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

LIGO-G020231-01-E

Outline for this talk

- 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

E7 Coincidence Run

28 Dec 2001 - 14 January 2002

E7 sensitivities for LIGO Interferometers

28 December 2001 - 14 January 2002

LHO2k: full configuration;

LHO4k & LLO4k : recombined configuration, no power recycling

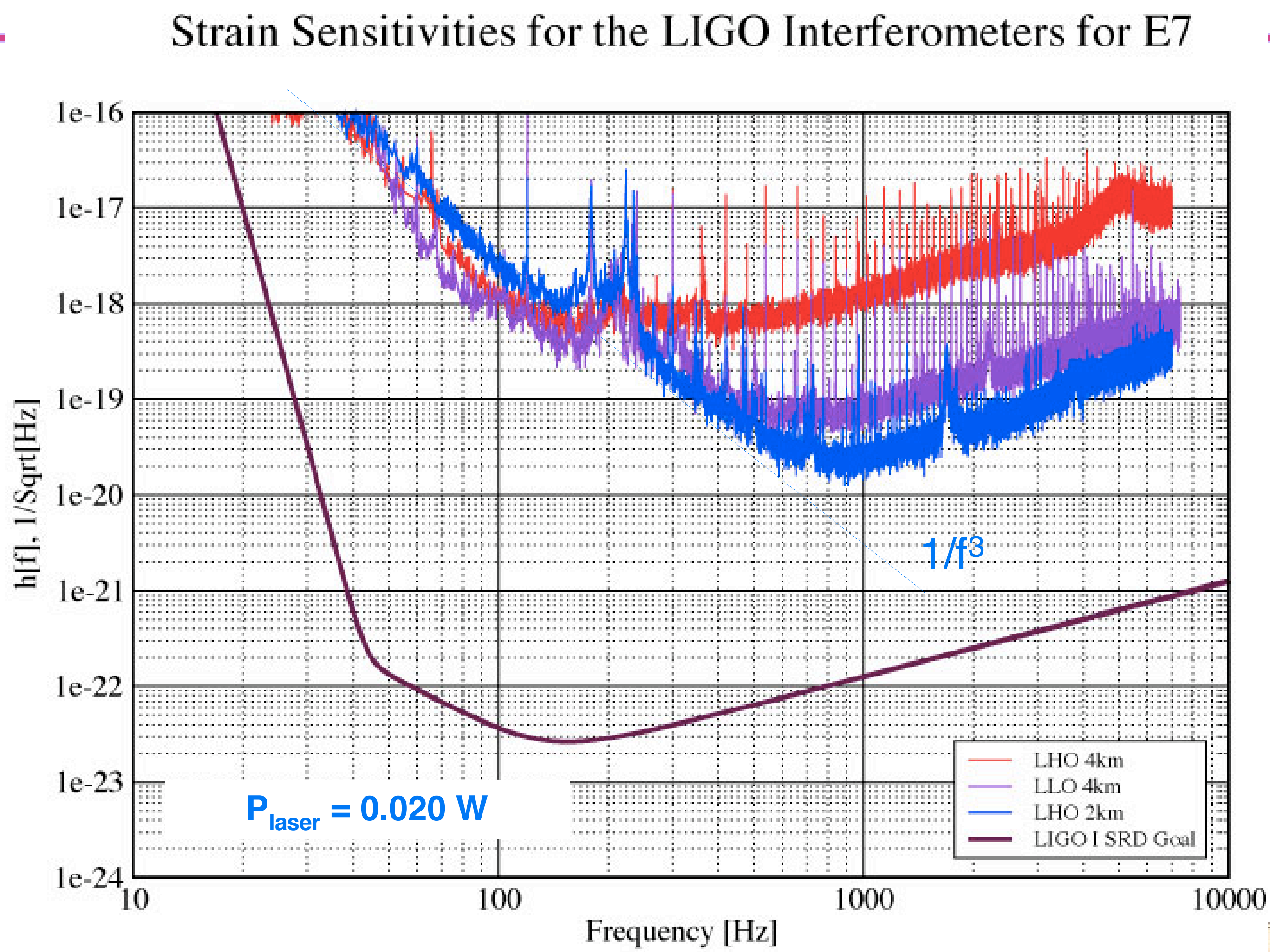
- Used 3 x 10 $^{-3}$ of design laser power

  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



LIGO-G020231-01-E

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

	All segments	Segments >15min
H1 locked	294hrs (72%)	231hrs (57%)
H1 clean	267hrs (62%)	206hrs (48%)

H1 longest clean segment: 4:04

	All segments	Segments >15min
H2 locked	214hrs (53%)	157hrs (39%)
H2 clean	162hrs (38%)	125hrs (28%)

H2 longest clean segment: 7:24

Coincidence Data

2X: H2, L1

	All segments	Segments >15min
locked	160hrs (39%)	99hrs (24%)
clean	113hrs (26%)	70hrs (16%)

H2,L1 longest clean segment: 1:50

3X : L1+H1+ H2

	All segments	Segments >15min
locked	140hrs (35%)	72hrs (18%)
clean	93hrs (21%)	46hrs (11%)

L1+H1+ H2 : longest clean segment: 1:18

4X: L1+H1+ H2 +GEO:

	All segments	Segments >15min
	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
Total Jobs	63600	48775	280	915	113570
Database Rows	4188188	2789132	1062	2096	6980478

- 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!*

Commissioning status

LHO 2 km interferometer
Status

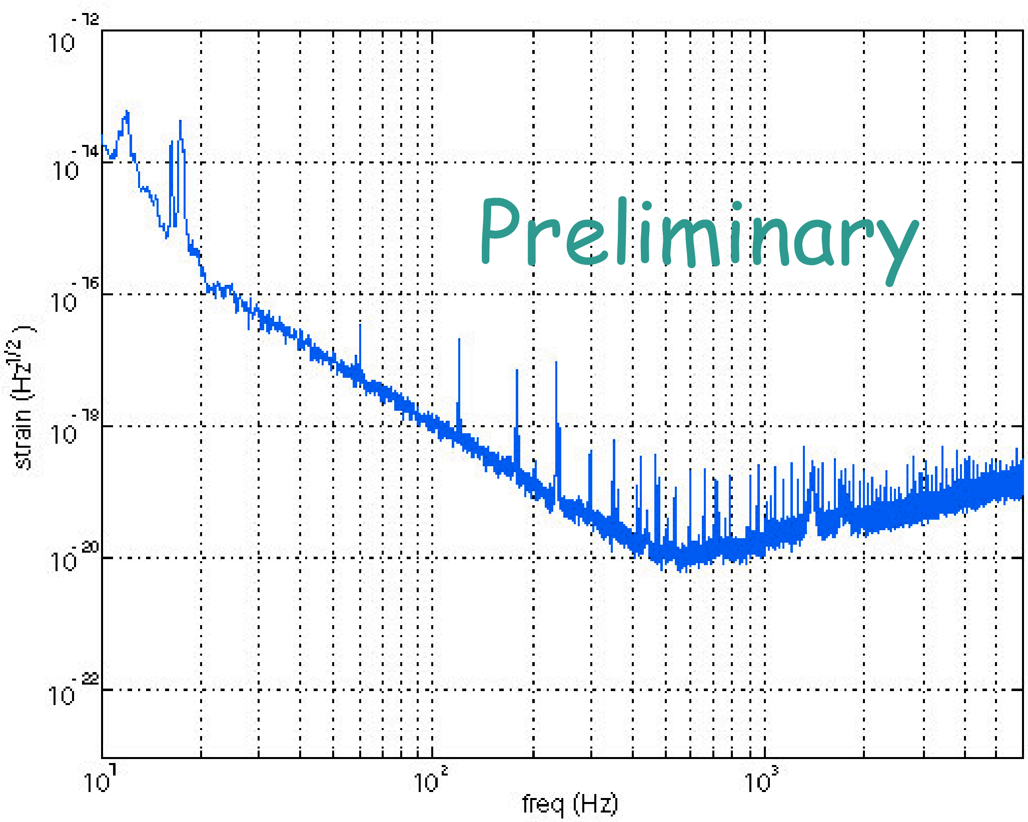
- Locked in full recycled configuration
  - » Operated in full recycled configuration (recycling factor up to 25, but typically ~15)
- Common mode servo implemented
  - » Frequency stabilization from average arm length
  - » Establishes control system "gain hierarchy"
- 5 W power into mode cleaner
 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

Summer 2001	$\sim 3 \times 10^{-16}$ m/Hz$^{1/2}$
December 2001 (E7)	$\sim 5 \times 10^{-17}$ m /Hz$^{1/2}$
Spring 2002	$\sim 2 \times 10^{-17}$ 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 ~2 x 10^{-16} m/$Hz^{1/2}$

LIGO-G020231-01-E

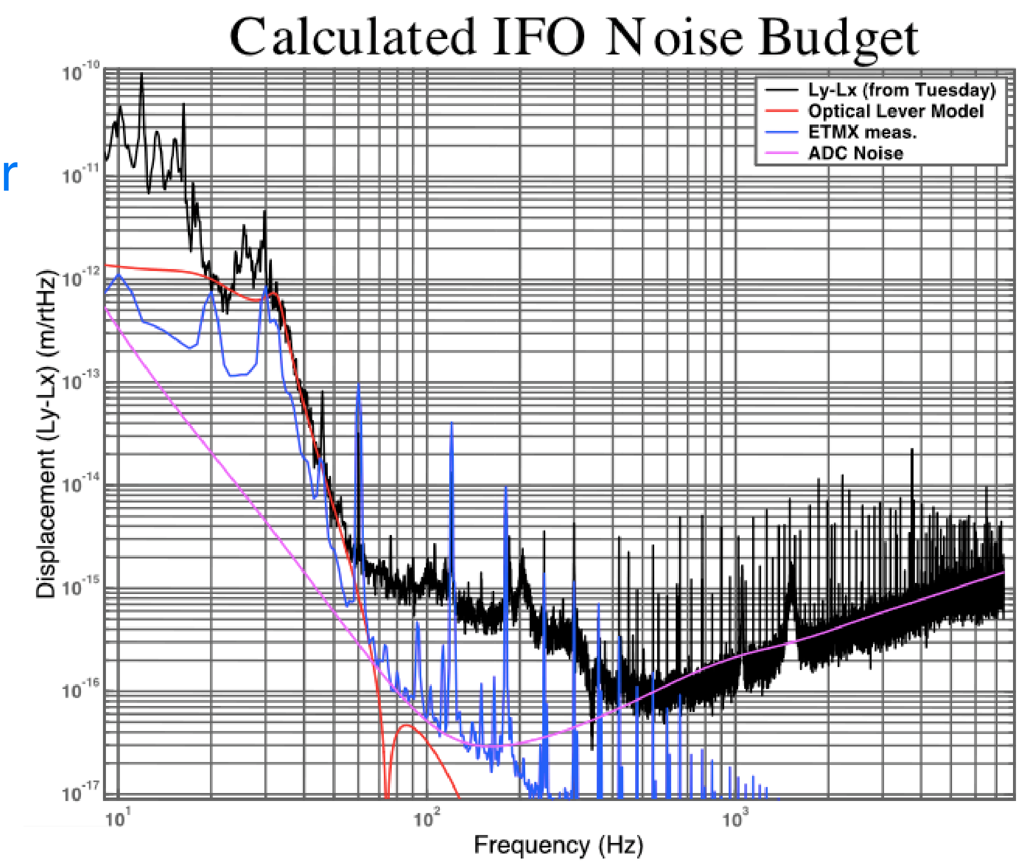
LLO 4 km Interferometer

Status

- Fully recycled configuration
- 1 W power input laser power into mode cleaner
  - » Power buildup of 1400 in each arm corresponds to recycling gain ~ 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 ~7 x 10^{-17} m/$Hz^{1/2}$ @ 500 Hz

Current LLO 4km Displacement Sensitivity

- f < 80 Hz limited by alignment servo noise
- 80 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 Scientific Collaboration

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

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

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

Compact Binary Inspiral 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 Creighten
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://feynman.utb.edu/~joe/research/stochastic/upperlimits/

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

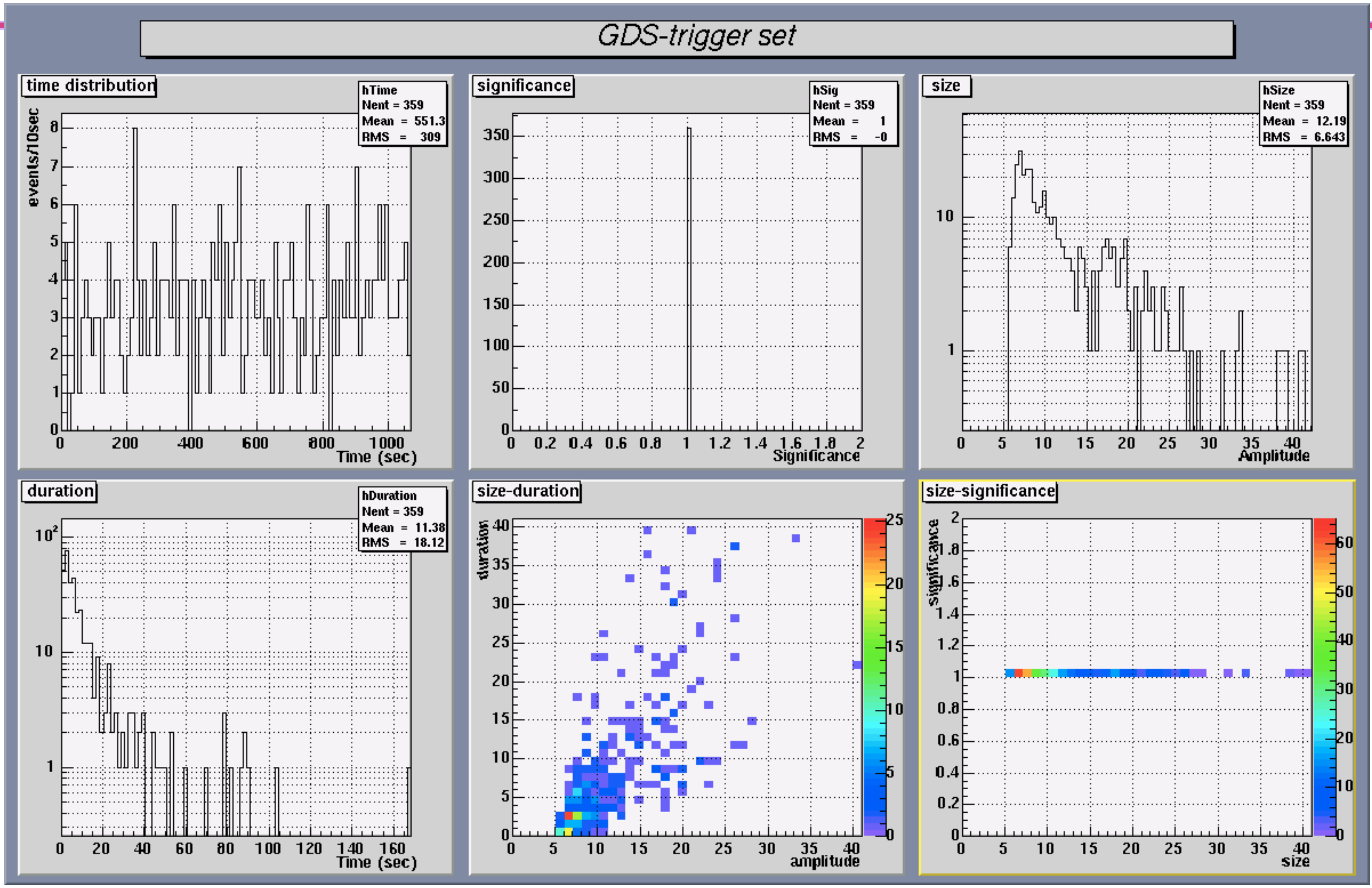
Pipeline analysis is very close to completion

- 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
  - 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



LIGO-G020231-01-E

Status of Analysis

- 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 <u>three</u> styles of interpretation.
  - o ***Search triggered by Gamma Ray Bursts***
    - => Interpretation issues are well understood.
  - o ***Instrumental interpretation***
    - => Description of strain *vs.* time-frequency character
    - => Straightforward in principle, still some open issues.
  - o ***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.

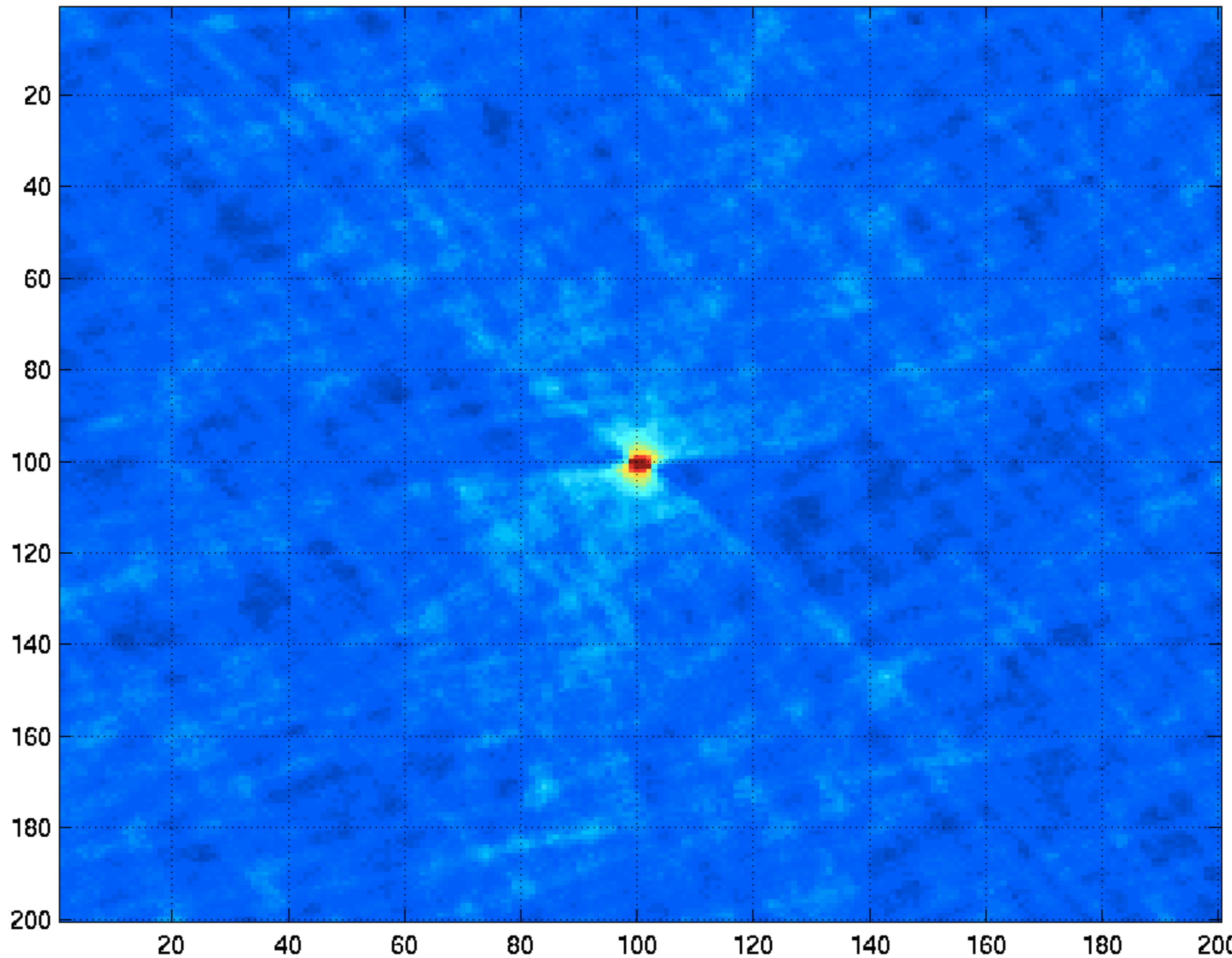
At AEI: ~150 dual AMD processor cluster has been designed (after extensive benchmarking and testing) and is being built. Will be operational in late spring. Name: Merlin.

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.**



LIGO-G020231-01-E

Analysis of the E7 Data: Upper Limit Groups

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

Inspiral search

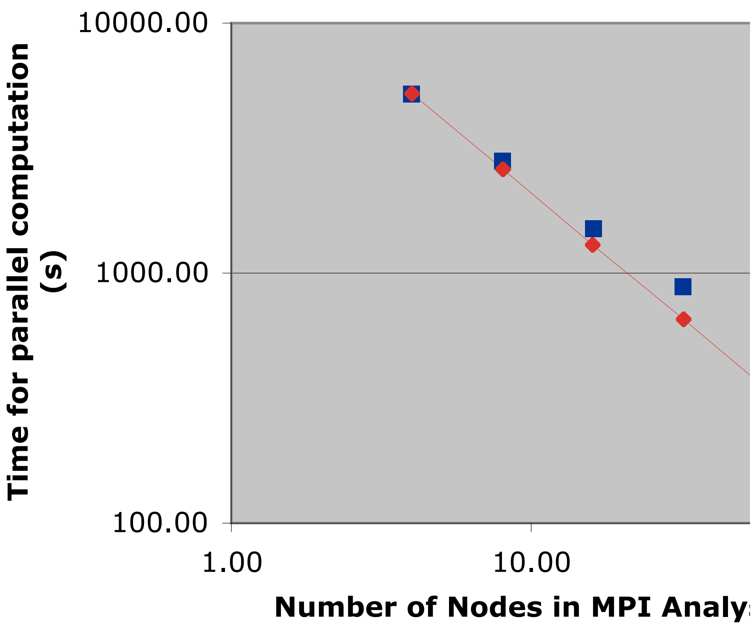
- Two approaches
  - » Conventional optimal Wiener filtering with chirp templates
    - – Flat search (based, e.g., on *Owen, PRD Vol. 53, No. 12 (1996) 6749*
      B.S.. Sathyaprakash, Vol. 50, No. 12 (1994) R7111
      - Implemented for analysis of 1994 40m data, TAMA data
  - » Fast Chirp Transform (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

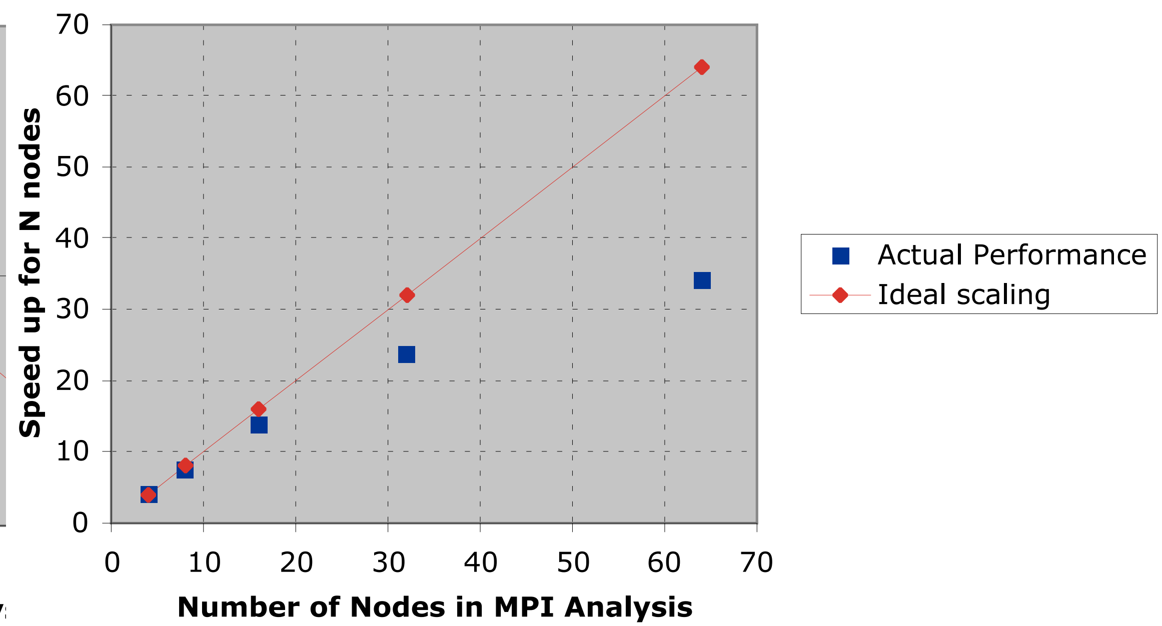
- *Hierarchical search - under development for both approaches*
  - » See, e.g., Class. Quant. Grav., **19**, 1507-1512 (2002)

Inspiral E7 tests - templated search

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

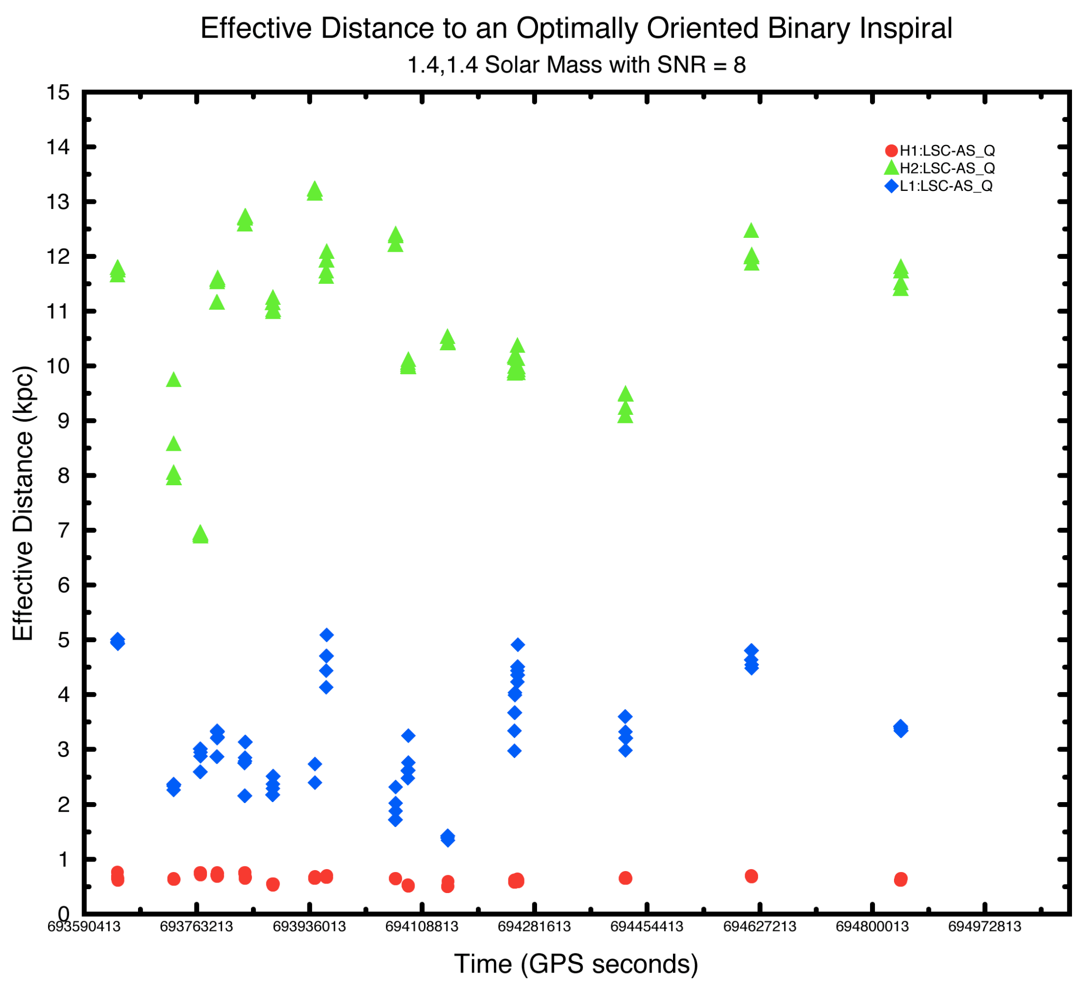
MPI computation performance with increasing number of nodes





Inspiral search with E7

Preliminary results with test set data

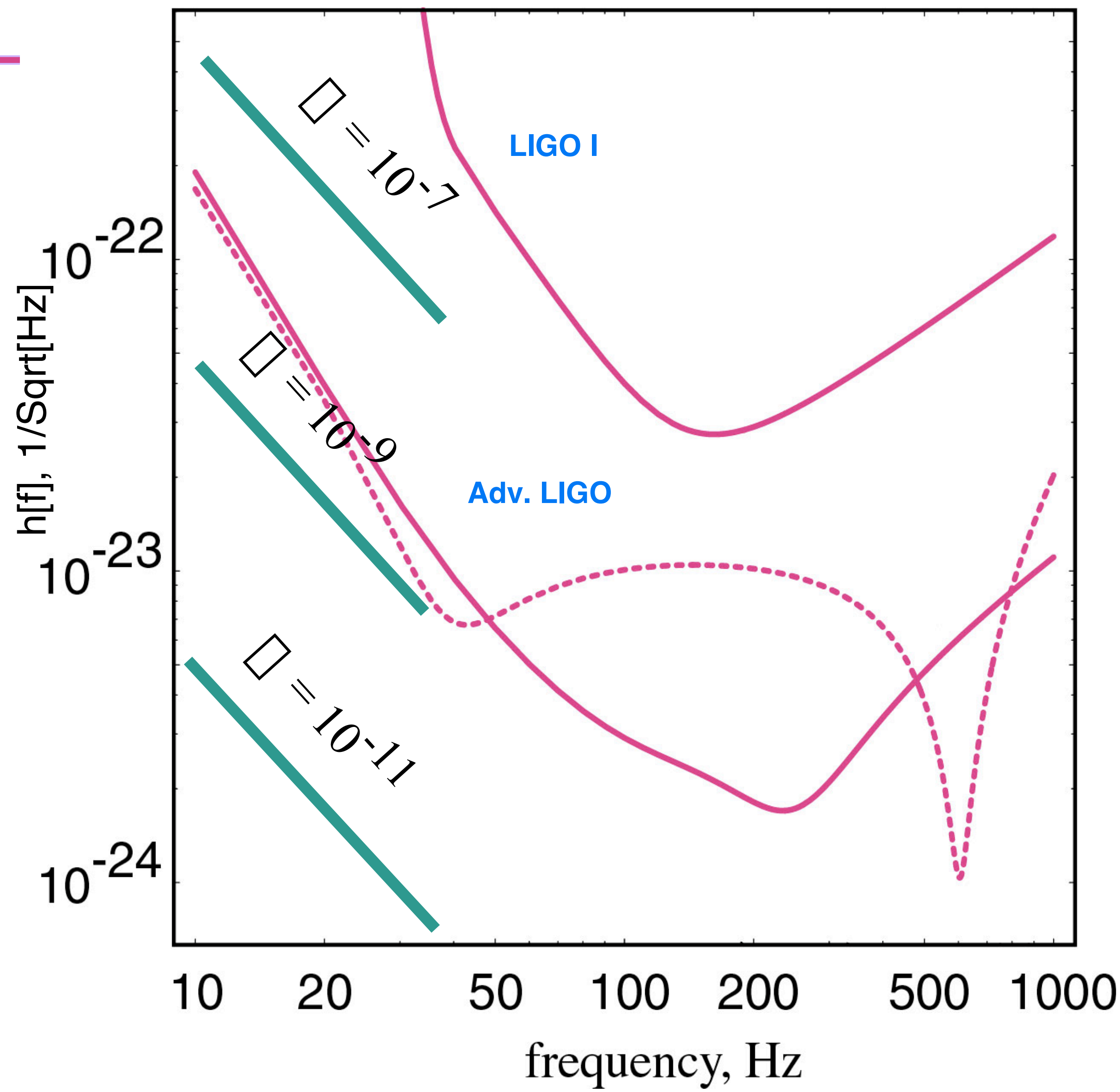


Analysis of the E7 Data: Upper Limit Groups

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

Stochastic Gravitational Wave Background

- Detect by cross correlating output of Hanford + Livingston 4km IFOs
- Peak of sensitivity:
  - $\square_{GW} \geq$ **2D** (D = 3000 km)
  - **f ≤ 40 Hz**
- Initial LIGO sensitivity:
  - $\square_{GW} \geq 10^{-5}$
  - Limited by h[f] seismic wall **f ≥ 50Hz**
- Advanced LIGO sensitivity:
  - $\square_{GW} \geq 5\times10^{-9}$



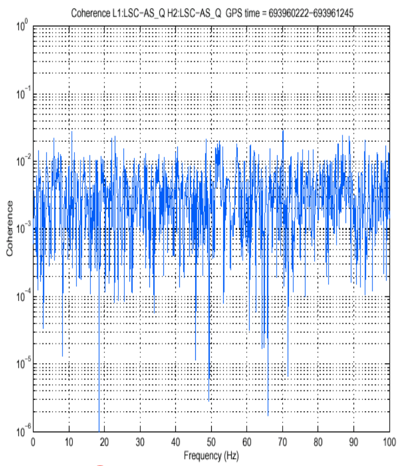
Stochastic Upper Limit Group Activities (E7 investigations – current/planned)

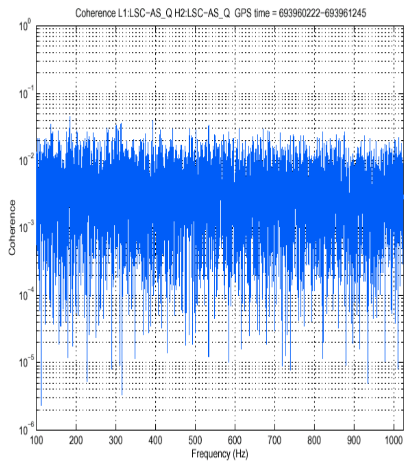
- ***Analytic calculation*** of expected upper limits (~50 hrs):

  □ $\sim 2 \times 10^{5}$ for LLO-LHO 2k, □ $\sim 6 \times 10^{4}$ 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*

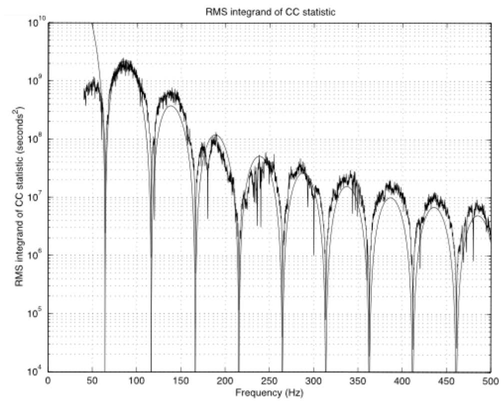
Preliminary results for E7 test set data (4200 s)

Cross-correlation between (LLO 4km -LHO 2km)

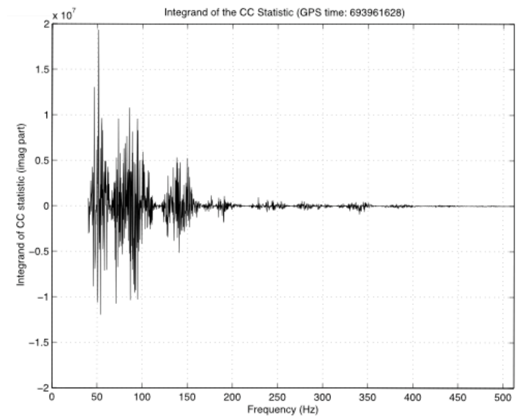




Spectral coherence over ~ 10 min.

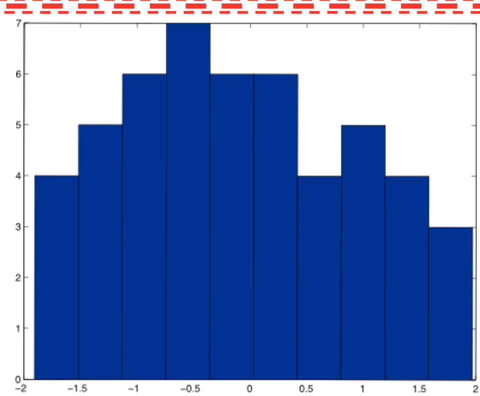


Optimal filter kernal theory & data

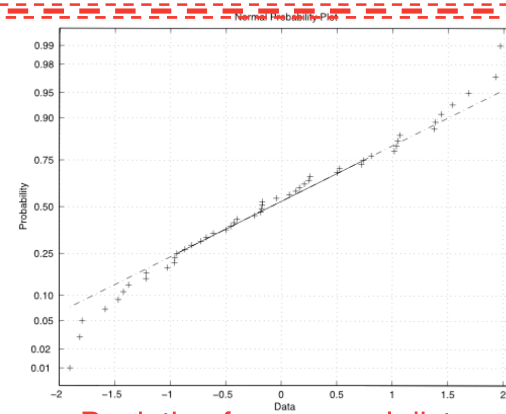


Spectrum of short-time cross-corelation

Needs to be Repeated!



Residuals of 50 data pts.



Deviation from normal dist.

LIGO-G020231-01-E

Beyond E7: Science runs

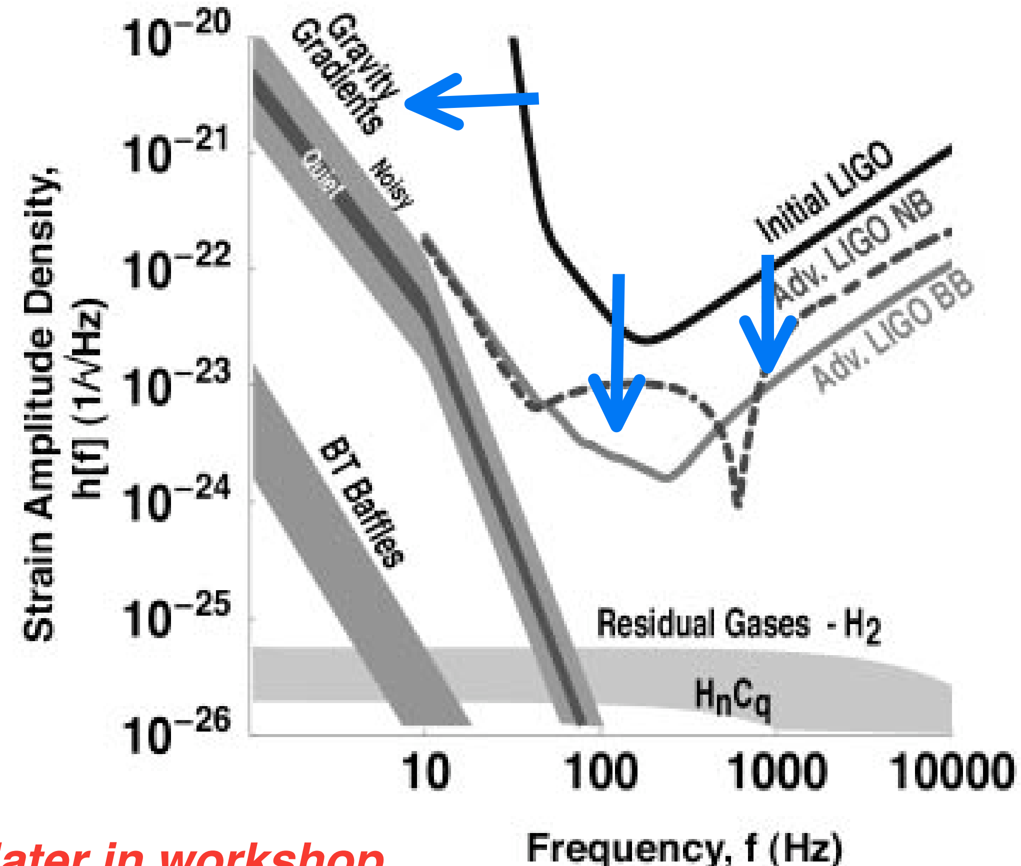
Beyond LIGO I: Advanced R&D

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 -- 1January 2004
  - 26 weeks -- 50% of 1 yr
  - Target sensitivity: 5x design

Focus of R&D: Advanced LIGO

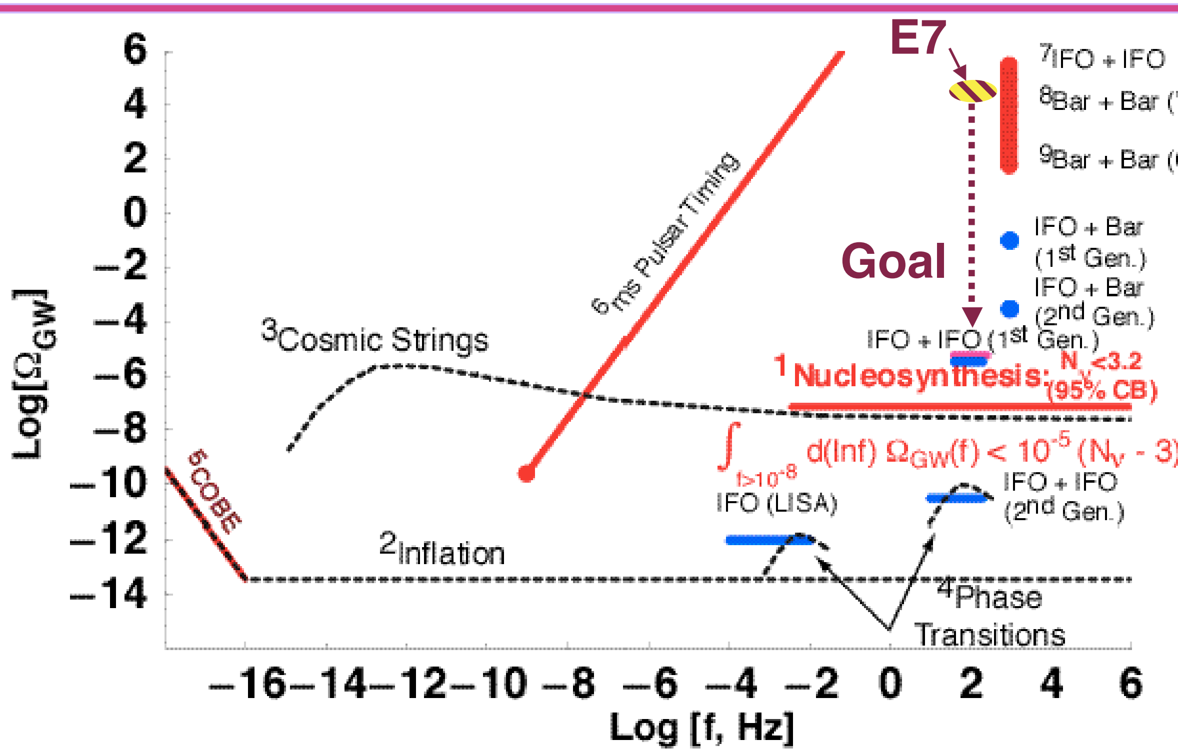
- Improvement in sensitivity
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
  - » Initial → Advanced: factor 10^3 - 10^4 in rate
- Key design features:
  - » Signal recycling
  - » 200 W Nd:YAG laser
  - » Sapphire test masses
  - » Fused-silica multiple suspensions
  - » 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***



LIGO-G020231-01-E

FINIS

Measurements of the Stochastic Background



[1] Kolb & Turner (The Early Universe, 1990)
Burles, Nollet, Trunan, Turner (PRL 82, 1999)
[2] Grishchuk (SPJETP 40, 1975)
[3] Allen & Brustein (gr-qc9609013)
Allen (gr-qc9604033)
[4] Kamionkowski, Kosowoski & Turner (PRD 49, 1994)
[5] Allen & Koranda (PRD 50, 1994)

[6] Thorsett & Dewey (PRD 53, 1996)
Kaspi, Taylor, Ryba (ApJ 428, 1994)
[7] Compton, Nicholson, Schutz, Proc. MG7 (1994)
[8] Hough, Pugh, Bland, Drever, Nature 254 (1975)
[9] Astone, et. al., Astr. Astroph. 351 (1999)