The Laser Interferometer Gravitational-Wave Observatory

General Relativity...

Astrophysics...

http://www.ligo.caltech.edu

Einstein...

A new window...

Supported by the United States National Science Foundation

LIGO Data Analysis Software & Systems

Gregory Mendell, LIGO Hanford Observatory

On behalf of the LIGO Science Collaboration

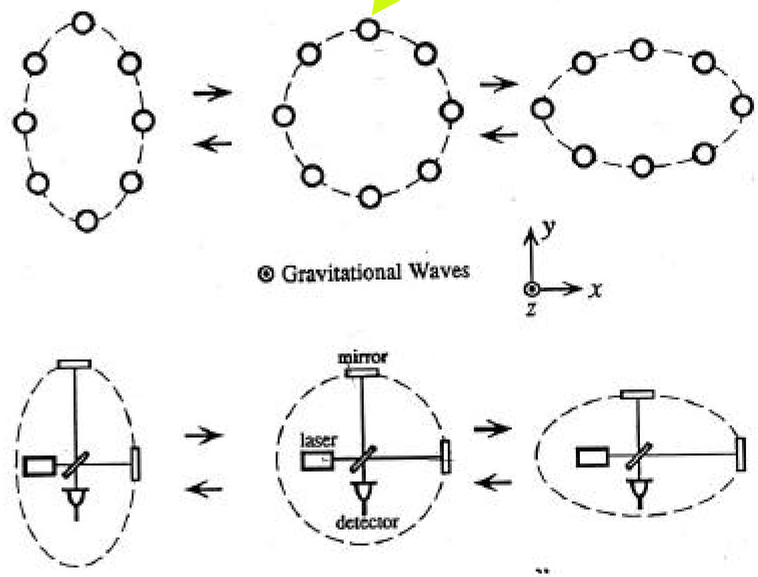
LIGO-G030532-00-W

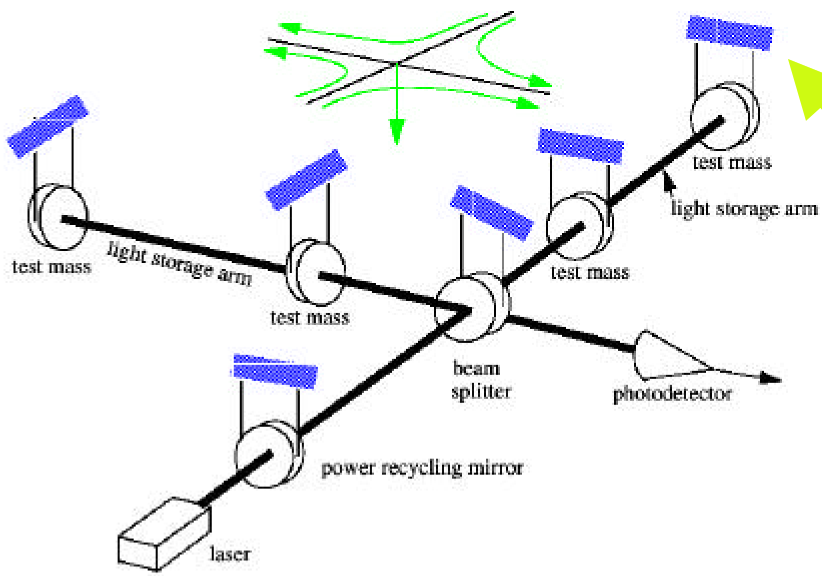
Terrestrial Interferometers

Mission:Gravitational Wave Searches ($h_{rms} \sim 10^{-21}$)

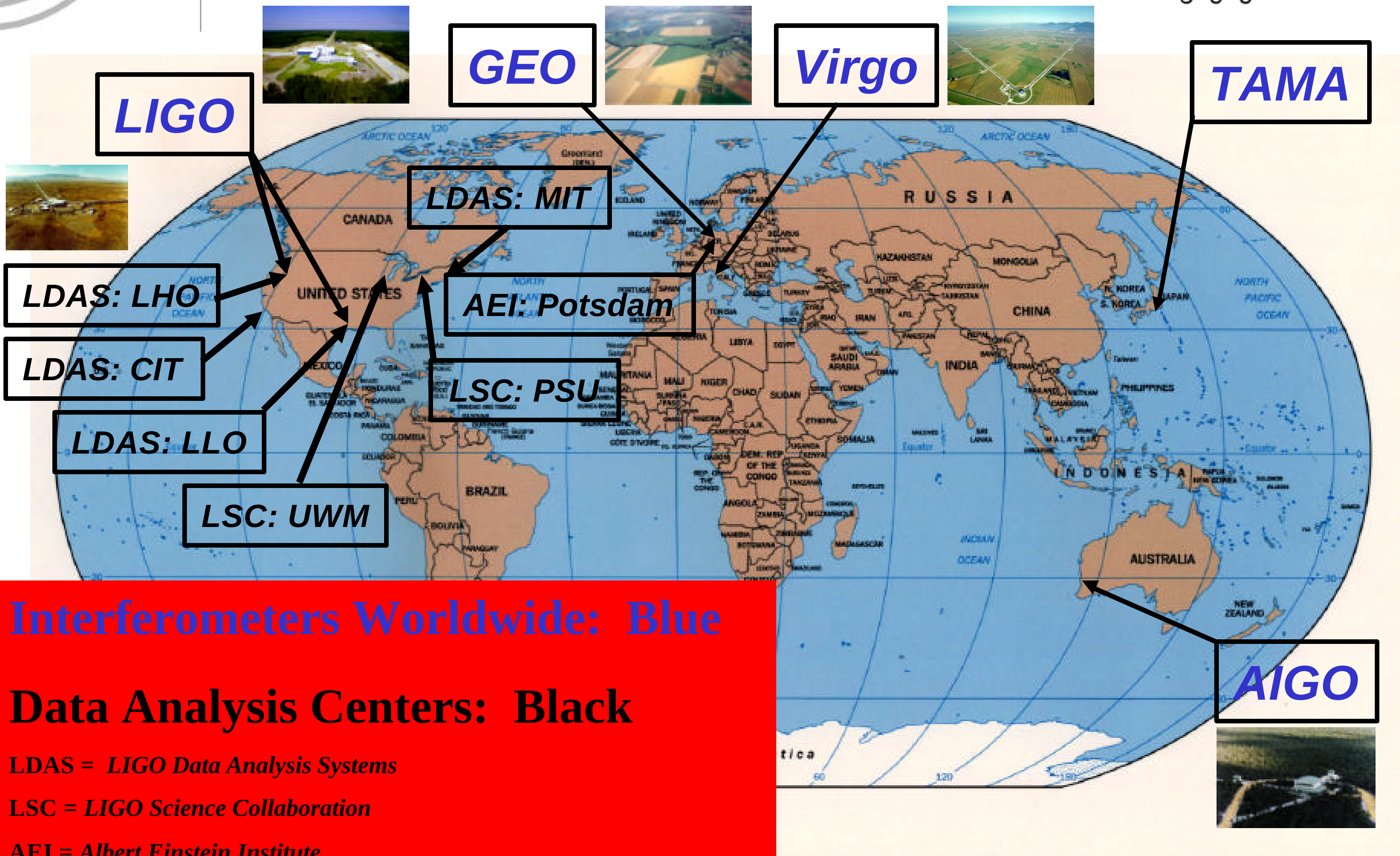
free masses

International network (LIGO, Virgo, GEO, TAMA) of suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources





suspended test masses



Interferometers Worldwide: Blue

Data Analysis Centers: Black

LDAS = *LIGO Data Analysis Systems*

LSC = *LIGO Science Collaboration*

AEI = *Albert Einstein Institute*

LDAS Sites & Hardware

- LDAS: CIT
  - 280 dual-CPU nodes (2GHz Xeon + 2 GB memory)
  - 10s of TBs of disk space
  - GigE network
  - Plus systems for development and testing:
    - LDAS-SW
    - LDAS-DEV
    - LDAS-TEST
- LDAS: LHO
  - 140 dual-CPU nodes (2GHz Xeon + 2 GB memory)
  - 17 TB disk space
  - GigE network

- LDAS: MIT
  - 112 dual-CPU nodes (2GHz P4 + 512 MB memory)
  - TBs of disk space
  - GigE network
- LDAS: LLO
  - 70 dual-CPU nodes (2GHz Xeon + 2 GB memory)
  - 10 TB disk space
  - GigE network

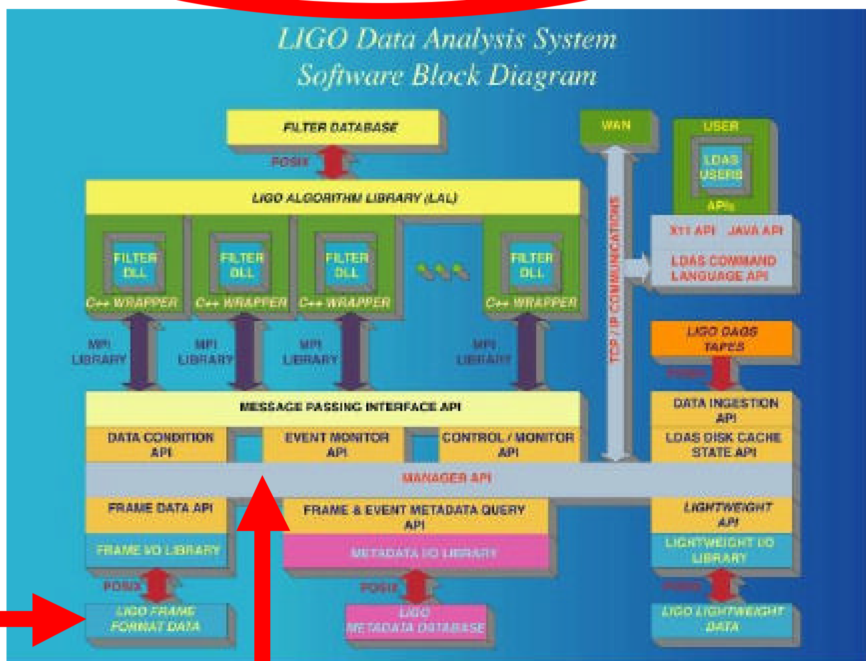
Many 100s of TBs Tape Storage.

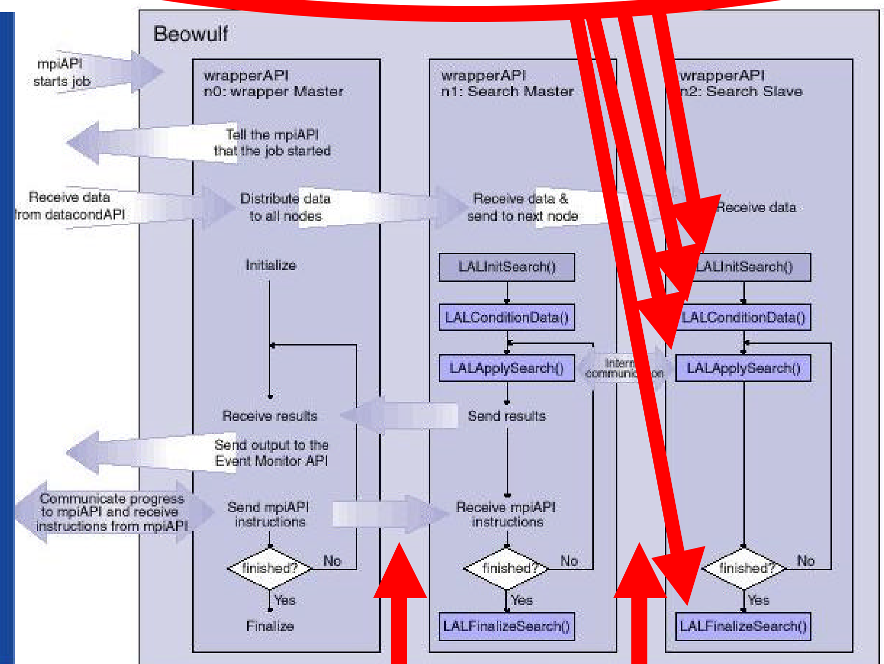
(LIGO outputs 1 TB/day!)

LDAS Software: 0.8.0 due Oct 2003

I/O to IBM DB2 database and disk

Scientist writes 4 functions loaded dynamically at runtime:





Manager controls request for jobs coming in from the Internet

MPI communication between nodes

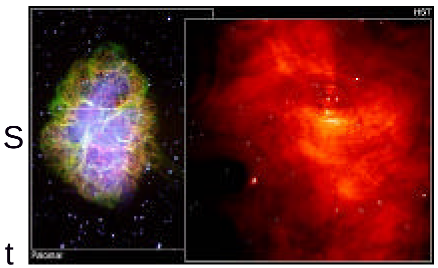
LSC Hardware

- Medusa cluster (UWM)
  - 296 single-CPU nodes (1GHz PIII + 512 Mb memory)
  - 58 TB disk space
- Merlin cluster (AEI)
  - 180 dual-CPU nodes (1.6 GHz Athlons + 1 GB memory)
  - 36 TB disk space

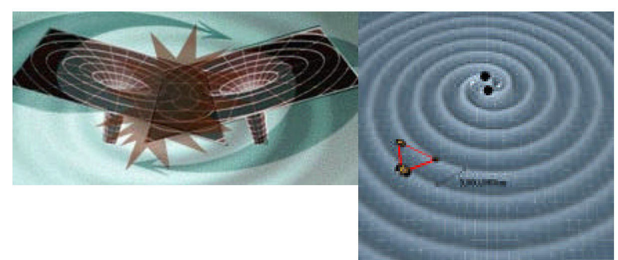
LIGO and Grid Computing

- Revealing the full science content of LIGO data is a computationally and data intense challenge
  - Several classes of data analysis challenges ***require*** large-scale computational resources

- Search for gravitational wave (GW) analogs of electromagnetic (EM) pulsars
  - GW sources not likely to have EM counterparts
    - Fast (millisecond) EM pulsars are stable, old neutron stars (NS)
  - GW emission likely to come shortly after birth of a rapidly rotating (deformed, hot) NS
  - GW sky is **unknown**
    - Searches will need to survey a large parameter space
  - All-sky search for previously unidentified periodic sources requires > 10^{15} floating point operations per second (FLOPS)



- Coalescence of compact binary systems ("inspiral chirps") which include spin-spin interactions will cover a huge parameter space (~ 10^{6} greater than spinless systems)
  - Important for more massive systems
  - Massive systems have greater GW luminosities
  - Likely to be the first detected



- **These analyses are ideally suited for distributed (grid-based) computing**

The LSC DataGrid
A Part of iVDGL, Grid2003, and GriPhyN

http://www.lsc-group.phys.uwm.edu/lscdatagrid/software.html
http.ivdgl.org; http://www.ivdgl.org.grid2003; http:://www.grphyn.org;

Data Intensive Science

What is the LSC DataGrid?

The LSC DataGrid is the combination of LSC computational and data storage resources with so called "Grid Computing middleware" to create a coherent and uniform LIGO data analysis environment.

More specifically, the LSC DataGrid is the combination of

•Linux clusters at the Tier-1 site Caltech

•Linux clusters at Tier-2 sites UW-Milwaukee and PSU

•Linux clusters at Tier-3 sites UT-Brownsville and Salish Kootenai College (SKC)

•Linux clusters at GEO sites Cardiff and the Albert Einstein Institute (AEI)

•LDAS instances at Caltech, MIT, PSU, and UWM

•Condor pools at Caltech, UWM, Cardiff, AEI, and UTB

•Data storage at each of the sites

Algorithm and Support Software:

•LIGO/LSC Algorithms Library (LAL) (*http://ww.lsc-group.phys.uwm.edu/lal/index.html)*

•LIGOtools (*http://www.ldas-sw.ligo.caltech.edu/ligotools/)*

Recent News:

•**9/25/2003**: A first draft of some LSC DataGrid details is available. See also the links under "DataGrid Details" on the left.

•**8/14/2003**: Version 1.0 of the LSC DataGrid Client software package is available for download. It includes a Grid-enabled OpenSSH client, Grid-enabled FTP client, Condor and CondorG for submitting jobs onto the LSC DataGrid, and LSCdataFind. It is built on top of the Virtual Data Toolkit (VDT) from the GriPhyN and iVDGL projects. LSC scientists who want to begin using grid tools should install this package on their workstations or laptops.

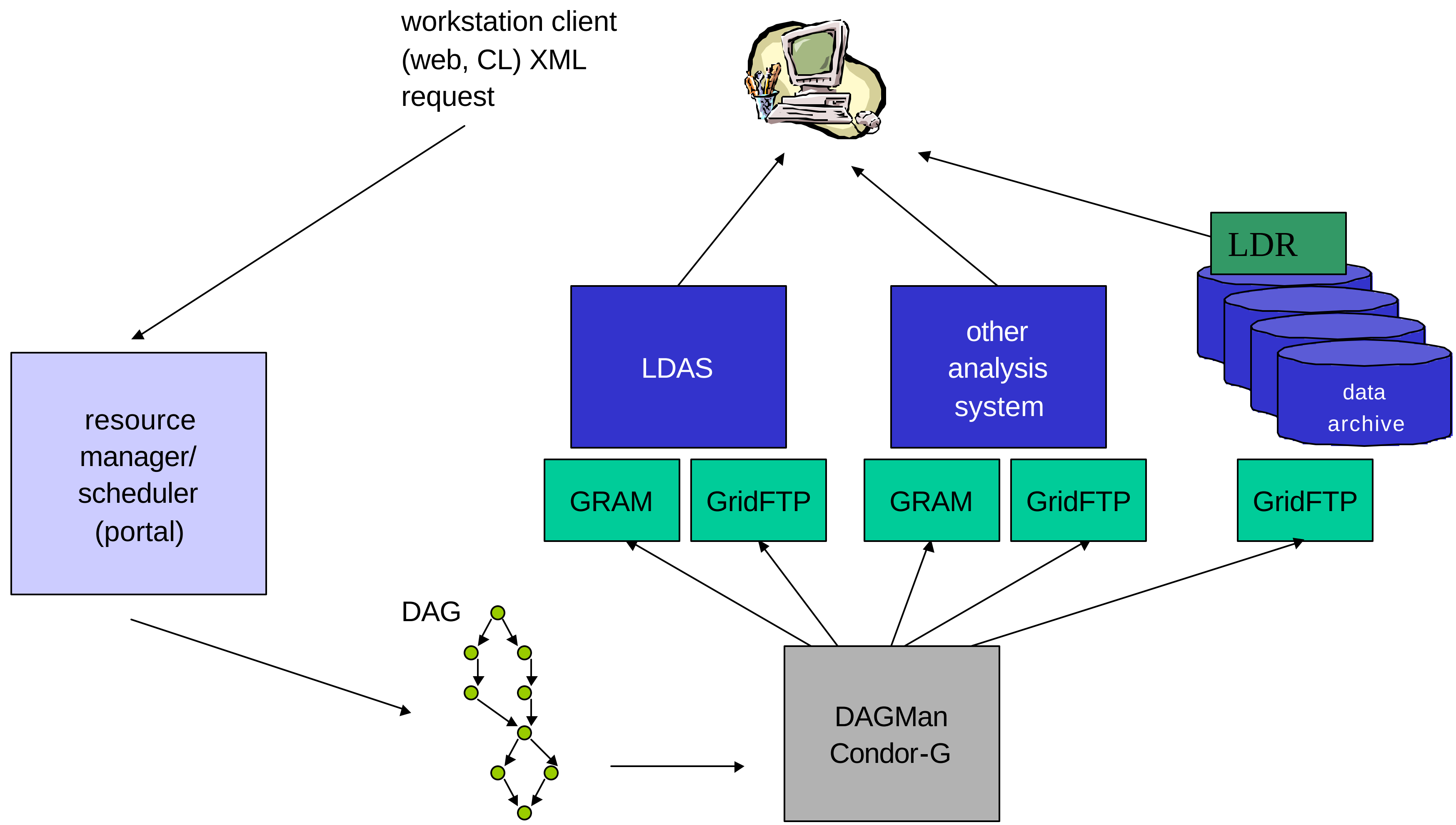
8/12/2003: Version 1.0 of the LSC DataGrid Server software package is available for download. It is built on top of the Virtual Data Toolkit (VDT) from the GriPhyN and iVDGL projects. LSC DataGrid administrators should install this package.

Condor High Throughput Computing

http://www.cs.wisc.edu/condor/
Condor is a full featured parallel computing batch system.

LIGO-G030532-00-W

LSC DataGrid Details



LSC First Science Results ("S1")

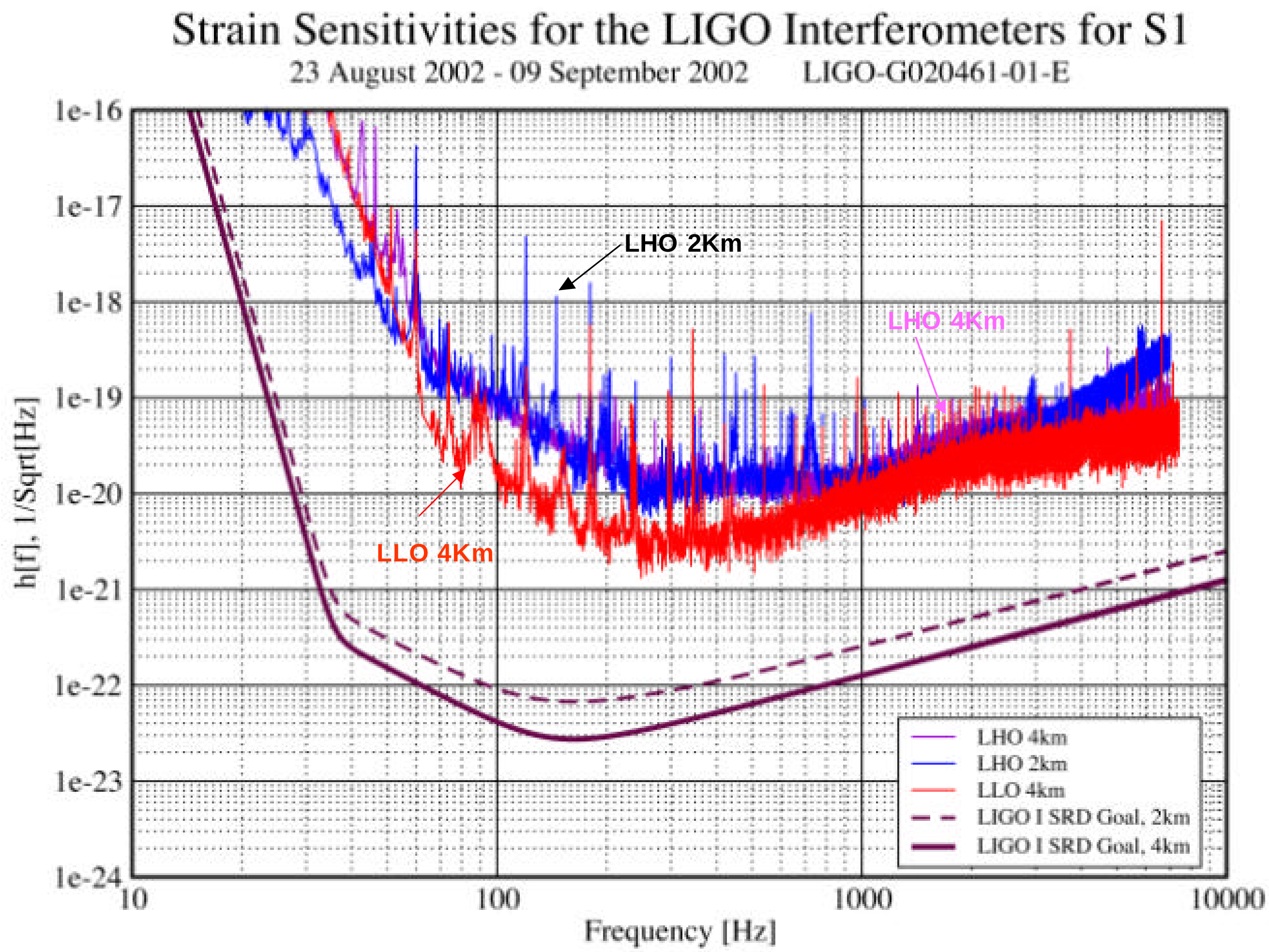
LIGO S1 Run

"First Upper Limit Run"

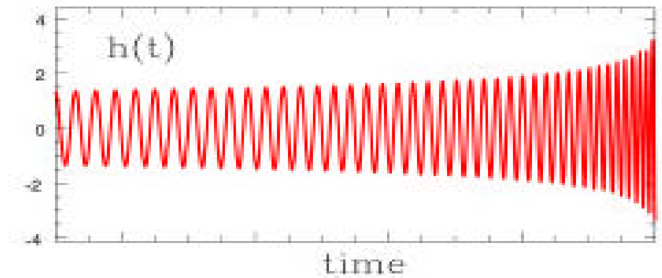
- 23 Aug–9 Sept 2002
- 17 days
- All interferometers in power recycling configuration

GEO in S1 RUN

Ran simultaneously
In power recycling
Lesser sensitivity



Results of the Inspiral Search



- Matched filter trigger:
  Threshold on SNR, and compute χ^2; t**hreshold on χ^2**, record trigger; triggers are **clustered** within duration of each template
- Auxiliary data triggers: **vetoes** eliminate noisy data

- Upper limit on binary neutron star coalescence rate
- Use all triggers from 214 hours data
  - Cannot accurately assess **background** (be conservative, **assume zero**).
  - Monte Carlo simulation **efficiency** = 0.51
  - 90% confidence limit = **2.3/ (efficiency * time).**
  - Express the rate as a rate per **Milky Way Equivalent Galaxies** (MWEG).

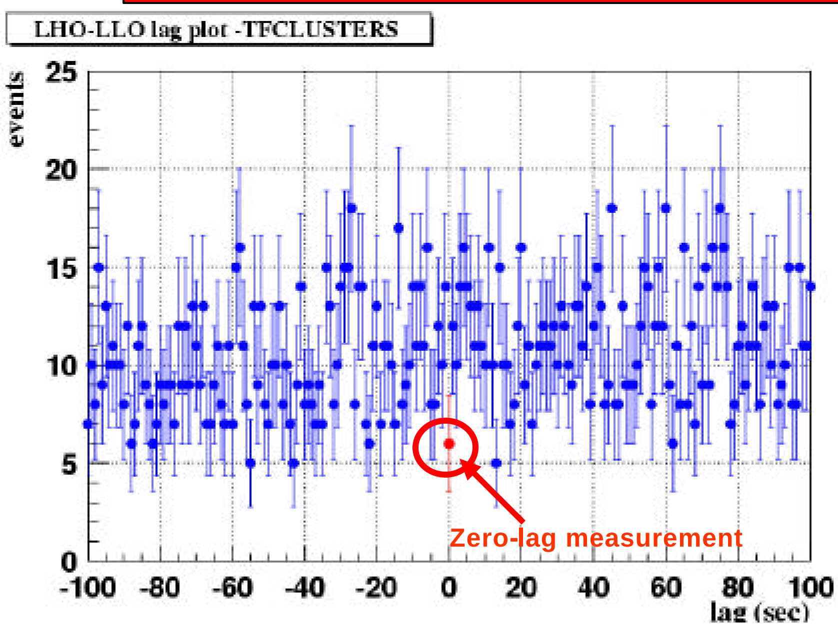
$R < 2.3 / (0.51 \times 214\ \mathrm{hr}) = 1.7 \times 10^2$ /yr/(MWEG)

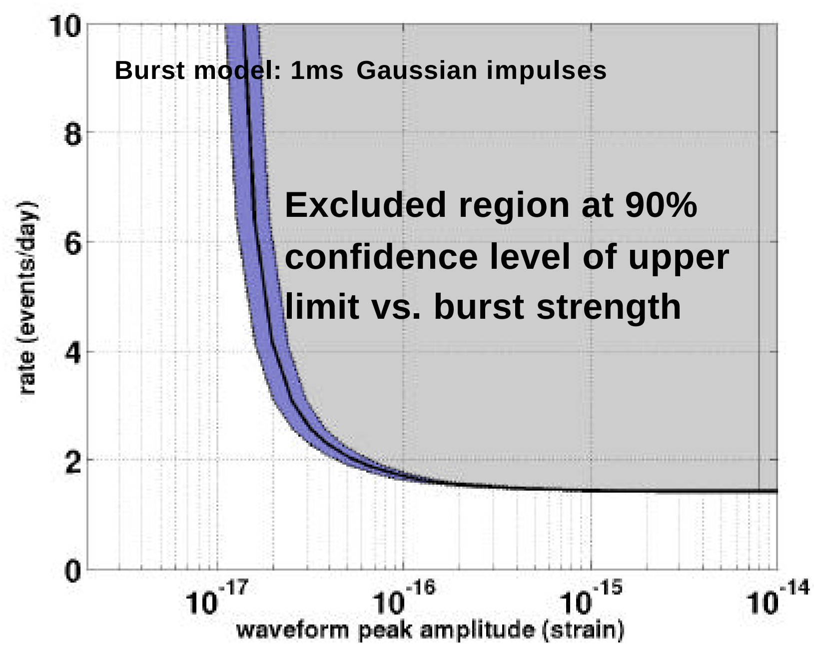
- Previous observational limits
  - Japanese TAMA → R < 30,000 / yr / MWEG ; Caltech 40m → R < 4,000 / yr / MWEG
- Theoretical prediction
  - $R < 2 \times 10^{-5}$ / yr / MWEG

Burst Search Results

- **Search method (generic, no templates):** A time-frequency domain algorithm (tfclusters) identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size).
- **End result** of analysis pipeline: **number of triple coincidence events.**
- Use **time-shift** experiments to establish number of **background events.**
- Use **Feldman-Cousins** to set **90%** confidence upper limits on rate of foreground events. result:

Upper Limit of < 1.6 Events/Day





Stochastic Search Results

- **Analysis goals:** **constrain** contribution of stochastic radiation's energy $\boldsymbol{r}_{GW}$ to the total energy required to close the universe $\boldsymbol{r}_{critical}$.
- **Method:** optimally filtered **cross-correlation** of detector pairs. Detector **separation** and **orientation** reduces correlations at high frequencies ($\lambda_{GW} \geq$ 2xBaseLine): **overlap reduction function**

=> H1-H2 cross-correlation contaminated by environmental noise (anticorrelation corresponds to –9.9 < h^2_{100} W_{GW} < -6.8)

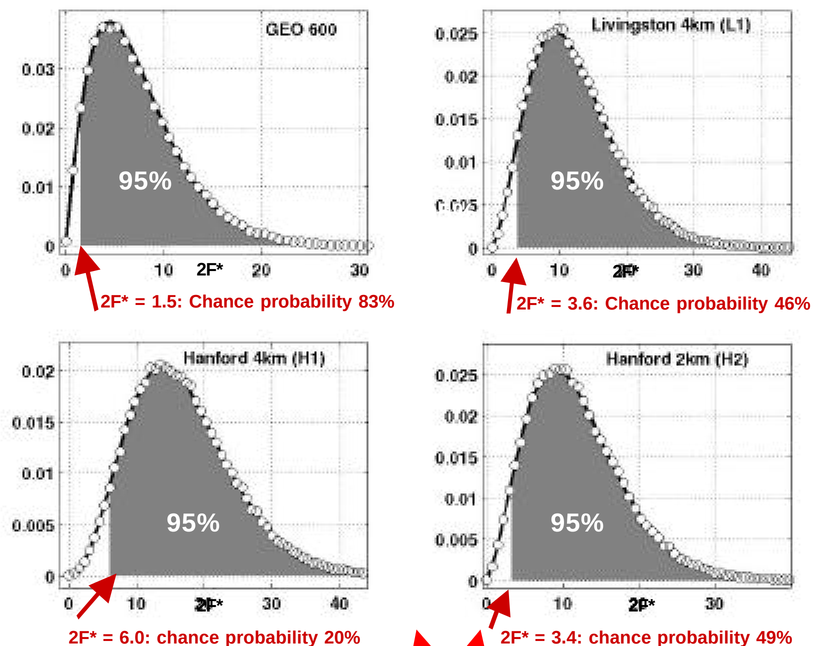
=> Limit from H2-L1 (with 90% confidence): $h^2_{100} W_{GW}$ (40Hz - 314 Hz) < 23±4.6

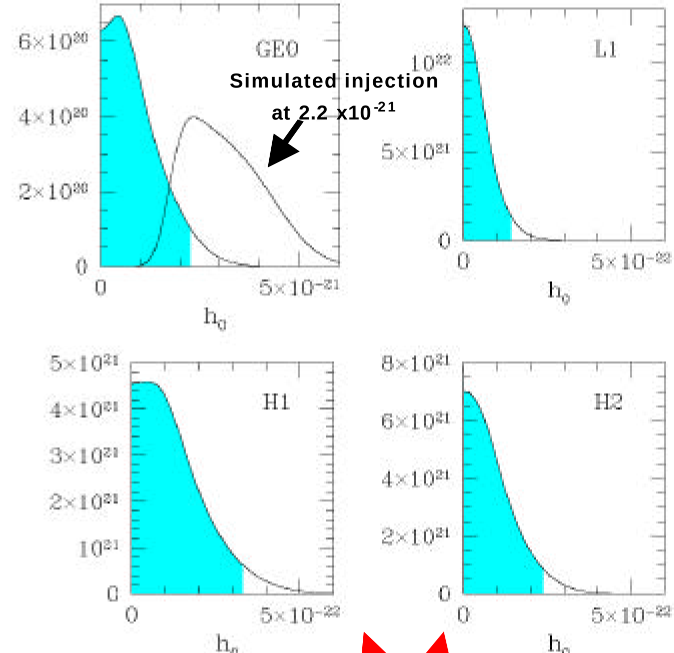
- Non-negligible LHO 4km-2km (H1-H2) cross-correlation; currently being investigated.
- Previous best upper limits:
  - *Measured:* Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times10^{5}$
  - *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907Hz) < 60$

Limits on Periodic GWs from 2nd Harmonic of Pulsar J1939+2134

$h_o < 1.4\times10^{-22}$ constrains ellipticity $< 2.9 \times 10^{-4}$ (I = 1E45 gcm^2)

$h_0 < $ 1.9E-21 | $h_0 < $ 2.7E-22 | $h_0 < $ 2.2E-21 | $h_0 < $ 1.4E-22





$h_0 < $ 4.0E-22 | $h_0 < $ 5.4E-22 | $h_0 < $ 3.3E-22 | $h_0 < $ 2.4E-22

Frequentist Distributions of Log Maximum Likelihood Estimator 2F

Previous results for PSR J1939+2134: **$h_o < 10^{-20}$** (Glasgow, Hough et al., 1983), **$h_o < 1.5\times10^{-17}$** (Caltech, Hereld, 1983).

Bayesian Distributions of Posterior PDF for h_0 for uniform priors

LIGO Science Has Started

- **Second science run** (“S2”): February 14 – April 14 2003
  - Sensitivity was ~10x better than S1
  - Duration was ~ 4x longer
  - Expectations:
    - Bursts: rate limits: 4X lower rate & 10X lower strain limit
    - Inspirals: reach will exceed 1Mpc -- includes M31 (Andromeda)
    - Stochastic background: limits on $\Omega_{GW} < 10^{-2}$
    - Periodic sources: limits on $h_{max} \sim$ few x 10^{-23} ($\varepsilon \sim$ few x 10^{-6} @ 3.6 kpc)
- **Third science run** (“S3”): October 31 2003 – January 2004

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(Dated: August 18, 2003)

Data collected by the GEO600 and LIGO interferometric gravitational wave detectors during their first observational science run were searched for continuous gravitational waves from the pulsar J1939+2134 at twice its rotation frequency. Two independent analysis methods were used and are demonstrated in this paper: a frequency domain method and a time domain method. Both achieve consistent null results, placing new upper limits on the strength of the pulsar's gravitational wave emission. A model emission mechanism is used to interpret the limits as a constraint on the pulsar's equatorial ellipticity.

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