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# LIGO: Status and Update

***The Aspen Winter Conference on Gravitational Waves,  
(GWADW) at Isola d'Elba, Italia  
20 May 2002***

*Albert Lazzarini  
LIGO Laboratory  
Caltech*

# Outline for this talk

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- Report on the E7 engineering run
- Commissioning activities and plans
- Analysis of E7 data
  - » Searches for bursts
  - » Searches for coalescences
  - » Searches for CW sources
  - » Searches for the stochastic GW background
- Plans beyond E7: scientific operations and advanced R&D



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# E7 Coincidence Run

*28 Dec 2001 - 14 January 2002*

*LIGO-G020231-00-E*

*Elba 2000.05.19 - 26*

*LIGO Laboratory at Caltech*

# E7 sensitivities for LIGO Interferometers

## 28 December 2001 - 14 January 2002

LHO2k: full configuration;

LHO4k & LLO4k : recombined configuration, no power recycling

Strain Sensitivities for the LIGO Interferometers for E7

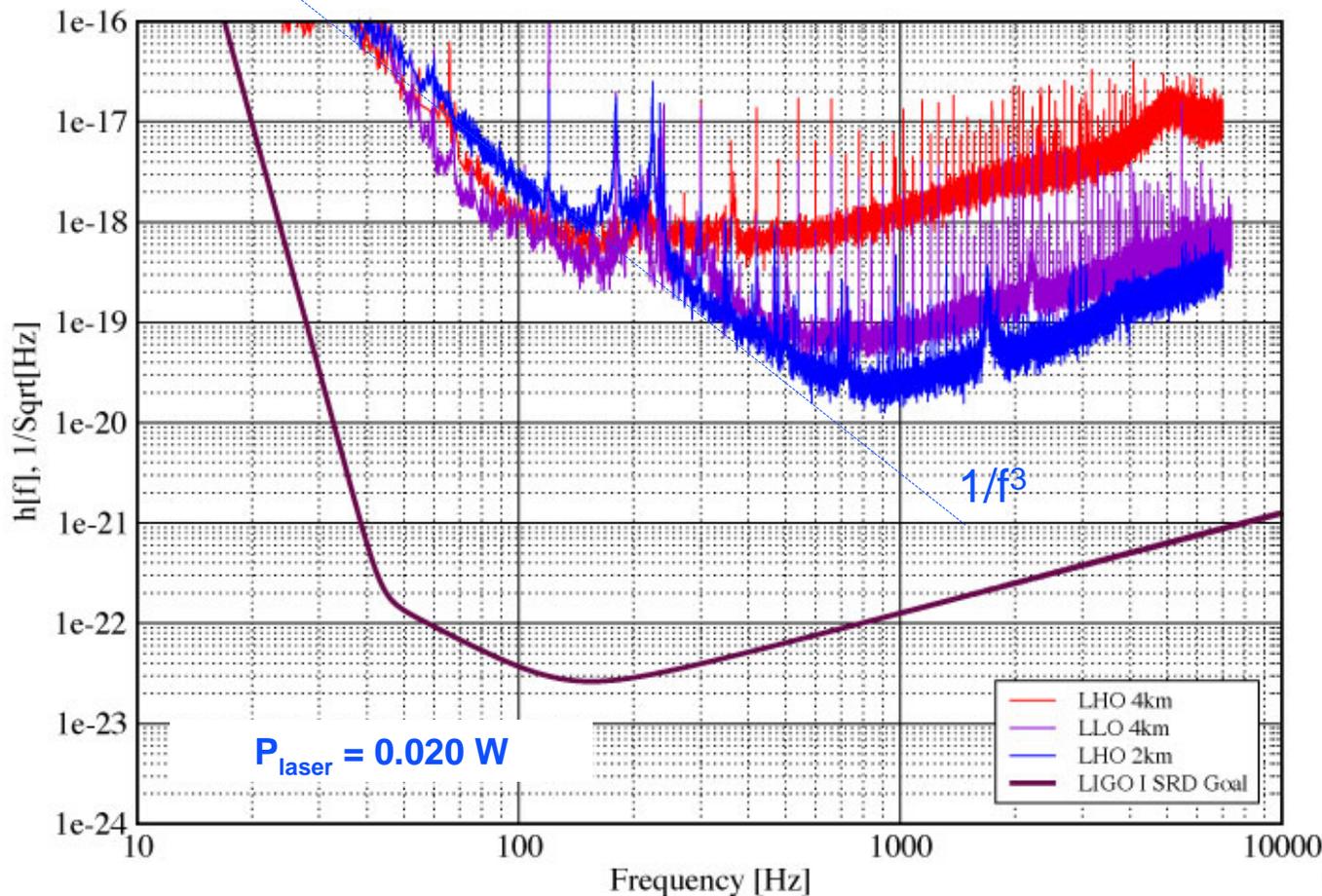
- Used  $3 \times 10^{-3}$  of design laser power

17x improvement at high f from P

- Source of  $1/f^3$  noise at low f under investigation

- Need additional damping of structural resonances near 200 Hz on optics benches

- Planned upgrade of seismic system at Livingston to provide greater availability



# E7 Run Summary

## LIGO + GEO Interferometers

Courtesy G. Gonzalez & M. Hewiston

**28 Dec 2001 - 14 Jan 2002 (402 hr)**

### Singles data

All segments      Segments >15min

L1 locked      284hrs (71%)      249hrs (62%)  
 L1 clean      265hrs (61%)      231hrs (53%)  
 L1 longest clean segment: 3:58

H1 locked      294hrs (72%)      231hrs (57%)  
 H1 clean      267hrs (62%)      206hrs (48%)  
 H1 longest clean segment: 4:04

H2 locked      214hrs (53%)      157hrs (39%)  
 H2 clean      162hrs (38%)      125hrs (28%)  
 H2 longest clean segment: 7:24

### Coincidence Data

All segments      Segments >15min

**2X: H2, L1**  
 locked      160hrs (39%)      99hrs (24%)  
 clean      113hrs (26%)      70hrs (16%)  
 H2,L1 longest clean segment: 1:50

**3X : L1+H1+ H2**  
 locked      140hrs (35%)      72hrs (18%)  
 clean      93hrs (21%)      46hrs (11%)  
 L1+H1+ H2 : longest clean segment: 1:18

**4X: L1+H1+ H2 +GEO:**  
 77 hrs (23 %)      26.1 hrs (7.81 %)

**5X: ALLEGRO + ...**



# E7 Data Analysis with LDAS

- » **LIGO Data Analysis System (LDAS) was used extensively during and after run to look at data**
  - Majority of upper limit analyses
  - Data conditioning, pre-processing
  - Database insertion for events, vetoes
  - Data distribution, on-line caches
  
- » **Data archive at Caltech:**
  - HPSS tape archive (pre-E1 through E7):
    - 40 TB and growing
    - 575,000 files
    - 10% of 1 year 7x24 science run
    - **One more order of magnitude to go**



# LDAS Job Summary

## *Analyses Performed During E7 Run*

	Hanford LDAS	Livingston LDAS	MIT LDAS	CIT-TEST LDAS	TOTAL
<b>Total Jobs</b>	<b>63600</b>	<b>48775</b>	<b>280</b>	<b>915</b>	<b>113570</b>
<b>Database Rows</b>	<b>4188188</b>	<b>2789132</b>	<b>1062</b>	<b>2096</b>	<b>6980478</b>

- LDAS for full E7 Run: Dec. 28th, 2001 - Jan. 14th, 2002
  - » Approximately *one job every 10 seconds* (averaged).
  - » Approximately *five rows every second* (averaged).
- Greater than 90% of jobs completed successfully
  - » LHO roughly **92%**; LLO roughly **95%** - not checked elsewhere
  - » *E7 release dominated by thread problems in pre-processing module (dataConditionAPI)*
  - » *Fraction due to MPI module communications issues (mpiAPI/wrapperAPI)*
- ***Latest release for S1 shows 99+% reliability!***



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# Commissioning status

*LIGO-G020231-00-E*

*Elba 2000.05.19 - 26*

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# *LHO 2 km interferometer*

## *Status*

- Locked in full recycled configuration
  - » Operated in full recycled configuration (recycling factor up to 25, but typically ~15)
- Common mode servo implemented
  - » Frequency stabilization from average arm length
  - » Establishes control system “gain hierarchy”
- 5 W power into mode cleaner
  - » Attenuators at photodiodes give effective input power 50-100 mW)
- Tidal feedback operational
  - » Lock duration up to 15 hours
- **DISPLACEMENT** Sensitivity

Summer 2001  $\sim 3 \times 10^{-16} \text{ m/Hz}^{1/2}$

December 2001 (E7)  $\sim 5 \times 10^{-17} \text{ m /Hz}^{1/2}$

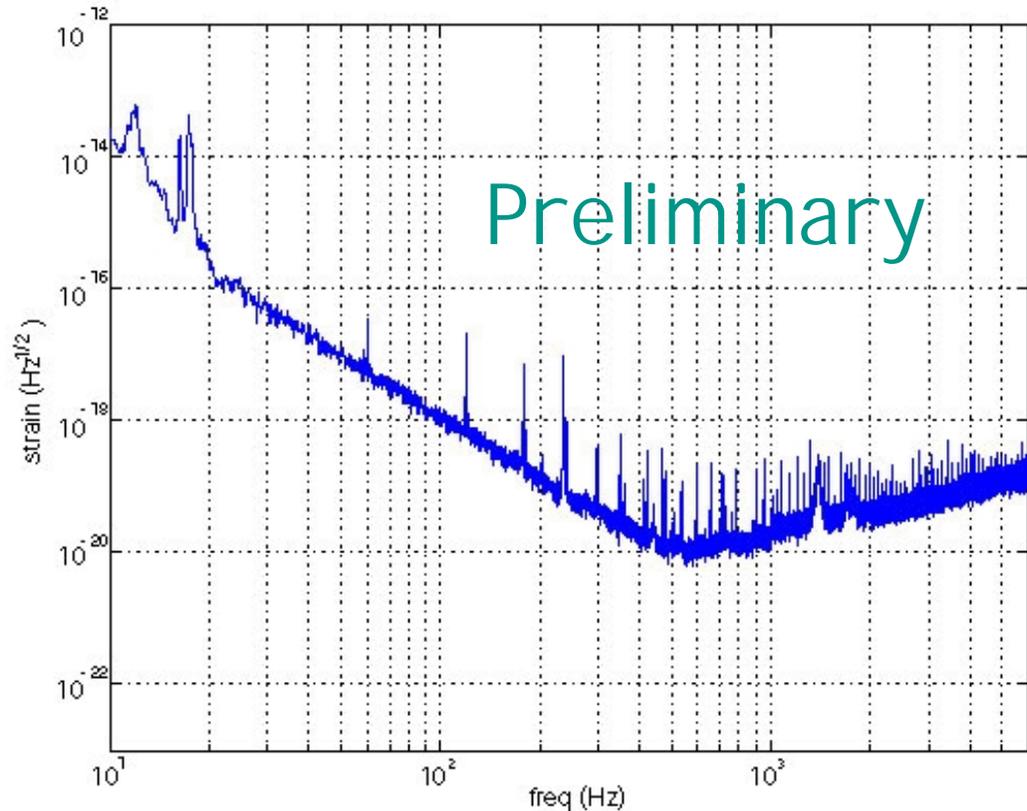
Spring 2002  $\sim 2 \times 10^{-17} \text{ m /Hz}^{1/2}$



# Current 2 km Sensitivity

## 2 km Spectrum (late January)

Still needs factor  
of 30-100  
improvement  
at high frequencies,  
factor of  $10^4$  near 100  
Hz.



# LHO 4 km Interferometer

## Status

- In-vacuum installation completed last summer
- Digital suspension controllers
  - » Greater flexibility for tuning servos to improve reliability/noise
  - » Example: Frequency dependent output matrices implemented and tested
  - » Will be implemented on other interferometers after test here
- 1 W power into mode cleaner
  - » Attenuators at photodiodes give effective input power 20 mW)
- Locked in full recycled configuration
  - » Recycling factor typically 40-50
- Tidal feedback operational
  - » Locks up to 4 hours
- **DISPLACEMENT** Sensitivity  $\sim 2 \times 10^{-16} \text{ m/Hz}^{1/2}$



# LLO 4 km Interferometer

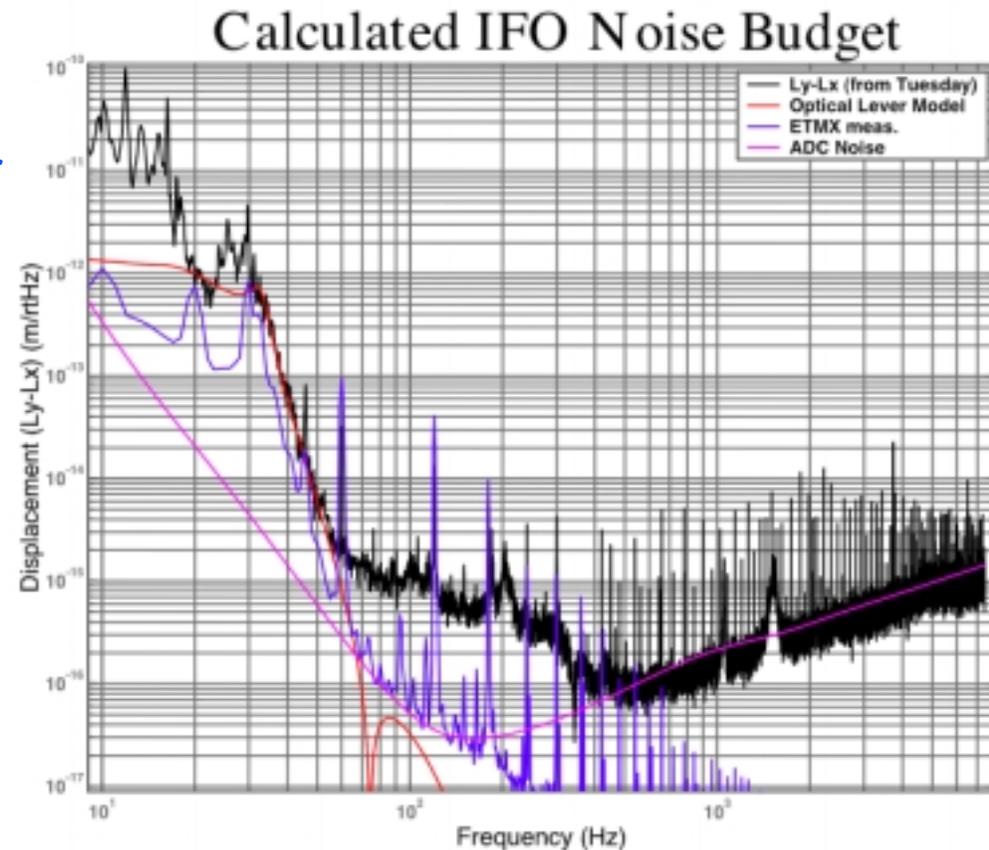
## Status

- Fully recycled configuration
- 1 W power input laser power into mode cleaner
  - » Power buildup of 1400 in each arm corresponds to recycling gain  $\sim 50$
  - » 60 dB attenuation at dark port
- Reasonably robust lock during day
  - » Up to 4 hours
  - » 15s - 60s lock acquisition time
  - » **Tidal feedback operational**
  - » **Wavefront alignment control operating on BS**
  - » **Microseismic feed-forward implemented to reduce dynamic range (unique to LLO at present time)**
- **DISPLACEMENT** Sensitivity  $\sim 7 \times 10^{-17} \text{ m/Hz}^{1/2}$  @ 500 Hz



## Current LLO 4km Displacement Sensitivity

- $f < 80$  Hz limited by alignment servo noise
- $80 \text{ Hz} < f < 300$  Hz limited by laser  $f$  noise
  - need larger gain on mode cleaner servo
- $f > 300$  Hz limited by photodiode electronics, A/D noise



# Significant, Planned Detector Modifications

- **Seismic Isolation:**
  - » Fine actuation system stack mode suppression
    - LLO End test mass chambers for S1
    - LLO Input test mass chambers also for S2
    - Possibly added to the Hanford observatory for S3
  - » Seismic retrofit with a 6-dof active pre-isolation system
    - Planned at the Livingston observatory right after S2
    - active pre-isolation system is placed under the existing passive stack, external to the chamber
- **Digital Suspension Controls**
  - » Currently implemented on the LHO 4km interferometer
  - » Plan is to install on the other two interferometers before S2
- **Laser intensity stabilization servo improvements**
- **Auto-alignment:**
  - » Automate Fabry-Perot cavity angular alignment for S1
  - » Centering of recycling cavity, dark port and end test mass transmission beams for S2



# Modeling and Simulation Activities

- **Simulation framework**
  - » Object Oriented time domain model written in C++
  - » GUI front-end ported to JAVA
  - » Lock acquisition design and realistic noise simulation
- **Lock Acquisition design (2000 - 2001)**
  - » 2mk interferometer simulation package based on scalar field approximation
  - » Input matrix (error signals to 4 DOF) designed and tested in this package
  - » Same source code used for Hanford 2km interferometer
    - Power recycled IFO locked robustly
- **Noise simulation (2001+)**
  - » Much more realistic simulation package to simulate the realistic noise curve
  - » Correlation of seismic motions, realistic servos with digitization, digital suspension controller, etc
  - » Major and secondary noises with as-built AND measured configurations
    - **Intrinsic:** Seismic, thermal, shot noise
    - **Technical:** Electronic, frequency and intensity, etc
  - » Studying effect of the thermal lensing
    - Locking servo and locked state performance
- **LIGO 1 commissioning**
  - » Various non-linear effects and bi-linear couplings
- **H. Yamamoto will give a talk later this week**



# Analysis of the E7 Data: Upper Limit Groups

- Burst sources
- *Continuous wave sources*
- *Coalescing sources*
- *Stochastic background*

LIGO I Development Group: 21 Institutions, 26 Groups, 281 Members

[http://www.ligo.caltech.edu/LIGO\\_web/lsc/lsc.html](http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html)

## US Universities:

- [Caltech LIGO/CaRT/CEGG/CACR](#)
- Carleton
- Cornell
- Cal State University Dominguez Hills
- Florida
- Louisiana State
- Louisiana Tech
- Michigan
- [MIT LIGO](#)
- Oregon
- Penn State
- Southern
- Syracuse
- Texas-Brownsville
- Wisconsin-Milwaukee

## International Members:

- ACIGA (Australia)
- GEO 600 (UK/Germany)
- IUCAA (Pune, India)

## US Agencies & Institutions

- FNAL (DOE)
- Goddard-GGWAG (NASA)
- Harvard-Smithsonian

*International partners (have MOUs with LIGO Laboratory, plans in progress for data exchanges):*

- TAMA (Japan)
- Virgo (France/Italy)



# The LIGO I Scientific Collaboration

## 4 Data Working Groups (“Upper Limits Groups”) - 85 Individuals

### Burst Sources Search

Rana Adhikari  
Warren Anderson  
Barry Barish  
Biplab Bhawal  
Jim Brau  
Kent Blackburn  
Joan Centrella  
Ed Daw  
Ron Drever  
**Sam Finn (co-chair)**  
Ken Ganezer  
Joe Giaime  
Gabriela Gonzalez  
Bill Hamilton  
Masahiro Ito  
Warren Johnson  
Sergei Klimenko  
Albert Lazzarini  
Szabi Marka  
Soumya Mohanty  
Benoit Mours  
Soma Mukherjee  
Fred Raab  
Ravha Rahkola  
**Peter Saulson (co-chair)**  
Robert Schofield  
David Shoemaker  
Daniel Sigg  
I.K. Siongheng  
Julien Sylvestre  
Alan Weinstein  
Mike Zucker  
John Zweizig

### Compact Binary Inspirals Sources Search

Bruce Allen  
Sukanta Bose  
David Churches  
**Patrick Brady (co-chair)**  
Duncan Brown,  
Jordan Camp  
Nelsen Christensen  
Jolien Creighton  
Teviet Creighton  
S.V. Dhurander  
**Gabriela Gonzalez (co-chair)**  
Andri M. Gretarsson  
Gregg Harry  
Vicky Kalogera  
Joe Kovalik  
Nergis Mavalvala  
Adrian Ottewill  
Ben Owen  
TomPrince  
David Reitze  
Anthony Rizzi  
B.S. Sathyaprakash  
Peter Shawhan,  
Julien Sylvestre  
Linqing Wen  
Alan Wiseman

<http://www.lsc-group.phys.uwm.edu/iulgroup/>

### Continuous Wave Search

**Stuart Anderson (co-chair)**  
Steven Berukoff  
Patrick Brady  
Dave Chin  
Bob Coldwell  
Teviet Creighton  
Curt Cutler  
Ron Drever  
Rejean Dupuis  
Sam Finn  
Dick Gustafson  
Jim Hough  
Soumya Mohanty  
Soma Mukherjee  
Maria Alessandra Papa  
Keith Riles  
Bernard Schutz  
Alicia Sintes-Olives  
Alberto Vecchio  
Harry Ward  
Alan Wiseman  
Graham Woan  
**Mike Zucker (co-chair)**

<http://www.lsc-group.phys.uwm.edu/pulgroup/>

### Stochastic Background Source Search

Bruce Allen  
Warren Anderson  
Sukanta Bose  
Nelson Christensen  
Ed Daw  
Mario Diaz  
Ronald Drever  
Sam Finn  
**Peter Fritschel (co-chair)**  
Joe Giaime  
Bill Hamilton  
Ik Siong Heng  
Waråren Johnson  
Erik Katsavounidis  
Sergi Klimenko  
Mike Landry  
Albert Lazzarini  
Martin McHugh  
Soma Mukherjee  
Tom Nash  
Adrian Ottewill  
Tania Regimbau  
Keith Riles  
John Ringland  
Jamie Rollins  
**Joe Romano (co-chair)**  
Bernard Schutz  
Antony Searle  
Alberto Vecchio  
Bernard Whiting  
Rainer Weiss  
John Whelan

<http://www.ligo.caltech.edu/~ajw/bursts/bursts.html>

# Analysis of the E7 Data: Upper Limit Groups

- **Burst sources**
- *Continuous wave sources*
- *Coalescing sources*
- *Stochastic background*



# Present status of Burst Group's E7 upper limit search

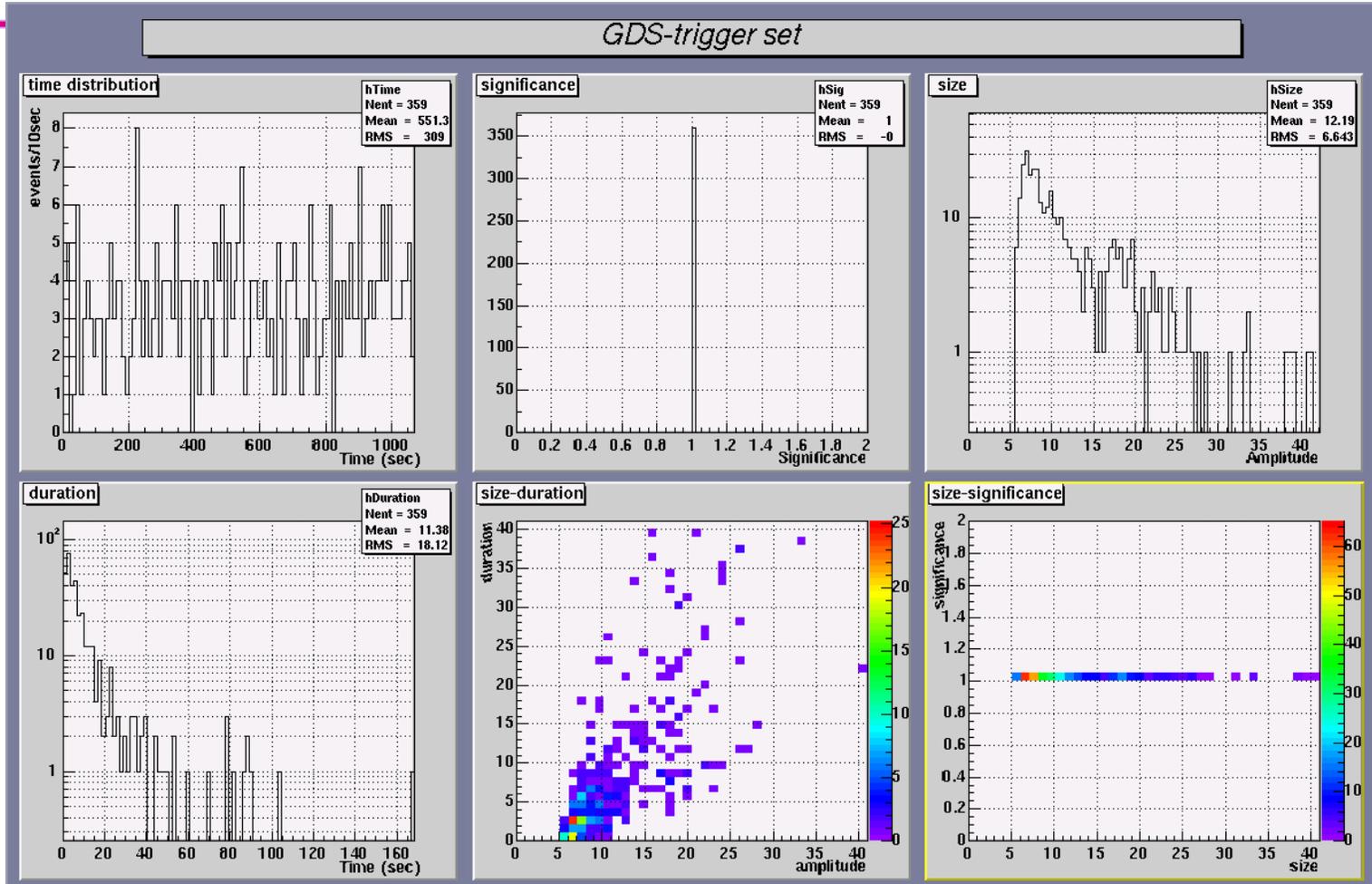
## Pipeline analysis is very close to completion

- Filters (dynamically loaded shared objects - DSOs - running in LDAS)
- Vetoes (derived from on line software, data monitoring tool -- DMT)
- Event analysis (eventTool -- based on ROOT)
- Interpretation strategies defined

## Searches based on 4 complementary DSOs

- **Search triggered by Gamma Ray Bursts**
  - Based on Finn et al., [gr-qc/ 9903101](#) and S. Marka (SNEWS), e.g., [http://www.ligo.caltech.edu/~ajw/bursts/LSC\\_proposal\\_snews.3.0.pdf](http://www.ligo.caltech.edu/~ajw/bursts/LSC_proposal_snews.3.0.pdf)
  - Software progressing rapidly
- **Time-frequency clusters**
  - Based on J. Sylvestre's work, e.g., <http://www.ligo.caltech.edu/docs/G/G020028-00.pdf>
  - Very mature, most of full pipeline exercised
- **Excess power statistic**
  - Based on work of Anderson et al., e.g., [gr-qc/0001044](#)
  - Long history, code needs informed tuning
- **Time-domain filter (slope detection and beyond)**
  - Based on Orsay group's work, e.g., [gr-qc/0010037](#)
  - Most recent, needs tuning

# Statistical study of vetoes using EventTool



- E7 data was full of glitches, which remain unexplained and unsolved.
  - => *Need help from instrumentalists.*
- Unprepared to fluently look for glitches in the data.
  - => *Need help from software people.*
- Burst search methods need tuning, a time-consuming activity.
  - => *Need more manpower in carrying out the searches.*
- Group will carry out three styles of interpretation.
  - ***Search triggered by Gamma Ray Bursts***
    - => Interpretation issues are well understood.
  - ***Instrumental interpretation***
    - => Description of strain vs. time-frequency character
    - => Straightforward in principle, still some open issues.
  - ***Astrophysically-motivated interpretation***
    - => Focus on bursts that look like something that is expected
    - => Still some open issues of modeling burst sources, understanding biases



# Analysis of the E7 Data: Upper Limit Groups

- Burst sources
- ***Continuous wave sources***
- *Coalescing sources*
- *Stochastic background*



# Periodic source searches

## *Upper Limit Group*

### 3 source categories and 4 algorithms

- » All sky unbiased
  - Sum short power spectra (no doppler correction)
  
- » Known pulsar
  - Heterodyne narrow BW
  - Coherent frequency domain
  
- » Wide area search
  - Hierarchical Hough transform
  - *Schutz & Papa gr-qc/9905018; Williams and Schutz gr-qc/9912029*



# Basic features of the algorithms and development status

All these routines have been successfully integrated in a first version of a driver code that performs a full hierarchical search over a specified frequency band and a small sky patch. For the E7 data run we expect to be able to search the galactic core or 47 Tuc in a band of several tens-few hundred Hz.

- designed to run on cluster of loosely coupled processors
- computational load is distributed with respect to searched signals frequency – this induces a natural distribution of data among nodes and simple hardware&software design.
- **coherent search method**: works on data in frequency domain, it is an *efficient* generalized FFT method. *General*: can demodulate for any phase evolution – defined by a timing routine.
- incoherent search method: **Hough transform** from time-frequency data sets to signal parameter space, where candidates are identified. Complex software.

For the E7 data run Medusa Beowulf cluster at UWM will be used.

At AEI: ~150 dual AMD processor cluster has been designed (after extensive benchmarking and testing) and is being built. Will be operational in late spring. Name: Merlin.

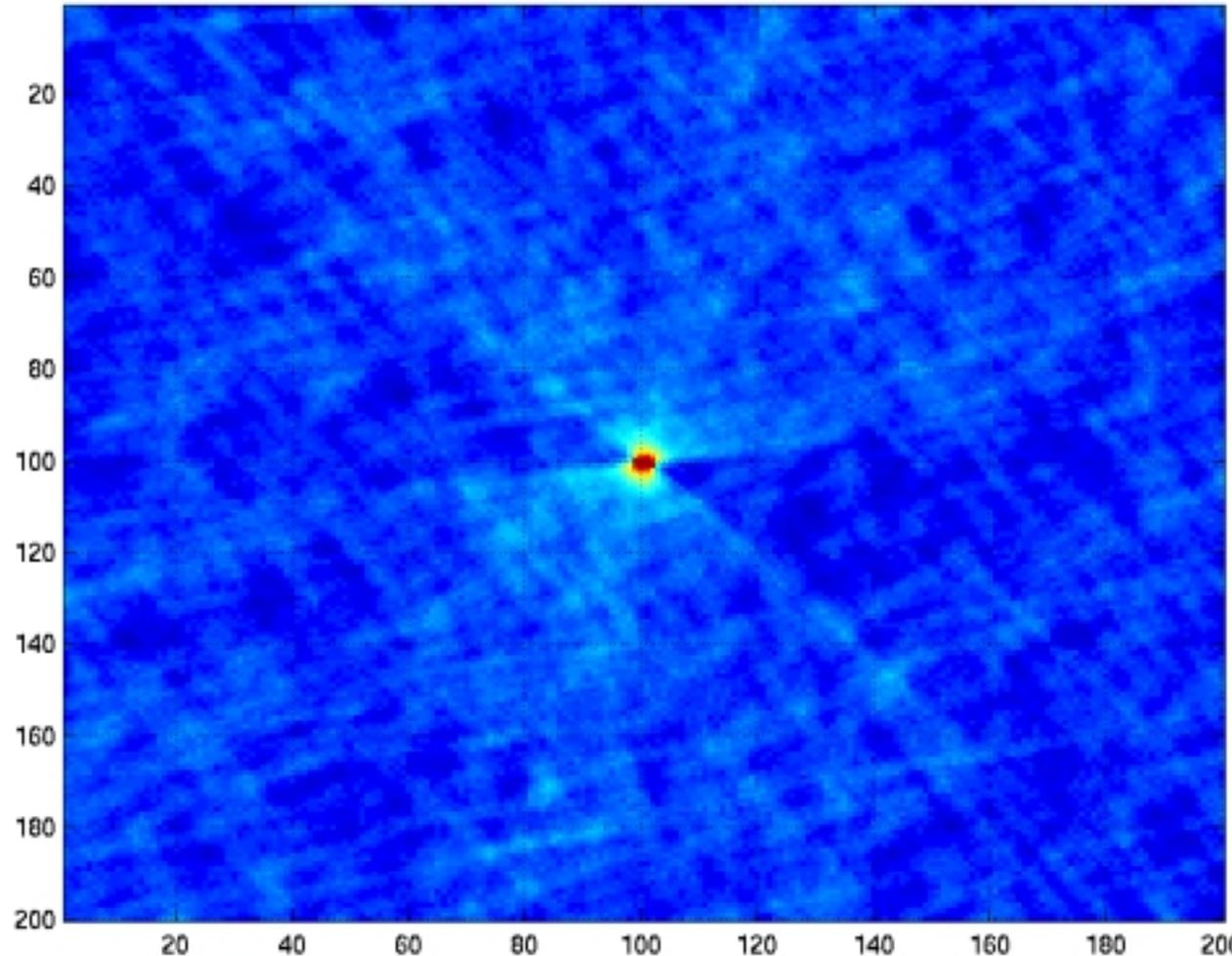
In LAL library since Jan 2000. Will also be used for targeted searches of known objects and run under LDAS (integration by Greg Mendell).

Several modules and more than 7000 lines of code, in LAL since fall 2001.

# Simulated Hough Transform Image

- **Image:**

- » **8 hours of integration per DeFT(column)**
- » **Total observation time of roughly 3 months.**
- » **SNR is such that 129 out of the 270 signal points were registered.**
- » **The source is located at  $\alpha=45$   $\delta=45$  degrees.**
- » **The source's intrinsic frequency is 400 Hz**
- » **Signal has no spindown.**



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# Inspiral search

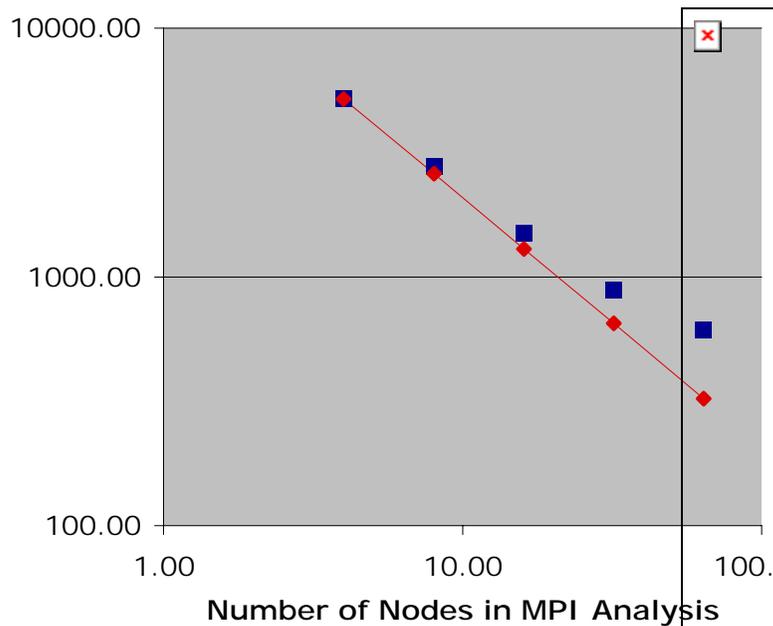
- Two approaches
  - » Conventional optimal Wiener filtering with chirp templates
    - Flat search (based, e.g., on *Owen, PRD Vol. 53, No. 12 (1996) 6749*  
*B.S.. Sathyaprakash, Vol. 50, No. 12 (1994) R7111*)
      - Implemented for analysis of 1994 40m data, TAMA data
  - » Fast Chirp Transform (FCT)
    - Based on *Prince, Jenet gr-qc/0012029*  
*Class. Quant. Grav., 19, 1493-1498 (2002)*
    - Starting with stationary phase approximation to phase evolution, linearize phase behavior locally to recast filter as multi-dimensional FFT
    - Generalized FT
- *Hierarchical search - under development for both approaches*
  - » See, e.g., *Class. Quant. Grav., 19, 1507-1512 (2002)*



# Inspiral E7 tests - templated search

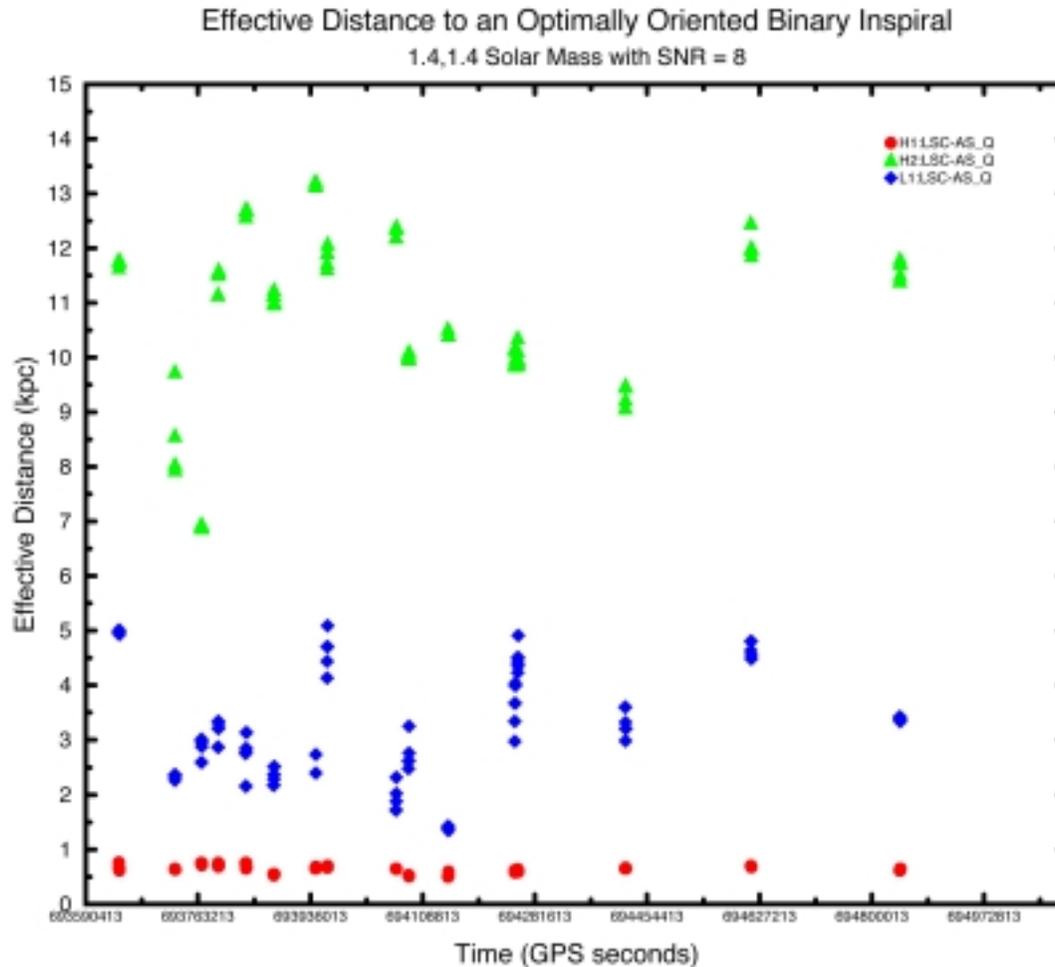
- Very preliminary results
  - » Code performance in a parallel linux cluster

*MPI computation performance with increasing number of nodes*



# Inspiral search with E7

Preliminary results with test set data



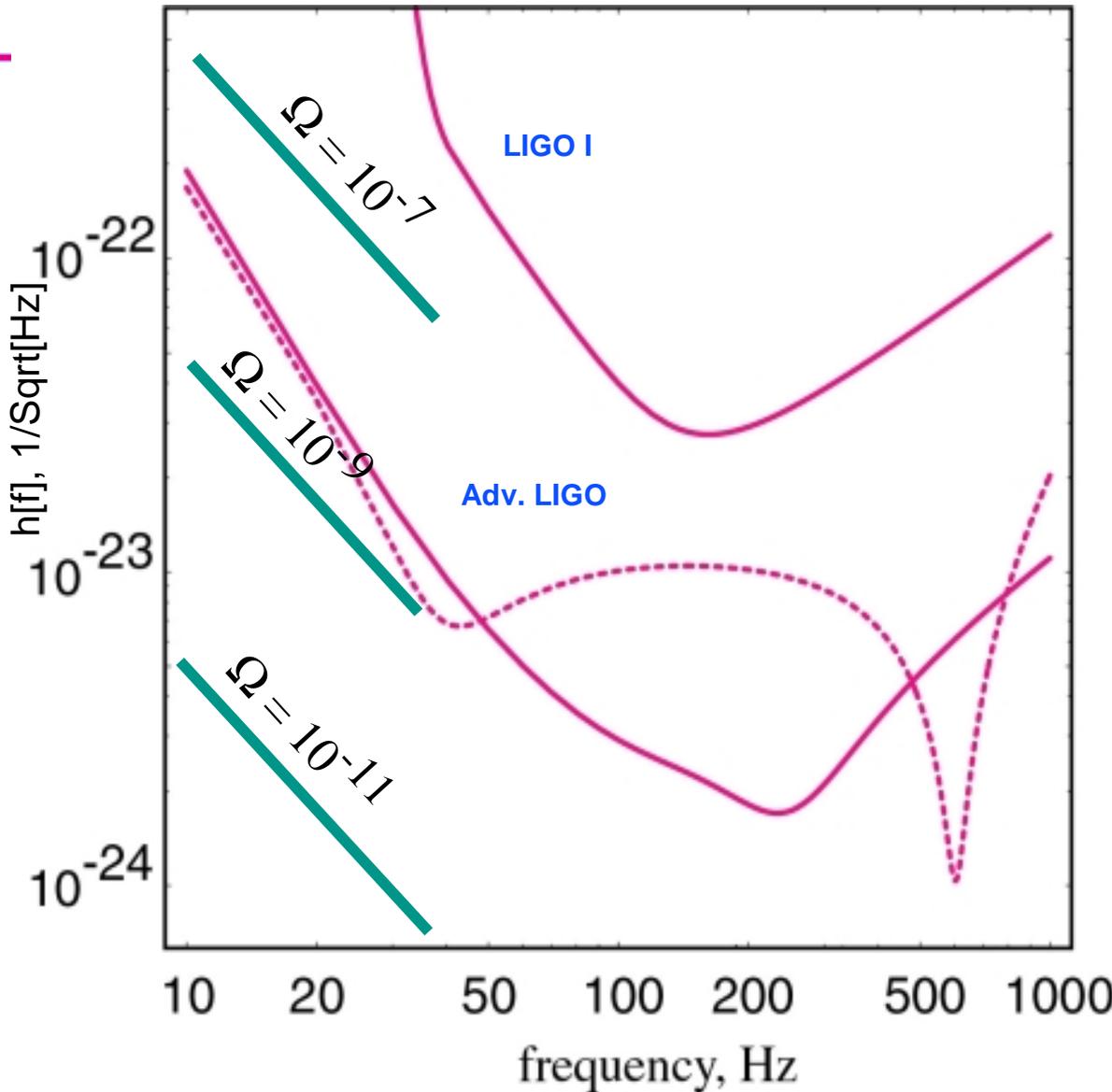
# Analysis of the E7 Data: Upper Limit Groups

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# Stochastic Gravitational Wave Background

- Detect by cross correlating output of Hanford + Livingston 4km IFOs
- Peak of sensitivity:
  - $\lambda_{\text{GW}} \gtrsim 2D$  ( $D = 3000$  km)
  - $f \lesssim 40$  Hz
- Initial LIGO sensitivity:
  - $\Omega_{\text{GW}} \gtrsim 10^{-5}$
  - Limited by  $h[f]$  seismic wall  $f \gtrsim 50$ Hz
- Advanced LIGO sensitivity:
  - $\Omega_{\text{GW}} \gtrsim 5 \times 10^{-9}$

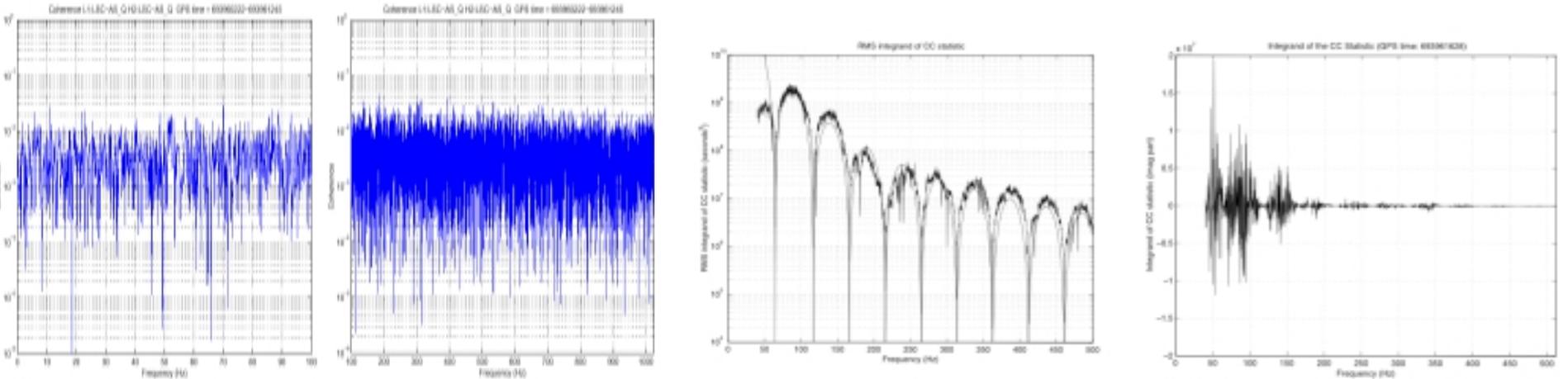


# Stochastic Upper Limit Group Activities (E7 investigations – current/planned)

- **Analytic calculation** of expected upper limits (~50 hrs):  
 $\Omega \sim 2 \times 10^5$  for LLO-LHO 2k,  $\Omega \sim 6 \times 10^4$  for LHO 2k-LHO 4k
- Coherence measurements of GW channels show little coherence for LLO-LHO 2k correlations
- Power line monitor coherence investigations suggest coherence should average out over course of the run
- Plan to investigate effect of line removal on LHO 2k-LHO 4k correlations (e.g., reduction in correlated noise, etc.)
- Plan to inject simulated stochastic signals into the data and extract from the noise
- Plan to also correlate LLO with ALLEGRO bar detector
  - » *ALLEGRO was rotated into 3 different positions during E7*



## Preliminary results for E7 test set data (4200 s) Cross-correlation between (LLO 4km -LHO 2km)

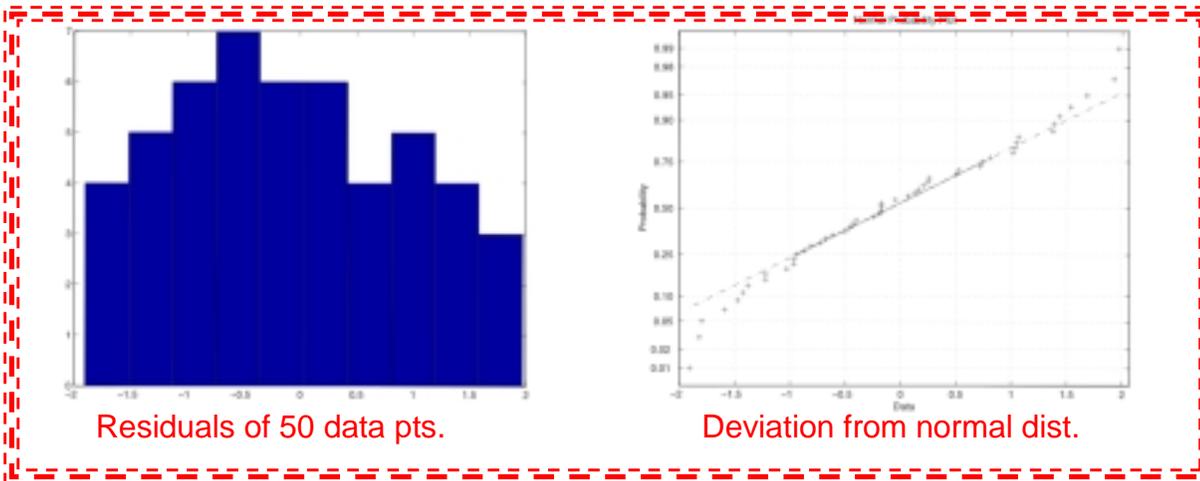
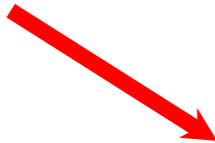


Spectral coherence over ~ 10 min.

Optimal filter kernel theory & data

Spectrum of short-time cross-correlation

**Needs to be Repeated!**



Residuals of 50 data pts.

Deviation from normal dist.





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# Beyond E7: Science runs

## Beyond LIGO I: Advanced R&D



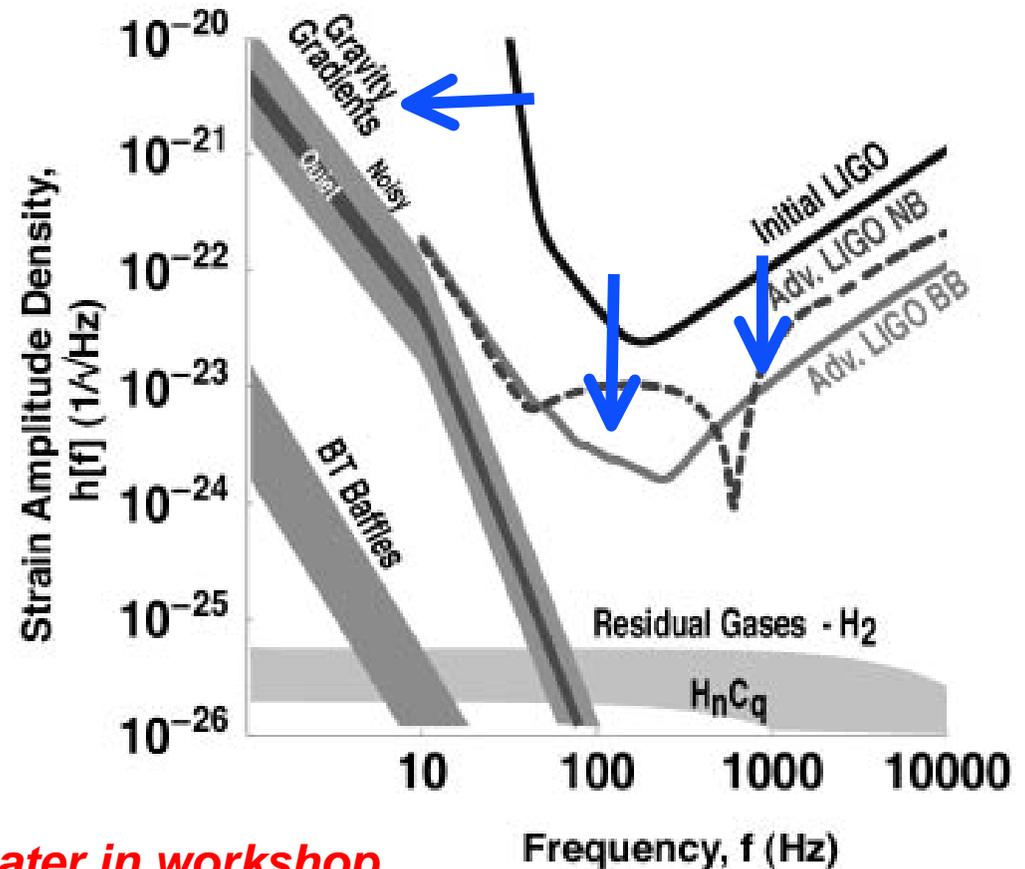
# Plans for CY 2002, 2003

- Science 1 run: 13 TB data
  - » 29 June - 15 July
  - » 2.5 weeks - comparable to E7
  - » Target sensitivity: 200x design
- Science 2 run: 44 TB data
  - » 22 November - 6 January 2003
  - » 8 weeks -- 15% of 1 yr
  - » Target sensitivity: 20x design
- Science 3 run: 142 TB data
  - » 1 July 2003 -- 1 January 2004
  - » 26 weeks -- 50% of 1 yr
  - » Target sensitivity: 5x design



## Focus of R&D: Advanced LIGO

- Improvement in sensitivity
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
  - » Initial → Advanced: factor  $10^3 - 10^4$  in rate
- Key design features:
  - » Signal recycling
  - » 200 W Nd:YAG laser
  - » Sapphire test masses
  - » Fused-silica multiple suspensions
  - » Active isolation system
- Upgrade after Initial LIGO run
  - » Proposal to NSF fall 2002
  - » Fabrication start early 2005
  - » Installation start ~2007



- **Talk by ~~Shoemaker~~ Sanders later in workshop**

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# FINIS

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# Measurements of the Stochastic Background

