New Science with LIGO: Past, Present and Future

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LIGO DCC: G020438-00-E

Acknowledgements

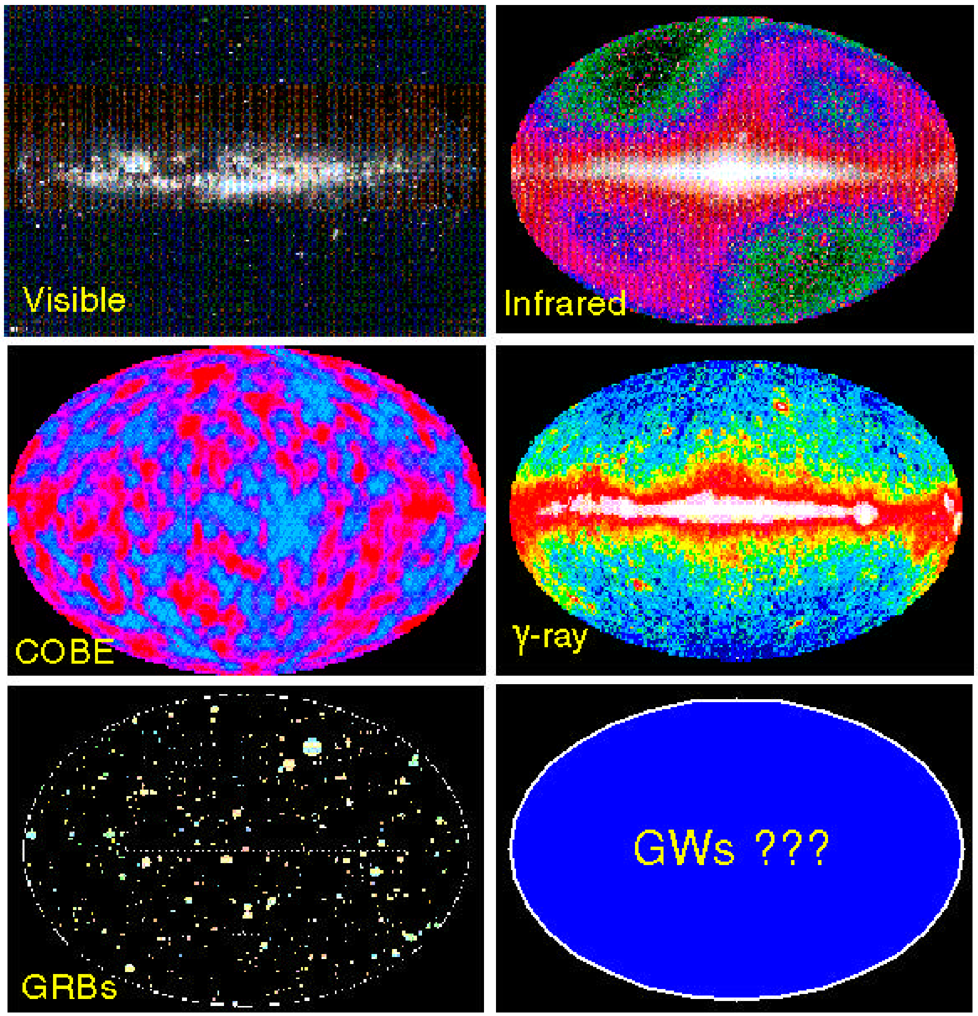
…just a few of the many individuals that have contributed to LIGO and this talk!

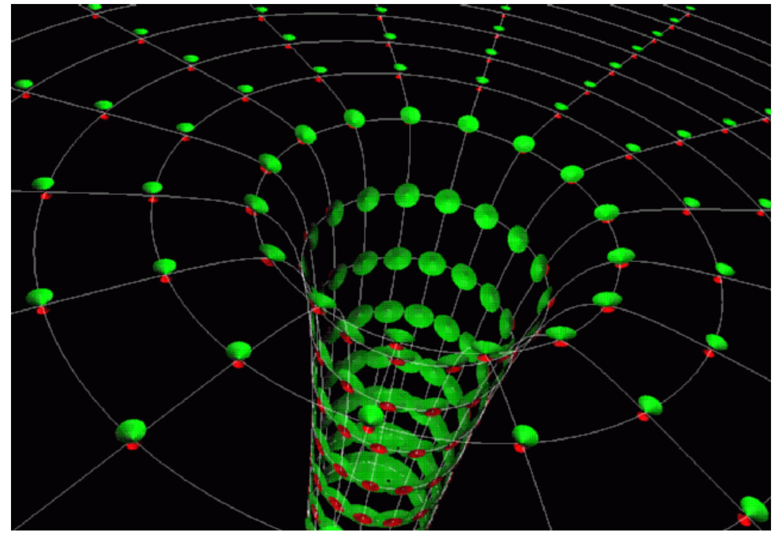
What is LIGO?

LIGO: Laser Interferometer Gravitational-Wave Observatory

- **US project to build observatories for gravitational waves (GWs).**
- **Funded by the National Science Foundation (NSF).**
- **Facility lifetime of greater than 20 years.**
- **Participate in a GW network with other interferometer projects.**
- **Operated by Caltech &MIT, with other institutions participating.**
  - **Scientific Community: LIGO Scientific Collaboration, (LSC)**
    - **Forum for organizing technical and scientific research within LIGO.**
    - **Over 300 members from over 30 institutions.**

New Window on Universe





GRAVITATIONAL WAVES WILL GIVE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

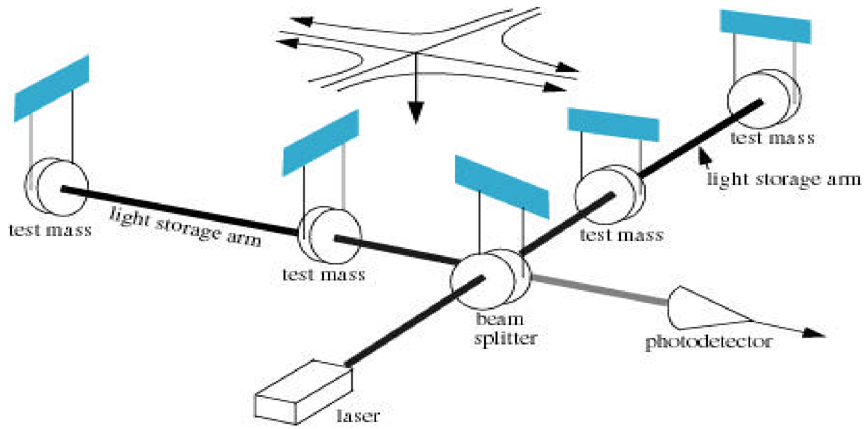
EXPECT SOURCES: BLACK HOLES, SUPERNOVAE, PULSARS AND COMPACT BINARY SYSTEMS.

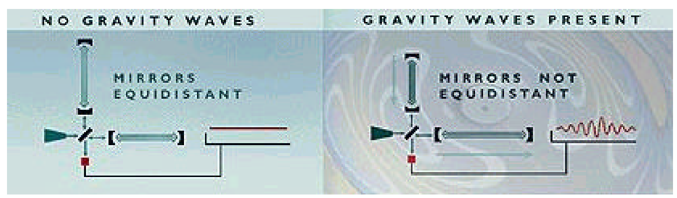
POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

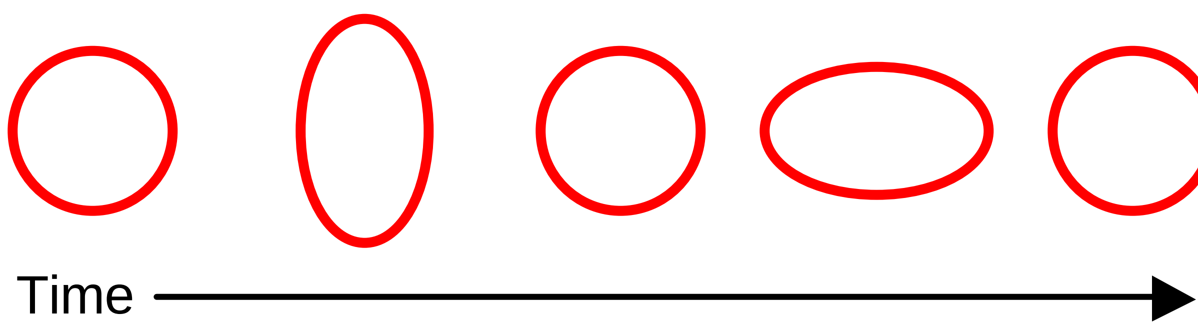
Interferometer GW Detectors

<u>Principle of Detection</u>:

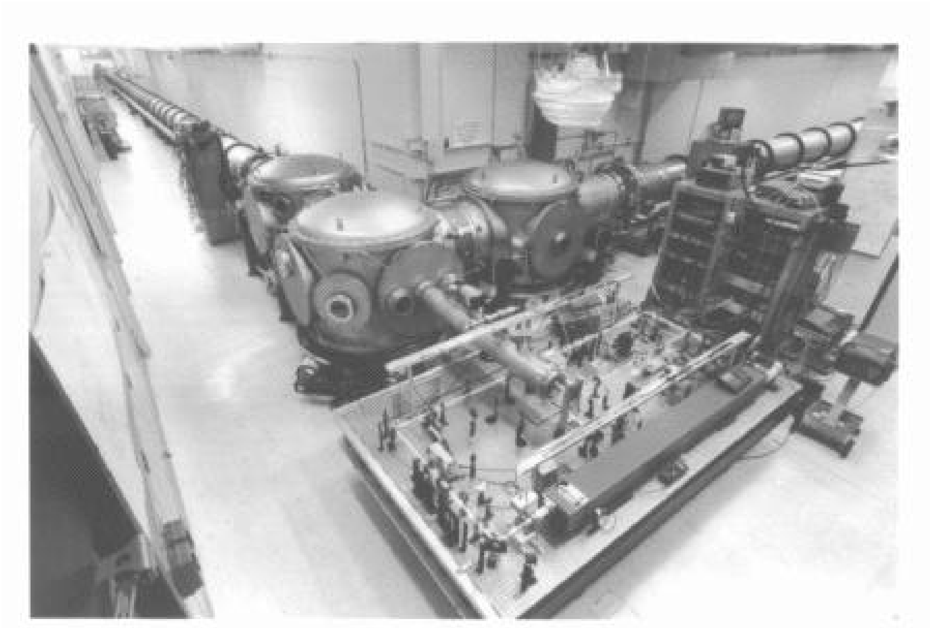
- **A gravitational wave causes the interferometers arm lengths to vary by stretching one arm while compressing the other, in the plane perpendicular to direction of travel.**

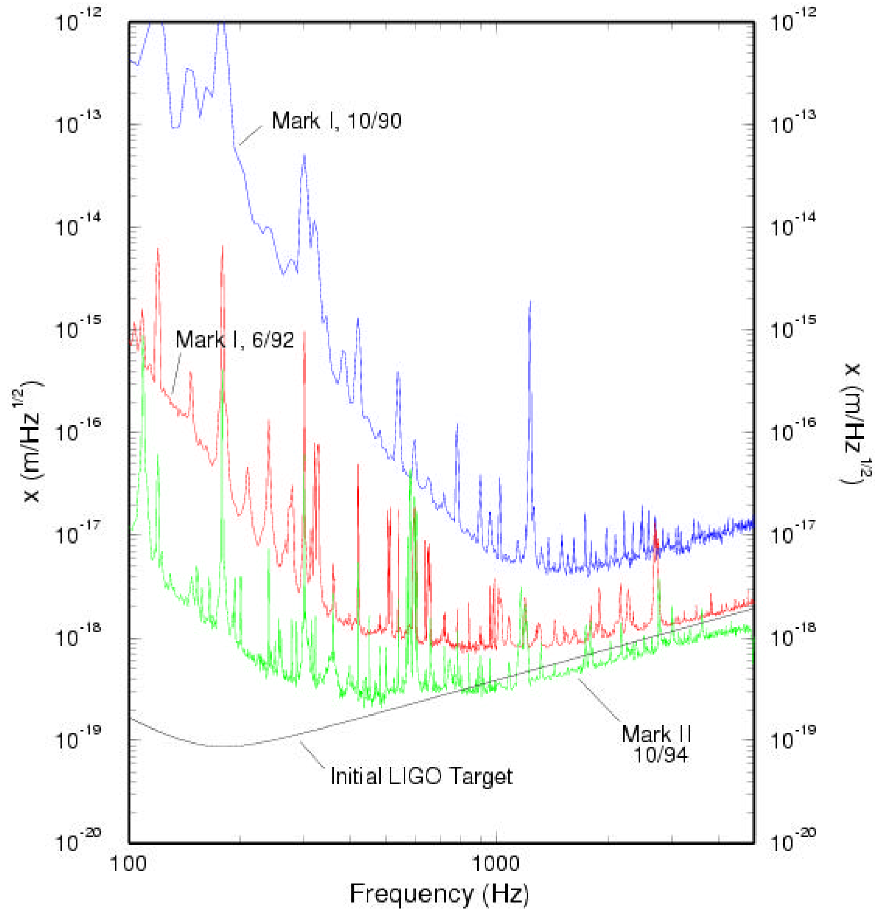






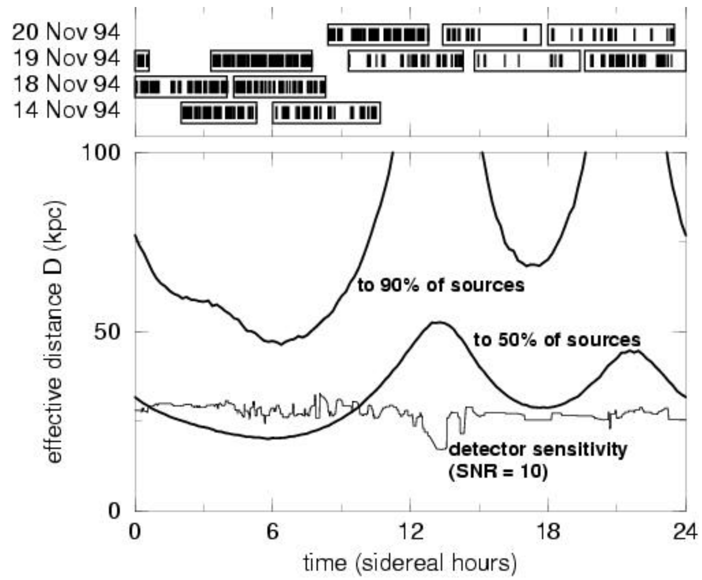
The Early Years:
Caltech 40 Meter Interferometer





- 1/100th scale prototype for LIGO.
- Characterized fundamental noise sources.
- Instrumental as a technology proving ground.

November 1994 40m Data Run



Data collected during one week test run;
25.0 hours analyzed for binary inspirals signals.

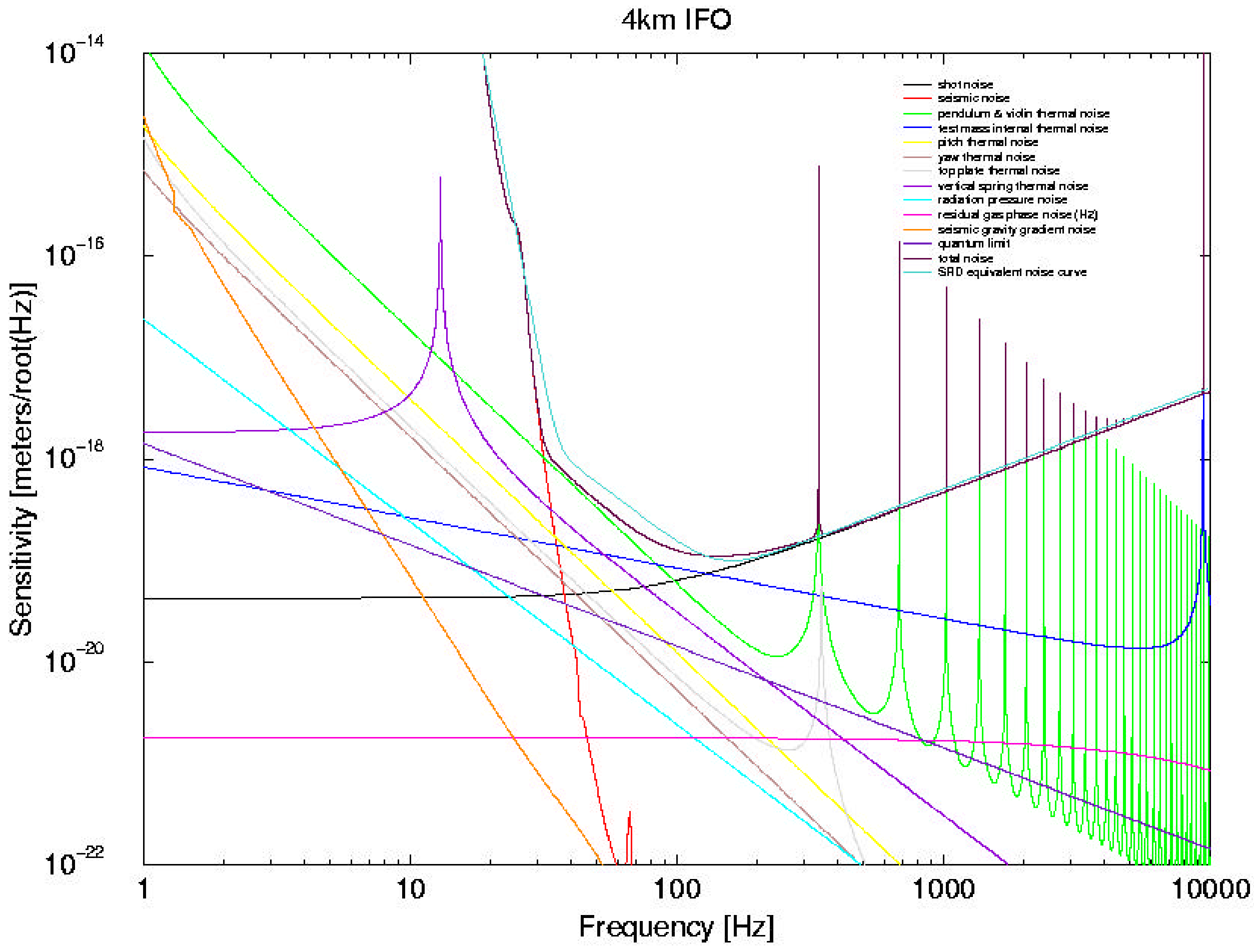
First Upper Limit Analysis for LIGO Project:
Binary inspiral rate less than ~0.5 per hour in our galaxy

B. Allen *et al*., Phys Rev. Lett. **83**, 1498 (1999).

LIGO Sensitivity

Compared to 40 meter:

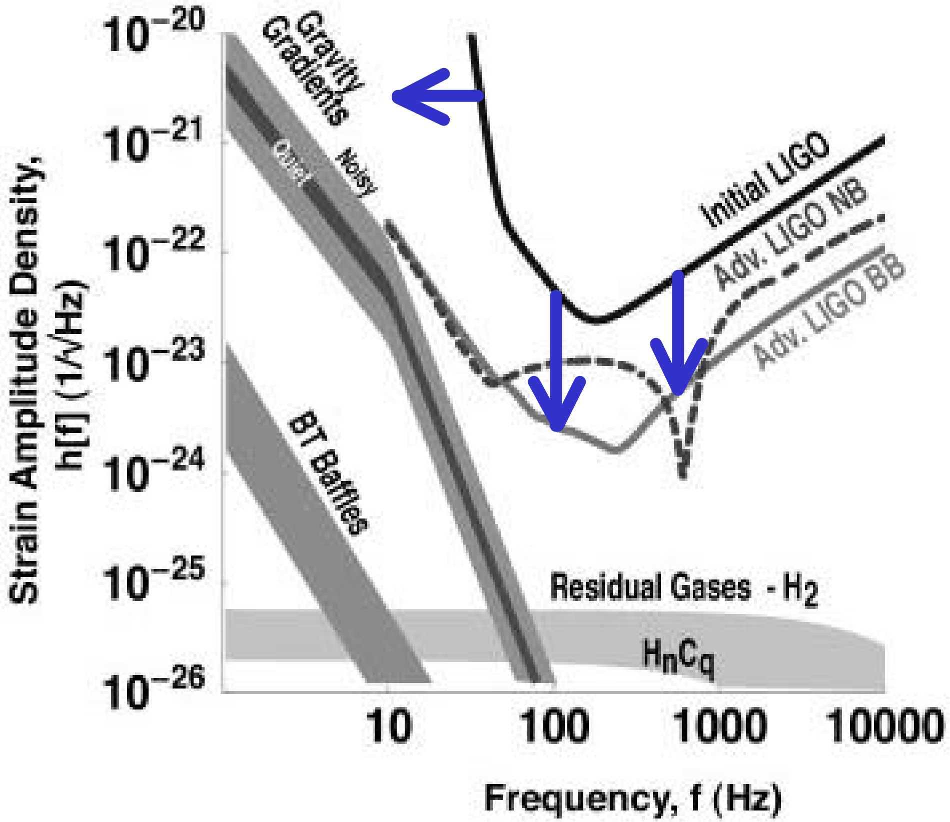
- **10x improvement in low frequency limit.**
- **1000x more sensitive.**
- **Has a billion fold increase in volume of the universe observed.**



A Look to the Future

- **Inherent facility limits**
  - Gravity gradients (seismic waves)
  - Residual gas (vacuum)
  - Room to improve…

- **Advanced LIGO**
  - R&D underway…
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15th
  - Shot noise 1/10th

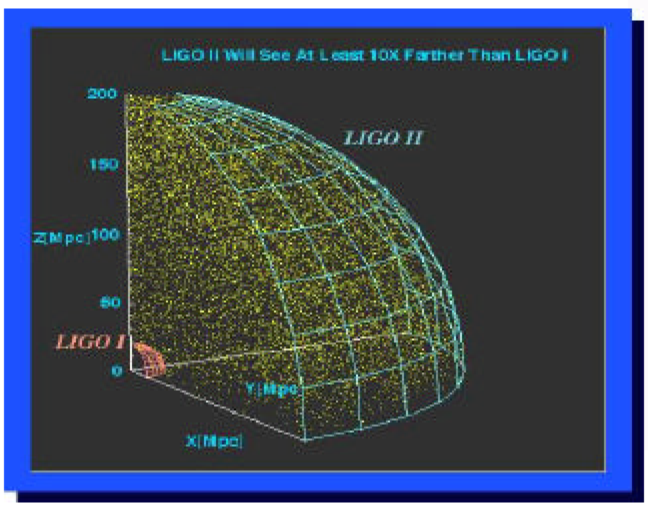


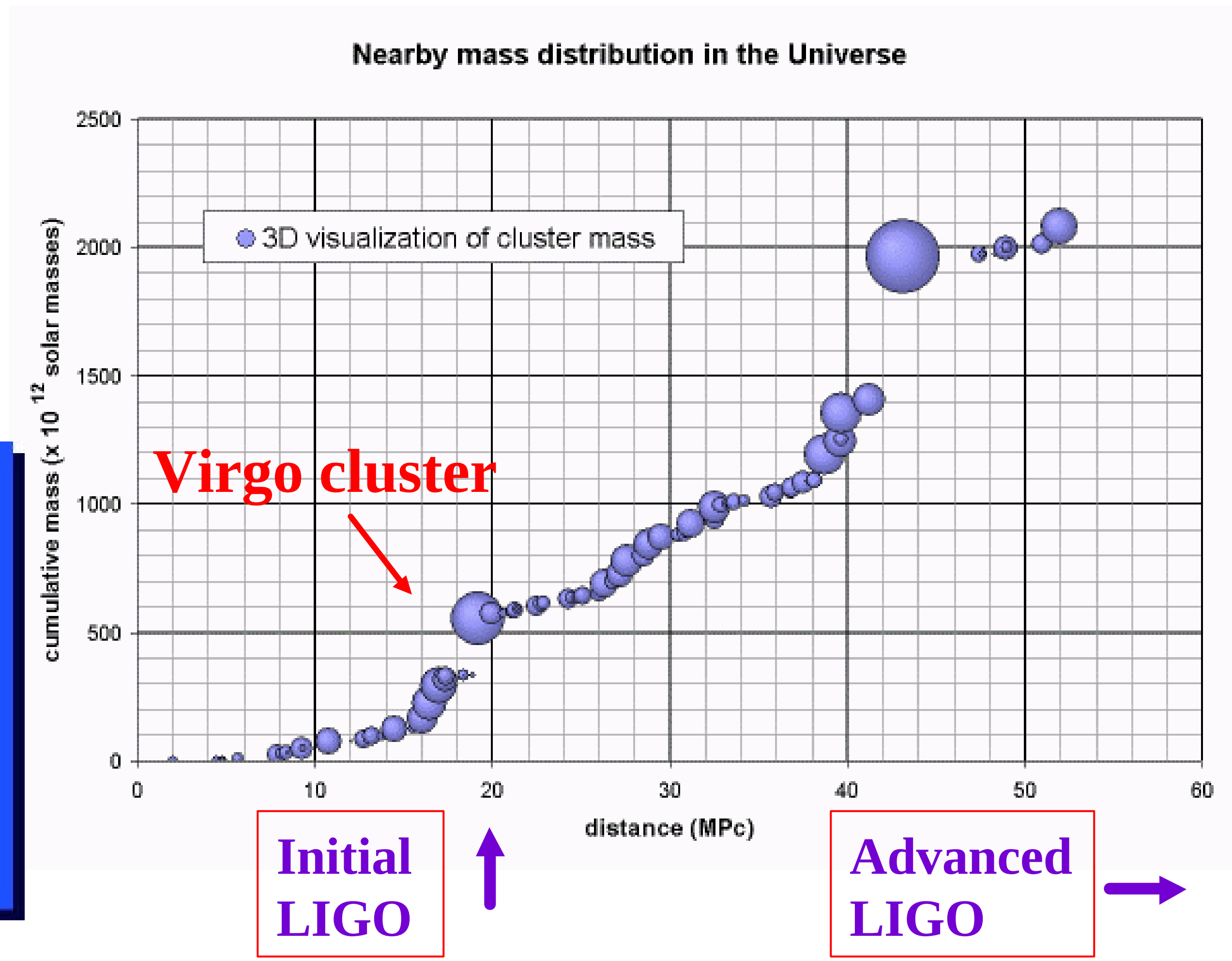
![LIGO logo]

Advanced LIGO:
Cubic Law for "*Window*" on the Universe

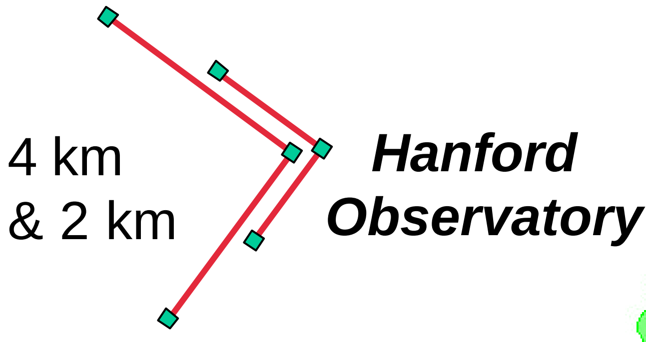
Improve amplitude sensitivity by a factor of <u>10x</u>…

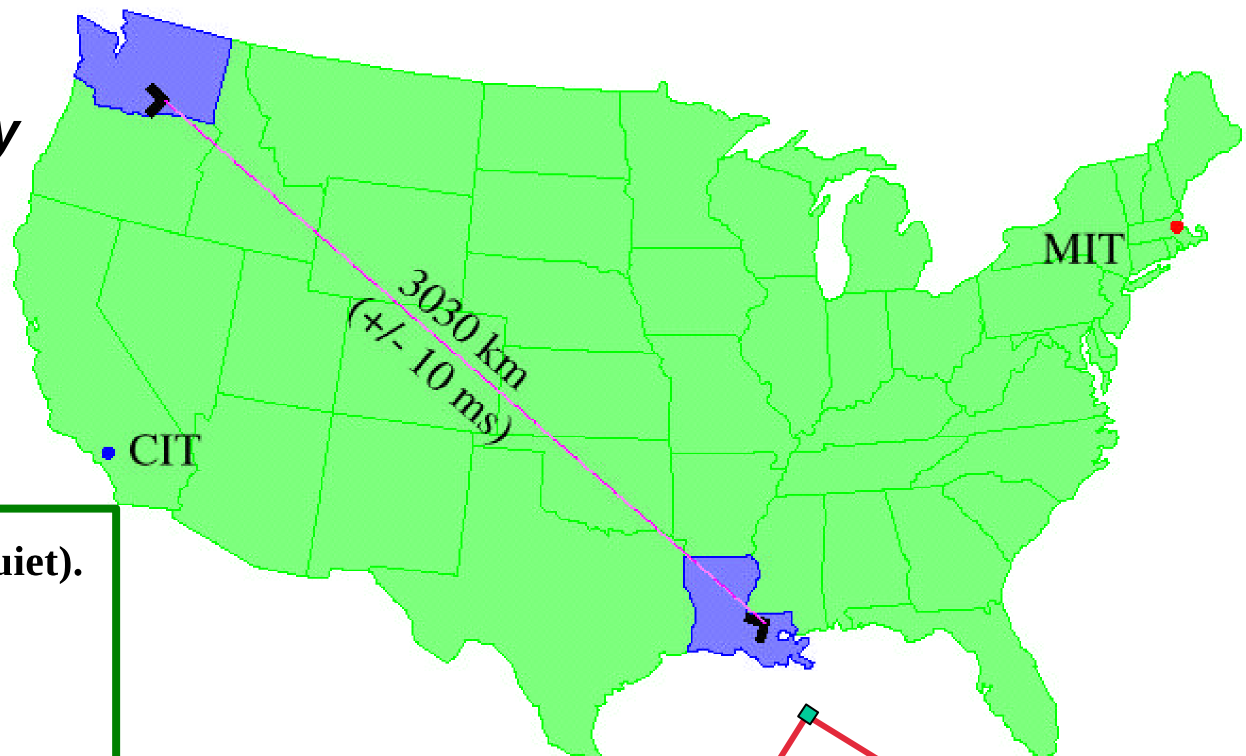
…number of sources goes up <u>1000x</u>!

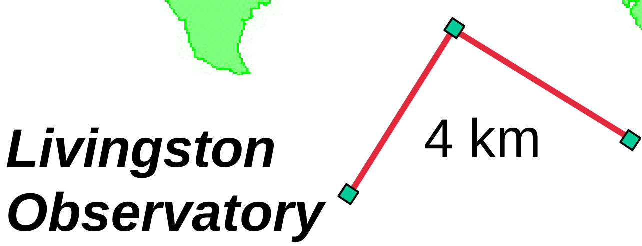




LIGO's Two Sites



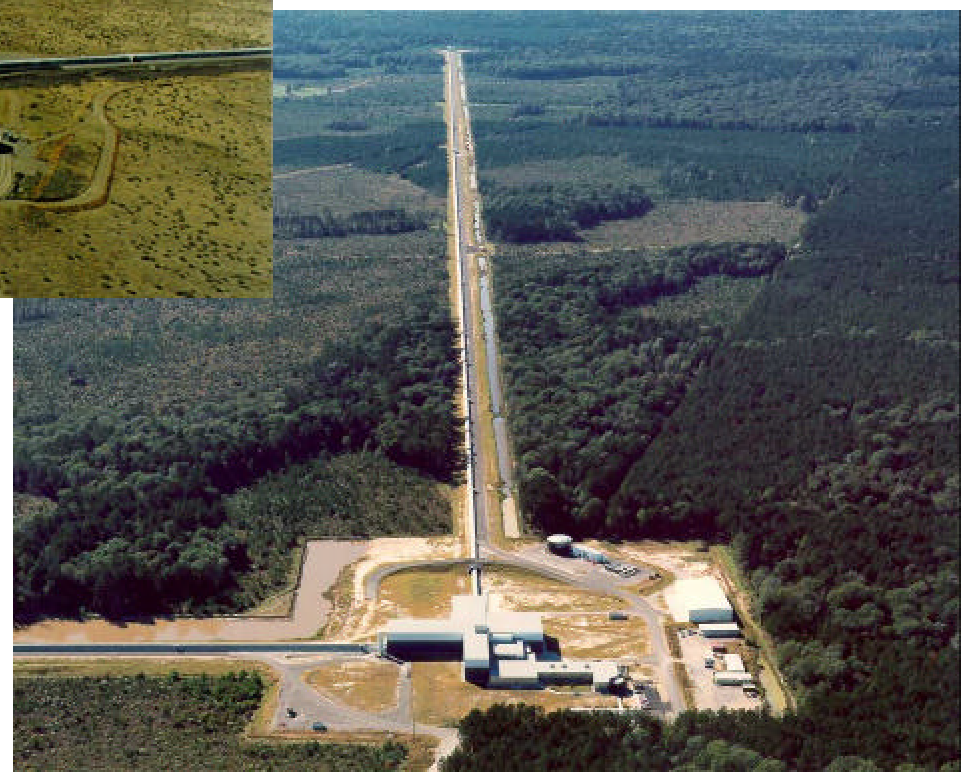




- **Both sites remote (seismically quiet).**
- **3030 km separation.**
- **10 millisecond light travel time separation.**
- **Facilities Complete!**
- **Detector being commissioned.**

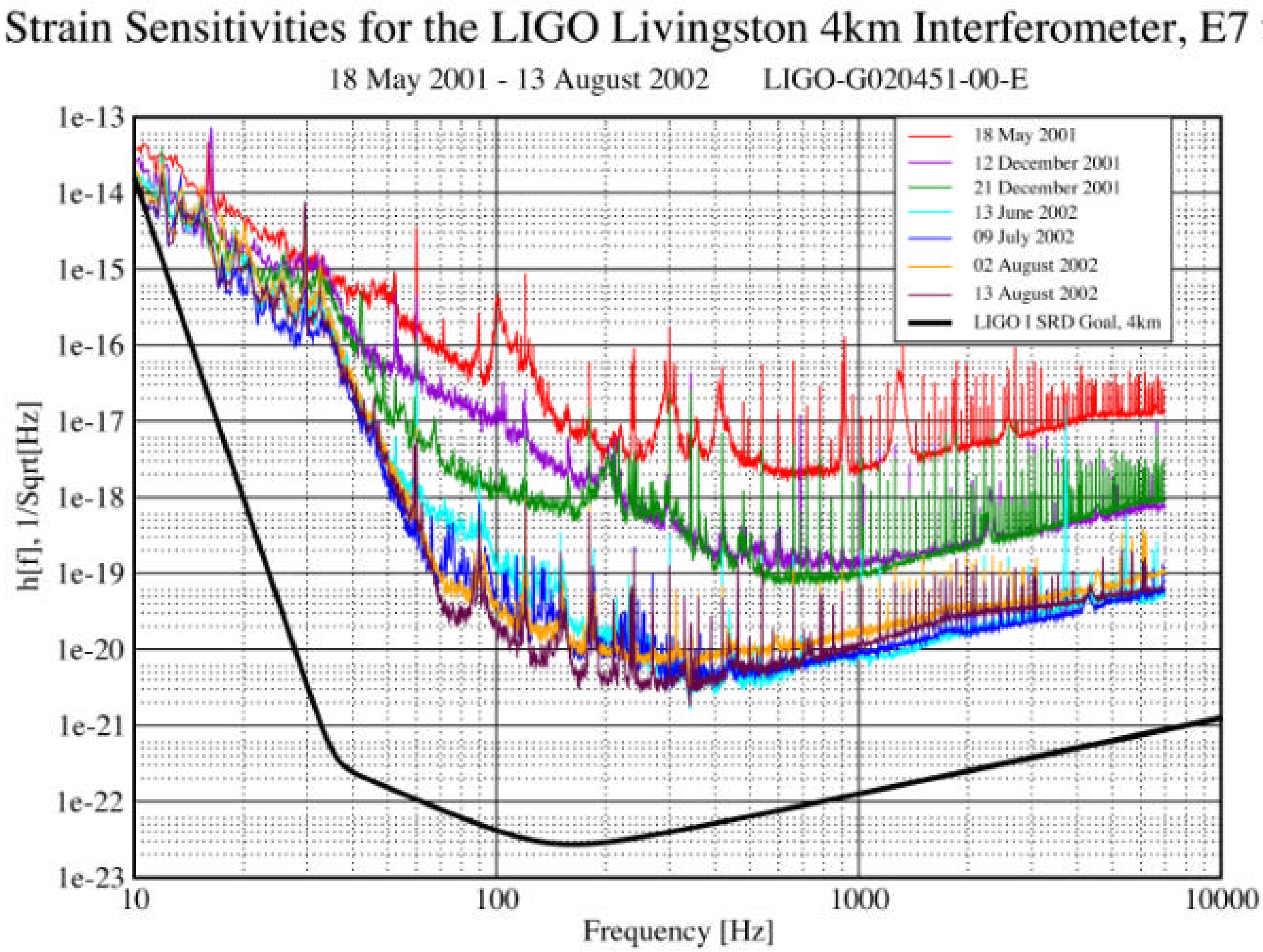
LIGO Observatories

Livingston Observatory
Louisiana
One interferometer (4km)



Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

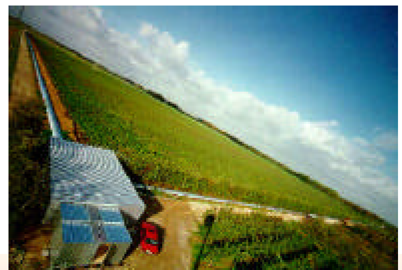
Sensitivity Steadily Improving!



Growing International Network of GW Interferometers

LIGO-LHO: 2km, 4km

GEO: 0.6km

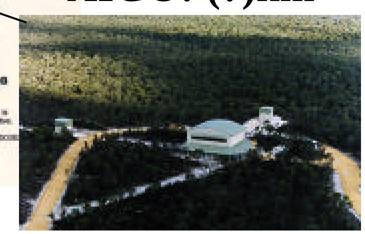


VIRGO: 3km

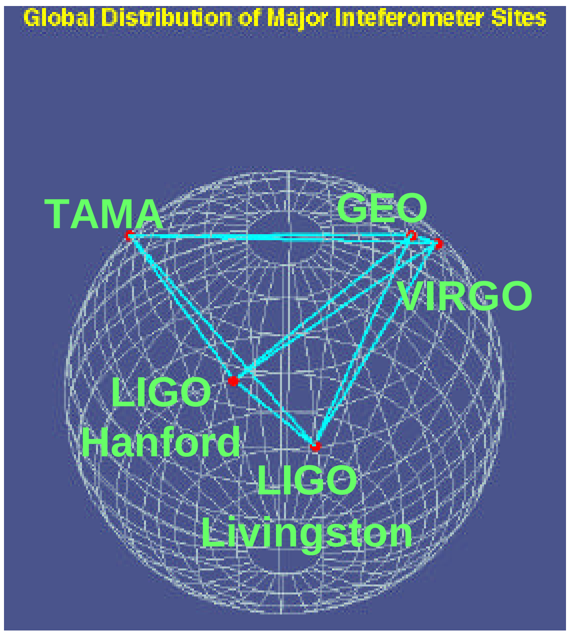
TAMA: 0.3km

LIGO-LLO: 4km

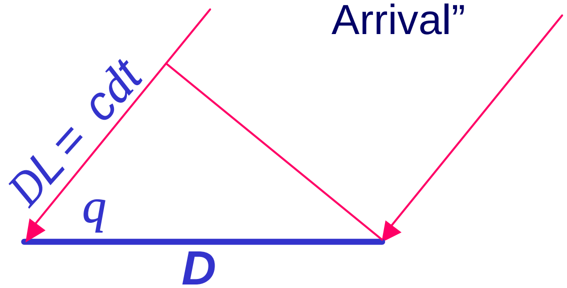
AIGO: (?)km



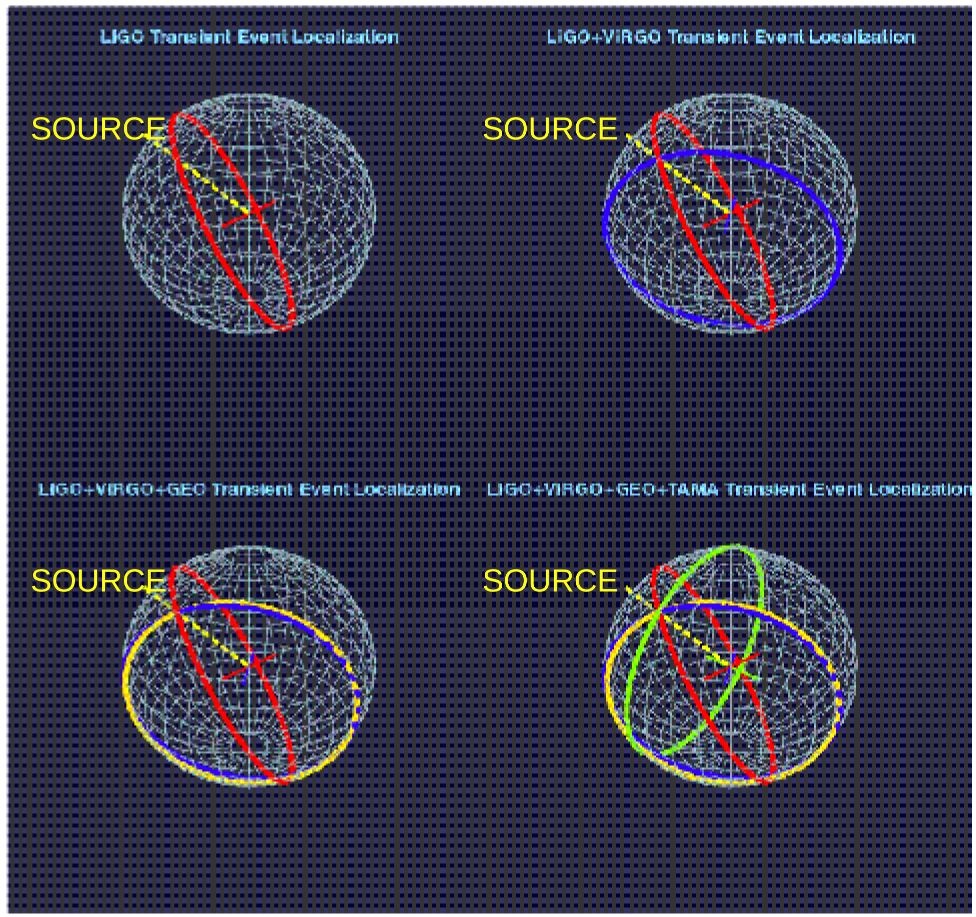
Source Localization with Network



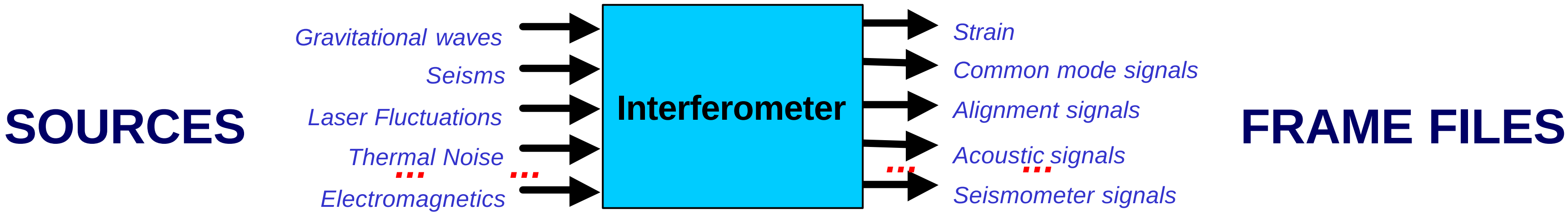
Determined from "Time of Arrival"

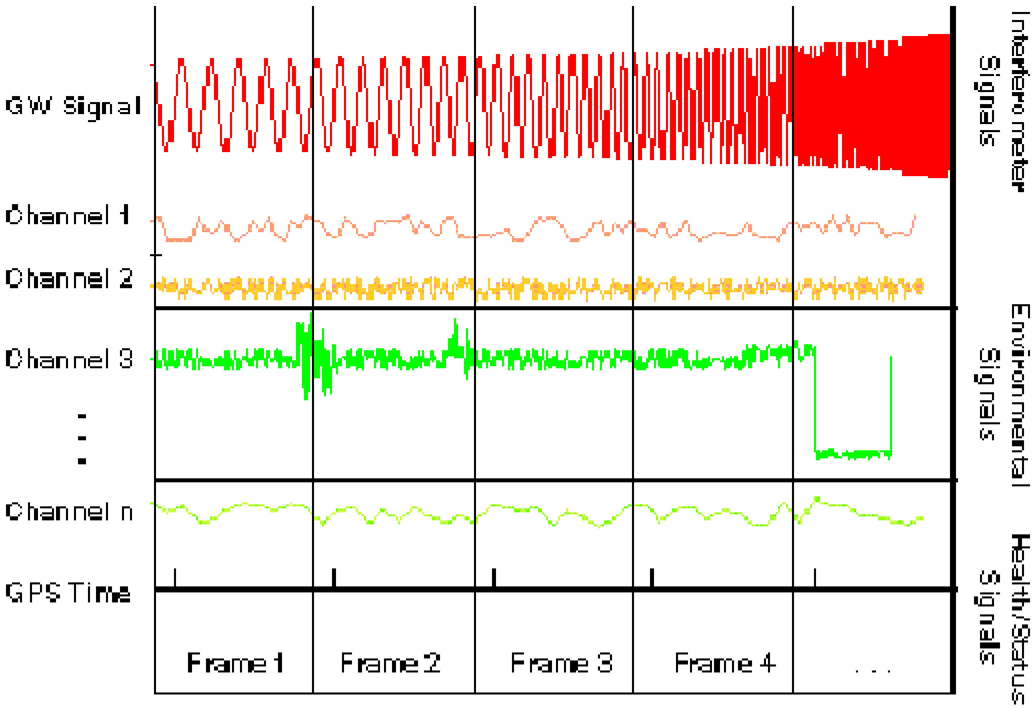


Single interferometer see whole sky!



Interferometer Data

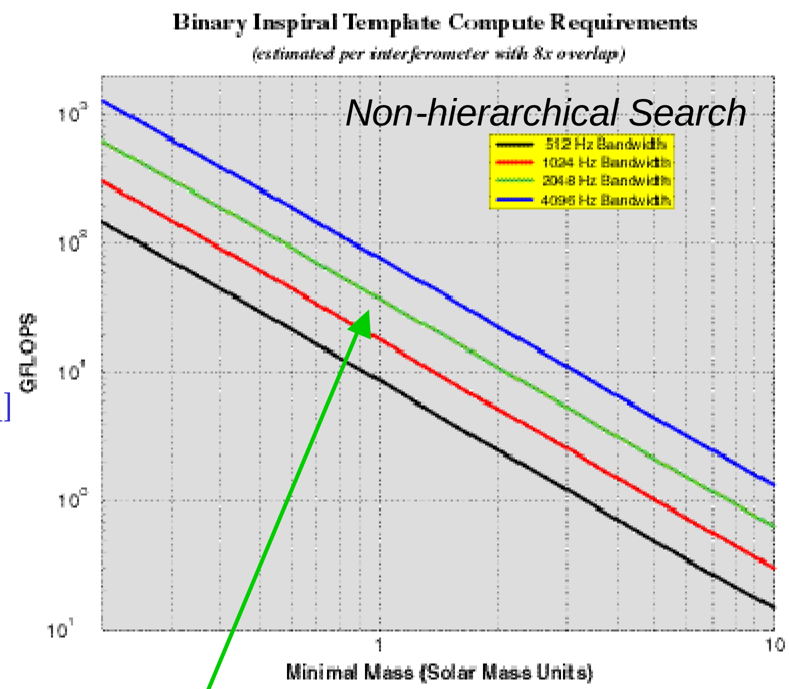




- <u>Frame Format</u>: All interferometric detector projects have agreed on this standard data format.
- LIGO writes Frames at a rate of ~3MB/s from ~5000 channels per interferometer.
    - *GW Strain is ~1% of all data.*
- 24x7 operations leads to 100-200 TB of data per year for LIGO.

LIGO Data Analysis

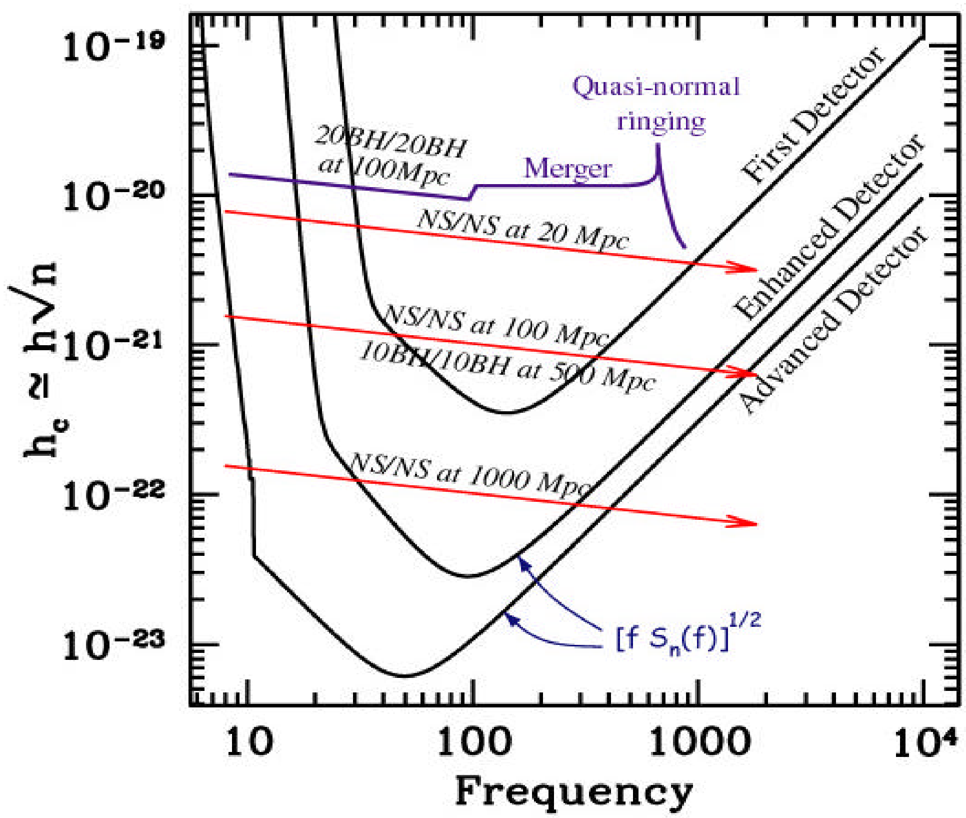
- **Different scientific topics - different analysis methods**
- **Searches for (short) transient signals**
  - Inspiral: optimal filtering.
  - Bursts: time-frequency methods.
- **Searches for (long) periodic signals**
  - Fourier transforms over Doppler shifted time interval
- **Search for stochastic GW background**
  - Optimally weighted cross-correlated data from different detectors.
- **Detector characterization**
  - Provide understand of instrumental couplings to GW channel.
  - Provide calibration for data analysis

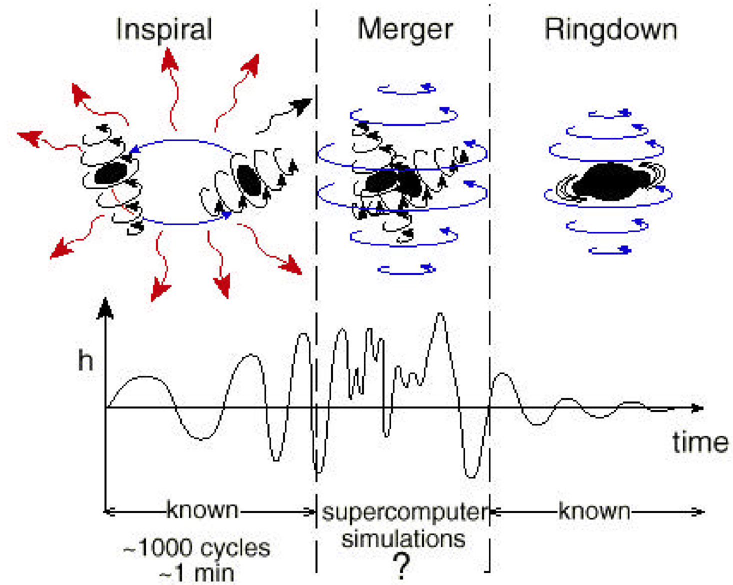


LIGO's computational needs dominates by binary inspiral …
100 GFLOPS @ 1 Solar Mass

Compact Binary Sources

Sensitivity of LIGO to coalescing binaries





Brief Summary of Detection Capabilities of Mature LIGO Interferometers

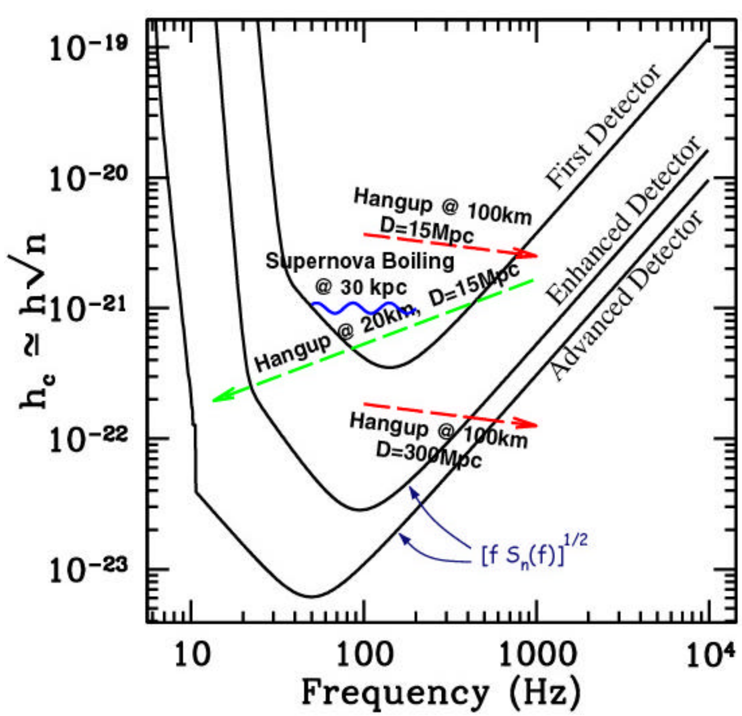
• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

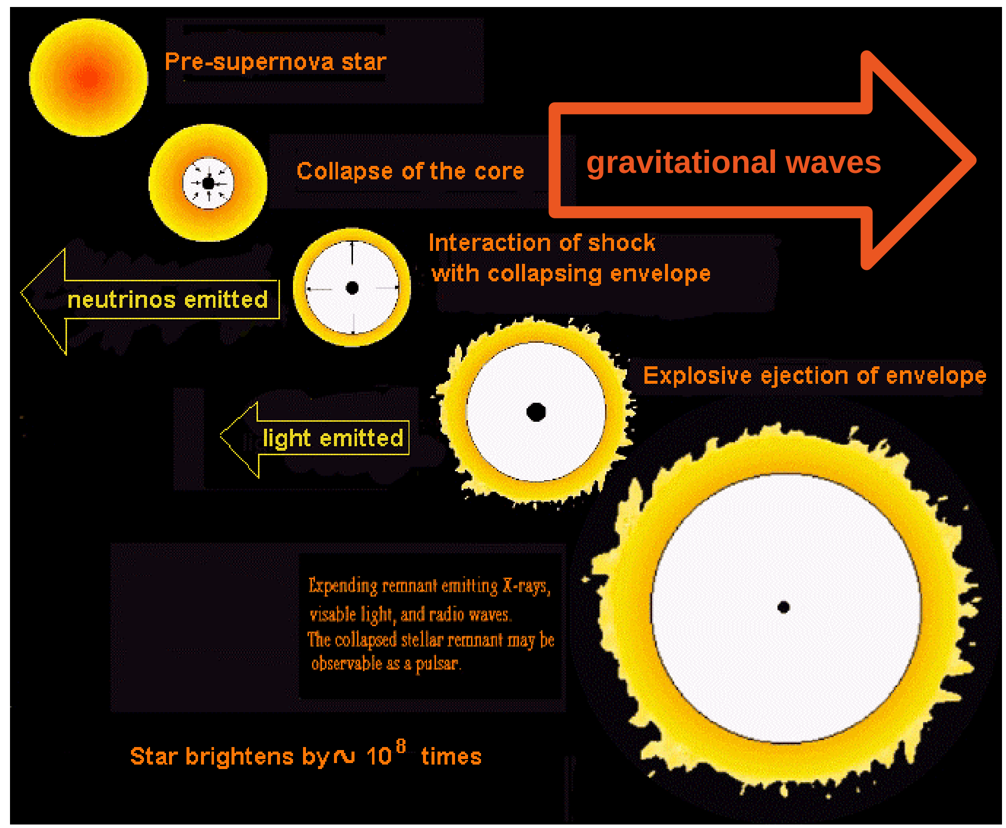
	NS/NS	NS/BH	BH/BH in field	BH/BH in globulars
$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	10^{-6}–10^{-5}
$D_{\rm I}$	20 Mpc	43 Mpc	100	100
$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
$D_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
$\mathcal{R}_{\rm WB}$, yr^{-1}	$0.5 - 100$	$\lesssim 0.5 - 1000$	$\lesssim 10 - 2000$	$100 - 2000$

V. Kalogera (population synthesis)

Burst Sources

Sensitivity of LIGO to burst sources



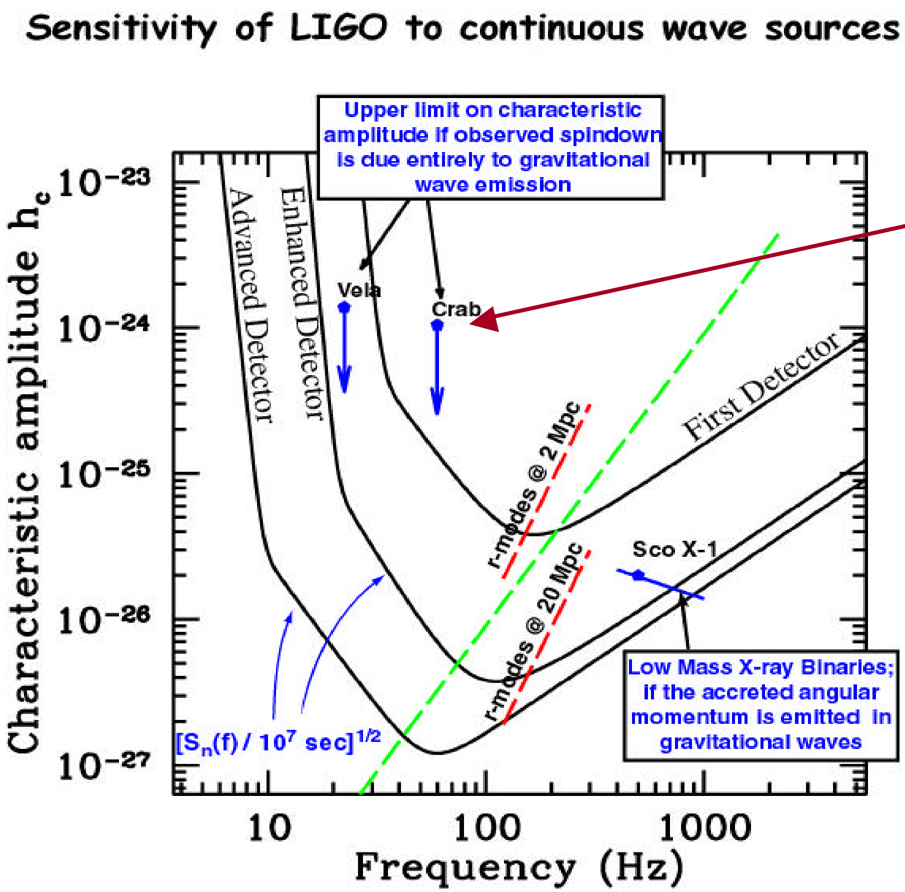


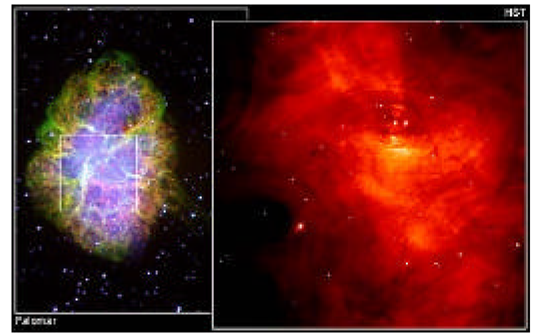
Rate

1/50 yr - our galaxy

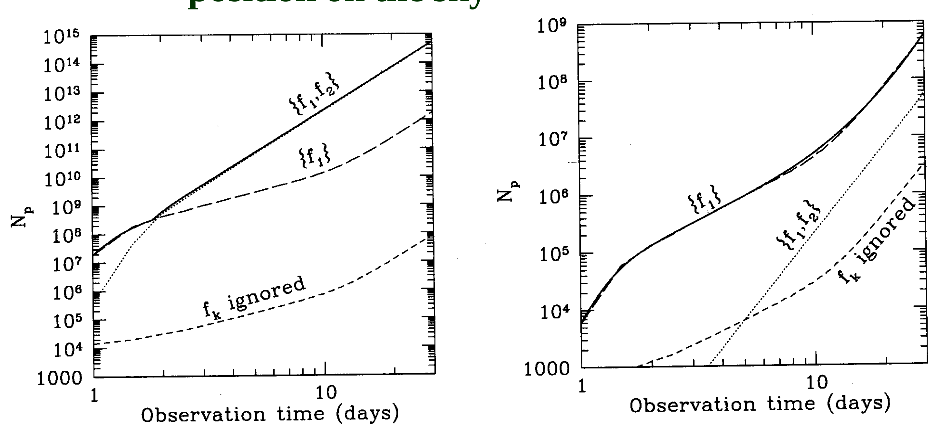
3/yr - Virgo cluster

Periodic Sources





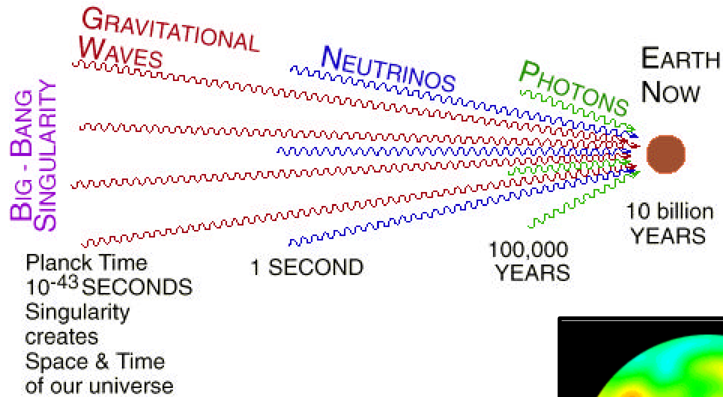
Data must be corrected for each source position on the sky



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

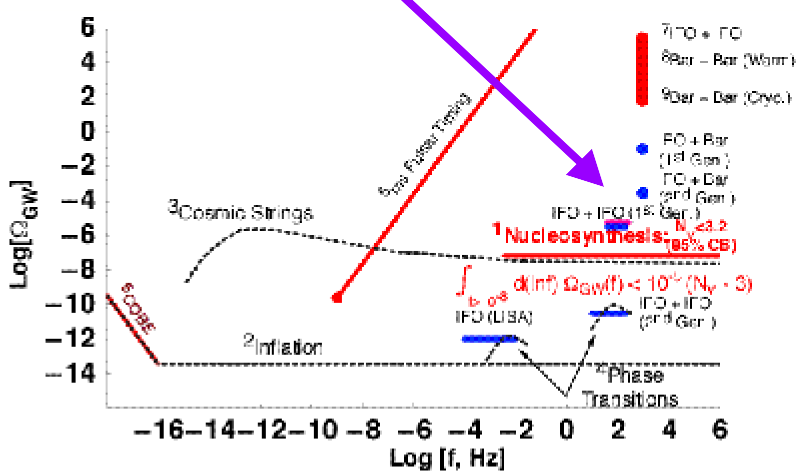
On a 1TFLOPS computer it would take more than 10,000 yr to perform an all-sky search over a 1000 Hz band for an observation time of 4 months.

Stochastic Background Sources

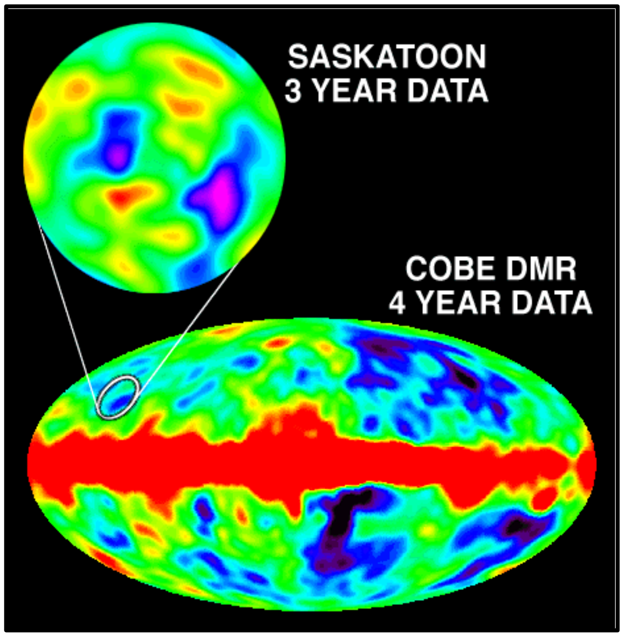


Upper limit possible with initial LIGO interferometers:

Omega$_{GW}$ ~10^{-5}



[1] Kolb & Turner (The Early Universe, 1990)
Burles, Nollet, Truran, 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)



Analog from electromagnetic spectrum

LIGO Data Analysis System (LDAS)

- **Follows a "computing center" model**
  - Uses dedicated hardware.
  - Machines are on a "private" network; no access from Internet except to a single "listening" gateway machine.
  - Main data archive is being housed at Caltech

Remote job submission and result retrieval via gateway

Uses socket-based job submission protocol; no Unix login by users.

Access requires an LDAS username / password.

LDAS systems currently at LIGO observatories, Caltech, MIT., and a few other institutions in the LIGO Scientific Collaboration.

Software now in beta release.

LDAS Implementation

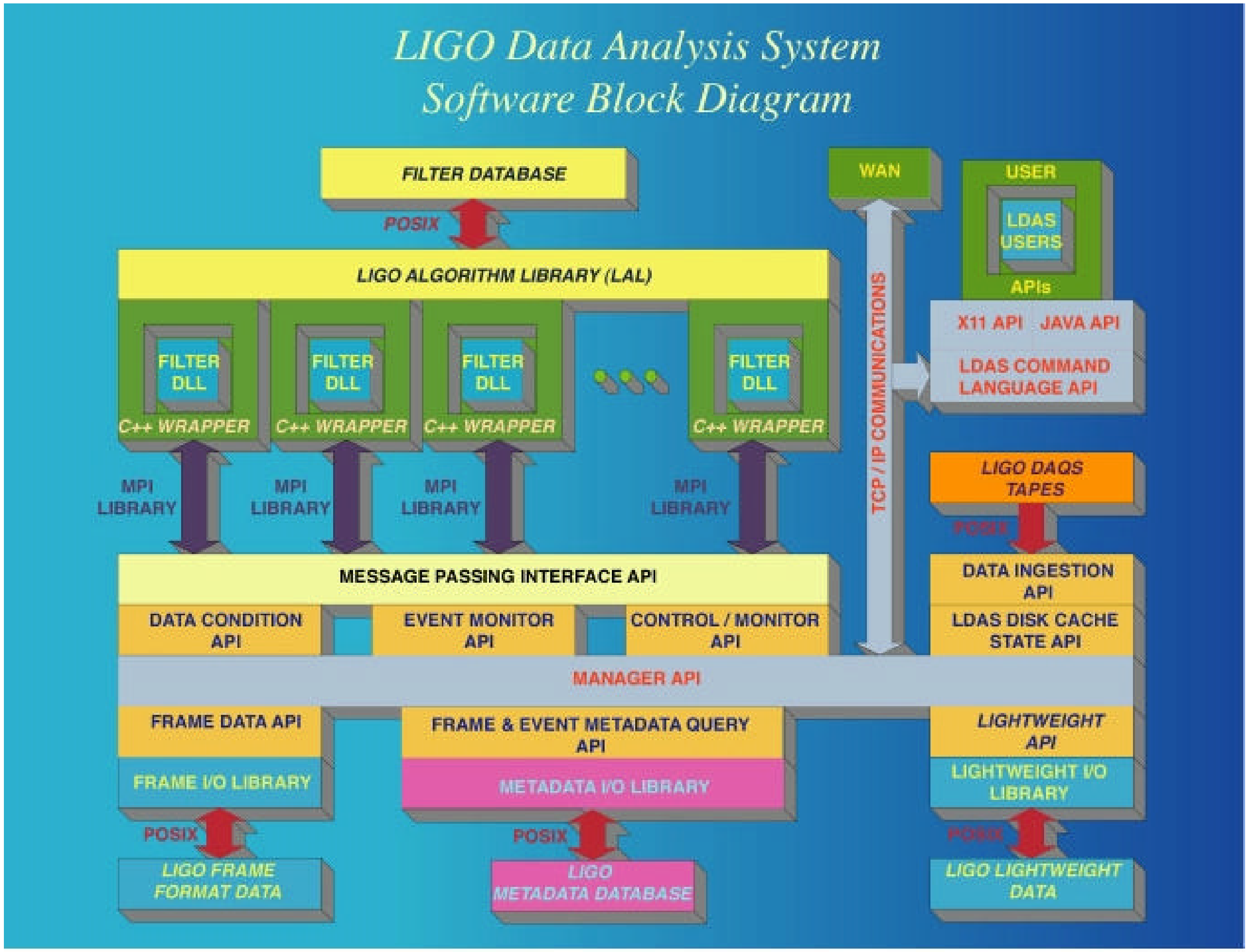
- **LDAS components (APIs) are separate unix processes**
  - Run on several different machines (distributed).
  - Socket-based job control and data transmission.
- **The LDAS Manager controls job scheduling, as well as the sequence of component operations for each job**

Components are written in Tcl and C++

Tcl is used for job control, inter-process communication, and high-level operations.

CPU-intensive operations on data objects are implemented in C++, called from the Tcl layer.

LDAS Software Components



12 Distributed Processes
- **managerAPI**
- **diskCacheAPI**
- **dataIngestionAPI**
- **frameAPI**
- **metaDataAPI**
- **lightWeightAPI**
- **dataConditionAPI**
- **mpiAPI**
- **wrapperAPI**
- **eventMonitorAPI**
- **controlMonitorAPI**

(*Server & Client*)

8 Shared Libraries

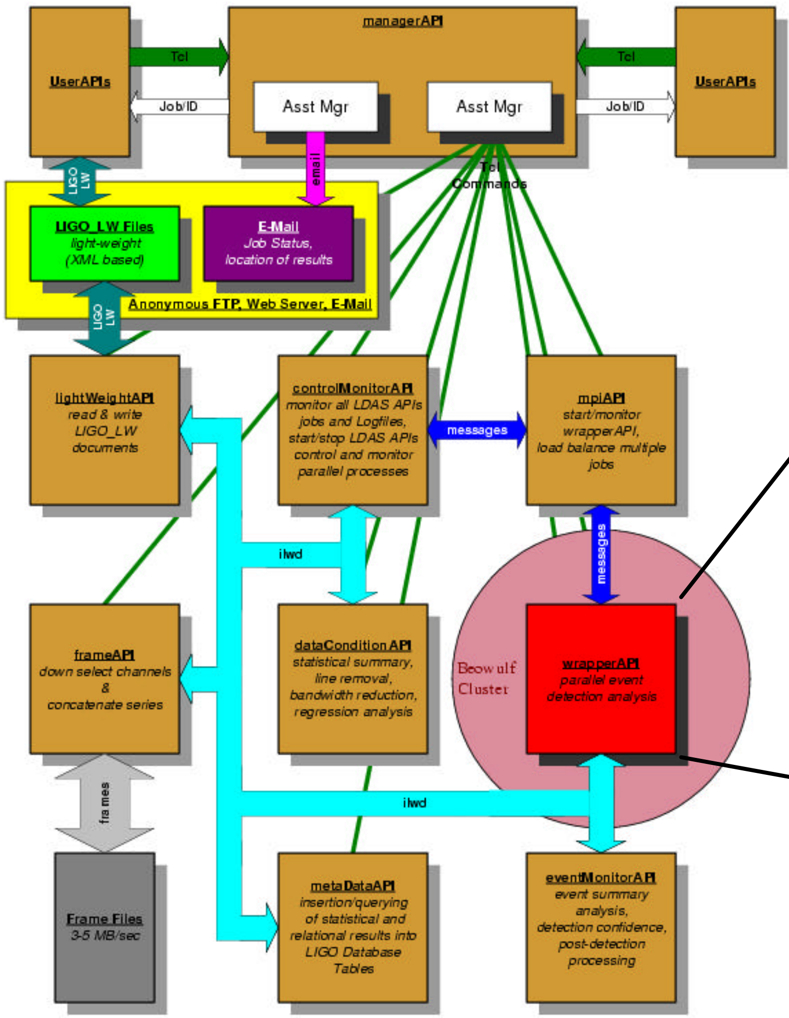
1 Relational Database
- **IBM's DB2**

5 SMP Class Servers
- **3 Sun**
- **2 PC Linux**

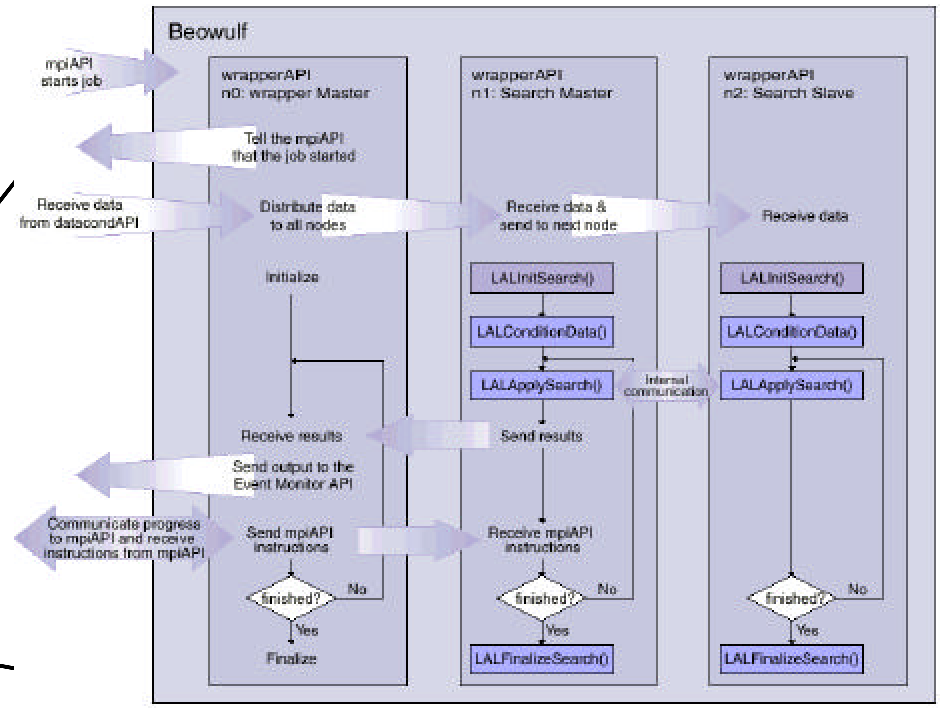
~100 Beowulf Nodes

Can be run on a laptop!

Plug-In for Scientific Codes



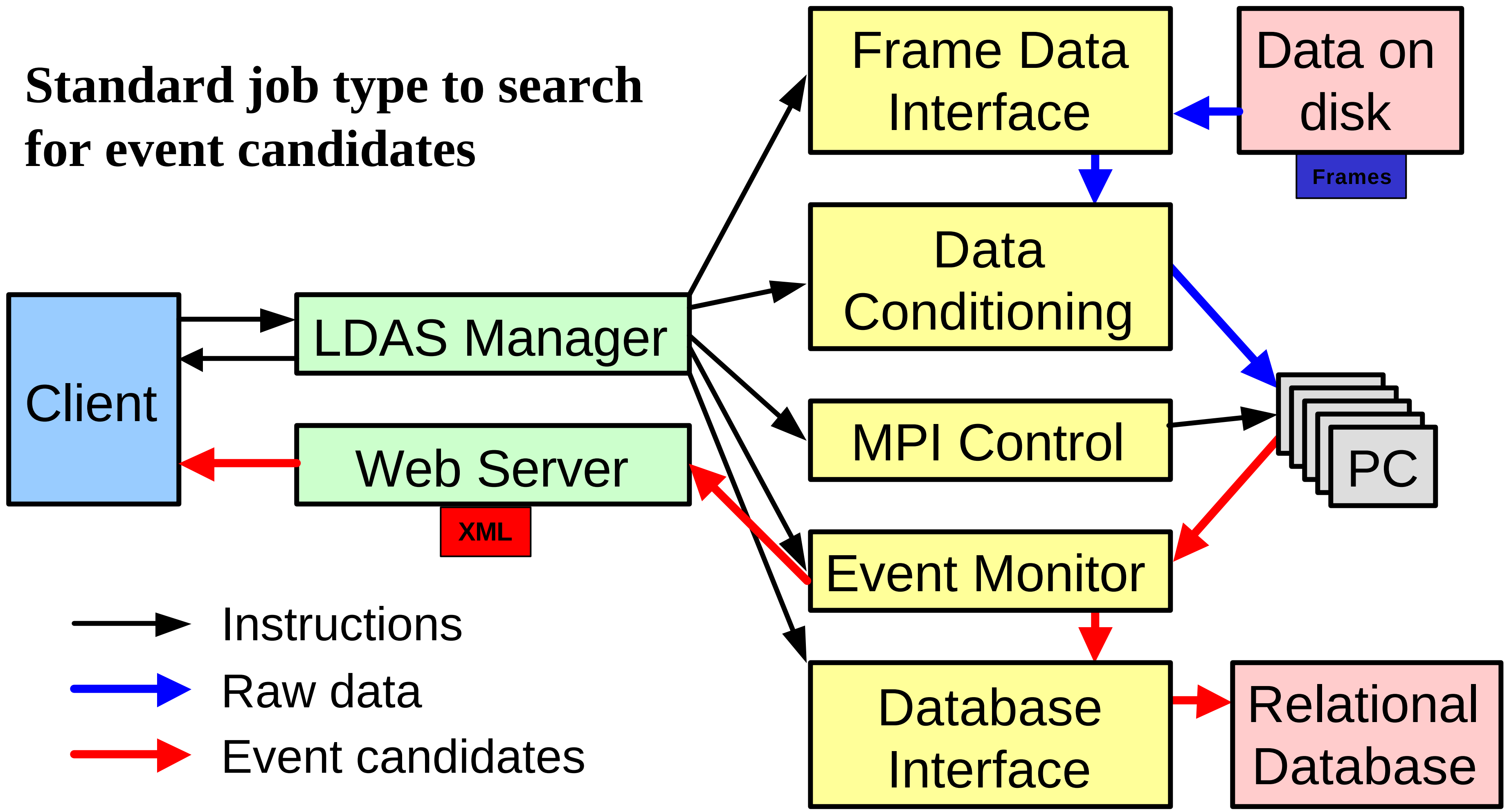
Parallel algorithms using MPI



Search algorithms dynamically loaded at runtime!

Simplified Job Flow:
LDAS DataPipeline

Standard job type to search for event candidates



LIGO Engineering Runs

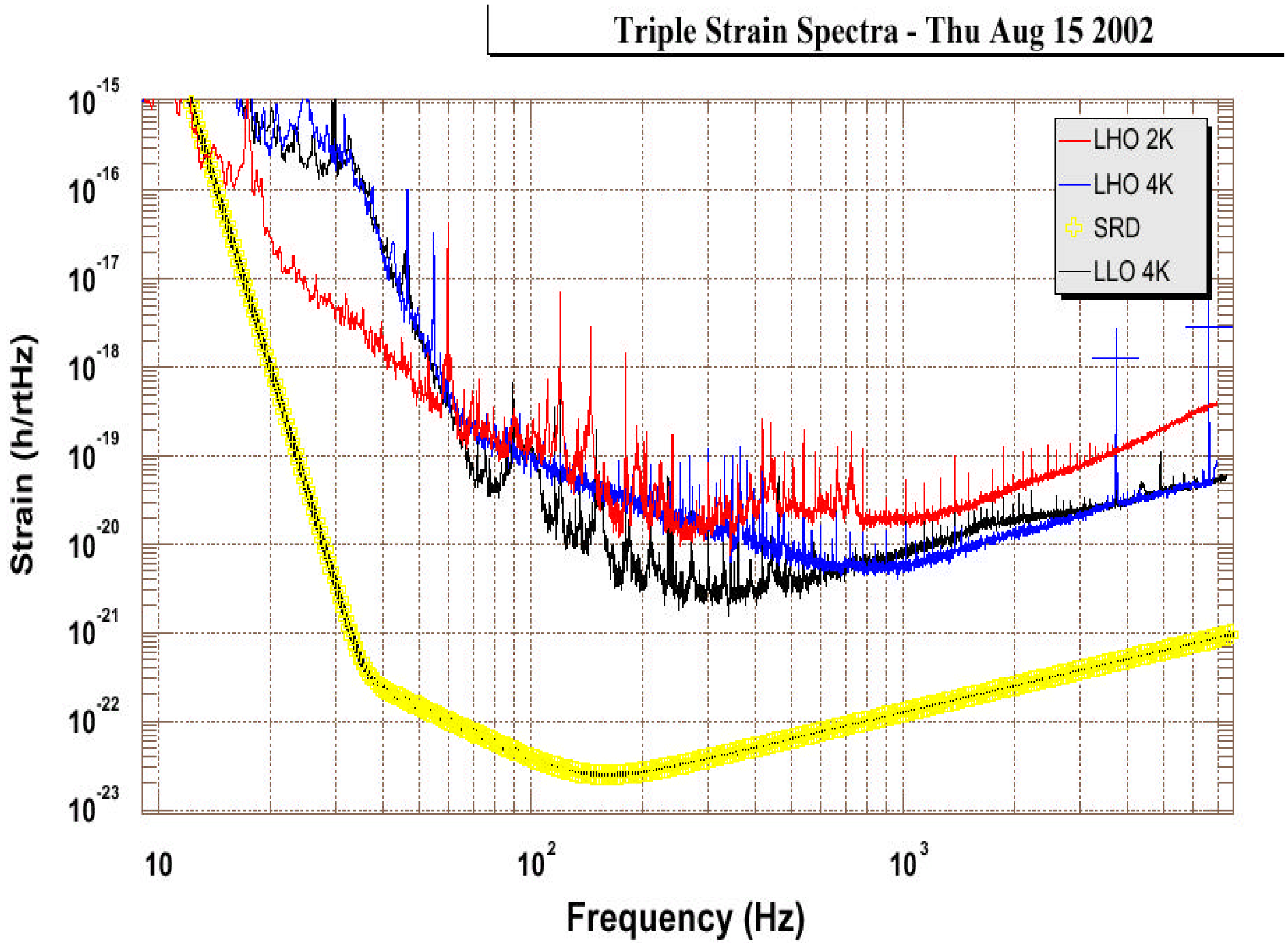
- Commissioning gravitational wave interferometers (IFOs) is tricky business!
  - First - get the IFO's to operate in the correct configuration, with all optical cavities resonating – "***In Lock***".
  - "First Lock" achieved at H2K on October 1999.
- Next - reduce the noise - improve sensitivity.
  - LIGO has had 8 engineering runs.
  - Engineering Run 7 (E7): (Dec 28th – Jan 14th, 2002) All 3 IFOs operated together.
- First Science Run (S1) "*Upper Limits Run*": (Aug 23rd – Sept 9th, 2002)
  - Post run data analysis currently underway by LSC sub-groups:
    - Binary inspiral upper limits group
    - Burst upper limits group
    - Stochastic gravitational wave background upper limits group
    - Periodic sources (pulsar) upper limits group.

LIGO Sensitivity Start of S1

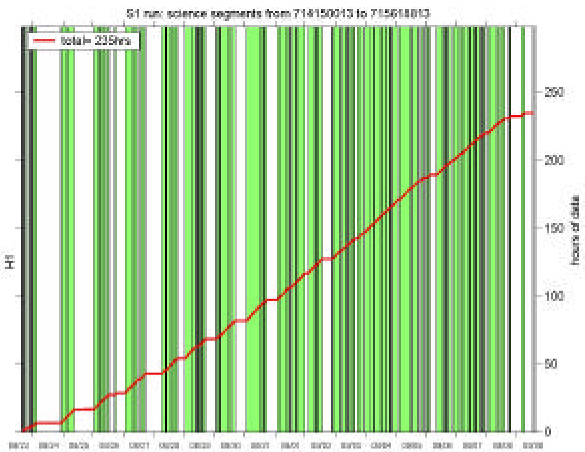
LIGO
S1 Run

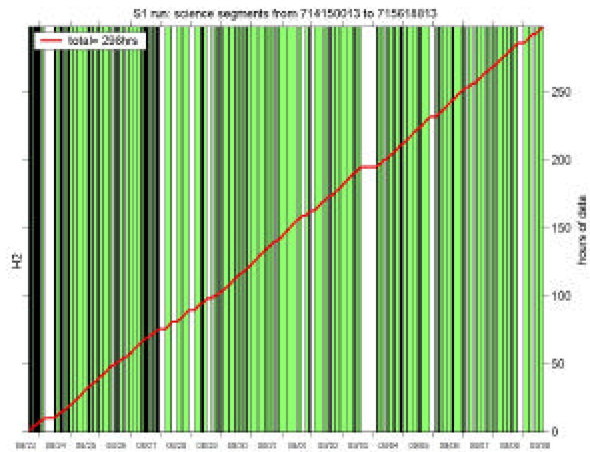
"First Upper Limit Run"

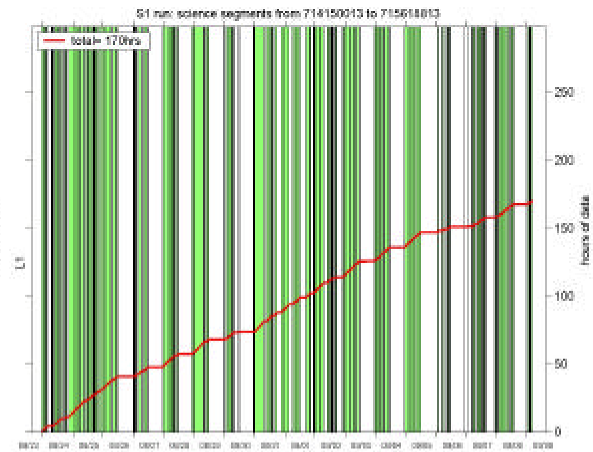
Aug – Sept 02



In-Lock Data from S1

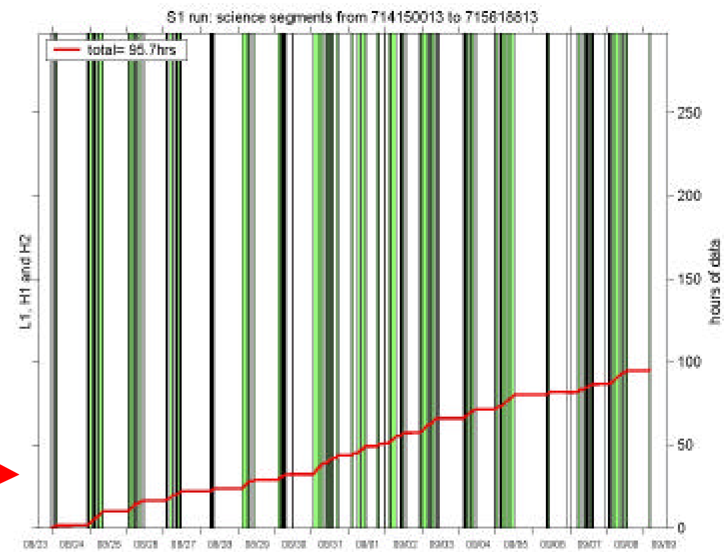






Livingston 4km: 170 hrs of lock
Hanford 4km: 235 hrs of lock
Hanford 2km: 298 hrs of lock

Triple Coincidence: <u>95.7 hrs</u> →



Data Analysis During S1

Science Run I:	*08/23/02 12:00:00 PDT - 09/10/02 12:00:00 PDT*								
		LHO			LLO			MIT	
User Command	Submitted	Failed	%	Submitted	Failed	%	Submitted	Failed	%
createRDS	18538	187	1	18413	42	0.2	58974	64	0.1
dataPipelines	28744	1866	6.5	8095	1044	13	2031	634	31
inspiral	13706	873	6.4	2464	482	19	0	0	0
power	5417	106	2	2003	7	0.4	167	15	9
slope	4829	387	8	1885	354	19	215	22	10
tfcluster	4787	495	10	1739	197	11	560	27	4.8
stochastic	0	0	0	0	0	0	93	71	76
exttrig	0	0	0	0	0	0	715	468	65
cohere	0	0	0	0	0	0	244	9	3.7
wave	0	0	0	0	0	0	11	9	82
correlation	0	0	0	0	0	0	3	0	0
no dso	0	0	0	0	0	0	23	13	56
getMetaData	9030	23	0.3	4987	111	2.2	67	0	0
putMetaData	24202	12	0.1	9725	15	0.2	0	0	0
All Jobs	109253	3949	3.5	49311	2252	4.4	63103	1332	2.1

Database	LHO	LLO	MIT	Total
Rows Inserted	2864599	4442117	797	7307513
Rows Quered	18090	8453	94	26637

- **Averaged approximately *one job every 5 seconds*.**
- **Averaged approximately *five rows inserted each second*.**
- **No Detections!**
- **Upper limits analysis underway – results expected by end of year.**

Summary

- **LIGO had extremely successful first science run this summer!**
  - **LSC Upper Limits Groups currently carrying out the data analysis!**
- **LIGO is taking its first steps to providing new scientific insight into the workings of the Universe.**
- **To learn more visit us on the web:**

http://www.ligo.caltech.edu

http://www.ligo.org

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