Data analysis with the E7 run data and plan for LIGO I Science Run(s)

Albert Lazzarini

15 March 2002

CaJAGWR Seminar at Caltech

LIGO-G020025-00-E

Outline of Talk

- Organization of the LIGO I Collaboration
- Data Access, Use Models
- Data Analysis Model
- E7 Run Summary
- Upper Limit Groups
  - » Burst search
  - » Continuous wave search
  - » Compact binary inspiral search
  - » Stochastic background search
- Science run schedule (tentative plans)

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):

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

The LIGO I Scientific Collaboration

281 Individuals

Abbott, Benjamin
Abbott, Rich
Adhikari, Rana
Ageev, Alexander
Allen, Bruce
Amin, Rupal S.
Anderson, Stuart
Anderson, Warren
Armandula, Helena
Aufmuth, Peter
Augst, Steven
Baker, John
Balasubramanian, R.
Barish, Barry
Barker, David
Barnes, Maria
Barr, Bryan
Barton, Mark
Belczynski, Kryzytstof
Berukoff, Steven
Bhawal, Biplab
Billingsley, GariLynn
Black, Eric
Blackburn, Kent
Bland (Weaver), Betsy
Borger, Simon
Bork, Rolf
Bose, Sukanta
Brady, Patrick
Brau, Jim
Brown, Duncan
Brulois, Frederick
Buonanno, Alessandra
Burgess, Ralph
Cagnoli, Geppo
Camp, Jordan
Capanelli, Manuela
Cardenas, Lee
Carsten, Aulbert
Casey, Morag
Centrella, Joan
Chacon, Manfredo
Chandler, Adam
Charlton, Philip
Chassande-Mottin, Eric
Chatterji, Shourov
Chen, Yanbei
Chin, David
Christensen, Nelson
Churches, David
Clay, Westbrook
Coldwell, Robert
Coles, Mark
Cook, Douglas
Coyne, Dennis
Craig, Stephen
Creighton, Jolien
Creighton, Teviet
Crooks, David
Cusac, Benedict
Cutler, Curt
D'Ambrosio, Erika
Danzmann, Karsten
Das, Tapas
Davies, Bob
Daw, Edward
Delker, Thomas
Dhurandar, Sanjeev
Diaz, Mario
Ding, Hongyu
Drasco, Steven
Drever, Ronald
Dupuis, Rejean
Ehrens, Phil
Elliffe, Eoin
Evans, Matthew
Evans, Tom
Finn, Lee Samuel
Flanagan, Eanna
Freise, Andreas
Frey, Ray
Fritschel, Peter
Fyffe, Michael
Ganezer, Kenneth
Garrison, David
Giaime, Joseph
Gonzalez, Gabriela
Gossler, Stefen
Graff, Richard
Grass, Walter
Gray, Corey
Greenwood, Zeno
Grote, Hartmut
Guagliardo, Dave
Guenther, Mark
Gustafson, Richard
Hamilton, William
Haupt, Klaus
Hawkins, Chris
Heefner, Jay
Helper, Natalie
Heng, Ik Siong
Hewitson, Martin
Hoang, Phuong (Phoenix)
Hough, James
Hsu, Mike
Ito, Masahiro
Ivanov, Alexander
Jennrich, Oliver
Johnson, Warren
Johnston, Kathleen
Jones, Larry
Kalogera, Vassiliki
Katsavounidis, Erik
Keig, William
Kells, Bill
Kern, Jonathan
King, Peter
Klimenko, Sergei
Kloevekorn, Patrick
Koranda, Scott
Kötter, Karsten
Kovalik, Joe
Kozak, Dan
Landry, Michael
Latta, Allan
Lazzarini, Albert
Lei, Mary
Leonor, Isabel
Libbrecht, Ken
Lindblom, Lee
Lindquist, Phil
Liu, Sander
Lousto, Carlos
Lubinski, Mark
Lueck, Harold
MacInnis, Myron
Mageswaran, Mohana
Mahood, Thomas
Mailand, Ken
Malec, Michaela
Marka, Szabolcs
Maros, Ed
Marsano, Joseph
Mason, Ken
Matherny, Otto
Matone, Luca
Mauceli, Evan
Mavalvala, Nergis
McCarthy, Richard
McClelland, David
McGuire, Stephen
McNamara, Paul
McNeil, Roger
Mendell, Gregory
Meshkov, Syd
Mitselmakher, Guenakh
Mohanty, Soumya
Mossavi, Kasem
Mueller, Guido
Mukherjee, Soma
Myers, Joshua
Nagana, Shigeo
Nash, Thomas
Nayak, Rajesh
Neilson, Chris
Newton, Gavin
Nocera, Flavio
O'Shaughnessy, Richard
Ottaway, David
Ottewill, Adrian
Overmier, Harry
Owen, Ben
Pai, Archana
Papa, Marialessandra
Patton, Christine
Patton, James
Penn, Steven
Petrac, Irena
Phelps, Larry
Plissi, Michael
Prince, Thomas
Purdue, Patricia
Raab, Frederick
Radkins, Hugh
Rahkola, Rauha J.
Rakhmanov, Malik
Rashad, Omar
Reitze, David
Ribichini, Luciano
Riesen, Rich
Riles, Keith
Rizzi, Anthony
Robertson, David
Robertson, Neil
Robertson, Norna
Roddy, Shannon
Romano, Joseph
Romie, Janeen
Rotthoff, Eric
Rowan, Sheila
Rupal, Amin
Russell, Paul
Ryan, Kyle
Ryder, Exyie
Salzman, Isaac
Sanders, Gary
Santostasi, Giovanni
Sathyaprakash, B.S.
Saulson, Peter
Savage, Richard
Sazanov, Andrei
Sazonov, Andrei
Schlaufman, Kevin
Schofield, Robert
Schutz, Bernard
Scott, Nathan
Scott, Susan
Searle, Antony
Sengupta, Anand
Shapiro, Charles
Shawhan, Peter
Shoemaker, David
Sibley, Allan
Sigg, Daniel
Simicevic, Neven
Sinev, Nikolai
Sintes-Olives, Alicia
Smith, Michael
Sneddon, Peter
Stacy, Gregory
Stapfer, Gerry
Stiff, Kerry
Strain, Kenneth
Strohmayer, Tod
Strom, David
Studnik, Alexei
Sukanta, Bose
Summerscales, Tiffany
Sumner, Matthew
Sutton, Patrick
Sylvestre, Julien
Tanner, David
Taylor, Ian
Thorne, Kip
Tibbits, Matthew
Tichy, Wolfgang
Tohline, Joel
Torrie, Calum
Traylor, Gary
Ugolini, Dennis
Vallisneri, Michele
Vecchio, Alberto
Vorvick, Cheryl
Wallace, Larry
Wang, Jin-Tong
Ward, Harry
Wehrens, Oliver
Weidner, Andreas
Weiland, Uta
Weiss, Rainer
Whelan, John
Whitcomb, Stan
Whiting, Bernard
Wiley, Sam
Willems, Phil
William, Keig
Williams, Roy
Willke, Benno
Winjum, Benjamin
Winkler, Walter
Wiseman, Alan
Woan, Graham
Wooley, Rusyl
Worden, John
Yakushin, Igor
Yamamoto, Hiro
Zhang, Cheng
Zucker, Michael
zur Mühlen, Heiko
Zweizig, John

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 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

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)

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

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Data Access, Use Models

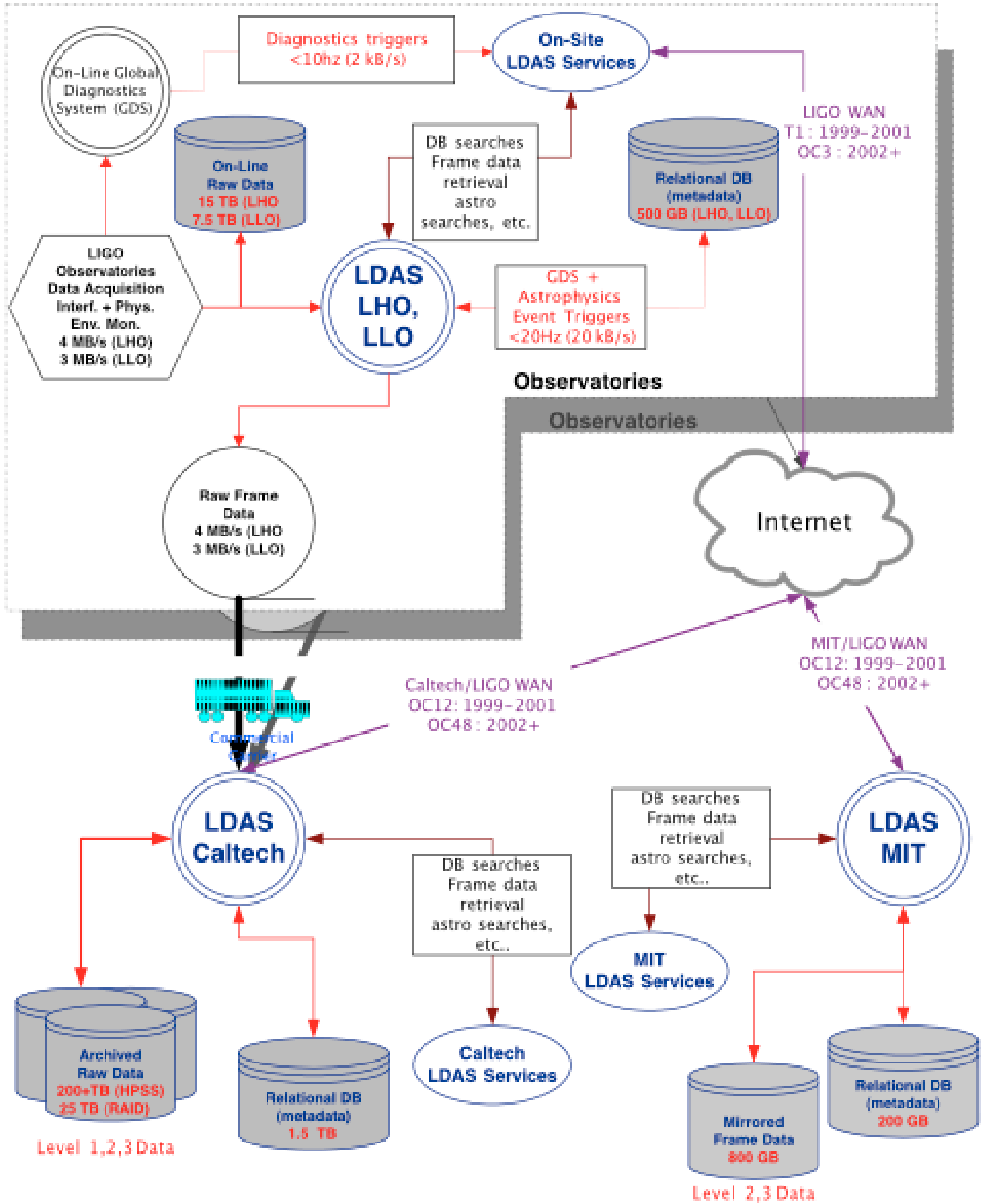
Data Analysis Model

- On-site operations
  - » LIGO observatories
  - » Keep up with the data rate, robust operation
    - – Principal driver for LDAS design, concept
    - – Pipeline process running 7x24 to provide near real time quick look at astrophysics searches
  - » Compare/exchange triggers for events that may be observed in coincidence with other detectors
    - – Inspirals -- other GW detectors, GRBs(?)
    - – Bursts --other GW detectors, SNe, ν detectors (SNEWS), GRBs(?)
  - » Feedback to interferometer operations
    - – *TAMA experience: Kanda's seminar 2002.03.01*
  - » Data reduction for local data caches

Data Analysis Model

- Off-site operations
  - » Caltech, MIT, LSC institutions (Tier 2 Centers)
  - » Pipeline processes running for deeper look at astrophysics searches
    - – Computationally intense searches
    - – Use on-site triggers to identify interesting stretches of data for network analysis, multi-detector analyses
    - – CW searches
    - – Stochastic background search
    - – Inspiral to lighter masses
  - » Data mining of events from relational databases
  - » Monte carlo, simulations
  - » Data distribution
    - – Reduced data set creation
    - – User access to deep data archive

LIGO Data Flow Model



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CaJAGWR Seminar

LIGO Data Products

Time series data

Mode	**Level 0** Raw and Derived Data for On-line Diagnostics	**Level 1** Full (100%) frame data for archiving	**Level 2** Strain and data summary, QA channels	**Level 3** Strain best estimate
Uncompressed Rate (MB/s)	LHO: 9.5 LLO: 4.7 Total: 14.2	LHO: 6 LLO: 3 Total: 9	Total: 0.300	Total: 0.006
w / 2x Hardware Compression MB/s onto tape media	-	LHO: 3 LLO: 1.5 Total:4.5	Total: 0.150	-
Data growth rate, per year of integrated running, ***TB/yr***.	-	LHO: 95 LLO: 47.5 Total:142	Total:9.5	***Total: 0.200***
Total including redundant 100% backup, ***TB/yr***.	-	LHO: 190 LLO: 95 ***Total:284***	***Total:19***	-
Purpose	For on-line monitoring of interferometers	Deep permanent archive	Science analysis, data exchange	Science analysis, data exchange
On-site look-back time	Must use real-time control and monitoring system (CDS) disk caches	LHO Disk cache: 3 wk LHO Tape robot: 49 d LLO Disk cache: 3wk LLO Tape robot: 100 d	-	In perpetuity
Off-site look-back time	-	In perpetuity	In perpetuity	In perpetuity

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Data Analysis Model

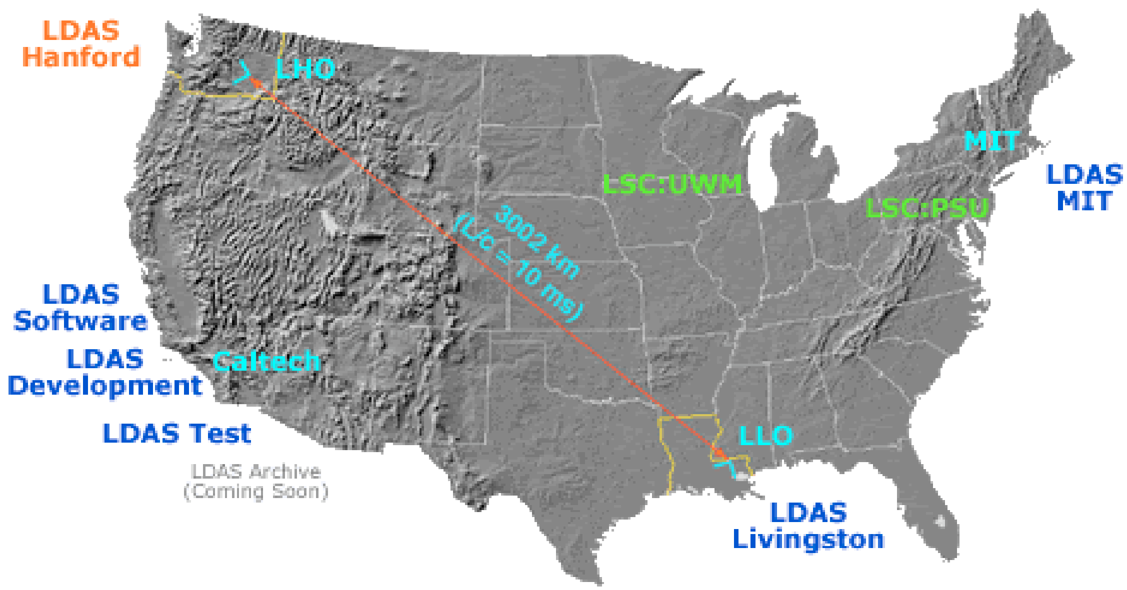
Credits

- The LIGO Laboratory Data and Computing Group at Caltech developed LDAS
  - » Assistance provided by a number of LSC groups
- Software development of LDAS:
  - » ***J. Kent Blackburn (Lead)***
  - » Scientists:
    - – P. Charlton, T. Creighton, *W. Majid* , P. Shawhan, *A. Vicere'* , L. Wen
  - » Programming team:
    - – M. Barnes, P. Ehrens, *A. Ivanov*, M. Lei, E. Maros, I. Salzman
  - » LSC support: *CACR*, PSU, ANU, UTB
- Hardware development of LDAS:
  - » ***Stuart Anderson (Lead)***
  - » Scientists:
    - – E. Katsavounidis (MIT) , G. Mendell (Hanford), I. Yakushin (Livingston)
  - » Network and systems administration;
    - – K. Bayer (MIT) D. Kozak, S. Roddy (Livingston), L. Wallace, A. Wilson
  - » LSC support: *CACR*

The LIGO Data Analysis System (LDAS)

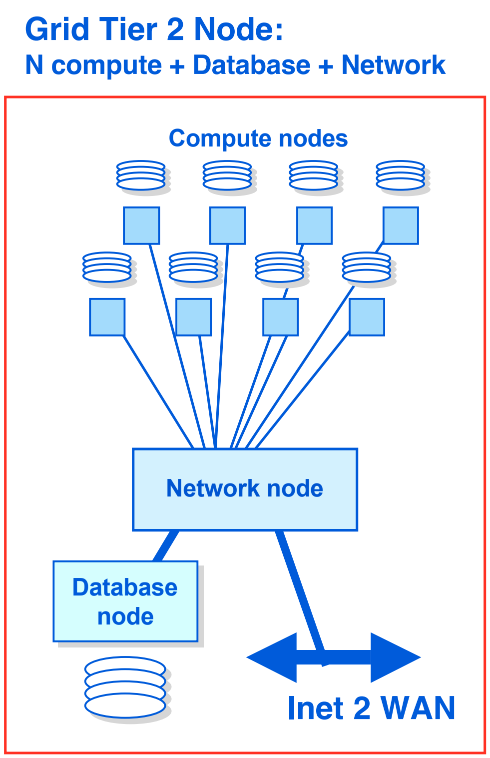
(http://www.ldas-sw.ligo.caltech.edu)

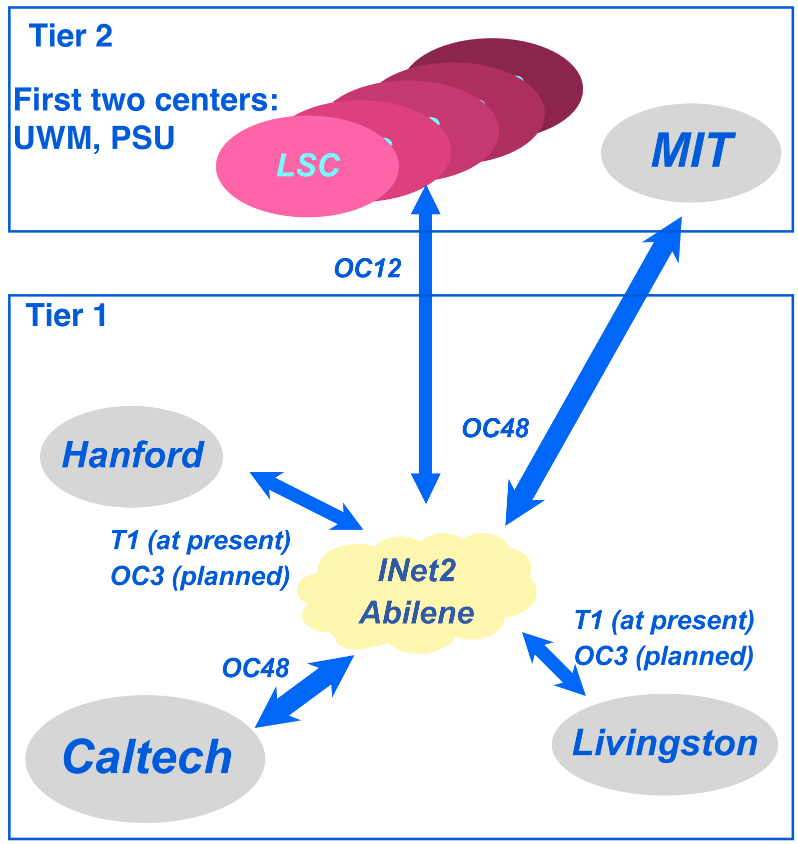
Geographically Dispersed Laboratory plus
LSC Institutional Facilities



Tiered Grid Hierachical Model for LIGO

(Grid Physics Network Project - http://www.griphyn.org)





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LDAS Hardware
(Hanford for E7 Run)

14.5 TB Disk Cache

Beowulf Cluster

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LIGO and LSC Computing Resources Serve Multiple Uses

Updated 2002.03.01

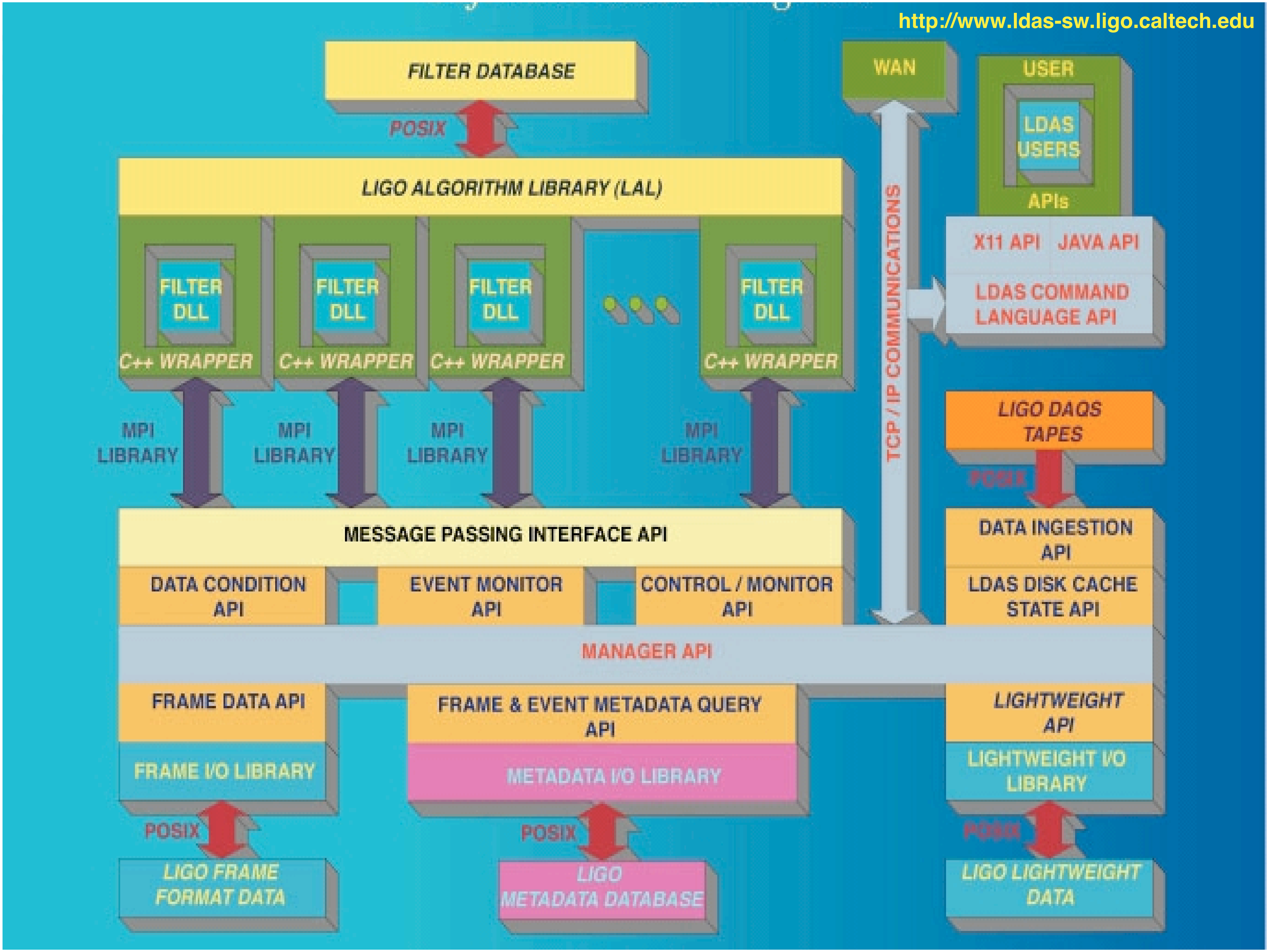
Resource Usage Model for LSC Computing

#	Function	LIGO Laboratory: DMT	LIGO Laboratory: CIT-Dev (LDAS)	LIGO Laboratory: CIT-Test (LDAS)	LIGO Laboratory: CIT-Production (LDAS)	LIGO Laboratory: LHO (LDAS)	LIGO Laboratory: LLO (LDAS)	LIGO Laboratory: MIT (LDAS)	LSC Institutions: PSU Tier II, iVDGL	LSC Institutions: UWM Tier II, iVDGL	LSC Institutions: UTB Tier III	Other Grid Collaborators: USC/ISI
1	***LDAS Software Development***		Priority 1 Color	Priority 2 Color				Priority 3 Color				
2	***LDAS Integration & Tests***											
3	LDAS CVS Software Distribution		Primary Site	Available Mirror Site	Available Mirror Site	Available Mirror Site	Available Mirror Site	Available Mirror Site				
4	***LAL Software Development***											
5	***LAL Scientific Validation***											
6	***LAL integration & Test Validation***											
7	LAL CVS Software Distribution		Sencondary Mirror Site						Sencondary Mirror Site	Primary Site	Available Mirror Site	
8	Production: Level 1 Data											
9	Archive/Distribute Level 1 Data											
10	Production: Level 2 Data											
11	Archive/Distribute Level 2 Data							Subset of Level 2	Subset of Level 2	Subset of Level 2		
12	***Production: Level 3 Data***											
13	***Archive/Distribute Level 3 Data***											
14	***On-site Searches***											
15	***Off-site Searches***											
16	***Multiple Detector Analysis***											
17	Monte Carlo Runs											
18	***Detector Characterization***											
19	***Grid SW Development***											
20	***Grid SW Integration & Testing***											
21	Numerical GR & Source Simulations											
22	Hardware Simulations	General Computing Resources within LIGO										

Row groups: Scientific & infrastructure Software Development (rows 1–7); Data Archival & Reduction (rows 8–13); Data Analysis (rows 14–17); Grid R&D (rows 18–20)

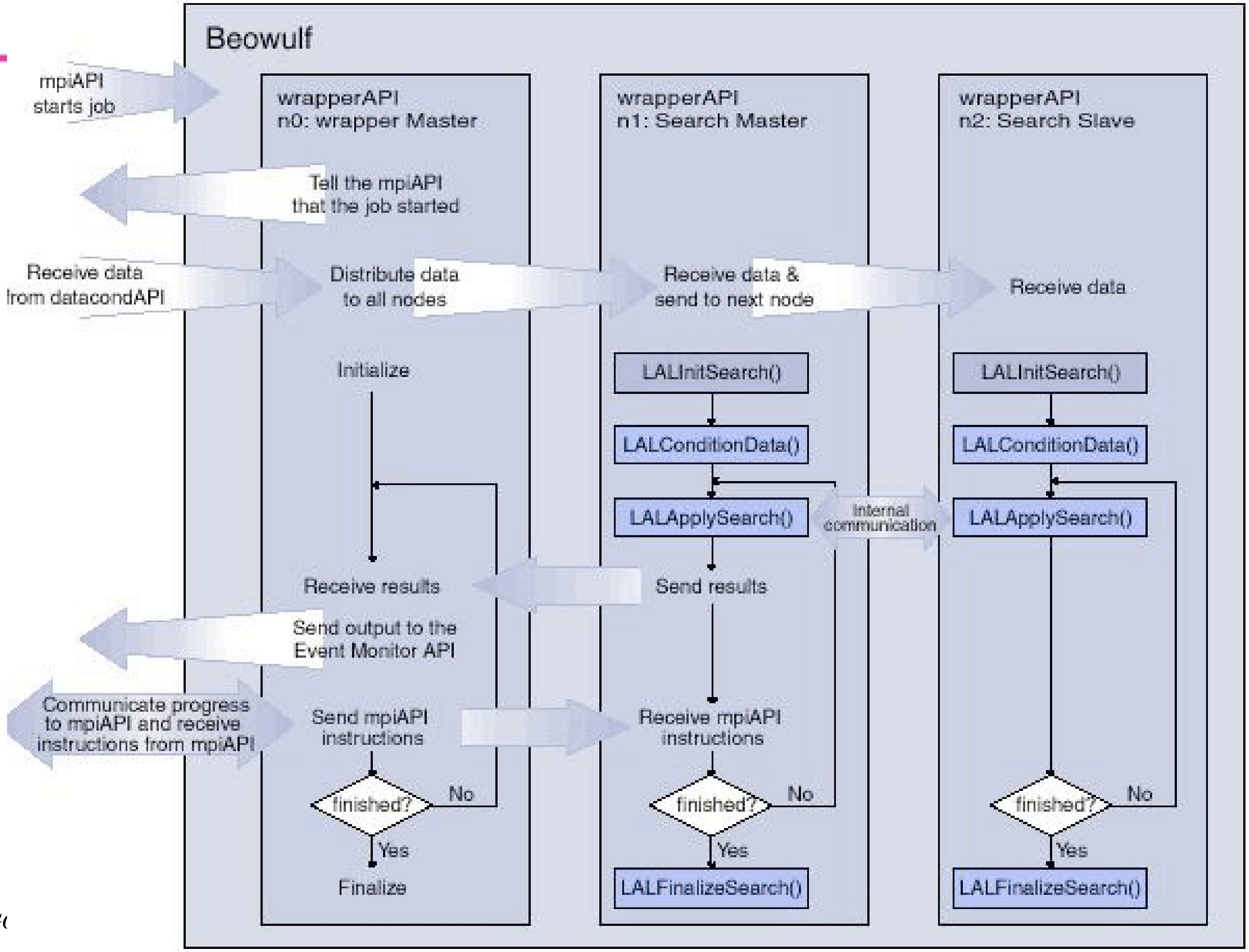
Priority Legend

- Priority 1
- Priority 2
- Priority 3



http://www.ldas-sw.ligo.caltech.edu
FILTER DATABASE
POSIX
LIGO ALGORITHM LIBRARY (LAL)
FILTER DLL
C++ WRAPPER
FILTER DLL
C++ WRAPPER
FILTER DLL
C++ WRAPPER
FILTER DLL
C++ WRAPPER
MPI LIBRARY
MPI LIBRARY
MPI LIBRARY
MPI LIBRARY
WAN
TCP / IP COMMUNICATIONS
USER
LDAS USERS
APIs
X11 API
JAVA API
LDAS COMMAND LANGUAGE API
LIGO DAQS TAPES
POSIX
DATA INGESTION API
LDAS DISK CACHE STATE API
MESSAGE PASSING INTERFACE API
DATA CONDITION API
EVENT MONITOR API
CONTROL / MONITOR API
MANAGER API
FRAME DATA API
FRAME & EVENT METADATA QUERY API
LIGHTWEIGHT API
FRAME I/O LIBRARY
METADATA I/O LIBRARY
LIGHTWEIGHT I/O LIBRARY
POSIX
POSIX
POSIX
LIGO FRAME FORMAT DATA
LIGO METADATA DATABASE
LIGO LIGHTWEIGHT DATA

Interface to the Scientist



E7 Run Summary

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 %)

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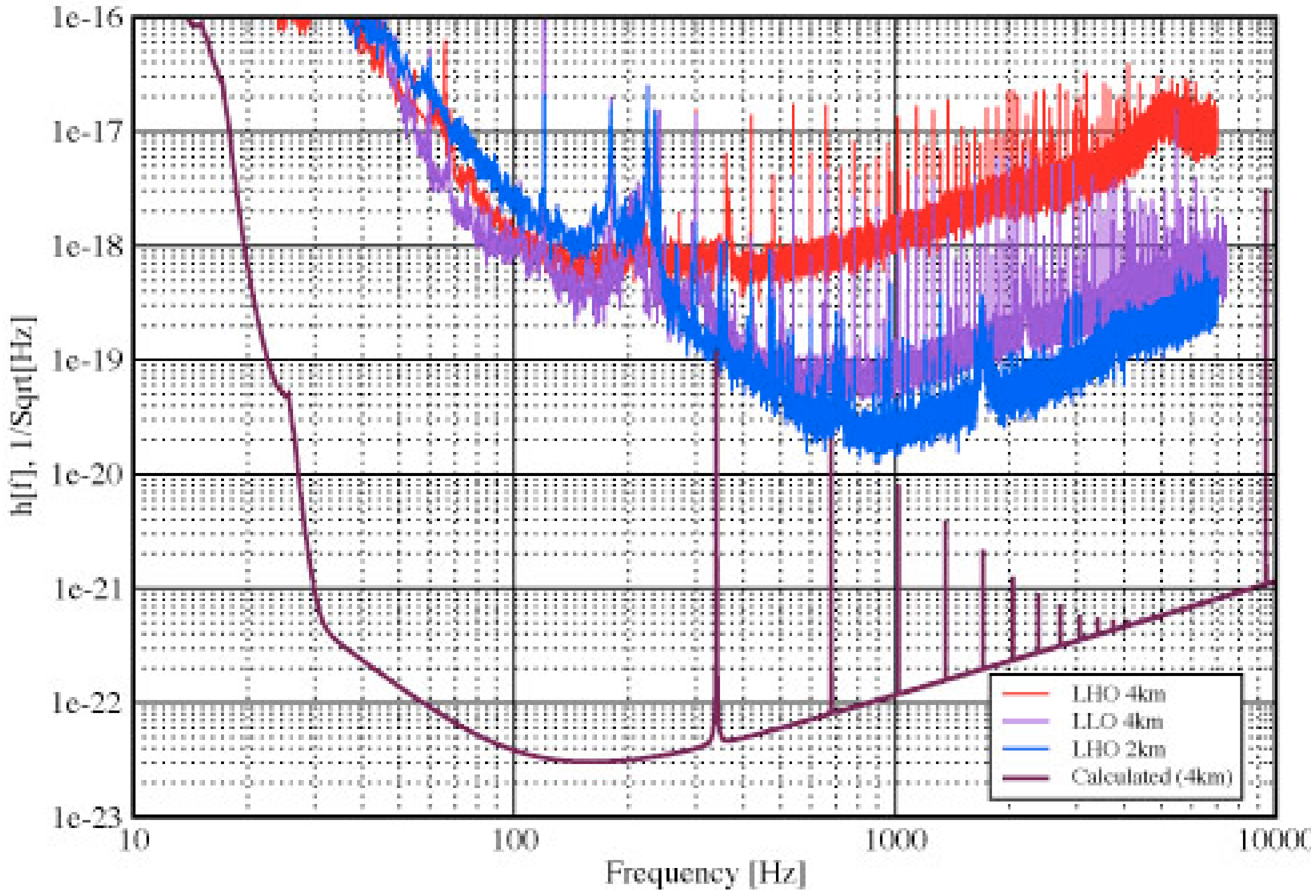
E7 sensitivities for LIGO Interferometers



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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.
- Pre-Release testing revealed 0.3% failure rate!
  - » Pre-release dominated by thread problems in pre-processing module (dataConditionAPI)
  - » Fraction due to MPI module communications issues (mpiAPI/wrapperAPI)

Database Insertion Statistics
During the E7 Run

		LHO	LLO	
Segments:	*IFOLocked*	*17919*	*5899*	
GDS triggers:	*BitTest*	*34640*	*17761*	
	ChannelReadOutError	*26*	–	
	eqMon	*28*	–	
	glitchMon	*1790683*	*1056375*	
	Glitch	*271430*	*201113*	*Instrumental Vetoes*
	Lock transition	*140468*	*11328*	
	MC_F violin mode	*11016*	*7156*	
	Rho2 [from CorrMon]	*511*	*195*	
	TFCLUSTERS	*290295*	*68551*	
	TimeSliceError	*1755*	*23762*	
	TID	*1663*	–	
LDAS inspiral:	template	428970	176655	
	FCT	2970	24295	
LDAS burst:	power	1082676	411127	*“Events”*
	slope	17561	58044	
	TFCLUSTERS	1700621	2519617	

E7 Data Volume Summary

» HPSS tape archive (pre-E1 through E7):

– 35 TB and growing

– 575,000 files

– 10% of 1 year 7x24 science run
  - One more order of magnitude to go

Upper Limit Groups

Burst search

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

Burst searches

- Three techniques are being explored to detect transients:
  - » Excess power detector (W. Anderson , P. Brady, E. Flanagan)
  - » Slope detector (E. Daw)
  - » Time-Frequency cluster analysis - "TFCLUSTERS" (J. Sylvestre)

Signal detection

- Choose between two hypotheses:

  H0: y = n vs. H1: y = s + n

- Two types of error:
  - False alarm:

    α = P(H1 | H0)

  - False dismissal:

    β(s) = P(H0 | H1)

LIGO

Signal Detection: optimization

- When ***s*** is a single, known waveform:
  - » Neyman-Pearson lemma:threshold on likelihood ratio minimizes □ for any constraint on □.
- Optimality not well defined when ***s*** can take values in a subspace W (i.e. when H1 is a composite hypothesis):
  - » Bayesian: assume prior p(s), integrate likelihood over W, obtain Neyman-Pearson:
    - – *Excess power (Anderson et al.)*
    - – Excess power for arbitrarily colored noise-- (Vicere)
  - » Average: minimize mean of □(s) over W, for a constraint on □
    - – *Time domain filters -- slope detection (Orsay group)*
  - » Minimax: minimize maximum of □(s) over W, for a constraint on □
    - – *TFCLUSTERS*

Burst Searches

Excess Power Statistic (W. Anderson et al.)

- The algorithm [1]:
  - » Pick a start time t_s, a time duration dt (containing N data samples), and a frequency band $[f_s; f_s + \Delta f]$.
  - » Fast Fourier transform (FFT) the block of (time domain) detector data for the chosen duration and start time.
  - » Sum the power in the frequency band $[f_s; f_s + \Delta f]$.
  - » Calculate the probability of having obtained the summed power from Gaussian noise alone using a χ^2 distribution with $2 \times \Delta t \times \Delta f$ degrees of freedom.
  - » If the probability is significantly small for noise alone, record a detection.
  - » Repeat the process for all desired choices of start times t_s, durations Δt, starting frequencies f_s and bandwidths Δf.

[1] A power filter for the detection of burst sources of gravitational radiation in interferometric detectors. Authors: Warren G. Anderson, Patrick R. Brady, Jolien D. E. Creighton, Eanna E. Flanagan. gr-qc/0001044

Burst Searches

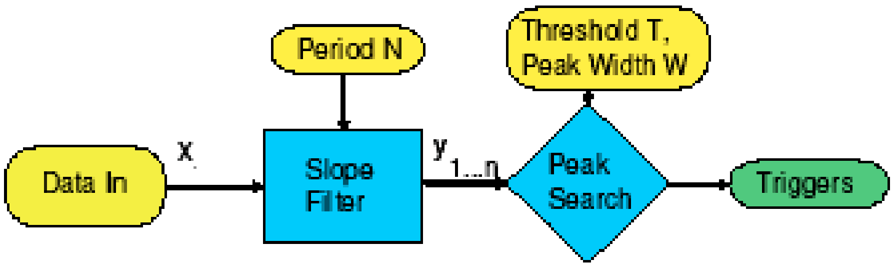
Excess Power Statistic (W. Anderson et al.)

- Search strategy is useful for signals where only general characteristics are known -- e.g. □t □ □f (bandwidth-time product)
  - » If one knows more, probably better to use some other method
- Search assumes that all signals (of same □t □ □f volume) are equally likely
  - » Not true, since psd in signal space is not white
  - » Need generalization to over-whitened data
    - – Divide by psd

Burst Searches

Slope Detector (E. Daw)

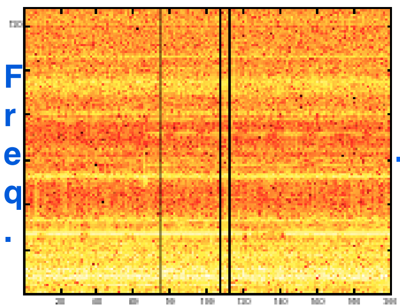
- Linear Fit Filters
  - For each input data segment x_{i+j}, $j = 1,\ldots,N$,
  - Fit a straight line $b_i + ja_i$.
    Related filter types are [1, 2]:
  - 'OD' (offset detector) filter.
    Filter output is b_i.
    - If the offset is significantly greater than for noise alone, record a detection
  - 'SD' (slope detector) filter. Filter output is a_i.
    - If the slope is significantly greater than for noise alone, record a detection
  - 'ALF'. Output is a quadratic function of a_i and b_i that depends on N.



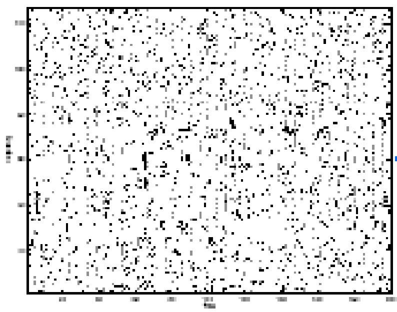
[1] Pradier et. al., An efficient filter for detecting gravitational wave bursts in interferometric detectors, gr/qc-0010037.
[2] Arnaud et. al., Detection of gravitational wave bursts in interferometric detectors, gr/qc-9812015.

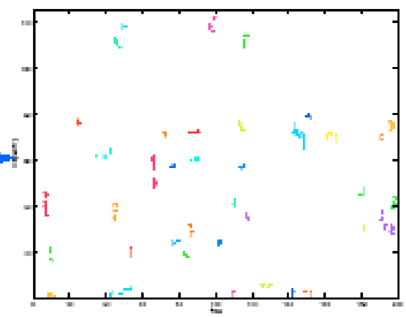
t-f clusters algorithm

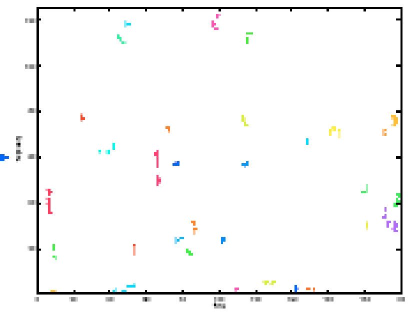
Freq.



time







construct spectrogram → first power threshold → clustering analysis → threshold on integrated power

time domain whitening filter

black pixel probability noise model

minimum cluster size distance thresholds

threshold type

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t-f clusters analysis

- Runs at 250-500x real-time
  - most expensive task is cluster identification
  - 1 CPU can handle hundreds of channels
- Approximate whitening important, especially at low frequencies
- Actual implementation models background power distribution with a Rice distribution

Upper Limit Groups

Continuous wave source search

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

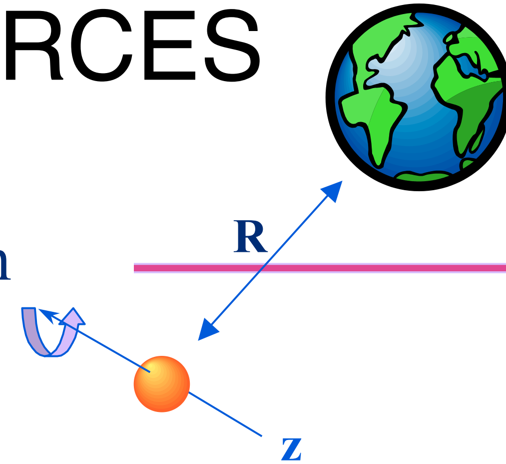
Periodic source searches
Upper Limit Group

3 source categories and 4 algorithms

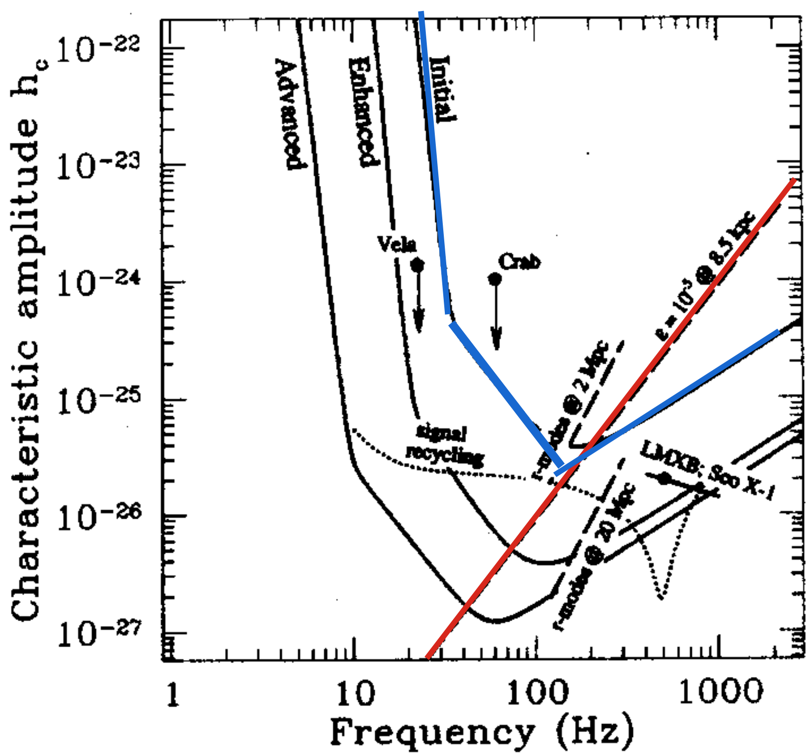
- All sky unbiased
  - Sum short power spectra (no doppler correction)
- Known pulsar
  - Heterodyne narrow BW
  - Coherent frequency domain
- Wide area search
  - Hierarchical Hough transform

INTERESTING SOURCES

- Target signals: slowly varying instantaneous frequency, e.g. rapidly rotating neutron stars in different moments of their evolution.



SENSITIVITY:



$$h_c = 2.3 \times 10^{-25} \frac{\varepsilon}{10^{-5}} \frac{I_{zz}}{10^{45}\, g\, cm^2} \frac{8.5\, kpc}{R} \left(\frac{f_0}{500\, Hz} \right)^2$$

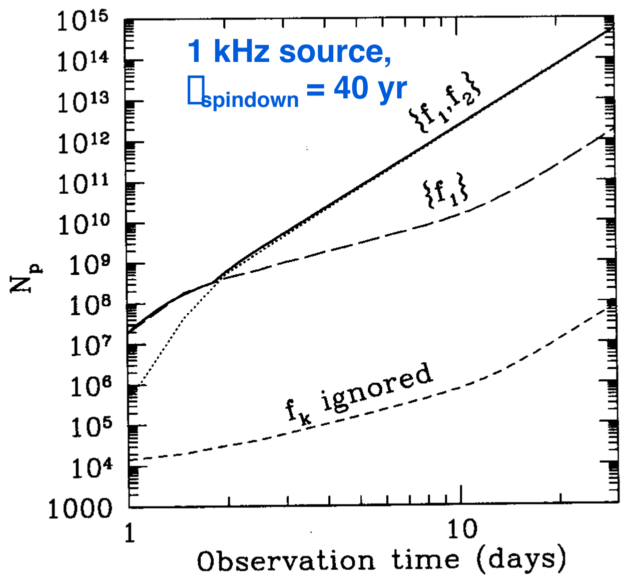
h_c: the amplitude of the weakest signal detectable with 99% confidence with 4 months of integration, ***if the phase evolution were known***.

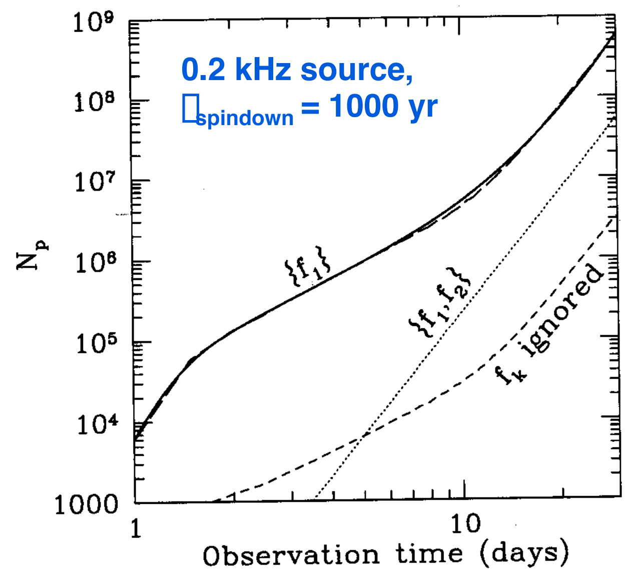
Brady&Creighton, Phys.Rev D, 61,2000,082001

THE PROBLEM

Generally the phase evolution of the source is not known and one must perform searches over some parameter space volume

- the number of templates grows dramatically with the coherent integration time baseline and the computational requirements become prohibitive:





On a 1TFLOPS computer it would take more than 10000 yr to perform an all-sky search over 1000 Hz for an observation time of 4 months.

** Graphs from Brady, Creighton, Cutler, and Schutz, gr-qc/9702050*

Basic features of the algorithm 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.

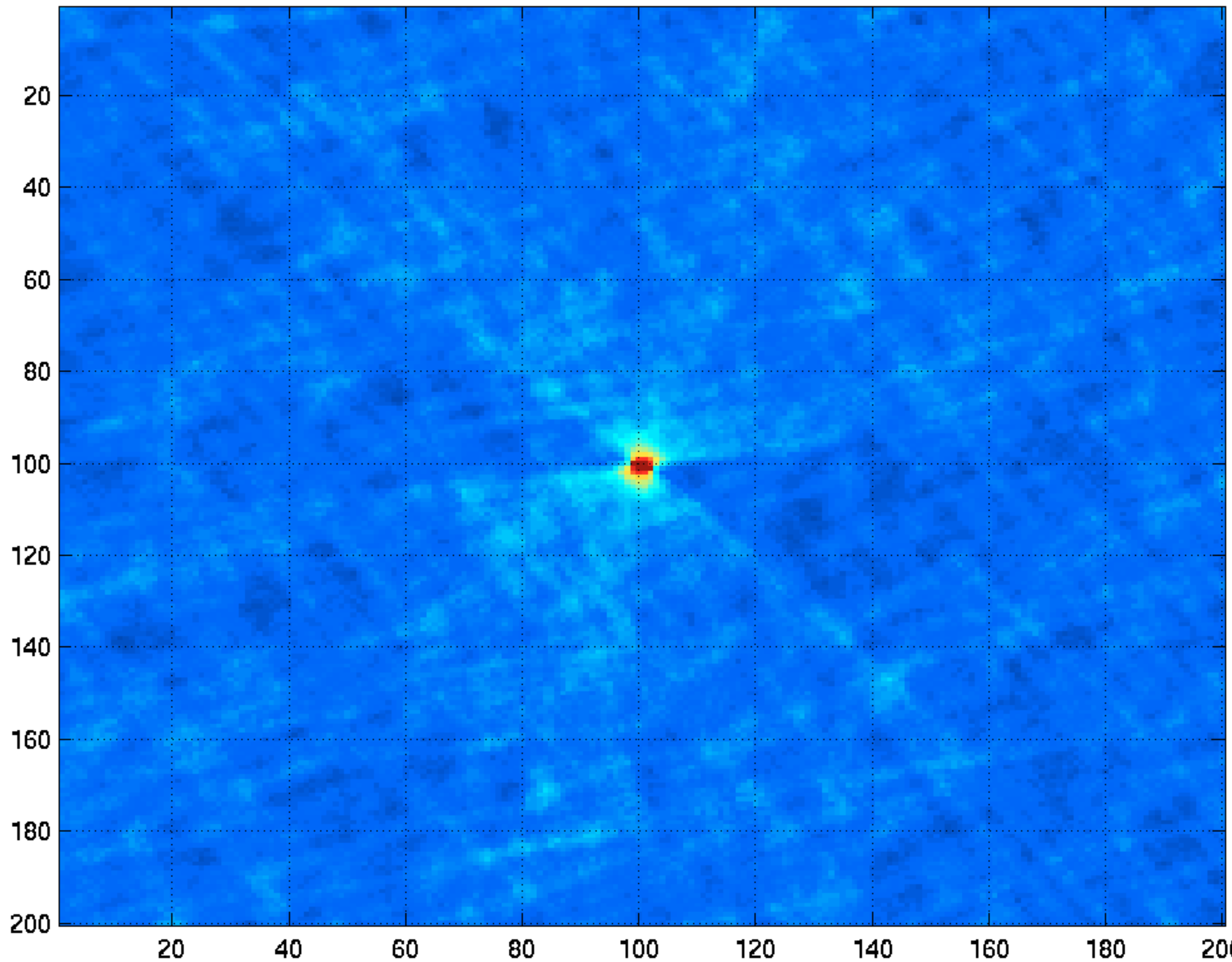
At AEI: ~150 dual AMD processor cluster has been designed (after extensive benchmarking and testing) and is being built. Will be operational in late spring. Name: Merlin.

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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Upper Limit Groups

Compact binary inspiral search

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

Inspiral search

- Dual approach
  - » Conventional optimal Wiener filtering with chirp templates
    - – Flat search
      - Implemented for analysis of 1994 40m data, TAMA data
  - » Fast Chirp Transform (FCT)
    - – Starting with stationary phase approximation to phase evolution, linearize phase behavior locally to recast filter as multi-dimentsional FFT
    - – Generalize FT: $\Phi_{FT}(t) = \int df \; h[f] \; e^{2\pi i f t} \Rightarrow \Phi_{CT}(t) = \int df \; h[f] \; e^{i\phi(f)}$
    - – Express phase as series in *f:* $\phi(f) = 2\pi f t + \Delta\phi(f); \Delta\phi(f) = \sum_{m>1} k_m [f\lambda_m]^m$
    - – Discretize to FFT, FCT:

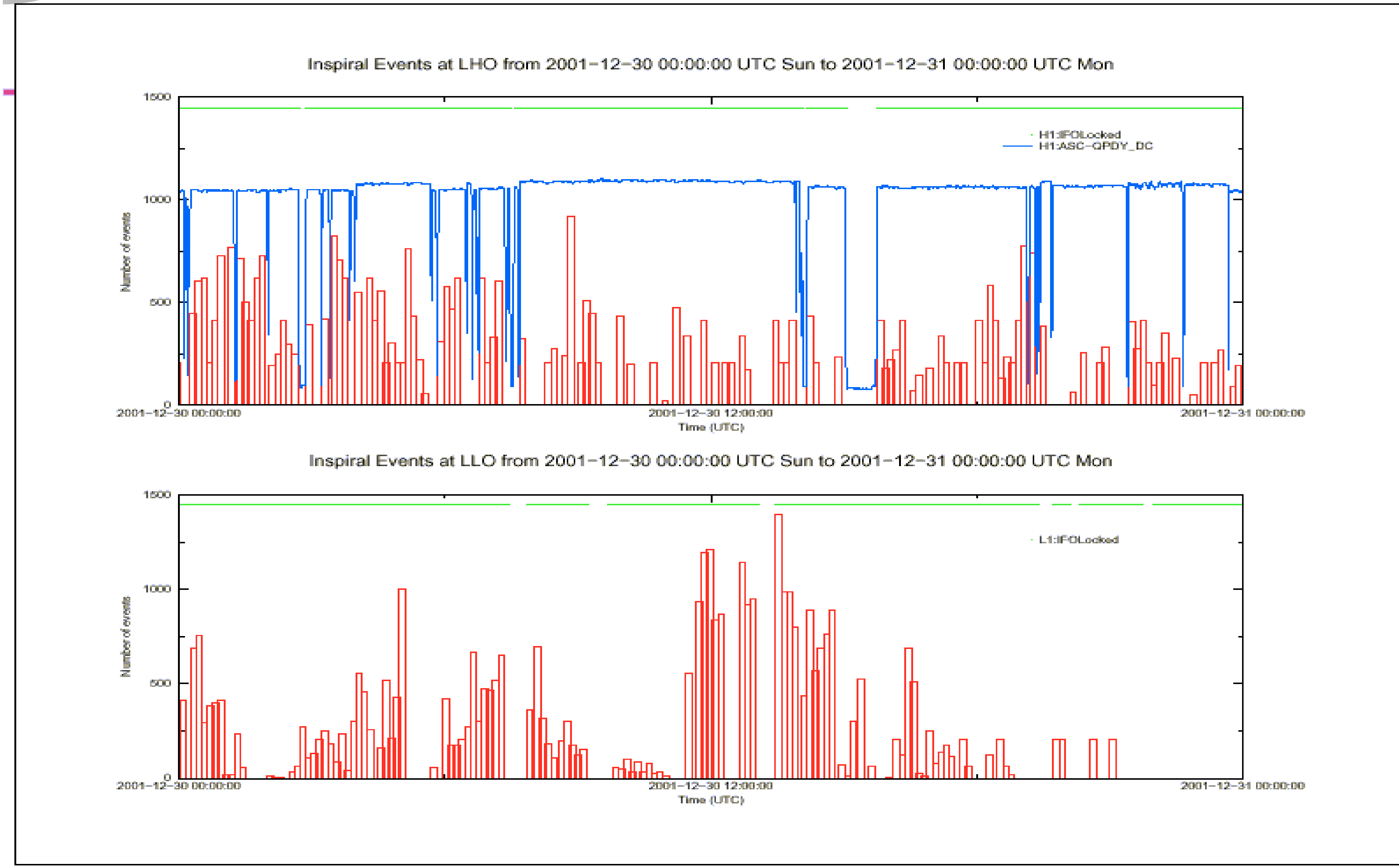
$$\Phi_{FFT}(k) = \sum_{j=0}^{N_0-1} h[j] \; e^{2\pi i\left(\frac{jk}{N_0}\right)} \Rightarrow \Phi_{FCT}(k,\{l_p\}) = \sum_{j=0}^{N_0-1} h[j] \; e^{2\pi i\left[\frac{jk}{N_0} + \sum_{p>1} l_p \left(\frac{j}{N_0}\right)^p\right]}$$

  - » *Hierarchical search - under development for both approaches*

Inspiral search on-site during E7

- Templated search
  - Used E6 calibrations (since E7 not yet available)
  - More details can be found on the web at:
    http://www.lsc-group.phys.uwm.edu/iulgroup/investigations/e7/inspiral/H1/summary
    http://www.lsc-group.phys.uwm.edu/iulgroup/investigations/e7/inspiral/L1/summary
  - Mass range: $5\ M_{sun} < m_1, m_2 < 10\ M_{sun}$
  - No. of templates: 207

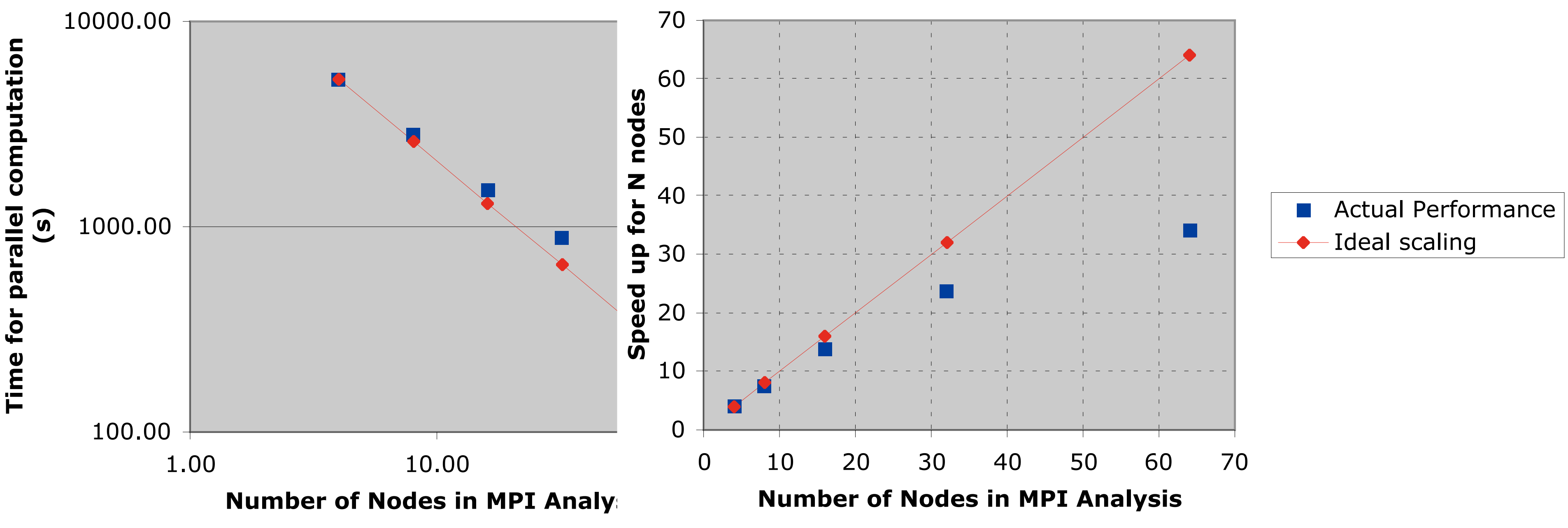
On line analysis -templated search



Inspiral E7 tests - templated search

- Preliminary results
  - » Code performance in a parallel linux cluster

MPI computation performance with increasing number of nodes



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Inspiral search

- **Database Tables Populated**
- Search code inserts events into the `sngl_inspiral` database table with the `search` colum set to `template`. The astrophysical columns currently populated during E7 were:

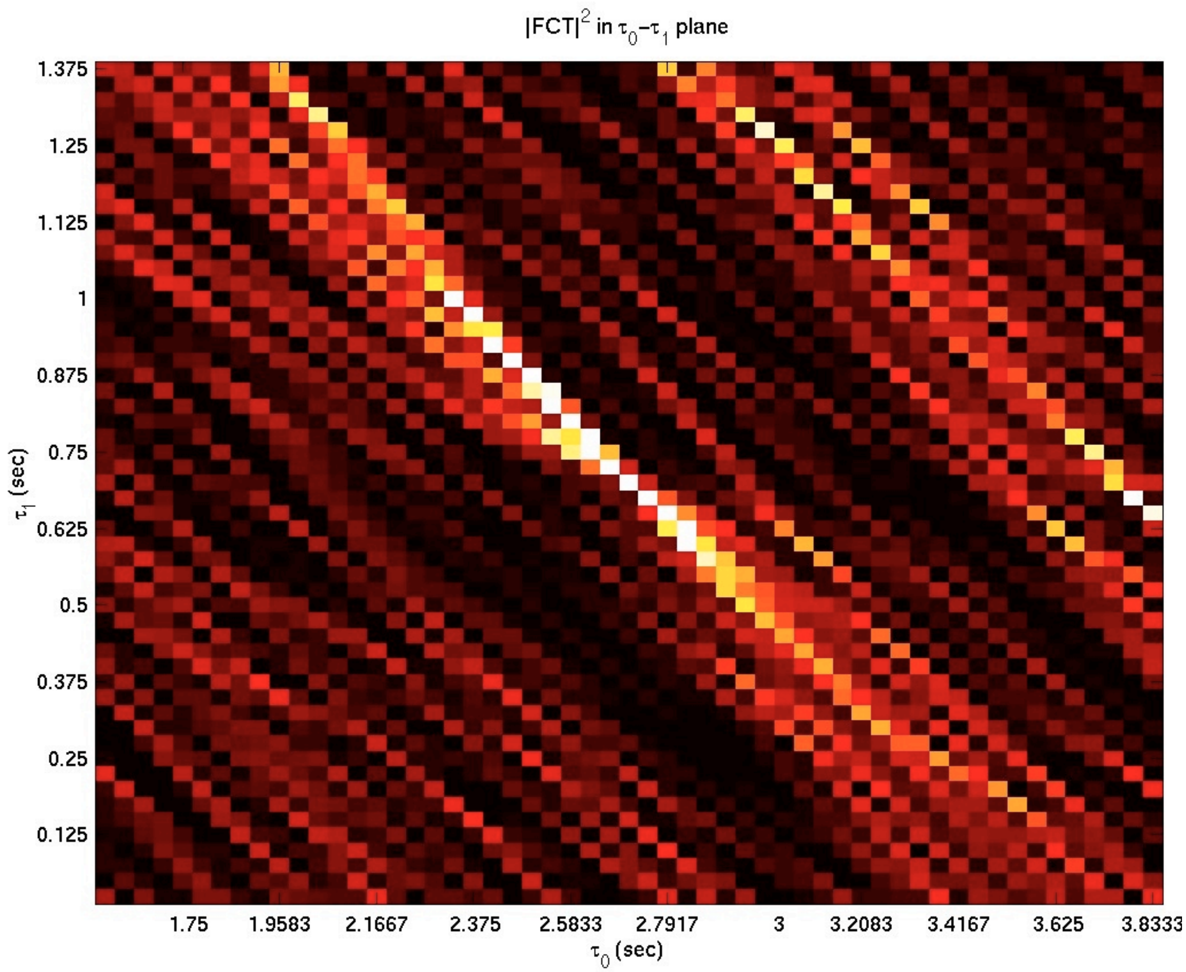
ifo	mass2
search	mchirp
end_time	eta
end_time_ns	snr
eff_distance	chisq
mass1	sigmasq

- A description of each of these columns is avaiable in at: http://ldas.ligo-wa.caltech.edu/ldas/ldas-0.0/doc/db2/doc/text/sngl_inspiral.sql for the `sngl_inspiral` table.

FCT Simulations -
Chirp Embedded in Gaussian Noise

$m1 = 37\ M_{sun}$
$m2 = 1.2\ M_{sun}$

$SNR_{integrated} = 20$



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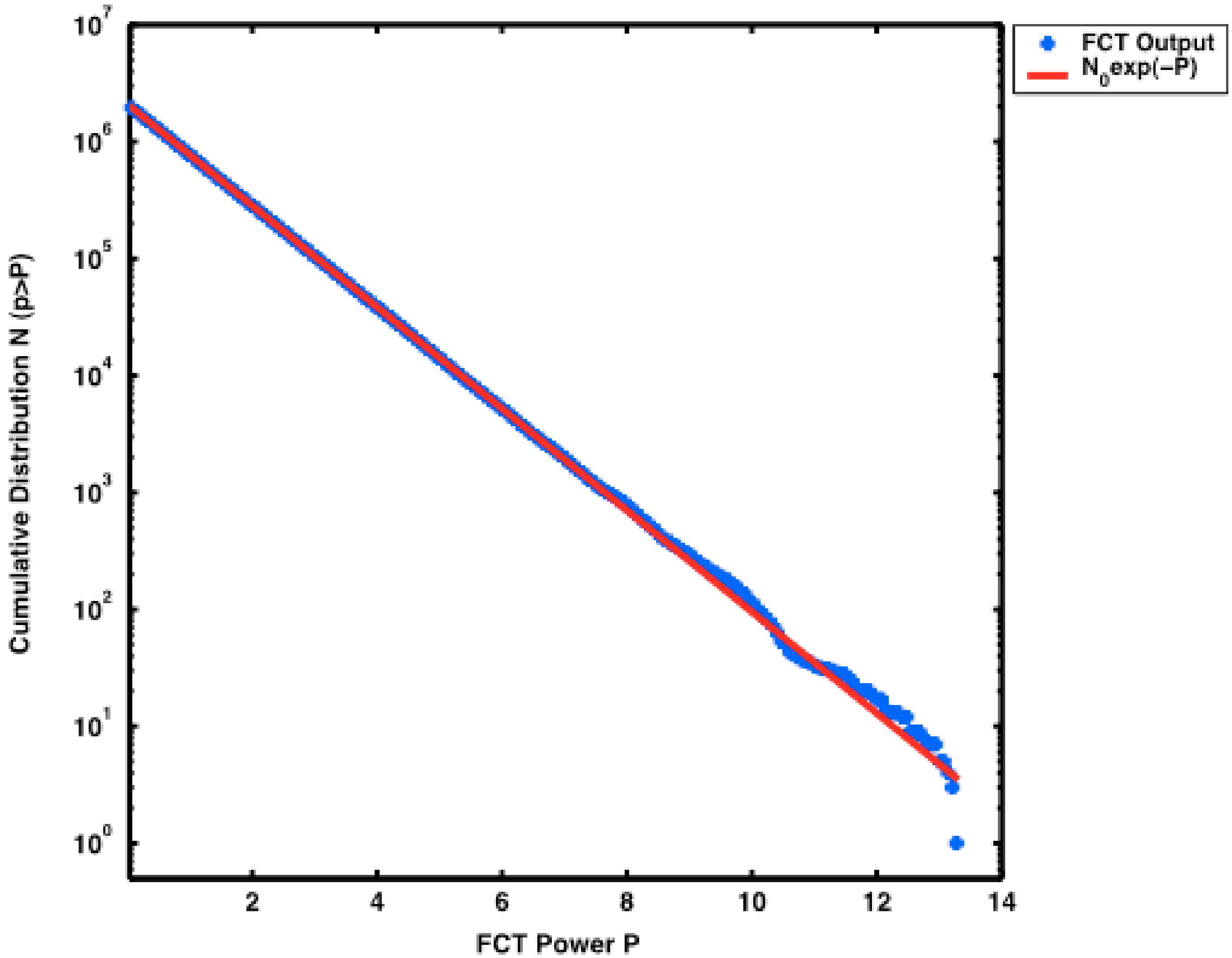
FCT Simulations -
False Alarms vs SNR for Gaussian Noise

✓Guassian noise behavior preserved in FCT

✓Follows expected dependence for 6+ orders of magnitude

✓2PN chirp for 1.4 + 1.4 M_{sun}



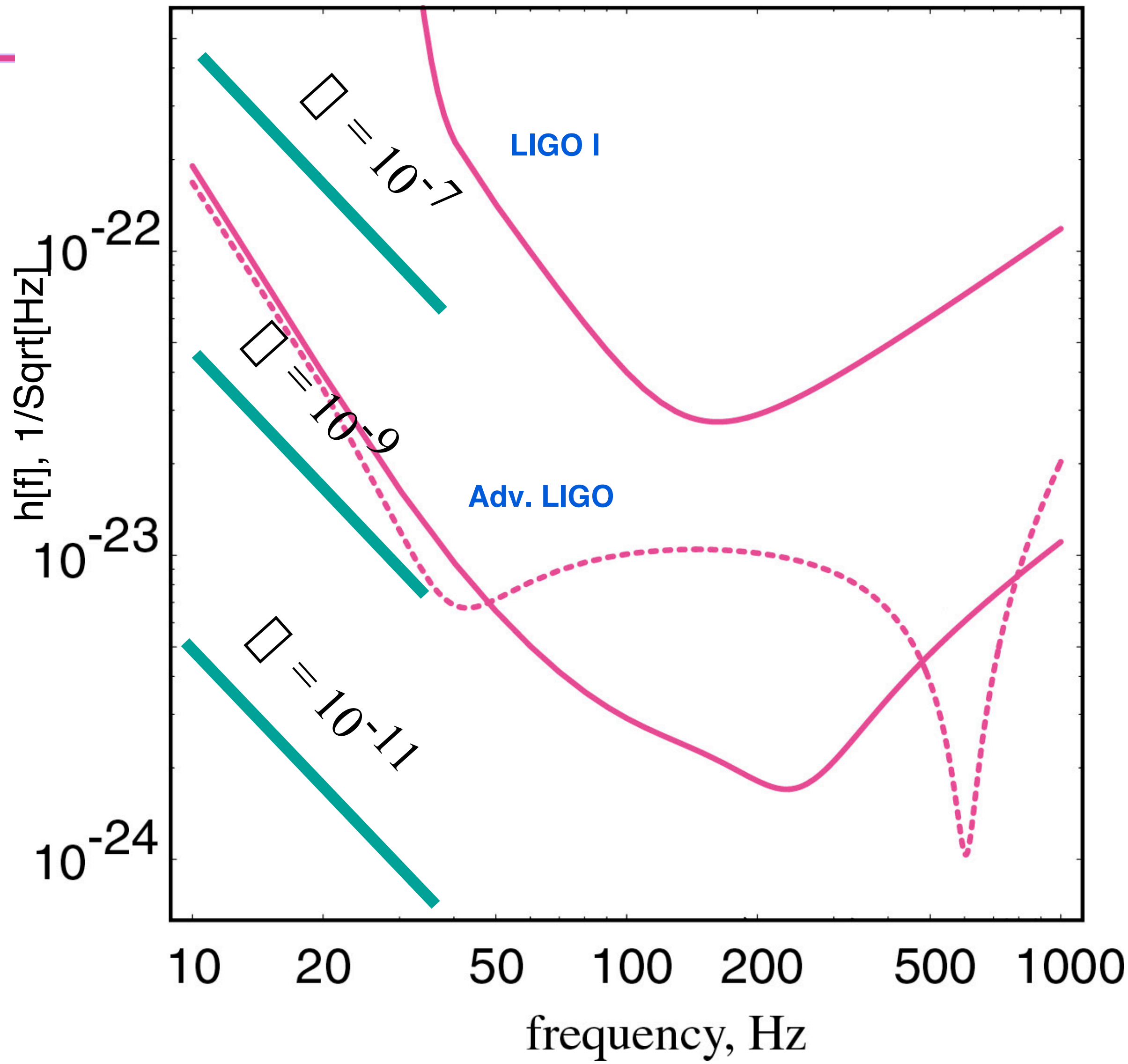
Upper Limit Groups

Stochastic background search

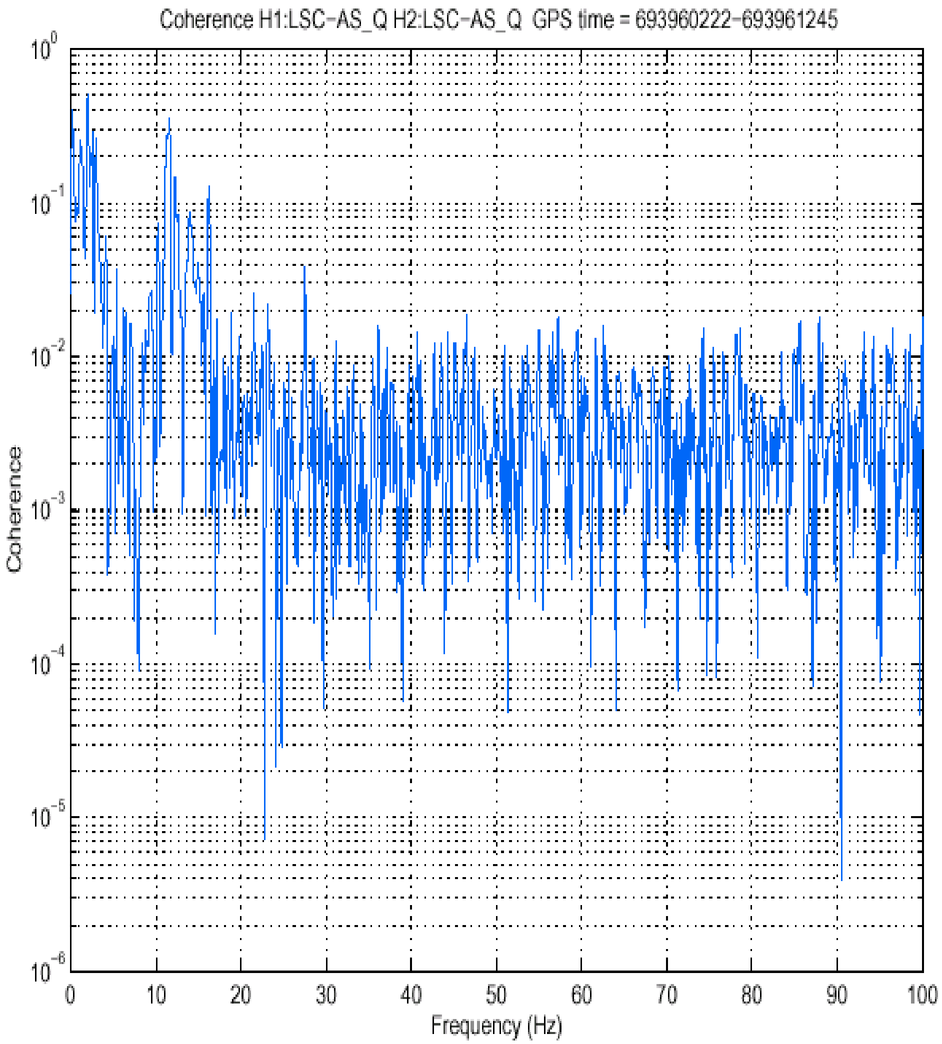
http://feynman.utb.edu/~joe/research/stochastic/upperlimits/

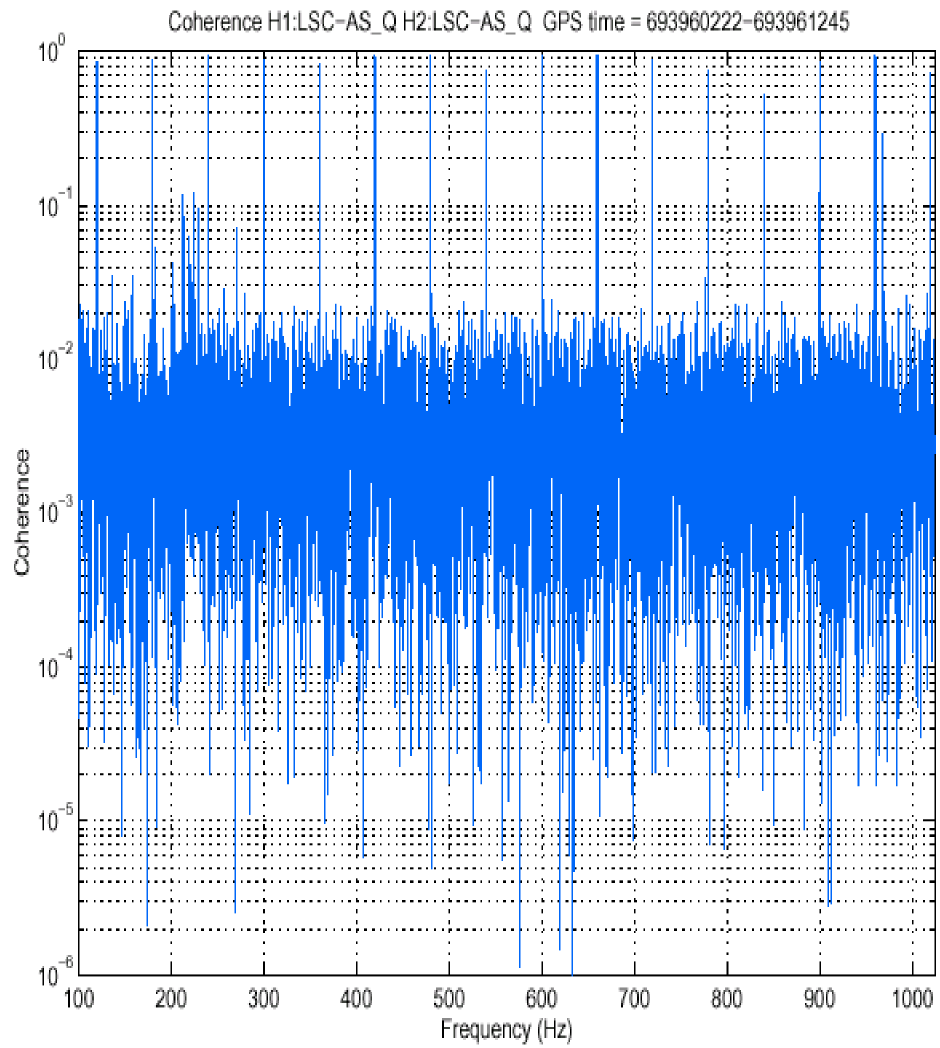
Stochastic Gravitational Wave Background

- Detect by
  - » cross correlating output of Hanford + Livingston 4km IFOs
- Good sensitivity requires
  - » (GW wavelength) $\gtrsim$ **2x** (detector baseline)
  - » f $\lesssim$ 40 Hz
- Initial LIGO sensitivity:
  - » $\Omega \gtrsim 10^{-5}$
- Advanced LIGO sensitivity:
  - » Ω $\gtrsim$ **5×10^{-9}**

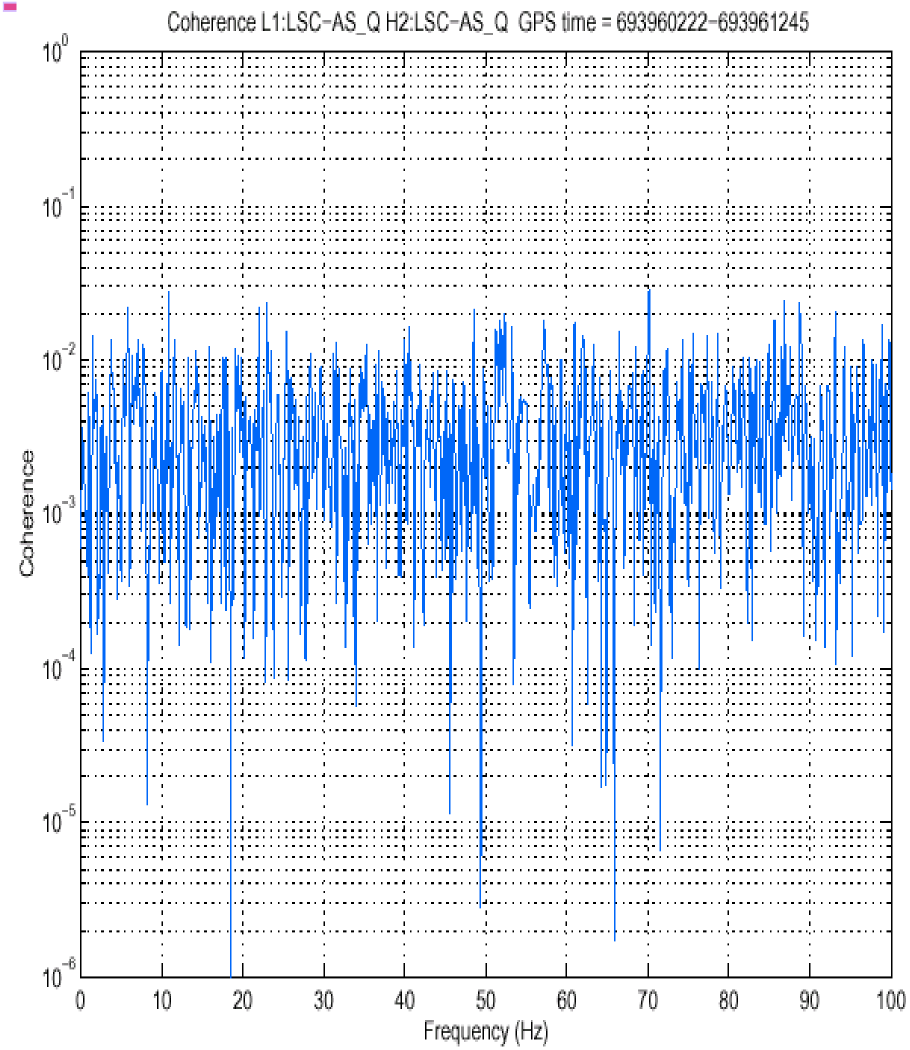


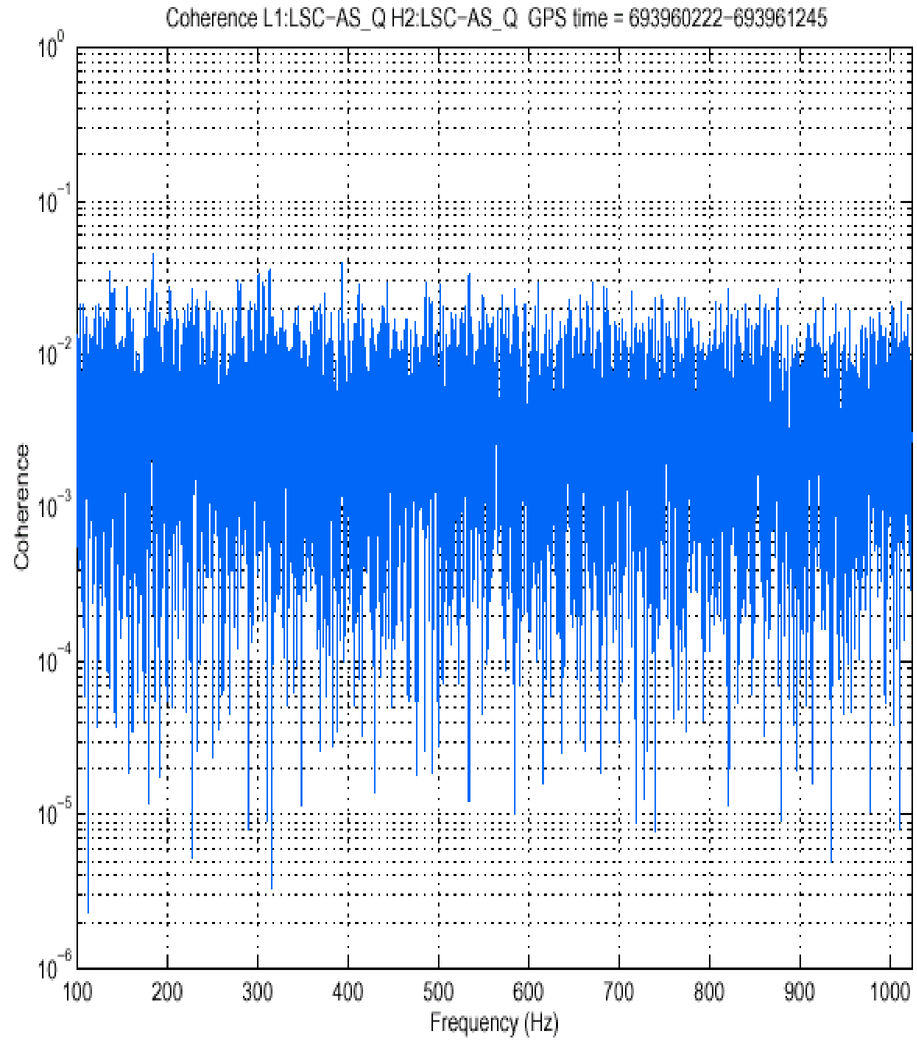
Coherence plots (LHO 2k-LHO 4k)





Coherence plots (LLO-LHO 2k)



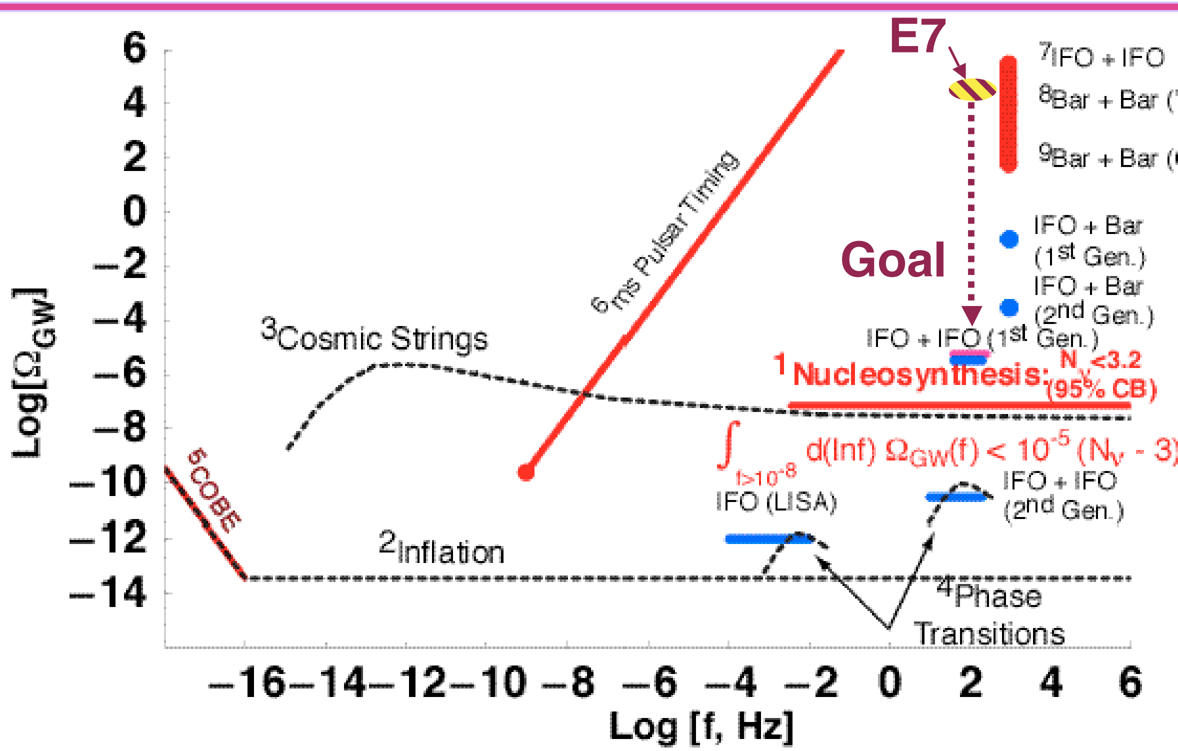


Stochastic Upper Limit Group Activities (E7 investigations – current/planned)

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

   ~2×10^5 for LLO-LHO 2k, ~ 6×10^4 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*

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)

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

FINIS