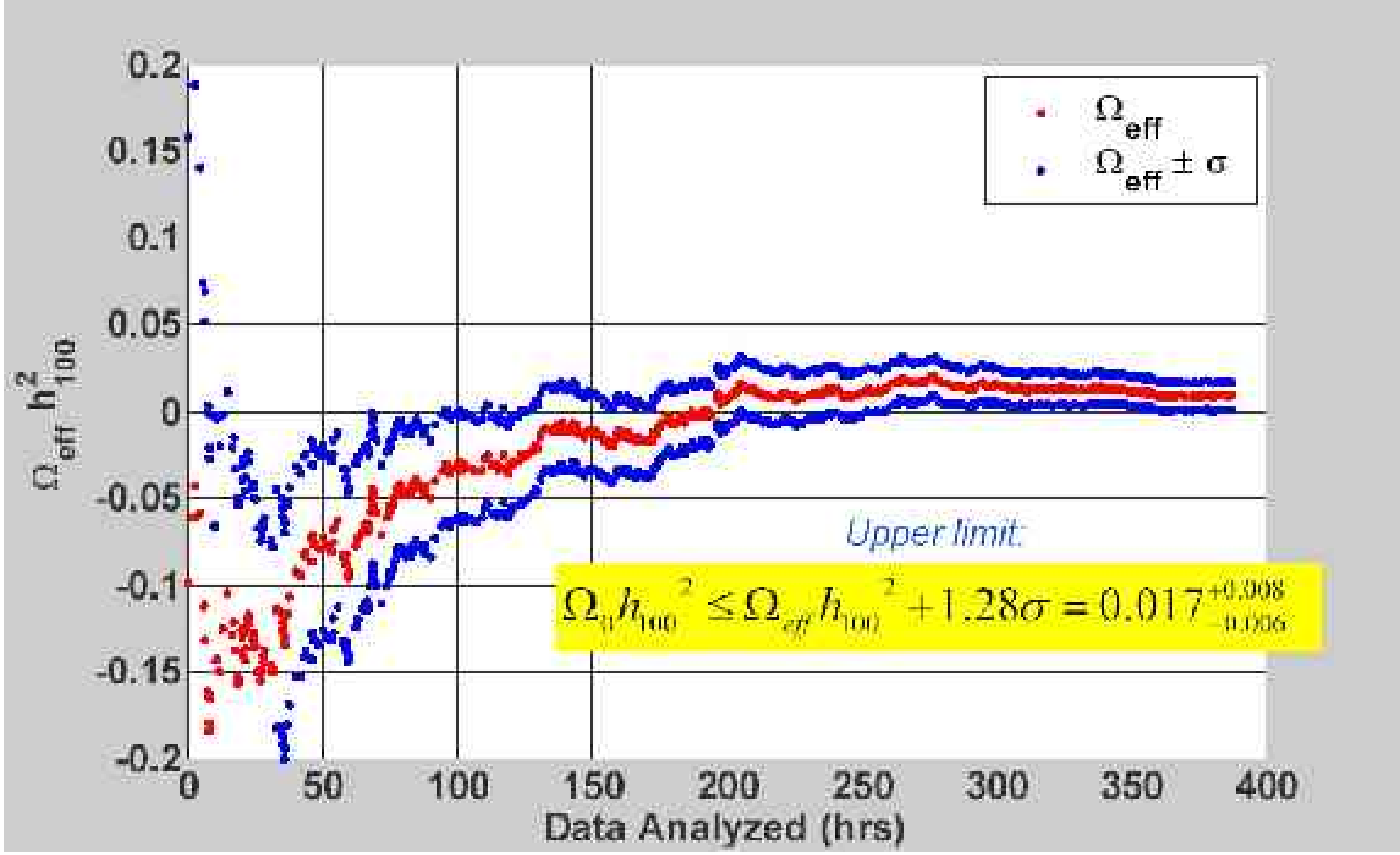
G040390-00-Z

Stochastic models, limits



G040390-00-Z

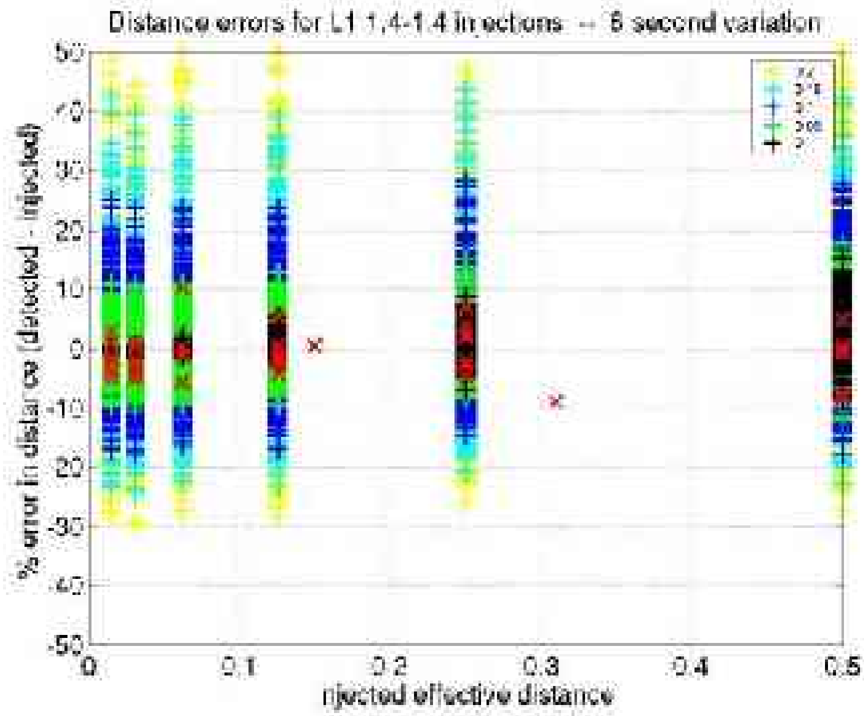
S2 stochastic search preliminary results



G040390-00-Z

End to End Check of the Analysis Pipelines

- Calibration lines are always present.
- At several times, we inject fake signals by shaking mirrors, to check that they are properly recovered by search pipelines.
- Those *hardware injections* are supplemented by many additional signals added in software.
- Extensive reviews of
  - » search software, and of
  - » complete analysis results.



G040390-00-Z

Concluding Remarks

- S1: Analyses are now complete and published
- S2: Broader base of analyses and explorations of data
  - » More sophisticated analyses now solidly underway
- S3: LIGO interferometers within a factor of 2-3 of design sensitivity
  - » Gearing up with possible approach to combine S2/S3 results in some cases
  - » Improved sensitivity provides access to many galaxies for binary inspiral searches
  - » Core searches are getting easier
- Expect a 6-month long run during 2005, at or near design sensitivity
- At LIGO-I design sensitivity, we might see
  - » a NS binary inspiral, a burst from cosmic string cusp, CW signals from the Crab pulsar, a cosmological stochastic background if we get lucky …… or, a surprise!
- Advanced LIGO ought to record many signals.

G040390-00-Z