



## LIGO and I2U2:

# Making LIGO Physical Environment Data Available for Discovery-based Learning

Eric Myers

with Fred Raab and Dale Ingram

**LIGO Hanford Observatory**

**Hanford, Washington**

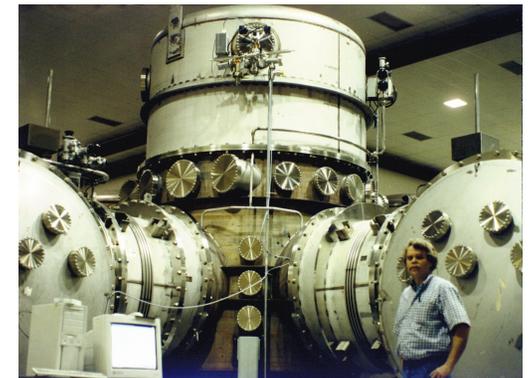
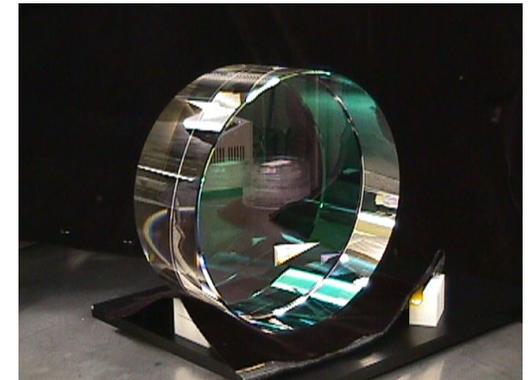
on behalf of the LIGO Scientific  
Collaboration

*"Physics in a New Light"*

*New York APS/AAPT Spring Symposium*

*West Point, New York*

*13-14 April 2007*





# Something for Everyone...



## Optics & Education

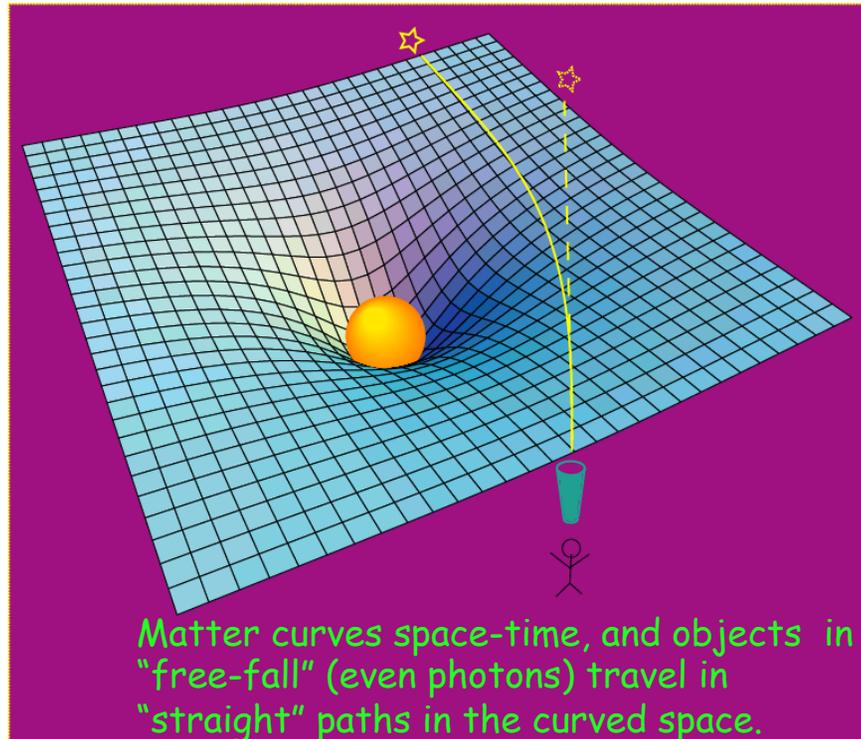
(for "Physics in a New Light", Joint NY APS/AAPT Spring Symposium 2007)

- LIGO interferometers are ultra-high precision optical devices  
(the largest on the planet, and largest optical instruments with their own overpass!)
- Operation of such ultra-high precision optics requires constant monitoring of the physical environment (seismic, magnetic, weather, ...)
- These data can be used by students and their teachers for discovery-based learning (real data, and possibly real research!)

## Astrophysics

(for "Recent Advances in Astrophysics", NY APS Fall Symposium 2007)

- LIGO seeks first to detect gravitational waves (non-optical waves), then
- To use gravitational waves (GW's) for astronomical observations



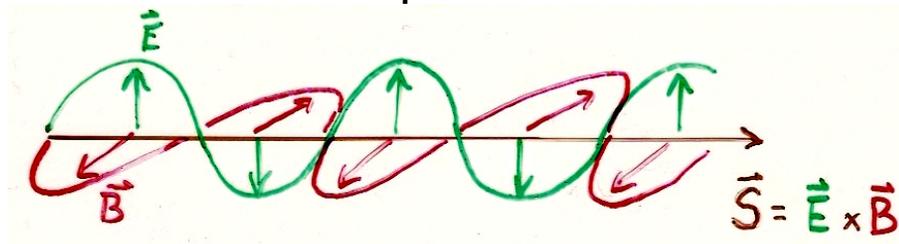
Rendering of space-time stirred by



Changes in space-time produced by moving a mass are not felt instantaneously everywhere in space, but propagates as a wave.

## Electromagnetic Waves

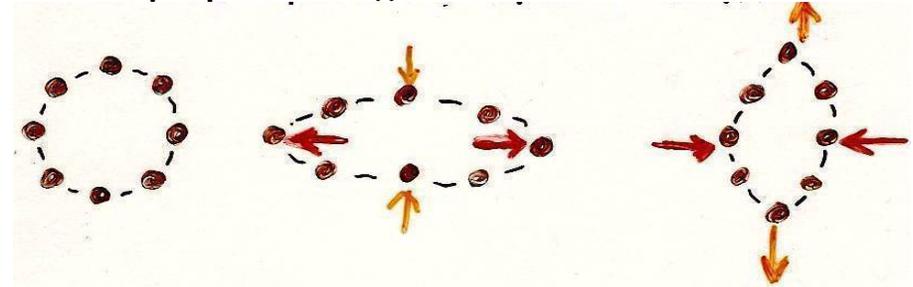
- Travel at the speed of light
- "transverse"
- Two polarizations: horizontal and vertical
- Vector - dipole in both E and B



- Solutions to Maxwell's Eqns.
- EM waves can be generated by a changing dipole charge distribution.

## Gravitational Waves

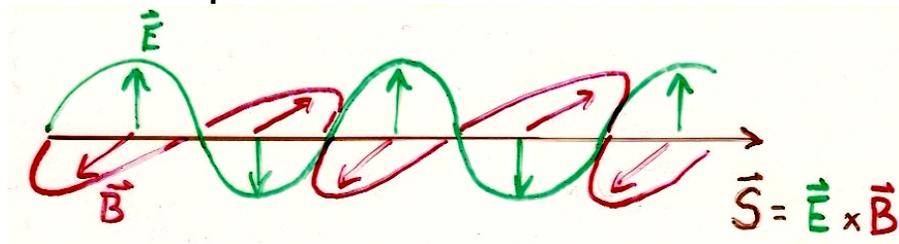
- Travel at the speed of light
- "transverse"
- Two polarizations, "+" and "x"
- Tensor - quadrupole distortions of space-time



- Solutions to Einstein's Eqns.
- Gravitational waves require a changing quadrupole mass distribution.

## Electromagnetic Waves

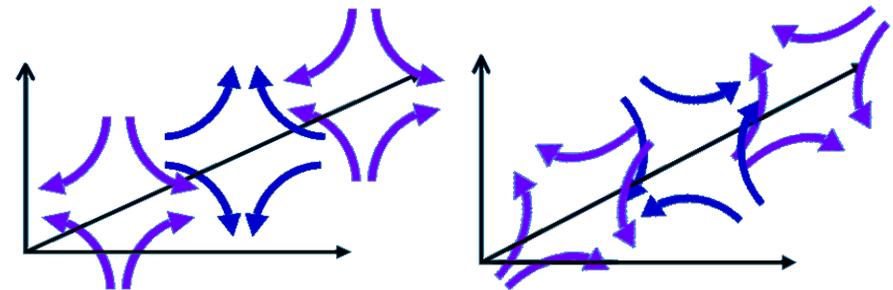
- Travel at the speed of light
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- Dipole in both E and B



- Solutions to Maxwell's Eqns.
- EM waves can be generated by a changing dipole charge distribution.

## Gravitational Waves

- Travel at the speed of light
- "transverse"
- Two polarizations, "+" and "x"
- Quadrupole distortions of space-time

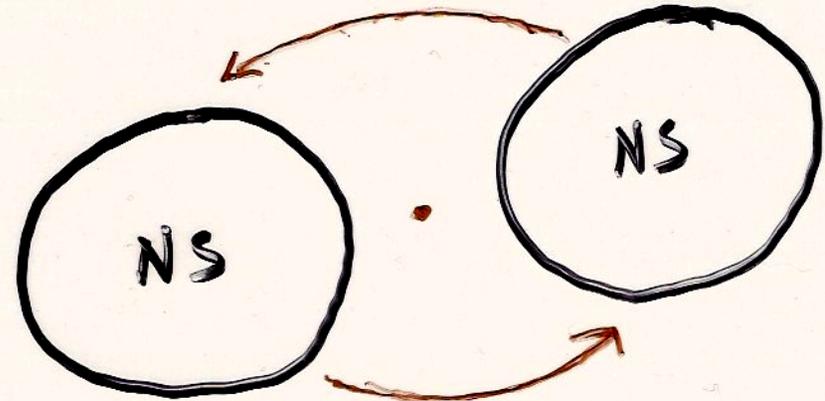


- Solutions to Einstein's Eqns.
- Gravitational waves require a changing quadrupole mass distribution.

A pair of  $1.4M_{\odot}$  neutron stars in a circular orbit of radius 20 km, with orbital frequency 400 Hz produces GW's (a strain of amplitude  $h = \Delta L/L$ ) at frequency 800 Hz.

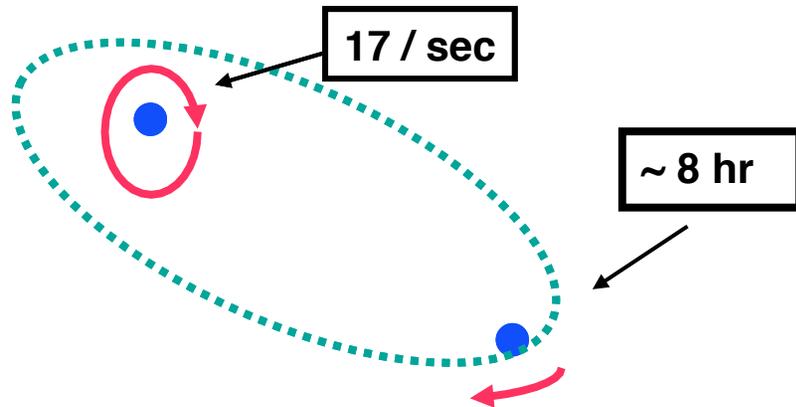
Wave frequency is twice the rotation frequency of binary.

(  $1.4M_{\odot}$  binary inspiral provides a useful translation from dimensionless strain  $h$  to “reach” of the instruments, in Mpc )



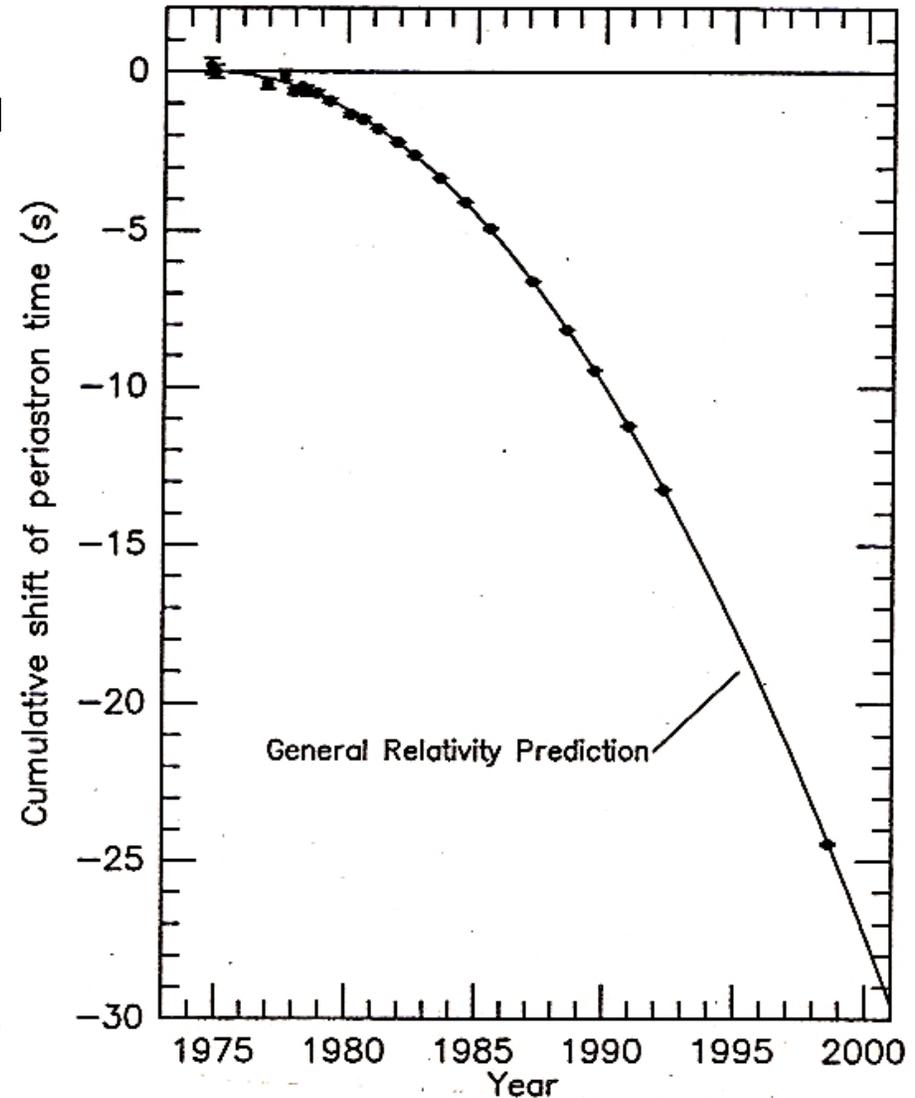
$$h \approx \frac{10^{-21}}{(r / 15 \text{ Mpc})}$$

Taylor and Hulse studied PSR1913+16 (two neutron stars, one a pulsar) and measured orbital parameters and how they changed:



The measured precession of the orbit exactly matches the loss of energy expected due to gravitational radiation.

(Nobel Prize in Physics, 1993)





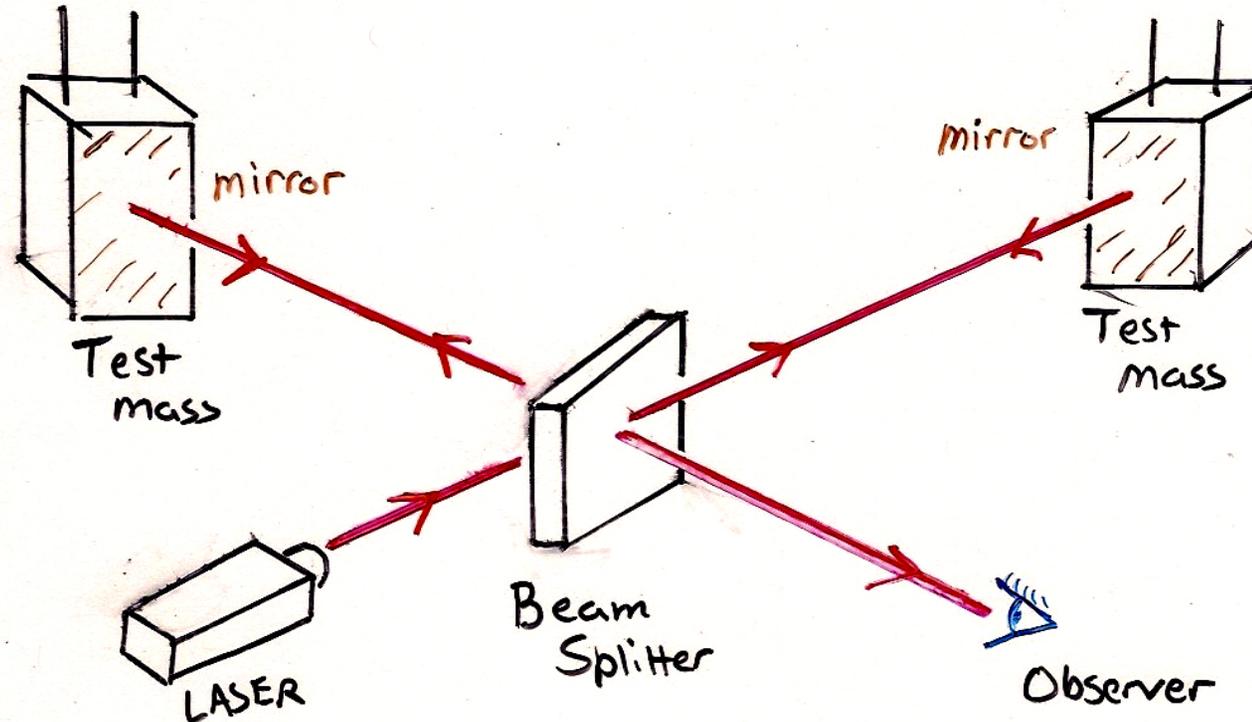
# How might GW's be produced?



Producing significant gravitational radiation requires a large change in the quadrupole moment of a large mass distribution.

The most likely astronomical sources are:

- 1) **Coalescence of binary systems**, such as the inspiral of pairs of neutron stars or black holes (NS-NS, NS-BH, BH-BH) *CHIRP!*
- 2) **Continuous Wave sources**, such as spinning (asymmetric!) neutron stars ("gravitational pulsars"), or body oscillations of large objects (neutron star "r-modes").
- 3) **Unmodeled Bursts from supernovae or other cataclysmic events** (spherical symmetric = no GW -- requires changing quadrupole!)
- 4) Stochastic background from the early universe (Big Bang! Cosmic Strings,...) - a "cosmic gravitational wave background" (CGWB)
- 5) **Something unexpected...!**



Measuring  $\Delta L$  in arms allows the measurement of the strain

$$h = \Delta L/L,$$

which is proportional to the gravitational wave amplitude  $h(t)$ .  
 (Larger  $L$  is better, and multiple reflections increase effective length.)

## Laser Interferometer Gravitational wave Observatory

LIGO Livingston Observatory (LLO)

Livingston Parish, Louisiana

L1 (4km)



LIGO Hanford Observatory (LHO)

Hanford, Washington

H1 (4km) and H2 (2km)

Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for ~ 500 LIGO Scientific Collaboration members worldwide.

# The LIGO Observatories

LIGO Hanford Observatory (LHO)

H1 : 4 km arms

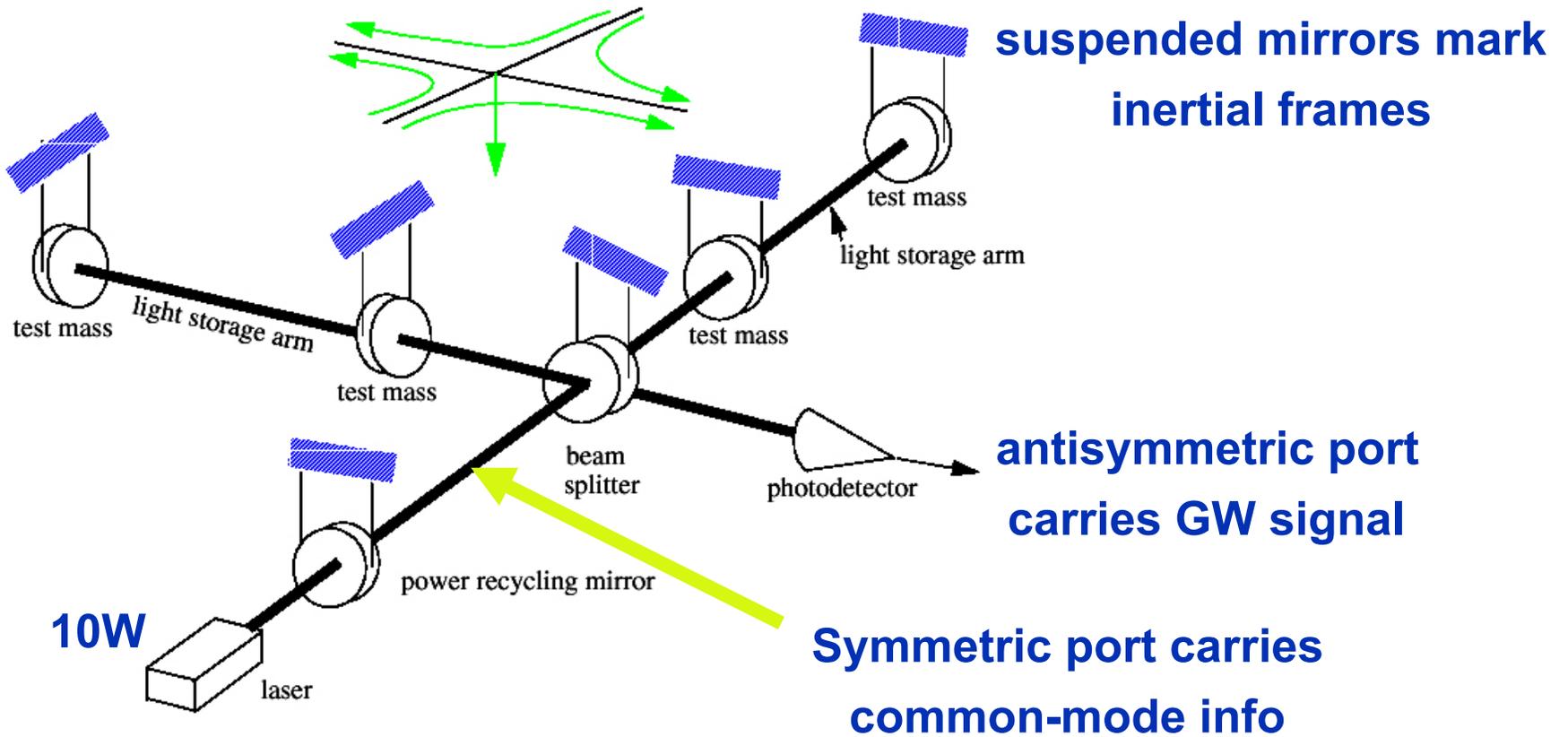
H2 : 2 km arms

10 ms

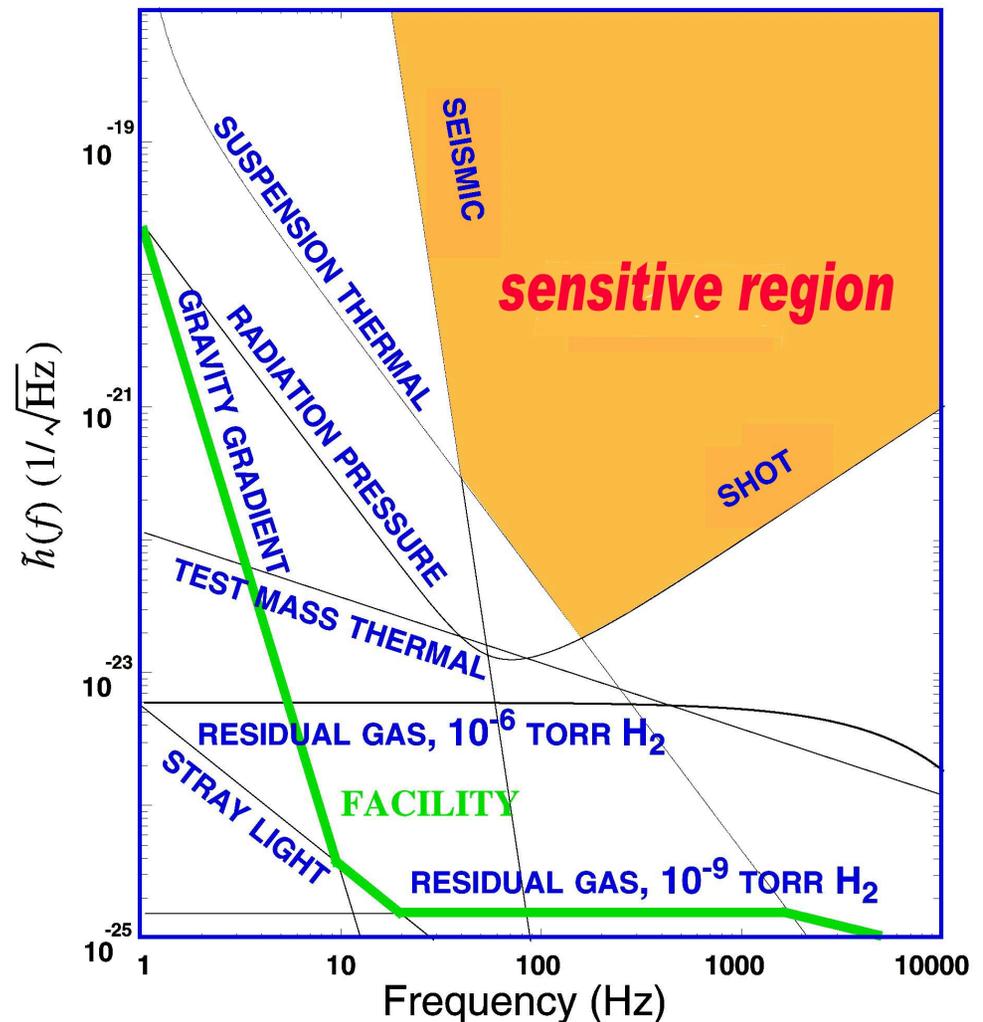
LIGO Livingston Observatory (LLO)

L1 : 4 km arms

- Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at [visibleearth.nasa.gov](http://visibleearth.nasa.gov)
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff



- ❑ Seismic noise & vibration limit at low frequencies
- ❑ Atomic vibrations (thermal noise) inside components limit at mid frequencies
- ❑ Quantum nature of light (*shot noise*) limits at high frequencies
- ❑ Myriad details of the lasers, electronics, etc., can make problems above these levels





# Technical Challenges

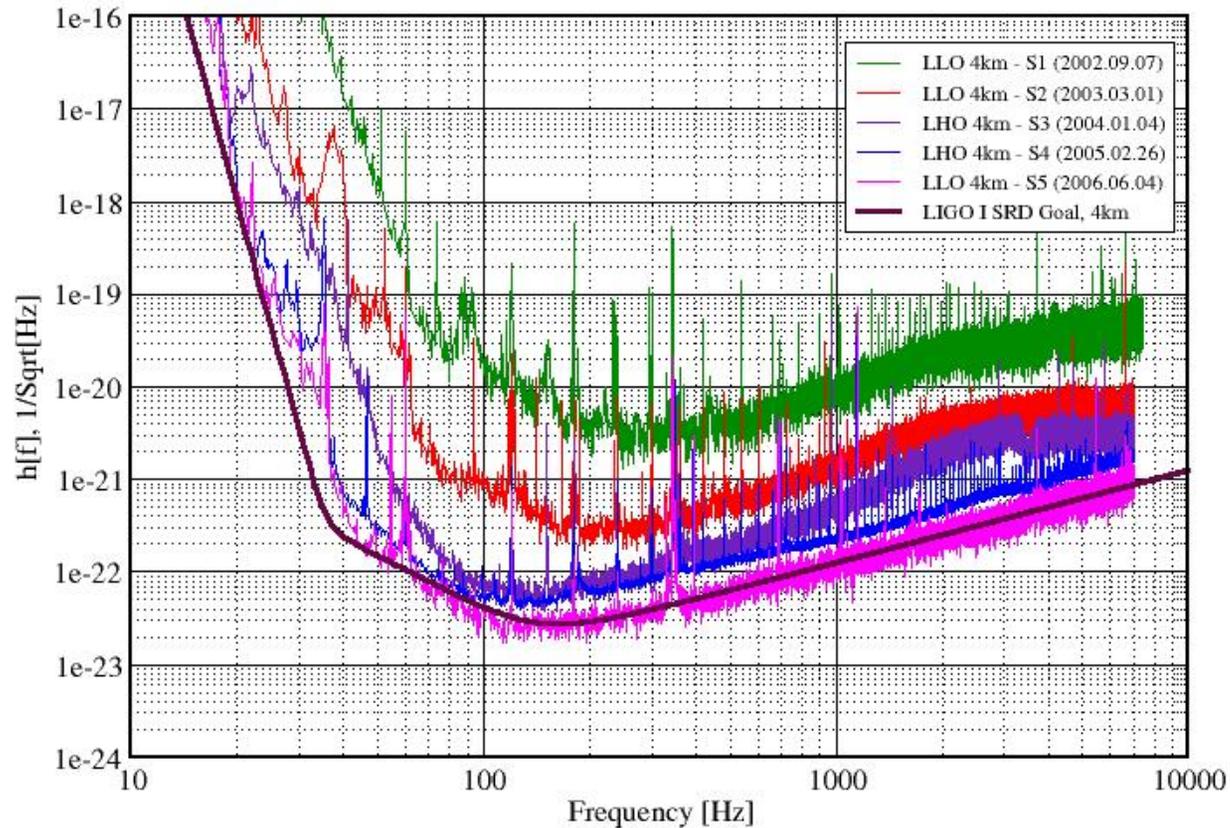
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- ✓• Typical Strains  $< 10^{-21}$  at Earth  $\sim$  1 hair's width at 4 light years
- ✓• Understand displacement fluctuations of 4-km arms at the millifermi level ( $1/1000^{\text{th}}$  of a proton diameter)
- ✓• Control the arm lengths to  $10^{-13}$  meters RMS
- ✓• Detect optical phase changes of  $\sim 10^{-10}$  radians
- ✓• Hold mirror alignments to  $10^{-8}$  radians
- ✓• Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- ✓• Do all of the above 7x24x365

*S5 science run started 14 Nov 2005...*

## Best Strain Sensivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-02-Z





## Educational use of LIGO PEM data

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- LIGO interferometers are ultra-high precision optical instruments!
- Operation requires careful monitoring of the physical environment of the instruments.
- PEM data (and data products derived from them, such as DMT BLRMS) can be used by students for inquiry-based learning projects:
  - LHO/Gladstone HS Program (1999-2004)
  - LIGO/I2U2 partnership (2005- )

LIGO lingo:

PEM = “Physics Environment Monitoring”

DMT = “Data Monitoring Tools”

BLRMS = “Bandwidth Limited RMS”

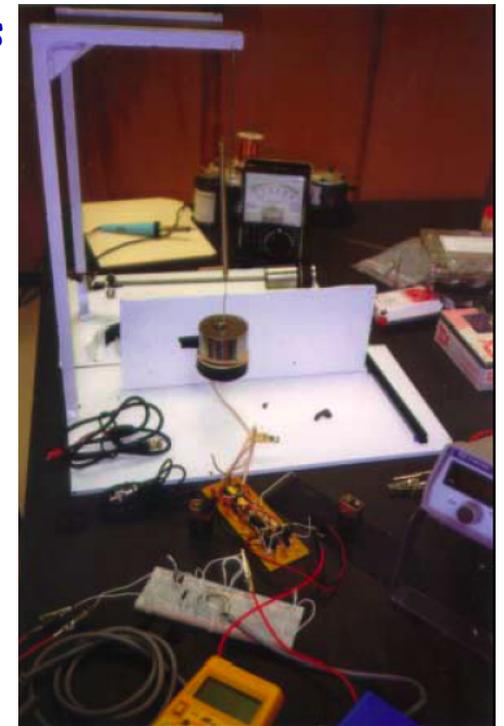


# LHO/Gladstone SST program



A partnership between LIGO Hanford Observatory and Gladstone High School (near Portland, OR), supported by NSF, and administered (1999-2001) under the Student, Scientist, Teacher (SST) program run by Pacific Northwest National Lab (PNNL). (Continued informally until 2004.)

- One teacher and three students spent 8 weeks at LHO in summers 1999 and 2000.
- Science classes during school year involved a variety of projects aimed at understanding PEM seismic data transferred to GHS via Internet.
- *The students who had hands-on experience from a summer internship were a key resource.*
- Students met with a LIGO scientist via telecon every 3 weeks, and they visited the LHO site once during year.
- Students built "demo" instruments which gave them hands-on experience with equipment without risk of breaking something.



- Students wrote software to translate data into a form they could more easily read
- Students viewed, modeled and analyzed data with Excel, MATLAB, perl, and C/C++
- Students found a correlation between *microseism* (sub-Hertz seismic motion) at LHO and wave heights reported by NOAA buoys off the Oregon and Washington coast:



Wave height can be used as a "proxy" to predict overall microseism activity at Hanford

- A microseism monitoring tool written by a GHS student was used for several years in the LHO control room until DMT Framework was developed and a new Monitor was written.

## A Sampling of Student Presentations (2002):

- "Accelerometer Measurements through a LabView Interface"
- "Running a LIGO Earth Tide Calculator at Gladstone"
- "Processing LIGO Microseism Data in MS Excel"
- "Processing Microseism Differences"
- "Modeling the GHS Microseism Software using MATLAB"
- "Twenty Years of Wave Heights and Wind Speeds from Pacific Ocean Buoys"
- "Examining the Magnetic Field of the Earth in Southeastern Washington"
- "Keeping the Wheels on the Bus--the Life of a Project Administrator"



# μseism and wave height



1.00E-05

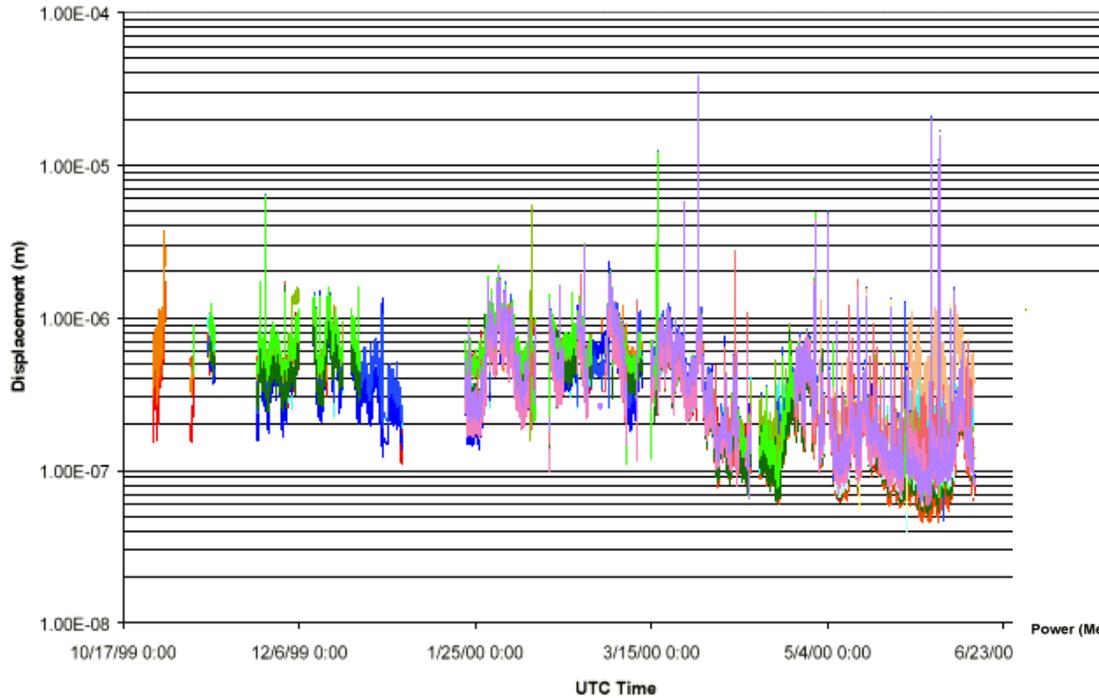
(wave heights rescaled by  $10^{-7}$ )



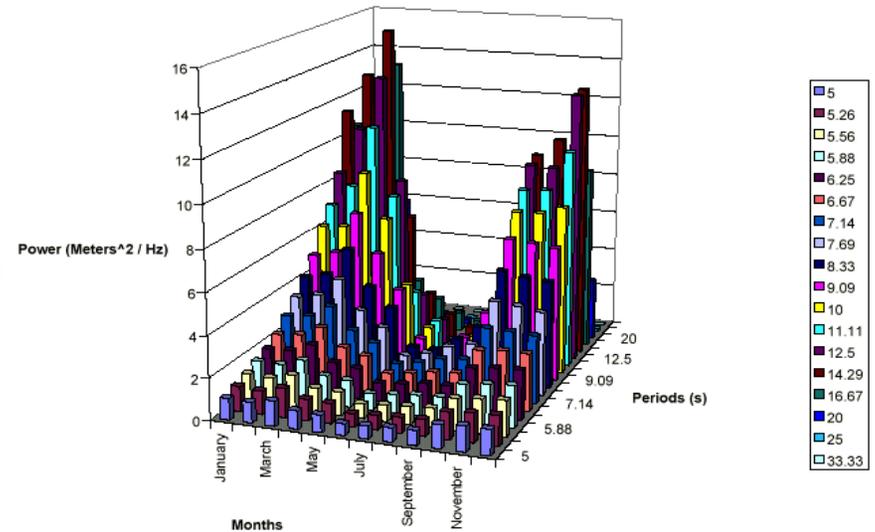
# Long-term microseism connection to ocean-wave activity



LHO Microseism 11/99 to 6/00

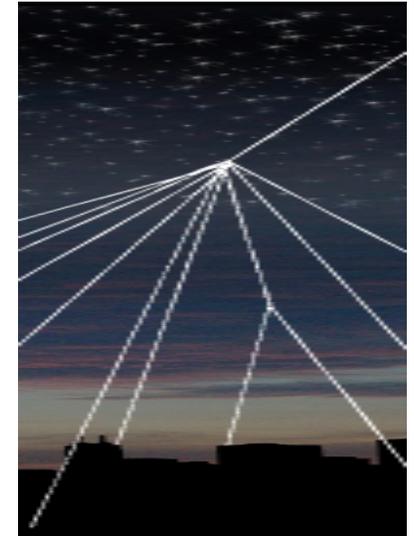


Spectral Data for 2000 Buoy 46005



Seasonal trend in microseism identified in early analysis (above) agrees qualitatively with ocean-buoy wave-height data (right)

- QuarkNet is a successful education project run by *Fermilab* E&O office
  - Network of in-school Cosmic ray detectors
  - Teaching materials for “*e-Labs*” (“*one stop shopping*”)
  - Collection of teachers making use of these
  - QuarkNet centers
- QuarkNet organizers sought to extend the idea, so invited large physics experiments to join the effort:
  - ATLAS, CMS, STAR, LIGO, with Adler Planetarium, U. Chicago
- Aimed at leveraging *Grid Computing* for educational use
- Title of project is “*Interactions in Understanding the Universe*” (I2U2)
- Initial pilot funding from NSF for 2005-2006, extended for 2006-2007.

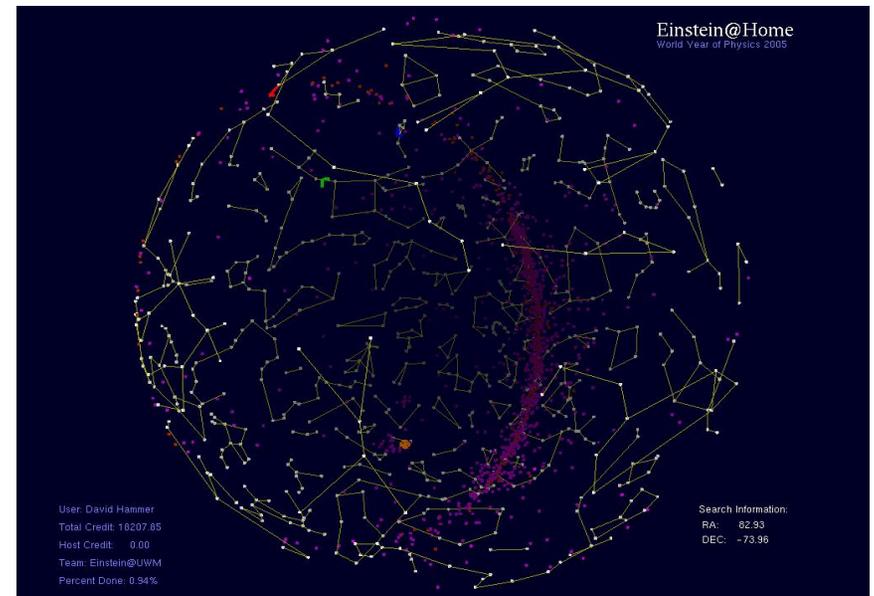


- Searching through the data streams for evidence of gravitational waves from a periodic source at an arbitrary sky position requires **an extremely large amount of computing power** - more than available Beowulf clusters!
- **Einstein@Home** uses the *Berkeley Open Infrastructure for Network Computing* (BOINC) to perform the search on a “small” chunk of data on a volunteer’s PC, all while displaying a nifty screensaver.

Anybody can join:

<http://einstein.phys.uwm.edu/>

- **Web site includes discussion “forums” for interaction between users, and with project developers.**





# LIGO I2U2 Software Development

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## --Goals --

- Provide easy access to LIGO environmental data (seismometers, magnetometers, tilt-meters, and weather stations)
- Provide analysis tools with functionality and feel similar to those available to scientists in the LIGO control rooms (such as DMT, DTT, DataViewer, ilog)
- Provide interface for use of “Grid” computing
- Provide supporting tools for interaction and collaboration between students, teachers, e-Lab developers, and possibly LIGO scientists (SST)

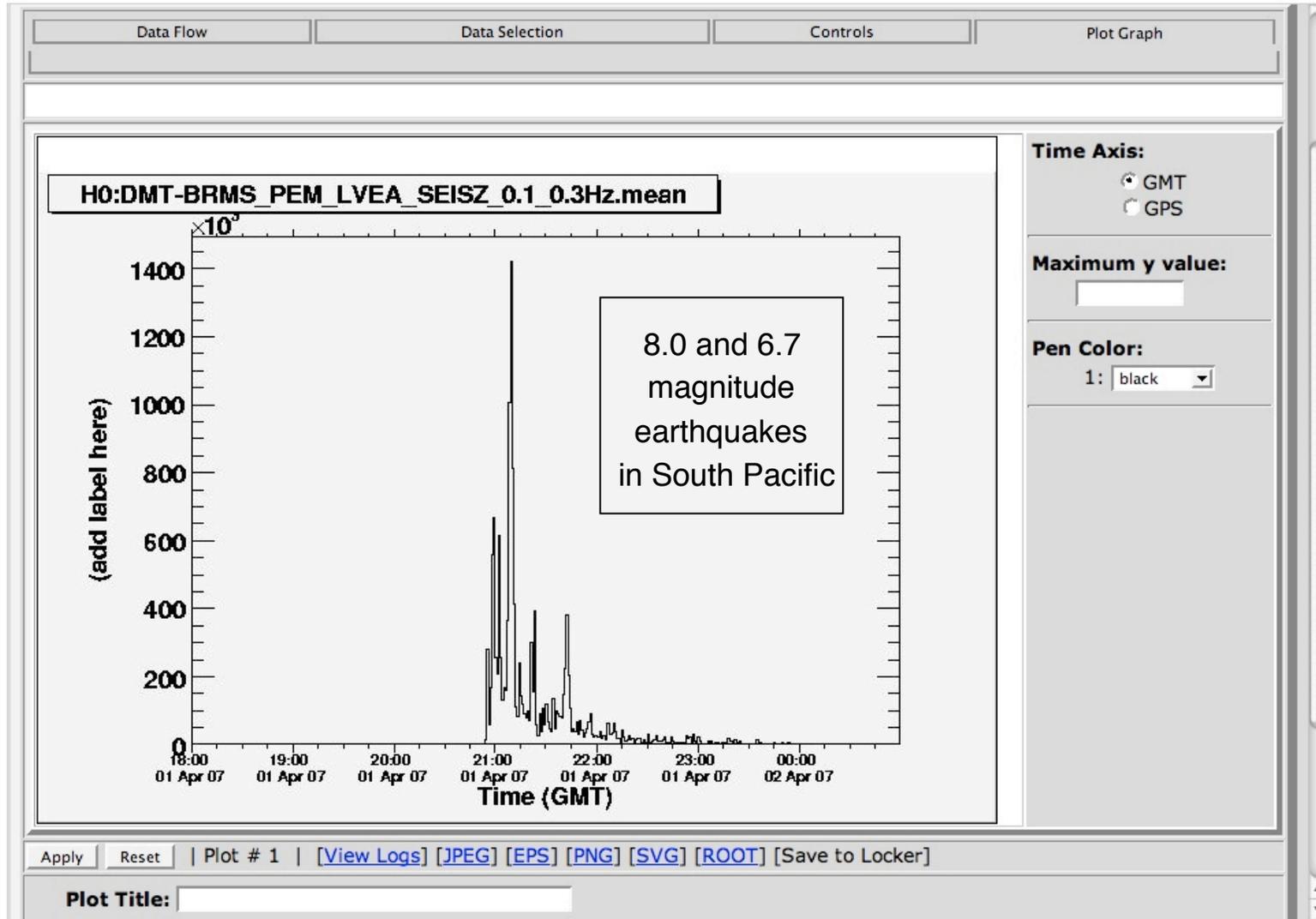


# Tool, LIGO Analysis (TLA)

A web based Analysis Tool which has a user interface (adjustable!) similar to LIGO control room tools (DMT, DTT, & ROOT) and with the potential to provide much of the same functionality (with influences from LabView)

Guest account: nyssaps / WestPoint

Tutorial available [as a PDF file](#)





## Analysis Tool Status

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- Basic functionality now works to plot a single channel ("*the circuit is complete*"), but there is much more to be added.
- Only minute-trend data, but soon to add second trends, raw data (256 Hz), and 10-min and 1-hr trends
- Potential to incorporate *DMT Monitor Framework*, first to use existing "monitors" (e.g. Bandwidth filtering of magnetometer data, as is now done for seismic data), but also possibly to turn an interesting student-designed data transformation into a control room Monitor.

Make Entry Latest Log Today Previous Next List Past 1 3 6 Months Calendar Search

LIVINGSTON Detector LOG: Wednesday, Mar 16, 2005

16:02:50 Wed Mar 16 2005 (Local)

Topic: RoboMon Author: Ashfaq Khan Wed Mar 16 22:02:50 2005 UTC

RoboScifom

**Figure of Merit 4**

End of Day Shift

This entry automatically elogged by ROBO SCIFOM

<http://ilog.ligo-la.caltech> (refu)

- [Ashfaq Khan](#)

NO\_KEYWORD

LIGO electronic logbook (the "ilog").  
<http://ilog.ligo-wa.caltech.edu/ilog>  
 (reader / readonly)

17:22:16 Wed Mar 16 2005 (Local)

Topic: Commissioning Author: Brian O'Reilly Replaces the [or](#)

**A new channel L0:PEM-**

During a short interruption of science mode today (for S. O'Keefe et. al. visit) I connected a new PEM channel. The channel is L0:PEM-RADIO\_ROOF and taken from a rooftop antenna. The idea is to monitor the 24.483 MHz radio sig which have been seen in L0:PEM-RADIO\_LVEA.

The ADCUPEM processor was reconfigured and both framebuilders were re...

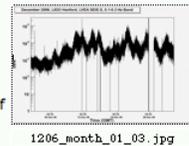
LIGO Prosser High, 12/06 270-1206\_month\_01\_03.jpg (JP...)

Washington LIGO Hanford ID: 269 | User ctrl:  | Rating: 0 | Rate:  /  [Post to thread] [Reply to THIS post]

Message 270 - Posted 3 Jan 2007 15:56:29 UTC - [delete post] - [move post]

Final Entry!

The 0.1-0.3 Hz band obviously carries a lot of earthquake information, but we saw in the group 1 plots that this band also is affected by other longer-term influences. I indulged in the luxury of running a 90-second analysis job to form the attached plot which shows the entire month of December 2006 at 0.1-0.3 Hz. At these frequencies there is more to the story seismic story than the occasional passing of earthquakes!

 1206\_month\_01\_03.jpg

Dale Ingram  
LIGO Hanford Observatory  
ID: 270 | User ctrl:  | Rating: 0 | Rate:  /  [Post to thread] [Reply to THIS post]

Message 287 - Posted 2 Feb 2007 18:05:11 UTC - in response to Message ID 248 - [delete post] - [move post]  
Last modified: 2 Feb 2007 18:10:51 UTC

Attached is a plot of the 0.1-0.3 Hz LVEA SEIS X channel that starts two days earlier than the previous plot. Could a single earthquake cause the activity that we see between 12/10 and 12/13? I'm inclined to say "no" because of the up-down-up pattern of the data over that time span. I think that an earthquake would produce an "up" and a "down" but not the second "up" a day later. If the seismic changes we see here are not due to an earthquake, what else could be the cause?

I agree with Mr. Ingram's inclination that this phenomenon is not earthquake related. From the fact that it rises gradually and takes about a day or so to play out in each rise/fall event, it would appear more likely to come from a weather related cause. Two candidates might be windy weather local to the observatory or perhaps a storm at sea whipping up wave action.

ID: 287 | User ctrl:  | Rating: 0 | Rate:  /  [Post to thread] [Reply to THIS post]

Message 288 - Posted 2 Feb 2007 18:18:12 UTC - in response to Message ID 252 - [delete post] - [move post]

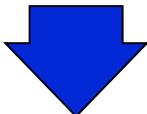
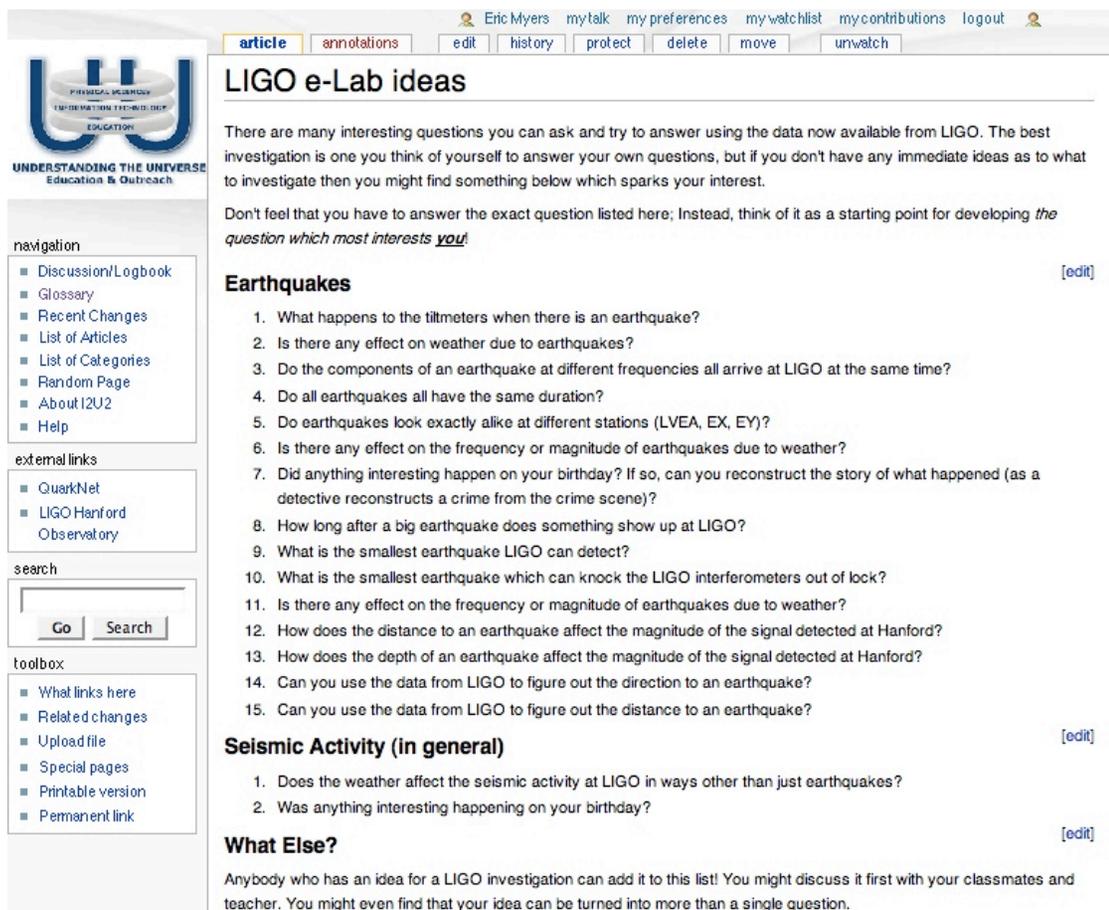
Dale Ingram wrote:

Group 1, Entry 6

I2U2 Prototype site  
 Discussion / Logbook,  
 Based on BOINC forums

- File attachments
- Keyword classifications

Project glossary, using same software that runs Wikipedia

The screenshot shows the 'LIGO e-Lab ideas' page. At the top, there's a navigation bar with 'article', 'annotations', 'edit', 'history', 'protect', 'delete', 'move', and 'unwatch'. Below this is a header for 'LIGO e-Lab ideas' with a sub-header 'There are many interesting questions you can ask and try to answer using the data now available from LIGO...'. The main content is a list of 15 questions under the heading 'Earthquakes'. Below the list are sections for 'Seismic Activity (in general)' and 'What Else?'. On the left side, there are navigation menus for 'navigation', 'external links', 'search', and 'toolbox'. The search bar contains the text 'Go Search'.

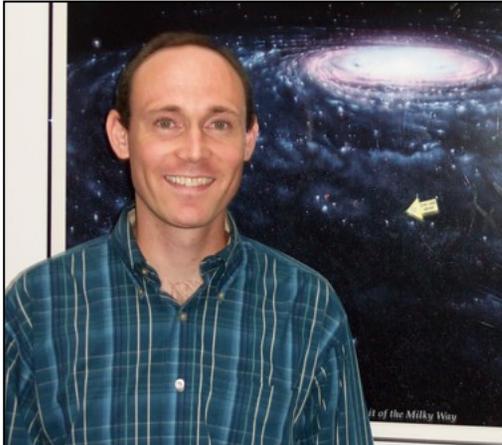


The screenshot shows the LIGO website home page. At the top, there's a greeting 'Hello, Eric Myers!' and a 'Select your e-Lab:' section with icons for QuarkNet, CMS, LIGO, STAR, and ATLAS. Below this is a 'Status' section with 'DISCUSSION ROOM ASSIGNMENTS' and a list of rooms like 'The Aquarium Room', 'Cosmic Ray's Diner', etc. There's also a 'News' section with dates and headlines like 'LIGO Data now flowing' and 'LHO Network Outage'. On the right side, there are sections for 'PARTICIPANTS', 'COMMUNITY', 'RESOURCES', and 'I2U2 LINKS'. At the bottom right, there's a 'POWERED BY' logo for BOINC.

RSS News subscription for project/server status



# Teacher Activities



Summer 2006 intern teacher John Kerr

- Used second-trend data (from control room) to study p-wave/s-wave timing
- Tested Analysis Tool when it was ready
- Wrote TLA tutorial

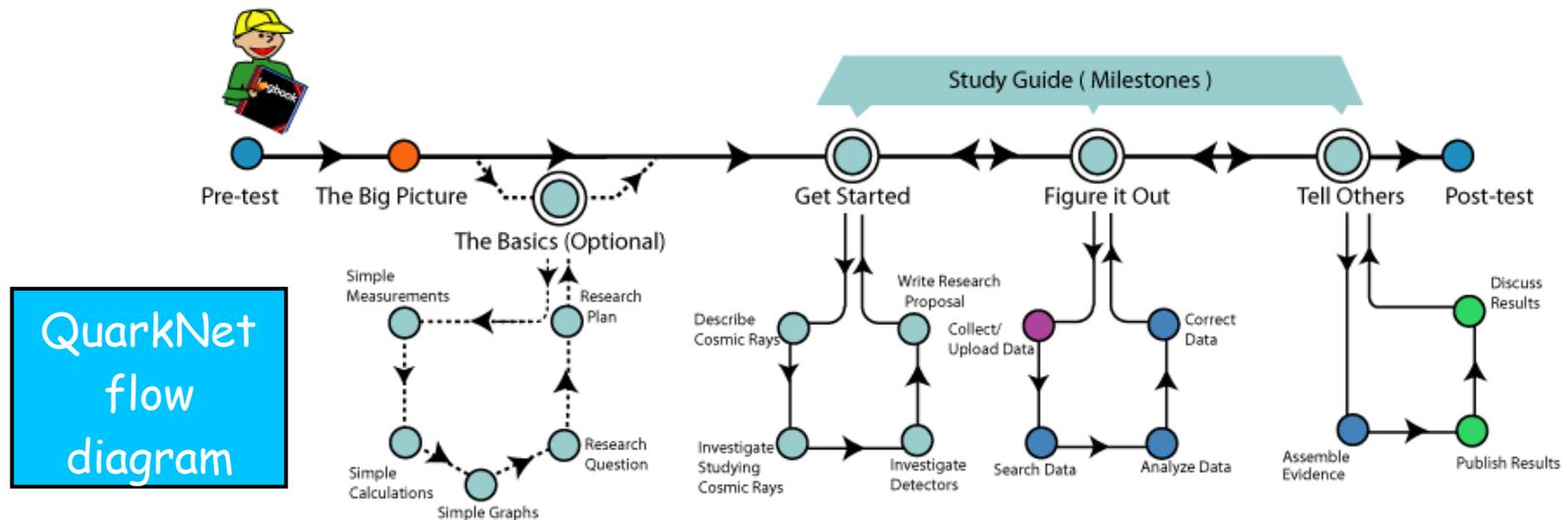


Teacher workshop, August 2006

At Hanford, included control room visits, training in use of Analysis Tool and discussion of classroom activities

## Initial student classroom trials in 2006-07

- Improvements to the Analysis Tool
- Create “e-Lab” teaching materials for I2U2 site



- LHO Teacher internships for Summer 2007
- LHO Teacher Workshop planned for Summer 2007



# Conclusions



- LIGO interferometers are ultra-high precision optical devices

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- Operation of LIGO instruments requires monitoring of the physical environment

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- PEM and related data can be used by students and their teachers for discovery based education.

Try it out:

<http://tekoa.ligo-wa.caltech.edu/tla>

(user: nyssaps / password: WestPoint)

*"A great discovery solves a great problem, but there is a grain of discovery in the solution of any problem."* - G. Polya, 1944