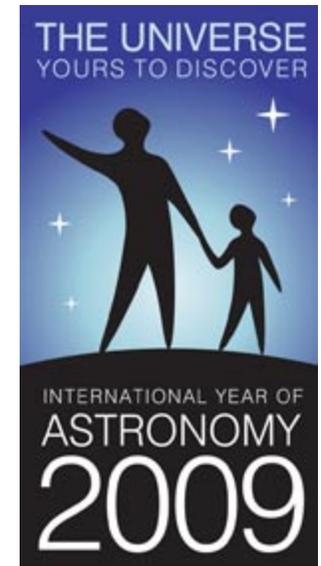


# *Einstein@Home: Gravitational Wave Astronomy with Your Home Computer*

Eric Myers



*Mid-Hudson Astronomy Association  
New Paltz, New York  
20 January 2009*



# Summary

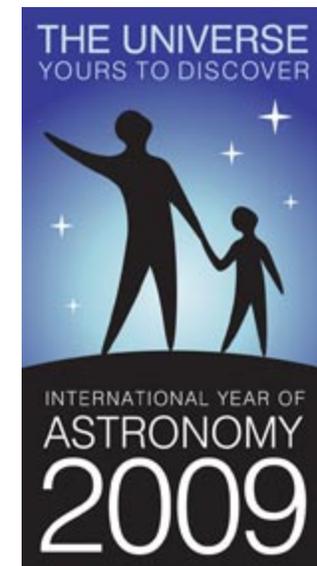
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- **LIGO** is a cutting-edge *physics experiment* which is attempting to detect gravitational waves, using the most sensitive optical devices on the planet.

*Detection of gravitational waves will likely open up an entirely new branch of astronomy!*

- The computational effort required to perform an “all-sky blind” search for the signal of a Continuous Wave source (like a neutron star) is so large that it requires a supercomputer.
- Einstein@Home is a distributed computing project which runs on thousands of computers to perform this task.

**You can join the search!**



# What are Gravitational Waves?

---

Astronomy now is done via **Electromagnetic Waves** (radio, infrared, visible, ultraviolet, gamma rays). These are time-varying oscillations of *electro-magnetic* fields.

**Gravitational Waves** are time-varying oscillations of the *gravitational* field.

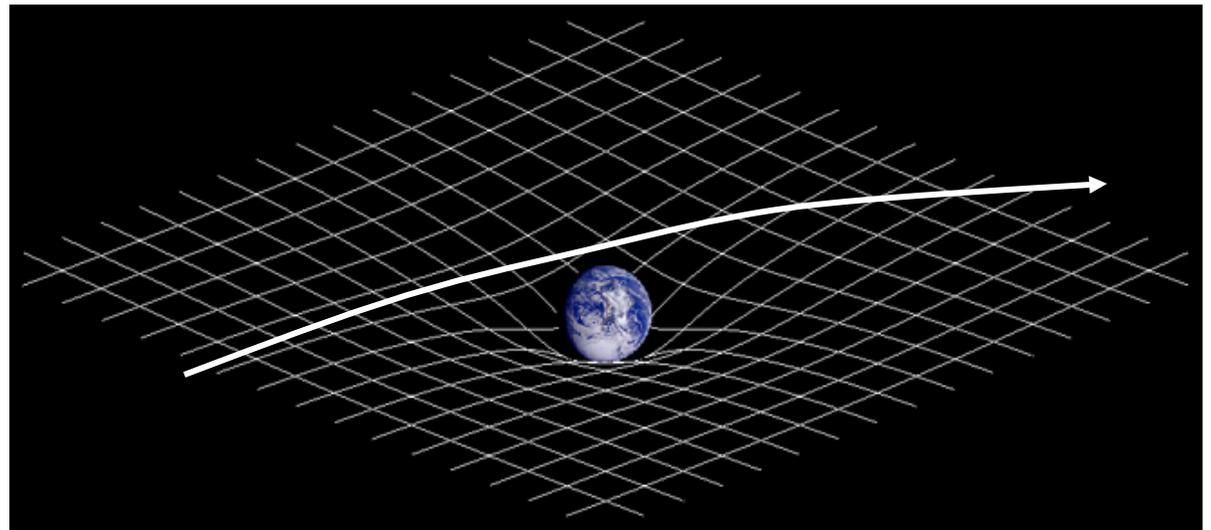
In *General Relativity* gravitation is described as being a property of the geometry of space+time=spacetime

## Principles:

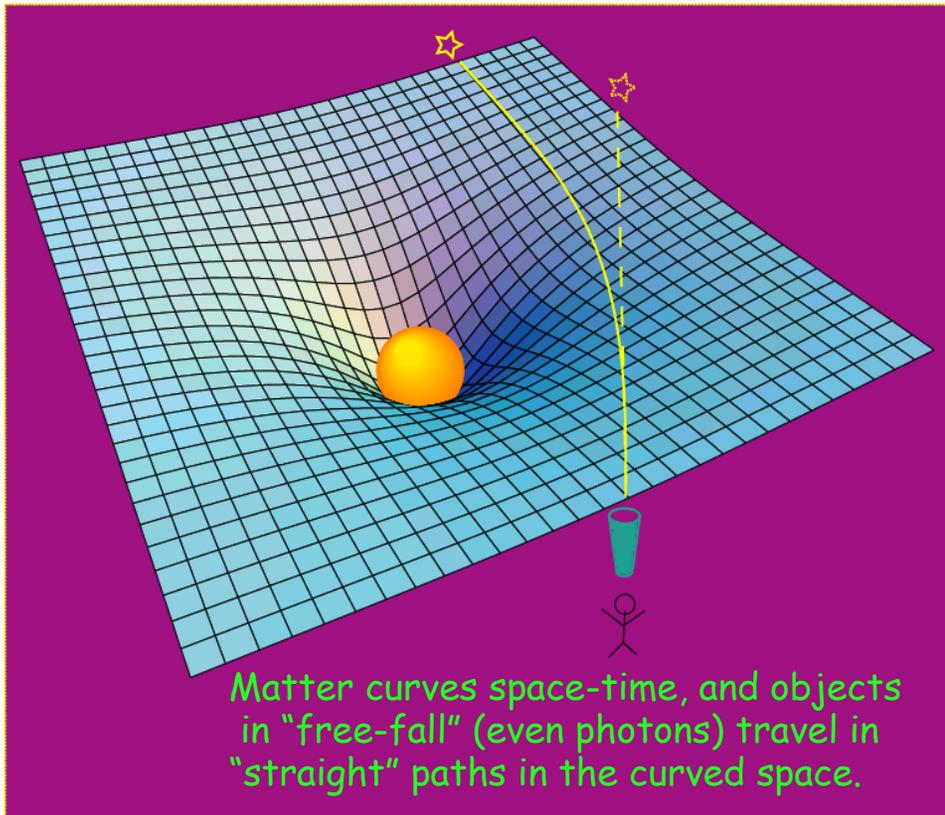
**Matter curves spacetime,**

and

Objects in "free-fall" travel in "straight" paths in the curved space.



# Gravitational Waves

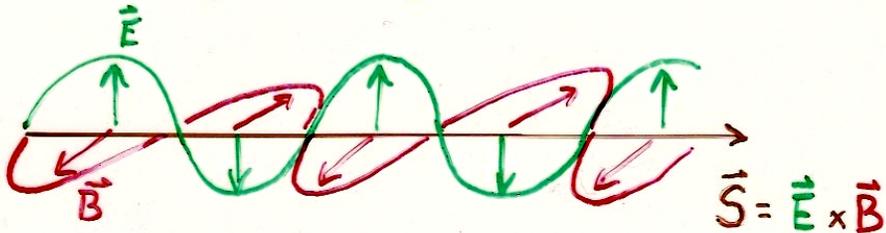


Changes in space-time produced by moving a mass are not felt instantaneously everywhere in space, but propagates as waves

# Comparison with EM waves

## Electromagnetic Waves

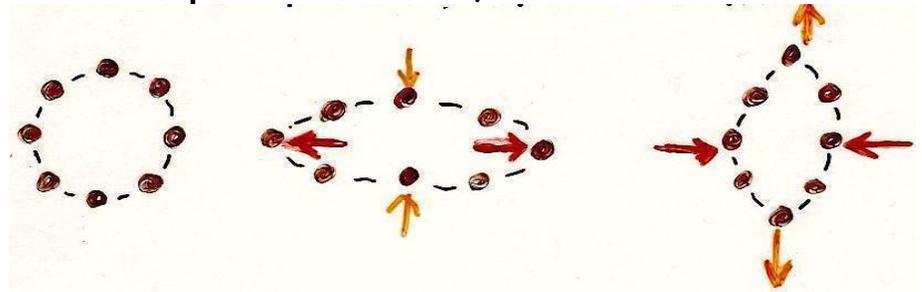
- Travel at the speed of light
- "transverse"
- Vector - dipole in both E and B
- Two polarizations: horizontal and vertical



- 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"
- Tensor - quadrupole distortions of space-time
- Two polarizations, "+" and "x"

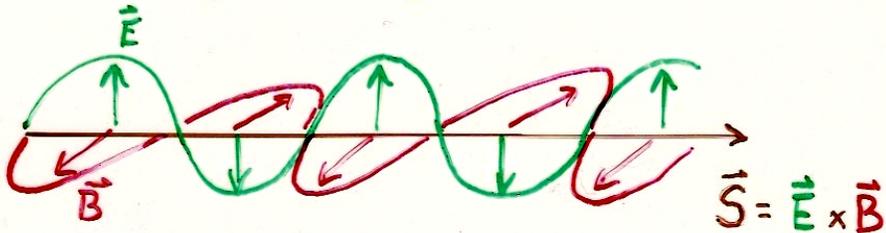


- Solutions to Einstein's Eqns.
- Gravitational waves require changing quadrupole mass distribution.

# Comparison with EM waves

## Electromagnetic Waves

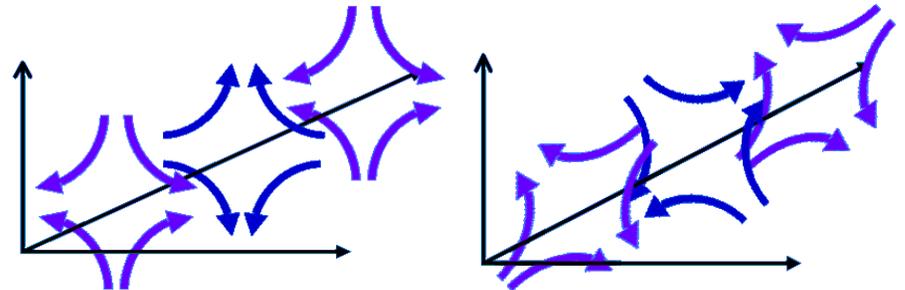
- Travel at the speed of light
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- Solutions to Maxwell's Eqns.
- EM waves can be generated by a changing dipole charge distribution.

## Gravitational Waves

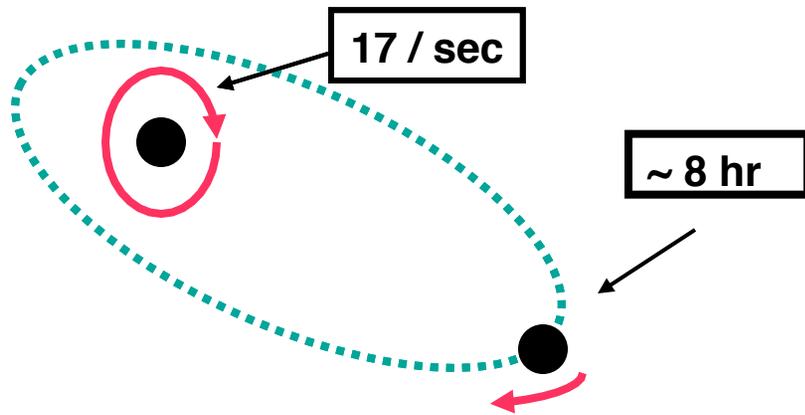
- Travel at the speed of light
- "transverse"
- Tensor - quadrupole distortions of space-time
- Two polarizations, "+" and "x"



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

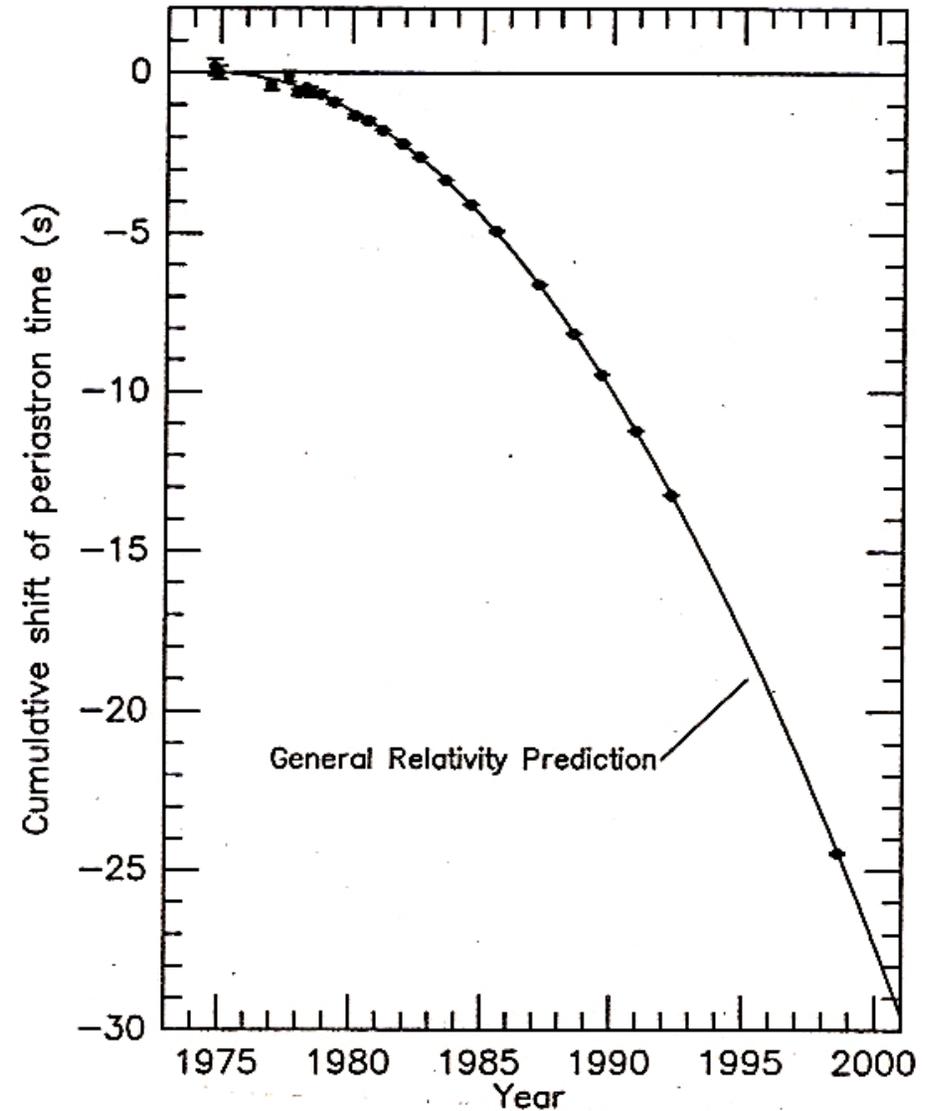
# Indirect Evidence for GW's

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

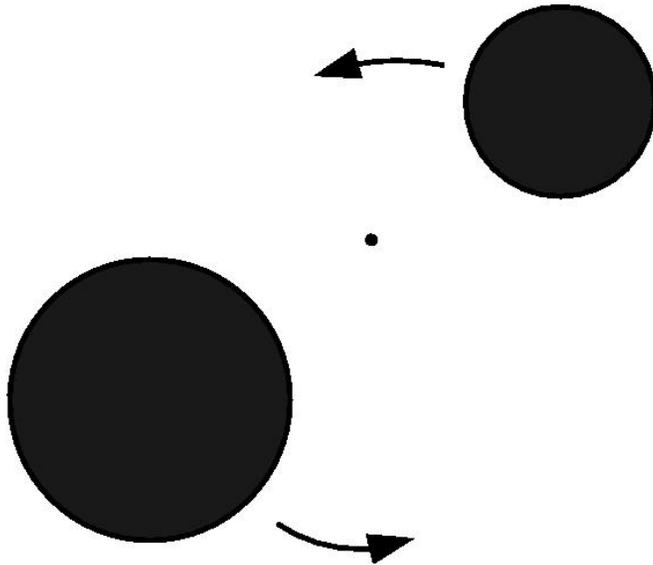


The measured precession of the orbit exactly matches the expected loss of energy due to gravitational radiation.

(Nobel Prize in Physics, 1993)



# Example: Binary Inspiral



A pair of  $1.4M_{\odot}$  neutron stars in a circular orbit of radius 20 km, has orbital frequency **400 Hz**.

This produces gravitational waves at frequency **800 Hz**.

Wave frequency is twice the rotation frequency of the binary!

Strength of wave is measured by "strain amplitude"

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

$1.4M_{\odot}$  binary inspiral provides a translation from dimensionless strain amplitude  $h$  to the "reach" of the instruments, measured in Mpc, much like like a "standard candle".

# How might GW's be produced?

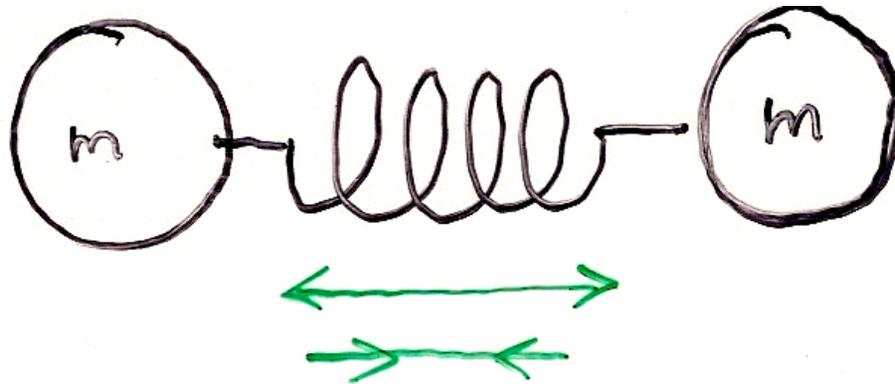
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The most likely astronomical sources are:

- 1) *Stochastic background* from the early universe (Big Bang! Cosmic Strings,...) - a "cosmic gravitational wave background"
- 2) *Bursts* from supernovae or other cataclysmic events  
(but requires changing *quadrupole*: spherical symmetry → no GW!)
- 3) *Coalescence of binary systems*, inspiral of pairs of neutron stars and/or black holes (NS-NS, NS-BH, BH-BH) **CHIRP!**
- 4) *Continuous Wave sources*, such as spinning (and asymmetric!) or oscillating neutron stars ("gravitational pulsars").
- 5) *Something unexpected...!*

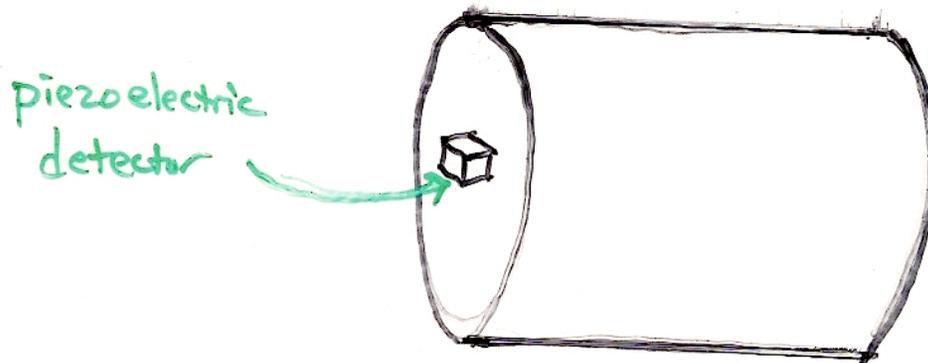
# How might GW's be detected?

Simplest example: the "bar-bell" detector

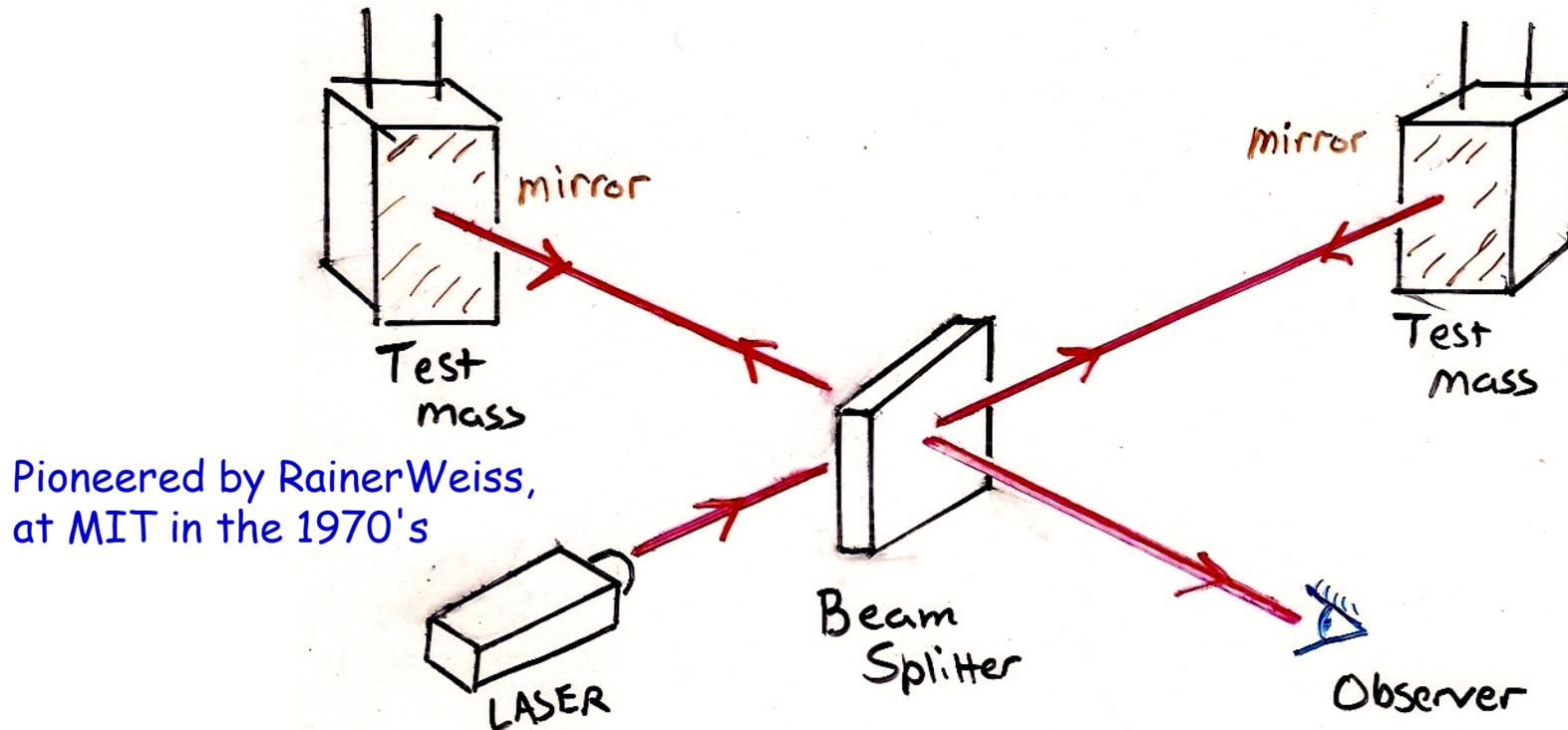


Pioneered by Joseph Weber at the University of Maryland in 1960's (no detection)

Practical implementation: a "bar" detector



# Michelson Interferometer



Measuring  $\Delta L$  in arms allows the measurement of the strain which is proportional to the gravitational wave amplitude

$$h = \frac{\Delta L}{L}$$

(Larger  $L$  is better, and multiple reflections increase effective length.)

# LIGO: Laser Interferometer Gravitational wave Observatory

LIGO Livingston Observatory (LLO)  
Livingston Parish, Louisiana

L1 (4km)

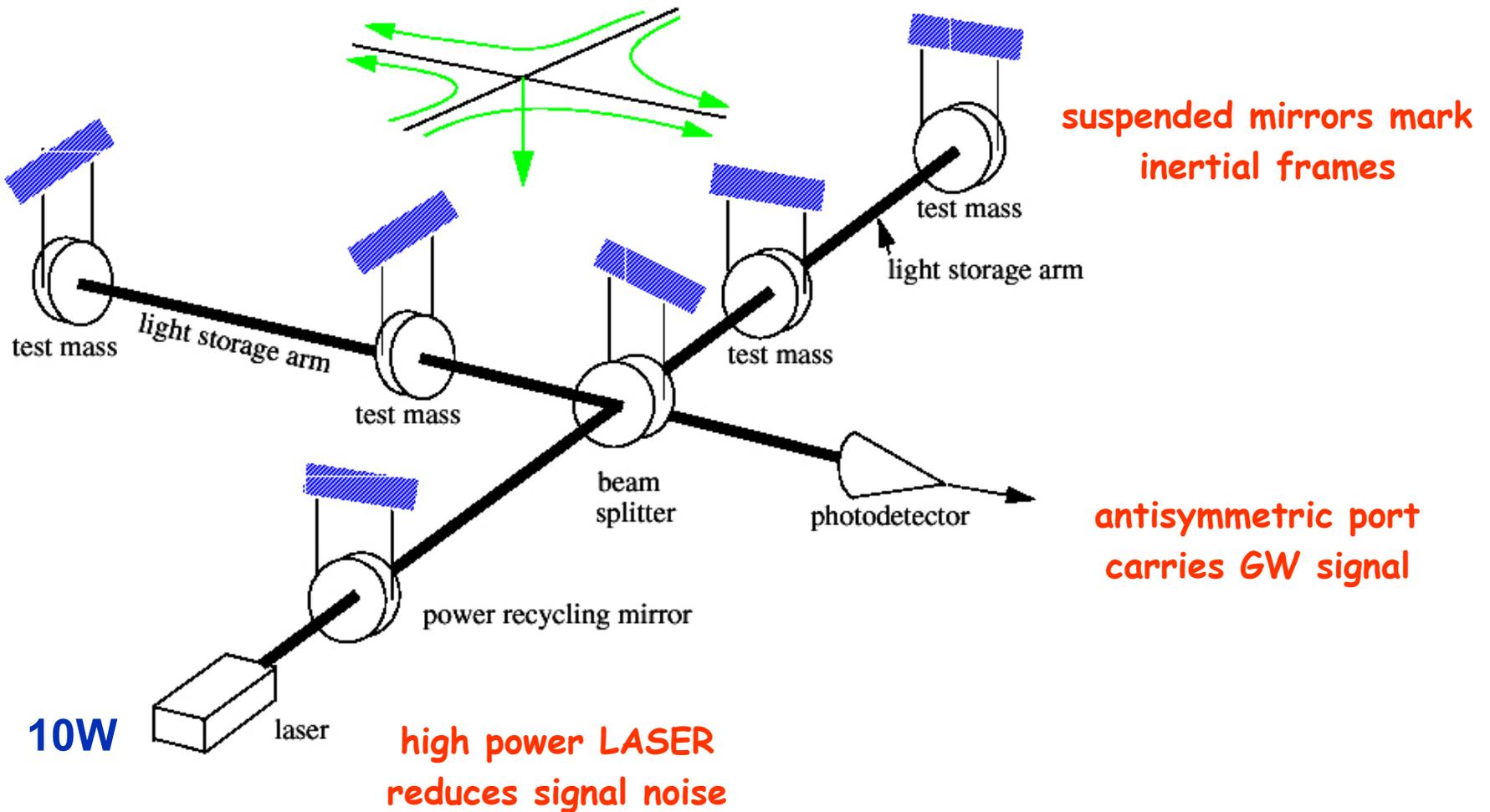


LIGO Hanford Observatory (LHO)  
Hanford, Washington

H1 (4km) and H2 (2km)

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

# Power-recycled Fabry-Perot-Michelson Interferometer



# 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

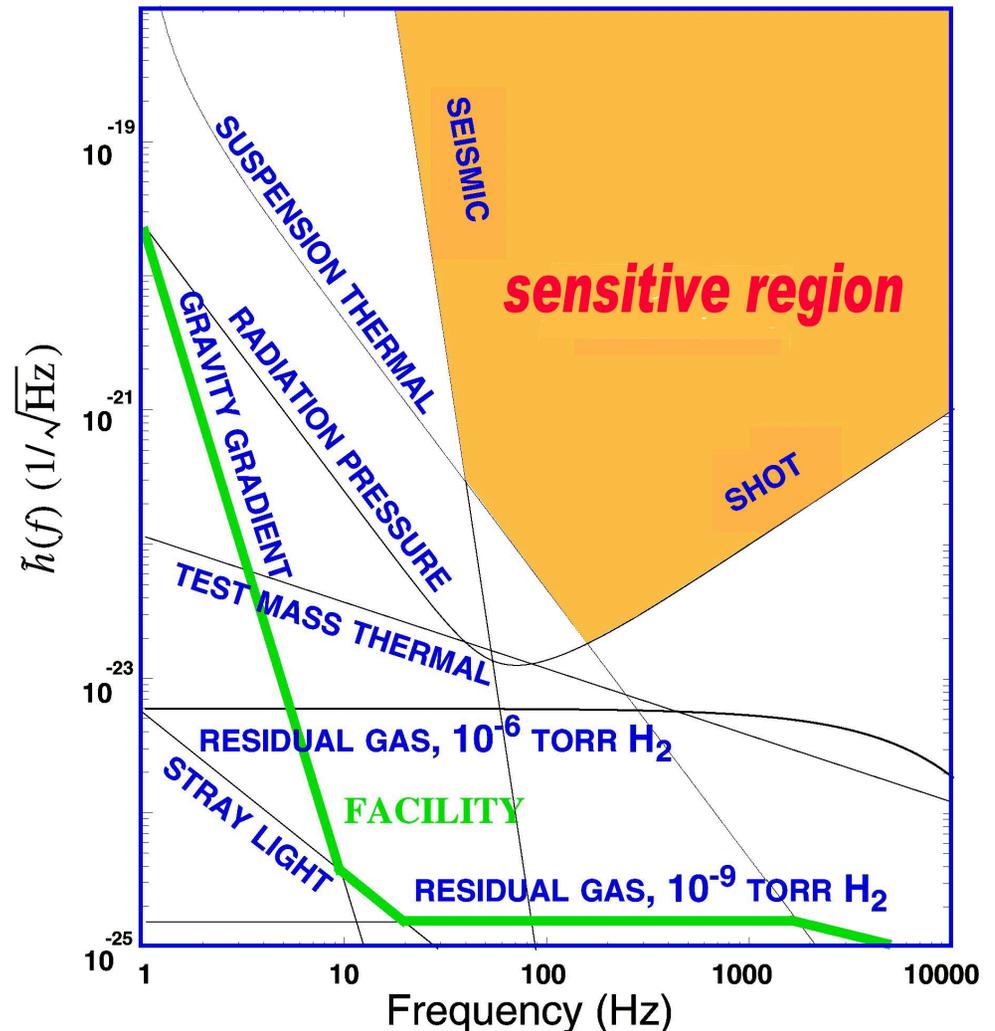
Adapted from "The Blue Marble: Land Surface, Ocean Color and Sea Ice" at [visibleearth.nasa.gov](http://visibleearth.nasa.gov)

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 Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).



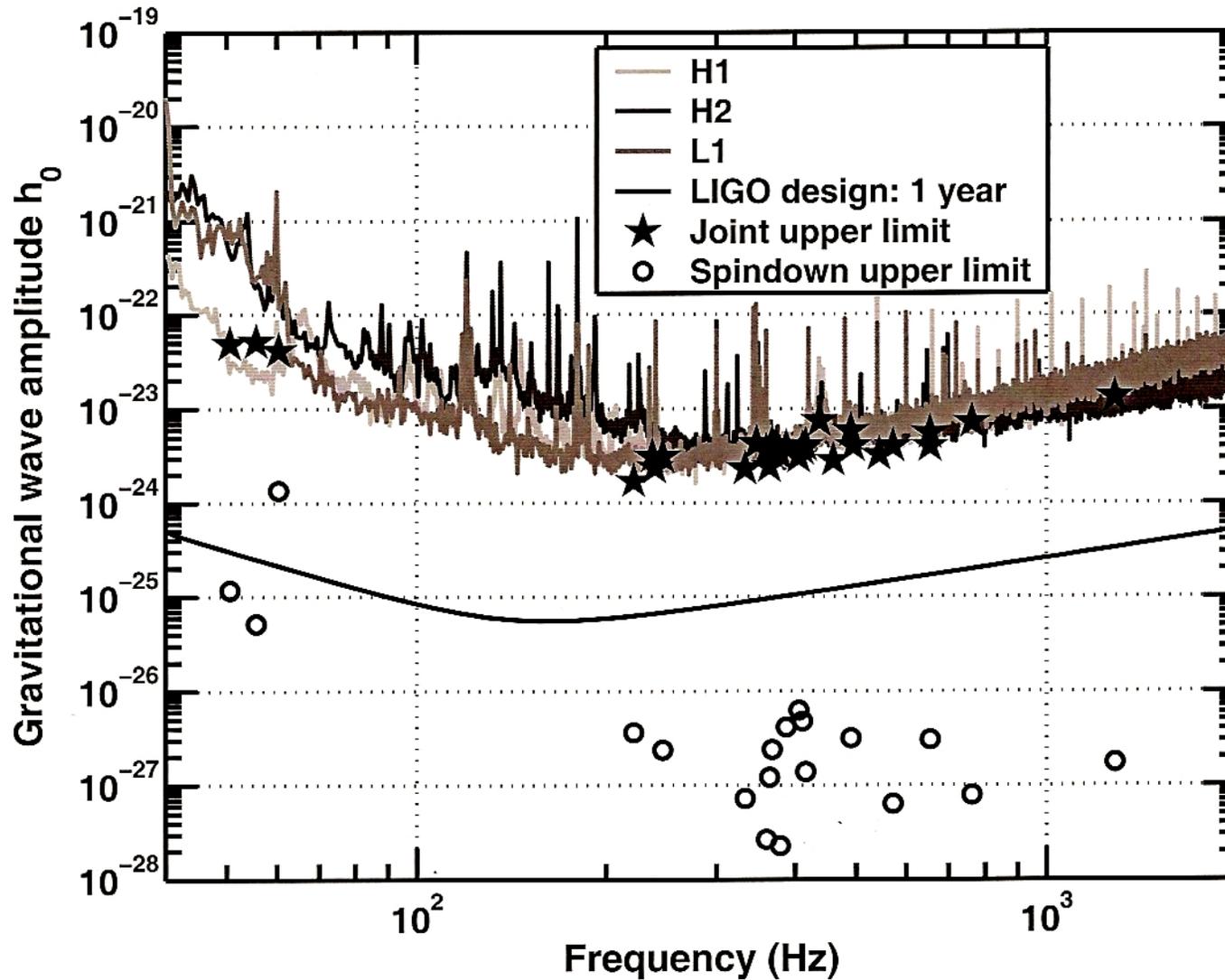
# What Limits Sensitivity?

- ❑ 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



# Pulsar Upper Limits (S2)

S2: 14 Feb to 14 April 2003

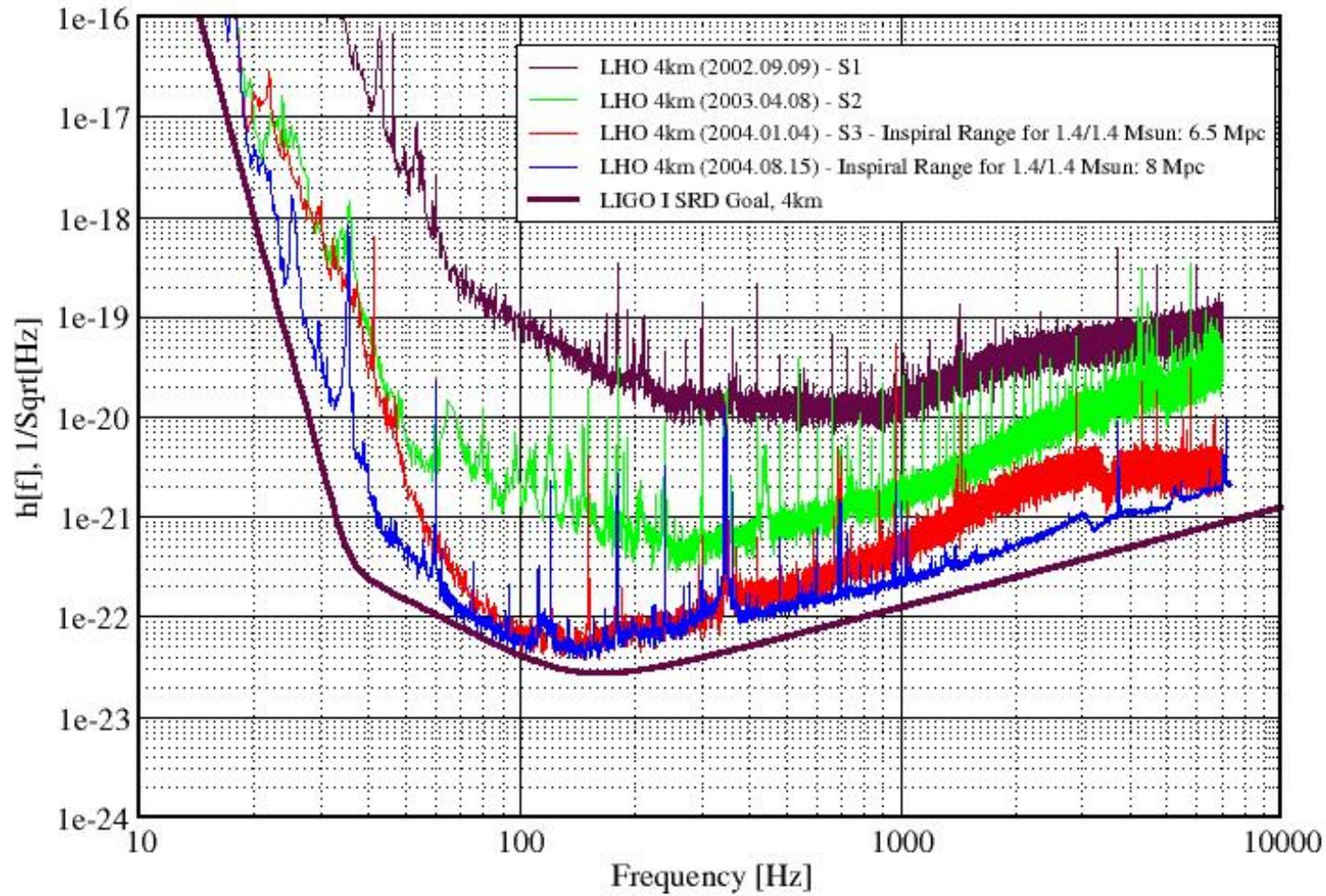


Mid-Hudson Astronomy Association, New Paltz New York, 20 January 2009

# S3 Sensitivity

S3: 31 Oct 2004 to 9 Jan 2005

Strain Sensitivities for the LIGO Interferometers  
H1 Performance Comparison: S1 through post S3 LIGO-G040439-00-E

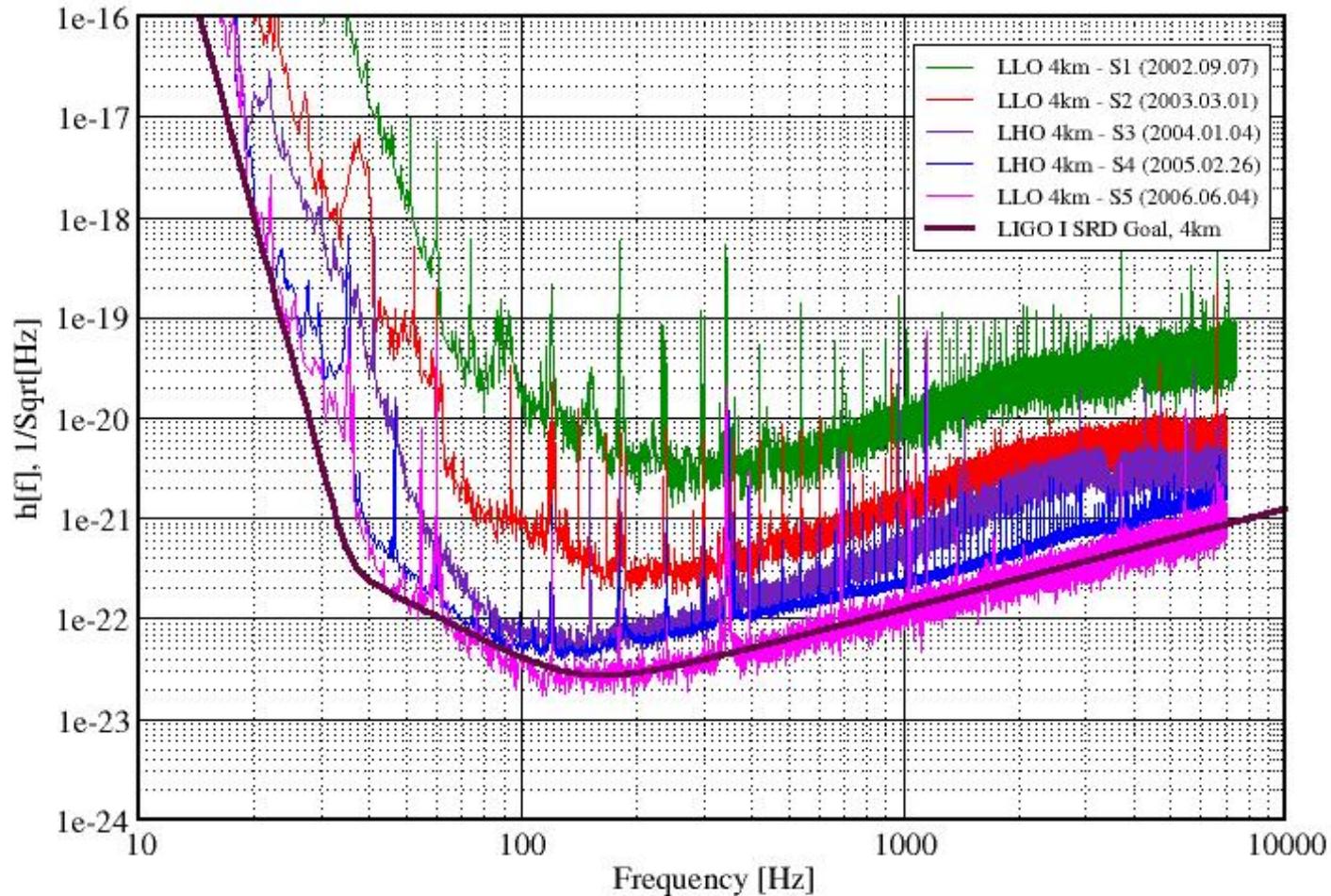


# Strain Sensitivity S1 - S5

S5: 4 Nov 2005 to 30 Sept 2007

## Best Strain Sensivities for the LIGO Interferometers

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



# Challenge of the NSB

## National Science Board Resolution (2005):

*"The Board approved the resolution [supporting funding for Advanced LIGO] with the understanding that the existing LIGO Program will collect at least a year's data of coincident operating at the science goal sensitivity before initiating facility upgrades to the new Advanced LIGO technology."*

Source: B. Berger, "View from the NSF", G050339-00

S5 completed successfully 30 Sept 2007!

Now upgrading to "Enhanced LIGO"

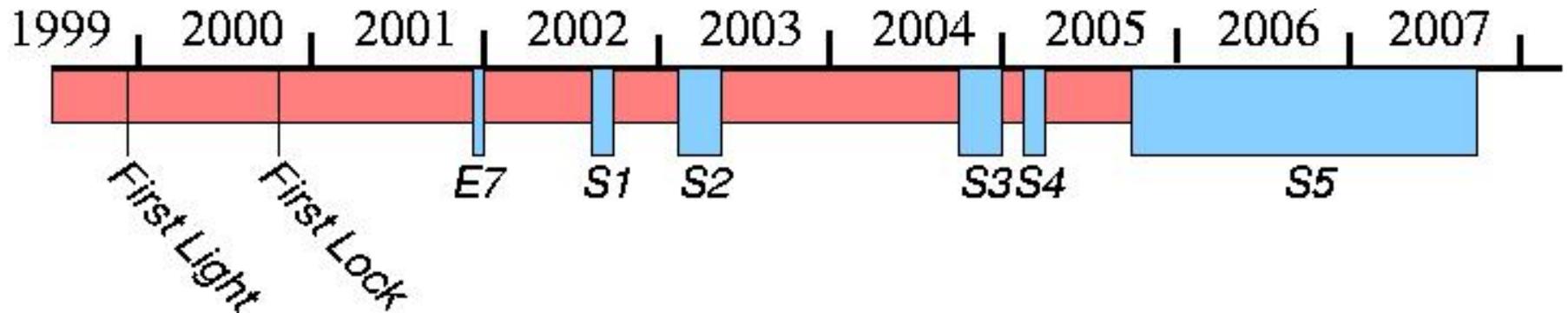


S6 run will start with "Enhanced LIGO" in mid 2009, with x2 sensitivity

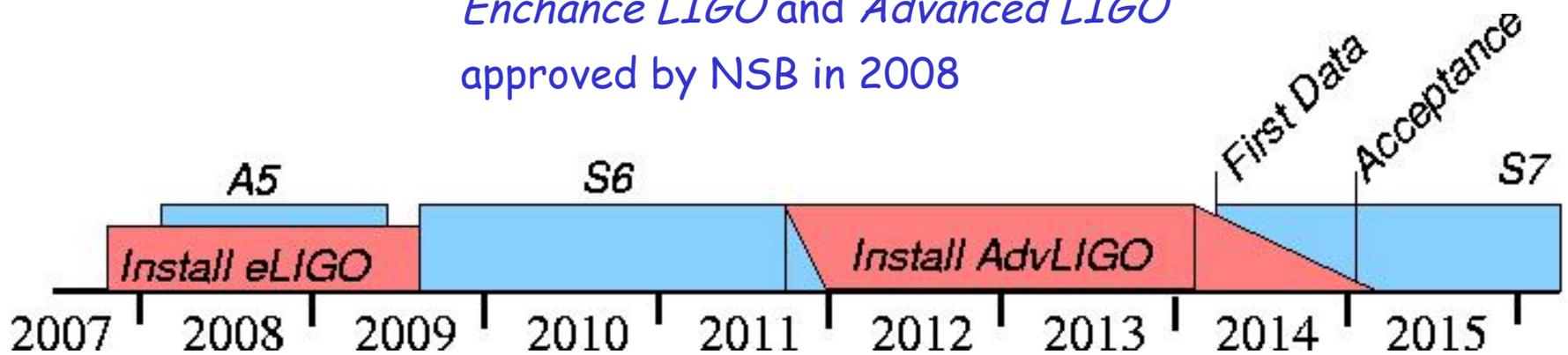
Advanced LIGO will begin taking data in 2013, with x10 sensitivity.

# LIGO Timelines

Construction began 1995

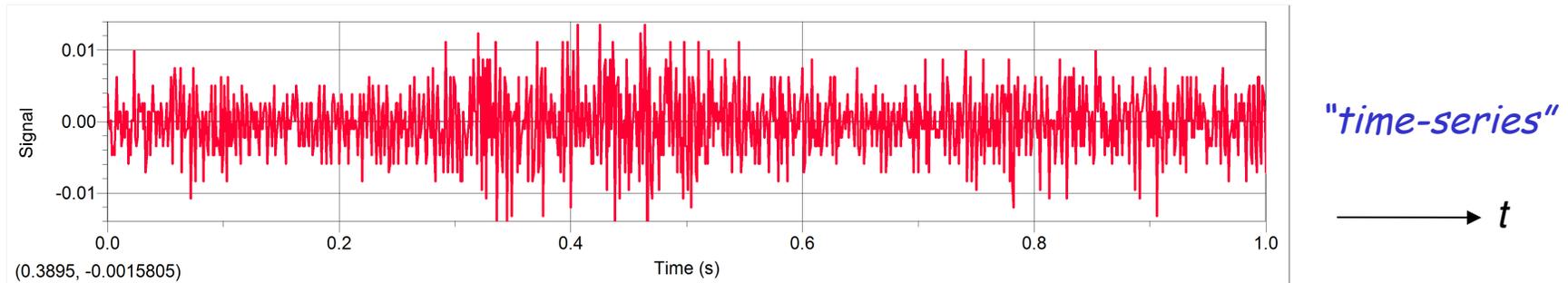


*Enhance LIGO and Advanced LIGO*  
approved by NSB in 2008



# How to search for CW signals?

If the frequency of the signal is constant, then searching for a signal is easy.  
Starting with Signal+Noise...

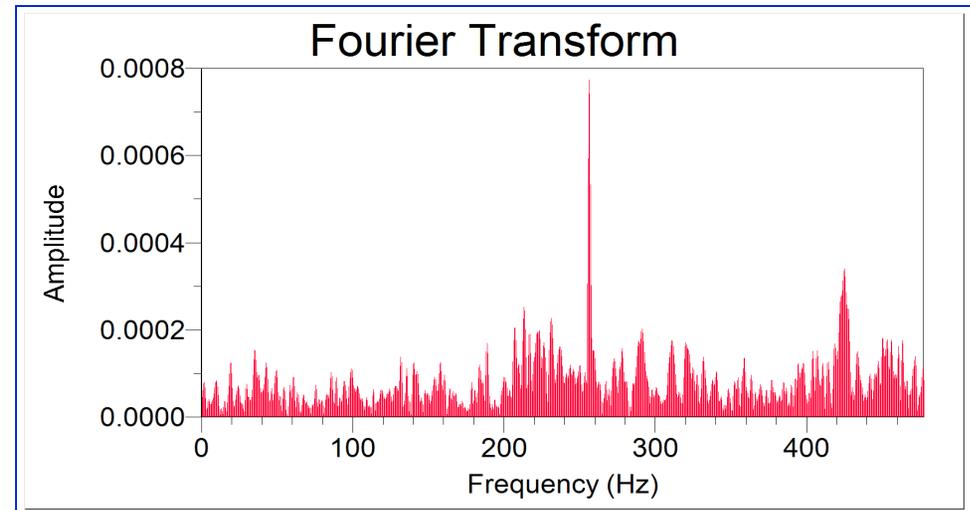


Take the **Fourier Transform** to obtain:

$$f(t) = \sum_{m=0}^{\infty} \left[ \tilde{A}_m \cos\left(\frac{2\pi mt}{T}\right) + \tilde{B}_m \sin\left(\frac{2\pi mt}{T}\right) \right]$$

$$\tilde{A}_m = \frac{1}{\sqrt{2\pi}} \int_0^T f(x) \cos\left(\frac{2\pi mt}{T}\right) dt$$

$$\tilde{B}_m = \frac{1}{\sqrt{2\pi}} \int_0^T f(x) \sin\left(\frac{2\pi mt}{T}\right) dt$$

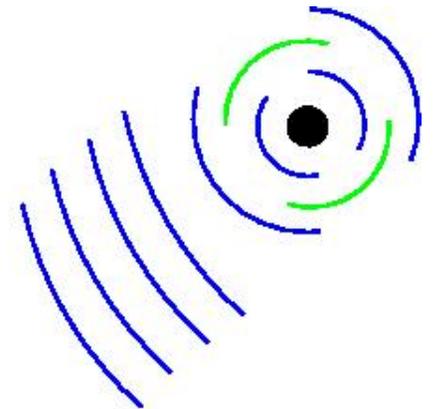
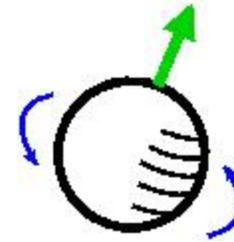


There is even a computationally fast algorithm for this, the **Fast Fourier Transform (FFT)**.

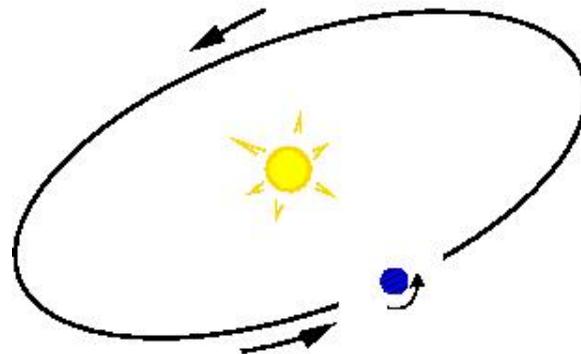
# But the frequency will change!

But the frequency is not expected to be constant, due to:

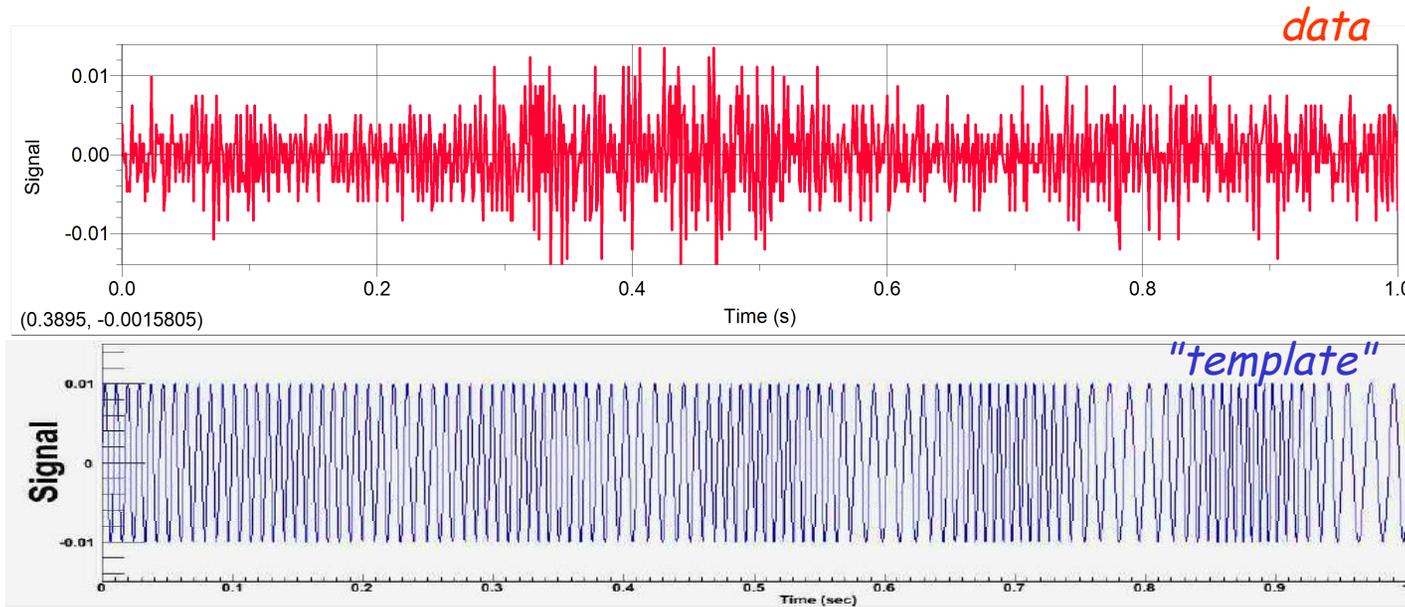
1. The source losing energy due to "spin down"
2. Doppler shift due to Earth's motion about the Sun (one part in  $10^4$ , with period of 1 year)
3. Doppler shift due to Earth's rotation about its axis (one part in  $10^6$ , with period 1 sidereal day)



Exact form of the modulations depends upon the sky location of the source!



# Matched Filtering



Assuming data

$$x(t) = h(t) + n(t) \text{ compute}$$

$$\mathcal{F} \approx \int_0^T \frac{h(t) x(t)}{S_h(t)} dt$$

In reality  $h(t)$  is more complex, and depends on sky position, frequency, spin-down, and signal phase!

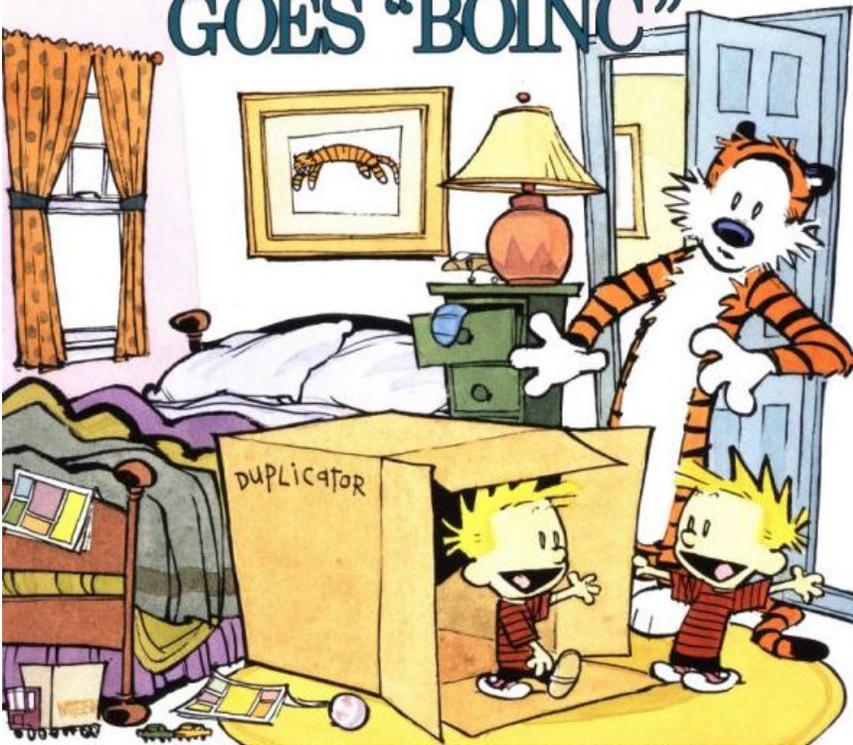
*"the F statistic"*

And computational effort goes up like  $T^6$ !

Looks like we're gonna need a bigger computer!

# BOINC to the rescue

## SCIENTIFIC PROGRESS GOES "BOINC"



SETI@home is a distributed computing project searching for distinctive peaks in Arecibo radio data. In 2004 they upgraded to BOINC:

Berkeley  
Open  
Infrastructure for  
Network  
Computing

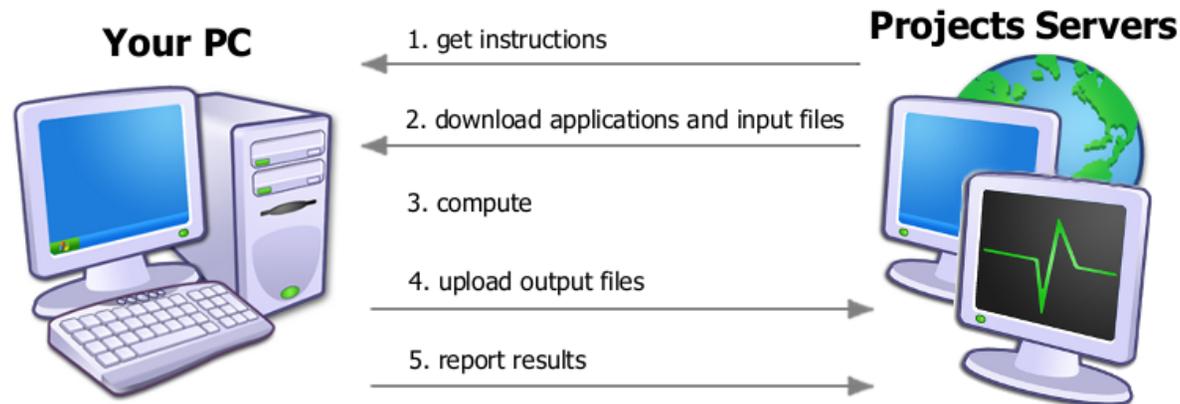
BOINC is modular, so that one can replace the "computation thread" and the "graphics thread".

So we did! → Einstein@Home

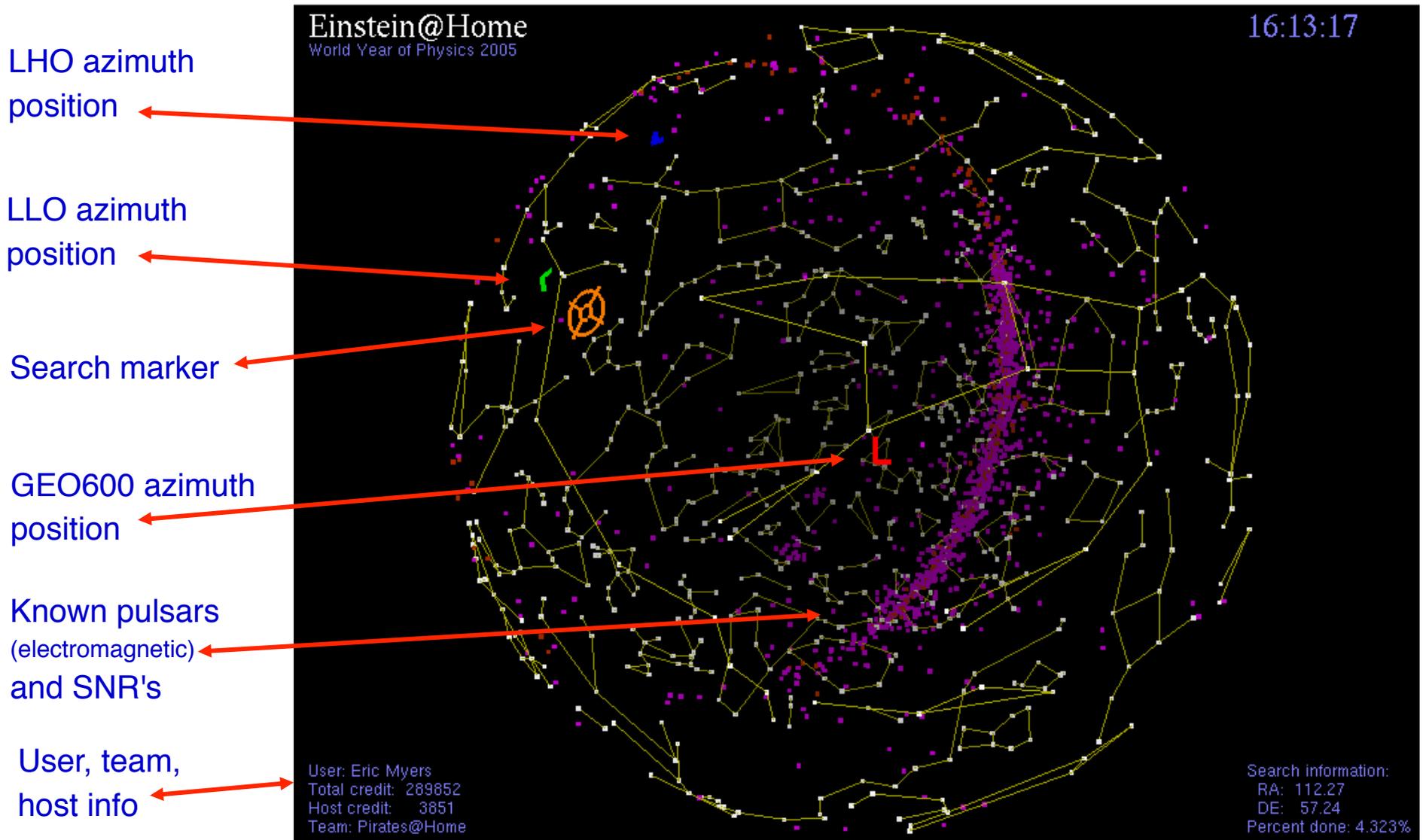
# Einstein@Home

How to use BOINC to search for a CW signal:

1. Break the computations up into smaller "workunits"
2. Send these workunits (WU's) to participating "clients"
3. Each WU searches the entire sky (~30,000 points!) for a narrow band of frequencies and the full range of spin-downs, computing the  $F$ -statistic.
4. Client returns top 13,000 candidates to the server for further processing, and receives new WU's.



# Screensaver graphics



Mid-Hudson Astronomy Association, New Paltz New York, 20 January 2009

# Einstein@Home status

As of 17 January 2009

## Einstein@Home - Server Status

Einstein@Home server status as of 5:40 PM UTC on Saturday, 17 January 2009 (updated every 20 minutes).  
The Einstein@Home main server has been continuously up for 167 days 4 hours 24 minutes.

### Server status

Program	Host	Status
Web server	einstein	Running
BOINC database feeder	einstein	Running
BOINC transitioner	einstein	Running
BOINC scheduler	einstein	Running
BOINC file uploads	einstein	Running
Einstein S5R4 generator	einstein	Not running
Einstein S5R5 generator	einstein	Running
Einstein S5R4 validator	einstein	Running
Einstein S5R5 validator	einstein	Running
Einstein S5R4 assimilator	einstein	Running
Einstein S5R5 assimilator	einstein	Running
BOINC file deleter	einstein	Running

### Download mirror status

Site	Status	Last failure
Albert Einstein Institute	Running	574 h 1 m ago
University of Glasgow LSC group	Running	2596 h 35 m ago
MIT LIGO Lab	Not running	1 h 40 m ago
Penn State LSC group	Running	9 h 45 m ago
Caltech LIGO Lab	Running	1514 h 14 m ago

### S5R5 search progress

Total needed	Already done	Work still remaining
10,949,633 units	180,730 units	10,768,903 units
100 %	1.651 %	98.349 %
242.8 days	4.0 days	238.8 days (estimated)

### Users and Computers

USERS	Approximate #
in database	439,762
with credit	218,958
registered in past 24 hours	157
HOST COMPUTERS	Approximate #
in database	1,547,449
registered in past 24 hours	1,825
with credit	788,393
active in past 7 days	1,777
floating point speed <sup>1</sup>	159.1 TFLOPS

### Work and Results

WORKUNITS	Approximate #
in database	514,250
with canonical result	282,783
no canonical result	231,467
RESULTS	Approximate #
in database	1,168,243
unsent	68,703
in progress	242,368
deleted	596,853
valid	567,003
valid last week	433,299
invalid	88
Oldest Unsent Result	6 d 23 h 59 m

# How you can join

Einstein@Home - Mozilla Firefox

File Edit View History Bookmarks Tools Help

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

Nexus Slashdot Prep Pirates@Home I2U2 RSS Feeds

Einstein@Home

World Year of Physics 2005

LSC

UNIVERSITY of WISCONSIN MILWAUKEE

LIGO

Einstein@Home

Join Einstein@Home

1. Read our [rules and policies](#).
2. **Download, install and run** the BOINC software used by Einstein@Home.
3. When prompted, enter the URL: <http://einstein.phys.uwm.edu/>

If you are a new user **and** you are using one of the following (outdated) BOINC clients, then please use this [old-fashioned sign up page](#).

- Pre-5.0 client
- Mac Menubar
- command-line

Returning participants

- [Your account](#) - view stats, modify preferences
- [Teams](#) - create or join a team
- [Download BOINC](#)
- [BOINC Add-ons](#)
- [Einstein@Home Applications](#)
- [Choose language](#)
- [BOINC introduction](#)

Community

- [Participant profiles](#)
- [Message boards](#) - Discussion and Help
- [Frequently asked questions](#)
- [BOINC Wiki](#) - BOINC documentation

Project totals and leader boards

- [Top participants](#)
- [Top computers](#)
- [Top teams](#)
- [Other statistics](#)

Science information and progress reports

1. Visit project web site at <http://einstein.phys.uwm.edu>
2. Follow download link to BOINC site at UC Berkeley
3. Download BOINC package
4. Double click package to install, follow directions
5. "Attach" to Einstein@Home

BOINC: compute for science - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://boinc.berkeley.edu/download.php

Nexus Slashdot Prep Pirates@Home I2U2 RSS Feeds

Einstein@Home

BOINC: compute for science

BOINC

BOINC is a program that lets you donate your idle computer time to science projects like SETI@home, Climateprediction.net, Rosetta@home, World Community Grid, and many others.

After installing BOINC on your computer, you can connect it to as many of these projects as you like.

[Download BOINC](#)  
5.10.45 for Windows (7.10 MB)

[System requirements](#) | [Release notes](#) | [Troubleshooting](#) | [All versions](#)

[Return to BOINC main page](#)

This page is [translatable](#).  
Last modified 6:05 PM UTC - March 31 2008

# Join others: Teams and Forums

Top teams - Mozilla Firefox

http://einstein.phys.uwm.edu/top\_teams.php

Rank	Name	Members	Recent average credit	Total credit	Country
1	<a href="#">SETI.Germany</a>	1975	1,155,166	167,644,259	Germany
2	<a href="#">Einstein at work</a>	512	949,298	212,350,781	Germany
3	<b>Special: Off-Topic</b>	680	260,175	140,727,706	Germany
4	<a href="#">University of Wisconsin - Milwaukee (Computer Labs)</a>	31	183,823	99,068,876	United States
5	<a href="#">Czech National Team</a>	1937	182,983	119,607,087	Czech Republic
6	<a href="#">Planet 3DNow!</a>	302	168,559	25,529,256	Germany

Possible new source of gravitational waves

Message boards : [Science](#) : Possible new source of gravitational waves

Reply to this thread  
Subscribe to this thread

Author	Message
 <b>Mahray</b> private message Joined: Nov 11, 2004 Posts: 43 ID: 2002 Credit: 250,989 RAC: 153	Message 83053 - Posted 2 Apr 2008 10:20:29 UTC An interesting article on NewScientist about mountains on neutrons stars causing gravitational waves. At Einstein@Home. Check it out at <a href="http://space.newscientist.com/article/dh13566-mountains-on-stars-could-trigger-gravitational-waves">http://space.newscientist.com/article/dh13566-mountains-on-stars-could-trigger-gravitational-waves</a>  <b>Come on Aussie Come on!</b> Join the #1 Aussie Alliance, ranked 10th in the world. Help us grow and maintain our top ten world position. <a href="http://www.boinc-australia.net">www.boinc-australia.net</a>
 <b>Chipper Q</b> private message Joined: Feb 20, 2005 Posts: 1429 ID: 22189 Credit: 374,860 RAC: 504	Message 83063 - Posted 2 Apr 2008 15:41:17 UTC So if gravitational waves can be inferred from measuring a change in the orbital period of a binary system (as with PSR 1913+16), then would it be possible to infer which neutron stars are good candidates for producing gravitational waves by measuring a change in the rotational period? I understand that pulsars rotate with a regularity that rivals atomic clocks with regard to timing, but wouldn't that make the measurement easier (or more precise) over time?

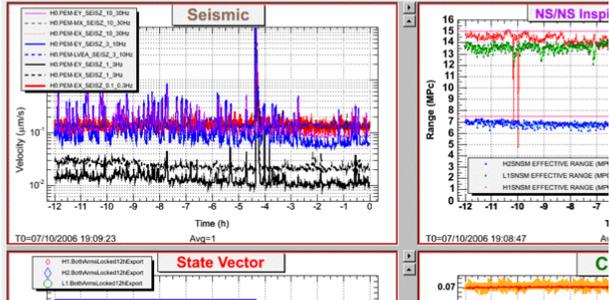
Detector Watch

advanced search

Message boards : [Science](#) : Detector Watch

Reply to this thread  
Subscribe to this thread

Author	Message
 <b>Mike Hewson</b> Forum moderator Joined: Dec 1, 2005 Posts: 986 ID: 135571 Credit: 1,969,877 RAC: 2,166	Message 49171 - Posted 8 Oct 2006 9:04:34 UTC Last modified: 9 Oct 2006 4:00:50 UTC I've taken a mind to browsing the detector logs regularly. I thought I'd try to kick off what any thread stickied let me know ). Would it be of interest if I report on anything there, but I quite like the technical side of these magnificent machines and I'm hoping few questions I may have... They are publicly viewable via the Username: 'reader' and Password: 'readonly' at either <a href="#">http://www.ligo.caltech.edu/~LIGO/</a> or <a href="#">http://www.ligo.caltech.edu/~LIGO/</a> I hope to keep images and sizes to a minimum, for the sake of non-broadbanders. Pl otherwise .... oh well :-) Anyhows I'll fire up by showing the effect of a nearby earthquake on Hanford:



The figure contains four subplots. The top-left plot is titled 'Seismic' and shows 'Velocity (µm/s)' vs 'Time (h)' from -12 to 0. It features several colored traces (blue, red, black) with a prominent spike at approximately -4 hours. The top-right plot is titled 'NS/NS Inspi' and shows 'Range (Mpc)' vs 'Time (h)' from -12 to 0, with multiple colored traces showing a sharp peak at the same time. The bottom-left plot is titled 'State Vector' and shows 'H0\_B0AmplitudeExport', 'H0\_B0AmplitudeExport', and 'L1\_B0AmplitudeExport' vs 'Time (h)'. The bottom-right plot is titled 'C' and shows a single trace with a sharp peak at the same time.

# Einstein@Home results

**No detections!** (except injections)

S3 final analysis is described on the project website: See <http://einstein.phys.uwm.edu/FinalS3Results>

S4 analysis is described in a paper:

*“The Einstein@Home search for periodic gravitational waves in LIGO S4 data”*

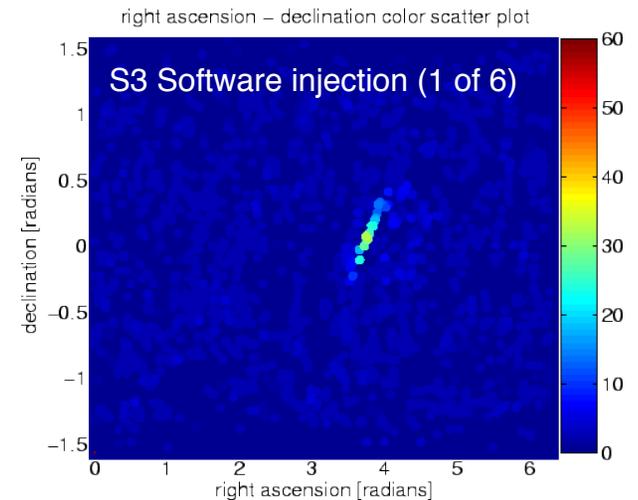
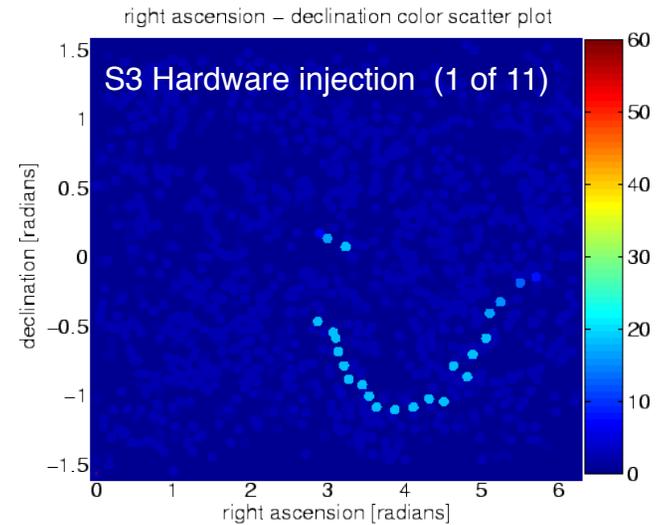
by the LIGO Scientific Collaboration

April, 2008 [e-print: <http://arxiv.org/abs/0804.1747/>]

Accepted for publication in *Physical Review D*

Analysis of S5 data still in progress.

New S5 "Run 5" analysis just started....



# Summary

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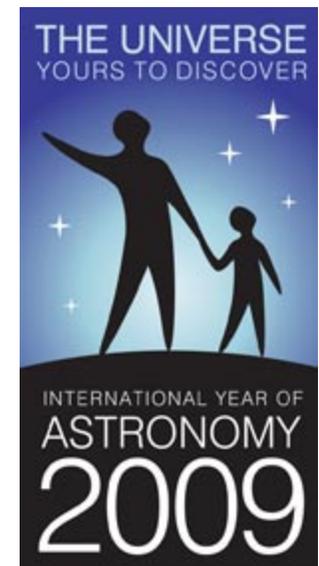
- **LIGO** is a cutting-edge *physics experiment* which is attempting to detect gravitational waves, using the most sensitive optical devices on the planet.

*Detection of gravitational waves will likely open up an entirely new branch of astronomy!*

- The computational effort required to perform an "all-sky blind" search for the signal of a Continuous Wave source (like a neutron star) is so large that it requires a supercomputer.
- Einstein@Home is a distributed computing project which runs on thousands of computers to perform this task.

**You can join the search:**

- <http://einstein.phys.uwm.edu>
- or just Google for "Einstein@Home"



# Einstein@Home contributors

Name	Institution	Contributions
Bruce Allen	UWM	Science code, Screensaver, BOINC locality scheduler, WU daemon, Assimilator, BOINC development, Management, Data preparation
David Anderson	UC Berkeley	BOINC development, Debugging
Teviet Creighton	Caltech/JPL	Validator
Steffen Grunewald	AEI	Validator, Download mirroring
Akos Fekete	AEI	Low-level code optimization
David Hammer	UWM	Server installation and administration, Screensaver, Website, Debugging, Data preparation
Yousuke Itoh	AEI and UWM	Science code, Post-processing and analysis
Gaurav Khanna	UMass Dartmouth	Code optimization/vectorization (especially on PPC)
Badri Krishnan	AEI	Einstein@Home S4/S5 search design
Mike Landry	LHO	APS web pages
Bernd Machenschalk	AEI	Science code, Application development and optimization/vectorization for all platforms, Forum moderation, Debugging, BOINC development
Greg Mendell	LHO	APS web pages
Eric Myers	Vassar	Screensaver, Website
Ben Owen	PSU	Message boards, Einstein@Home S4/S5 search design
Marialessandra Papa	AEI	Science code
Holger Pletsch	UWM	Post-processing and analysis
Reinhard Prix	AEI	Science code, Search design, Linux and Mac builds, Optimization, Debugging, BOINC development
James Riordon	APS	Publicity
Xavier Siemens	UWM	Science code, Testing, Data preparation

**...and 220,000 volunteers!**