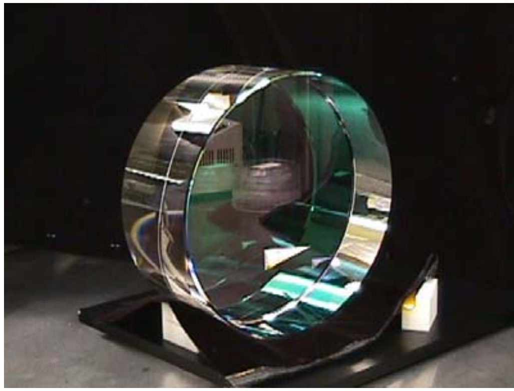
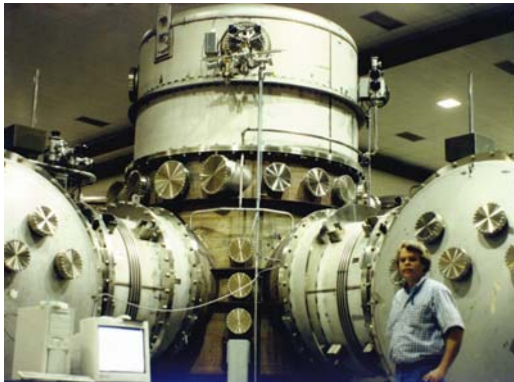
Einstein@Home: Searching for Ripples in Space-Time with Your Home Computer

Eric Myers

LIGO Hanford Observatory

Hanford, Washington





Amateur Astronomers Association of New York

11 April 2008

LIGO-G080289-00-Z

Overview

- What are Gravitational Waves?
- What is LIGO? How well does LIGO work?
- What is Einstein@Home? How does it work?
- How can you join the effort?

What are Gravitational Waves?

Just as Electromagnetic Waves (radio, infrared, visible, ultraviolet) are time-varying oscillations of electric and magnetic fields, Gravitational Waves are time-varying oscillations in the gravitational field. But…

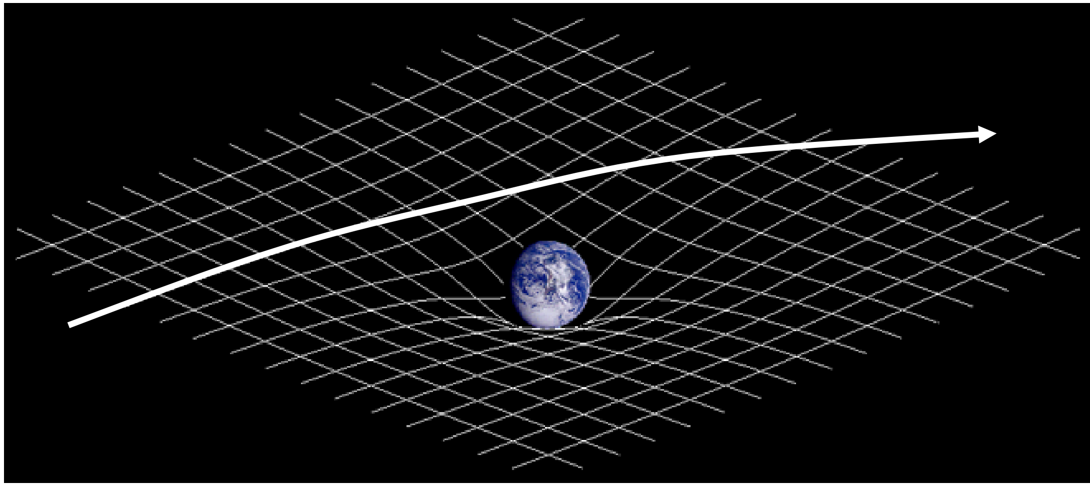
In Einstein's General theory of Relativity ("GR") gravitation is described as being a property of the geometry of space+time=spacetime

<u>Principles:</u>

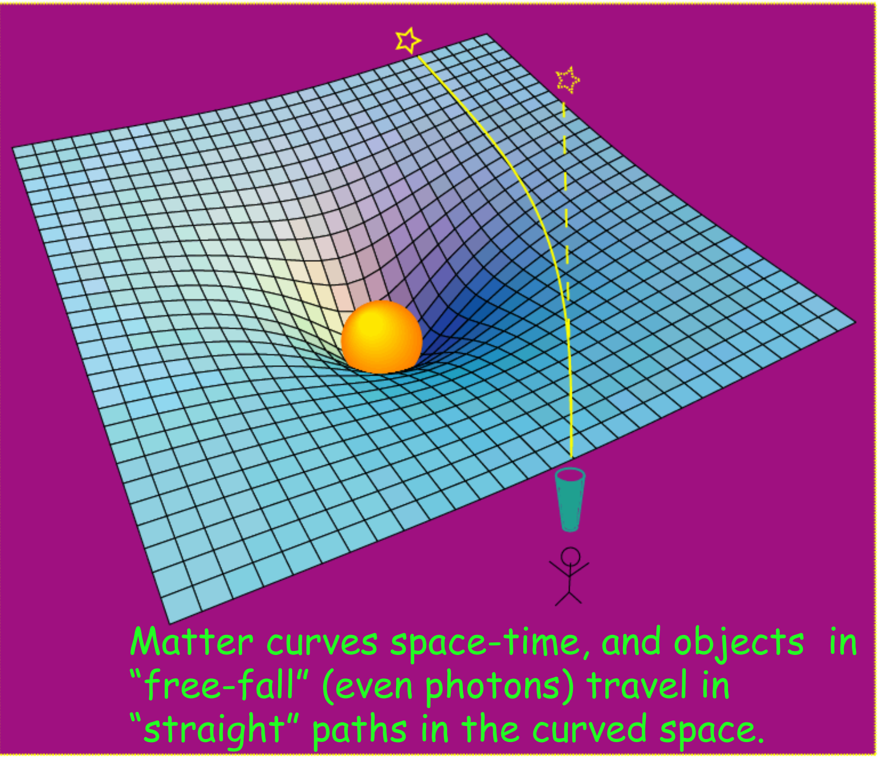
Matter curves spacetime,

and

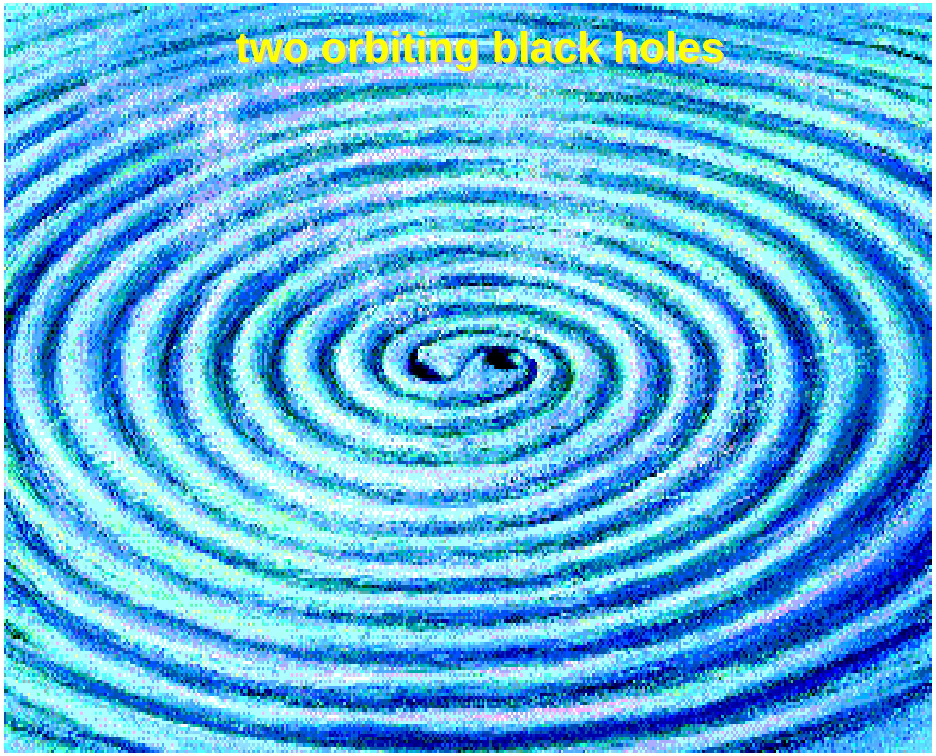
Objects in "free-fall" travel in "straight" paths in the curved space.



Gravitational Waves



Rendering of space-time stirred by

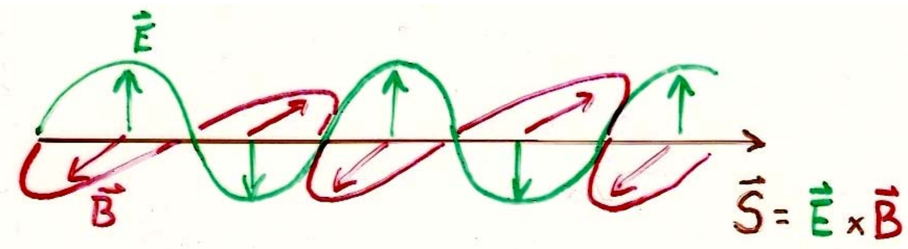


Changes in space-time produced by moving a mass are not felt instantaneously everywhere in space, but propagates as a wave.

Comparison with EM waves

Electromagnetic Waves

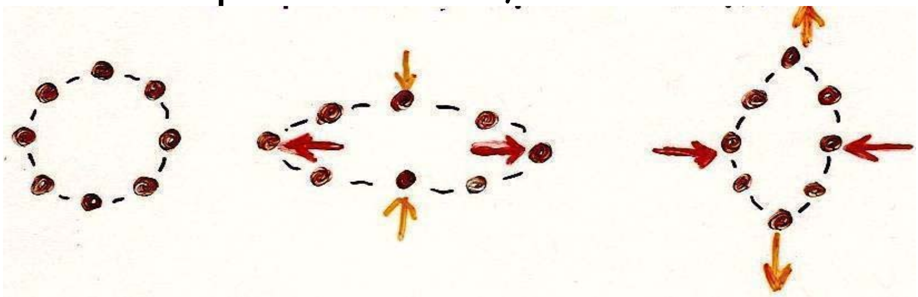
- Travel at the speed of light
- "transverse"
- Vector - dipole in both E and B
- Two polarizations: horizontal and vertical



- 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

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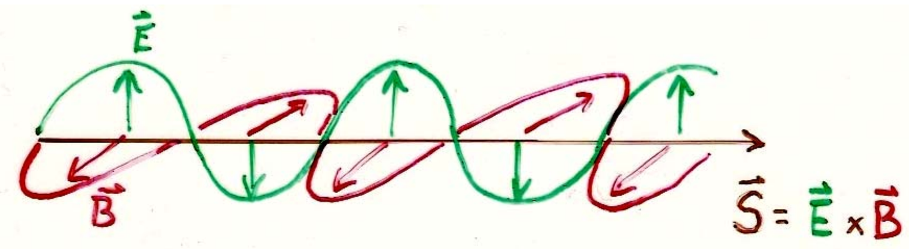

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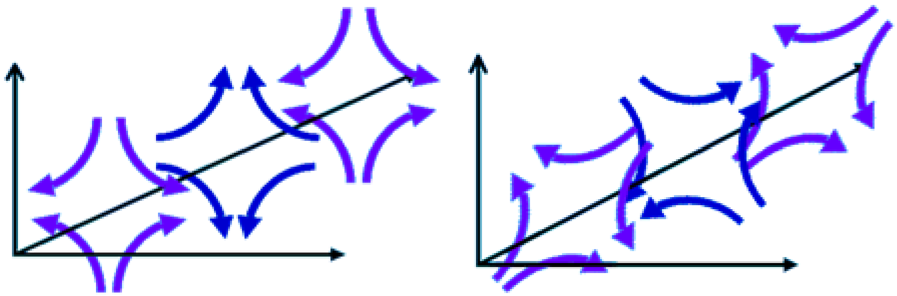
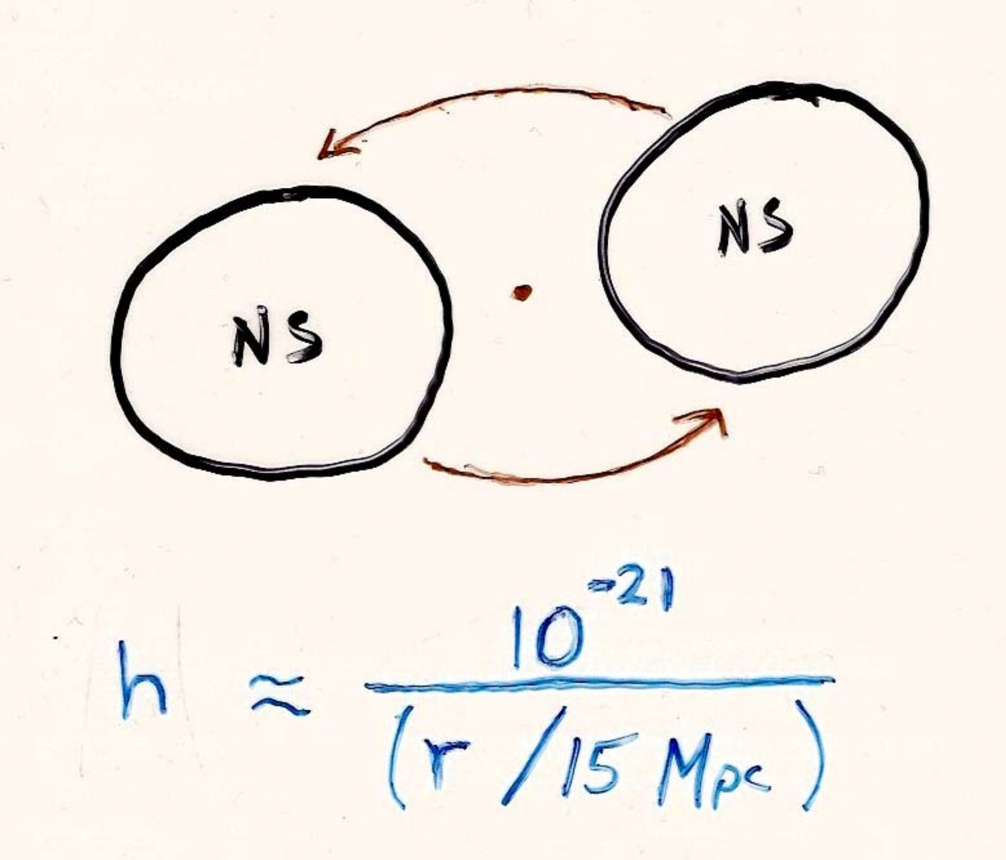


- Solutions to Einstein's Eqns.
- Gravitational waves require *changing* quadrupole mass distribution.

Example: Binary Inspiral

A pair of 1.4$M_\odot$ 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.

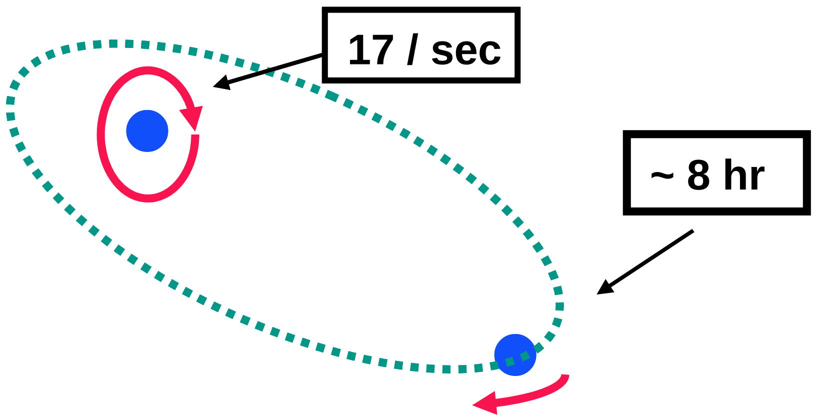
Wave frequency is *twice* the rotation frequency of binary!



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

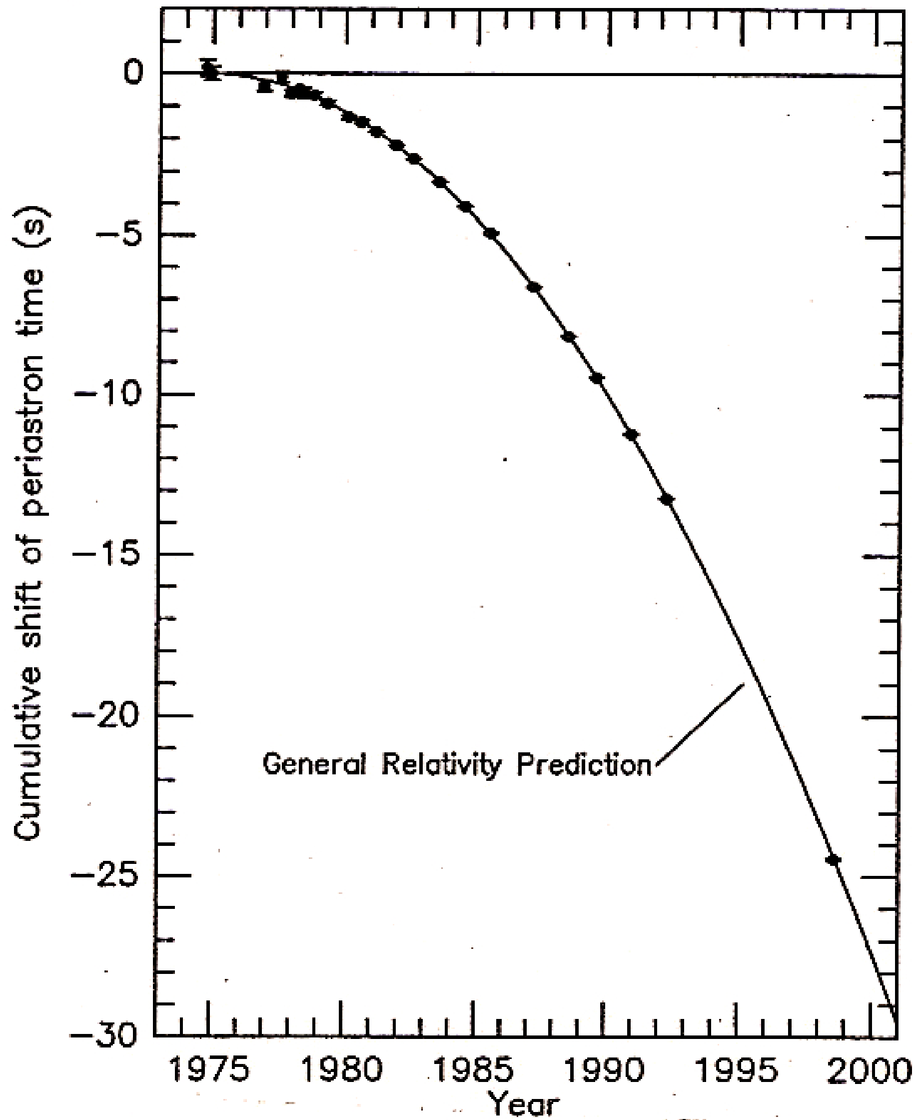
Indirect Evidence for GW's

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 loss of energy expected due to gravitational radiation.

(Nobel Prize in Physics, 1993)



How might GW's be produced?

The most likely astronomical sources are:

1) *Stochastic background* from the early universe (Big Bang! Cosmic Strings,...) – a "cosmic gravitational wave background" (CGWB)

2) *Bursts* from supernovae or other cataclysmic events (requires changing quadrupole. Spherical symmetric ⇒ no GW!)

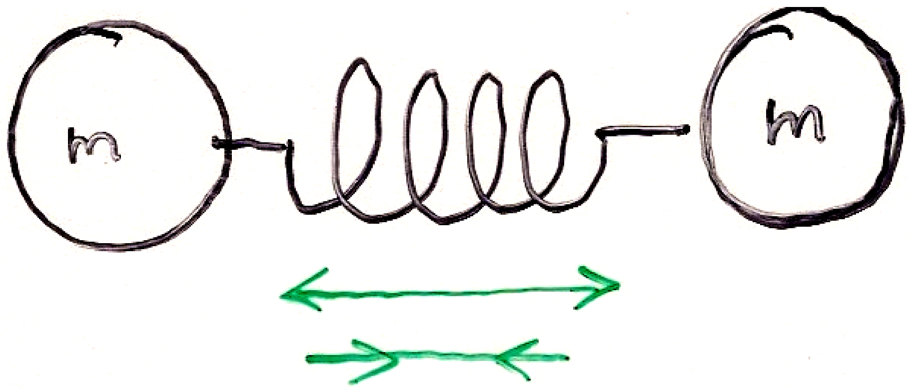
3) *Coalescence of binary systems*, inspiral of pairs of neutron stars and/or black holes (NS-NS, NS-BH, BH-BH) *CHIRP!*

4) *Continuous Wave sources*, such as spinning (and asymmetric!) neutron stars ("gravitational pulsars").

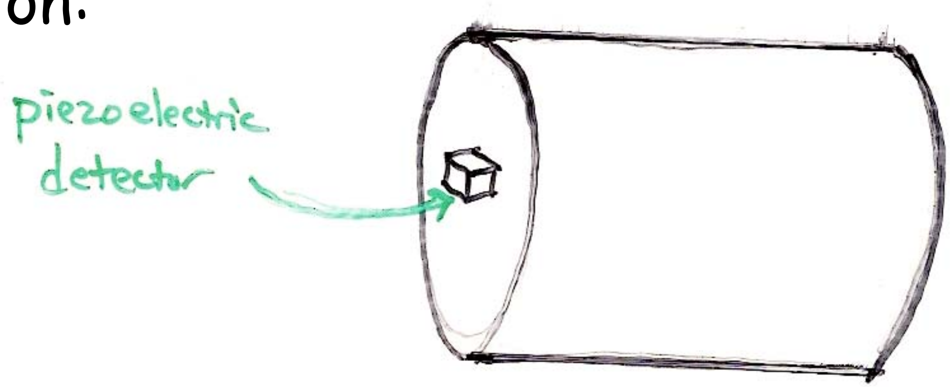
5) Something unexpected...!

How might GW's be detected?

Simplest example: the "bar-bell" detector.

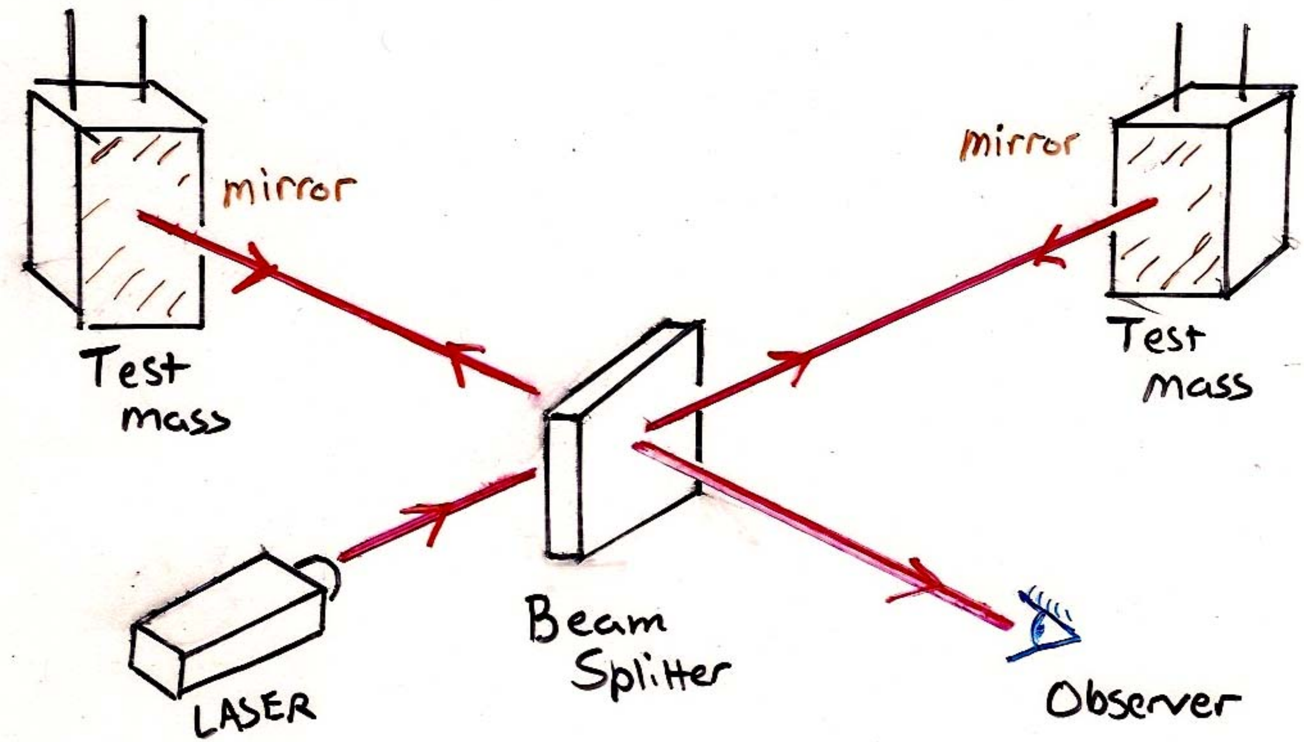


Practical implementation: a "bar" detector



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

Michelson Interferometer

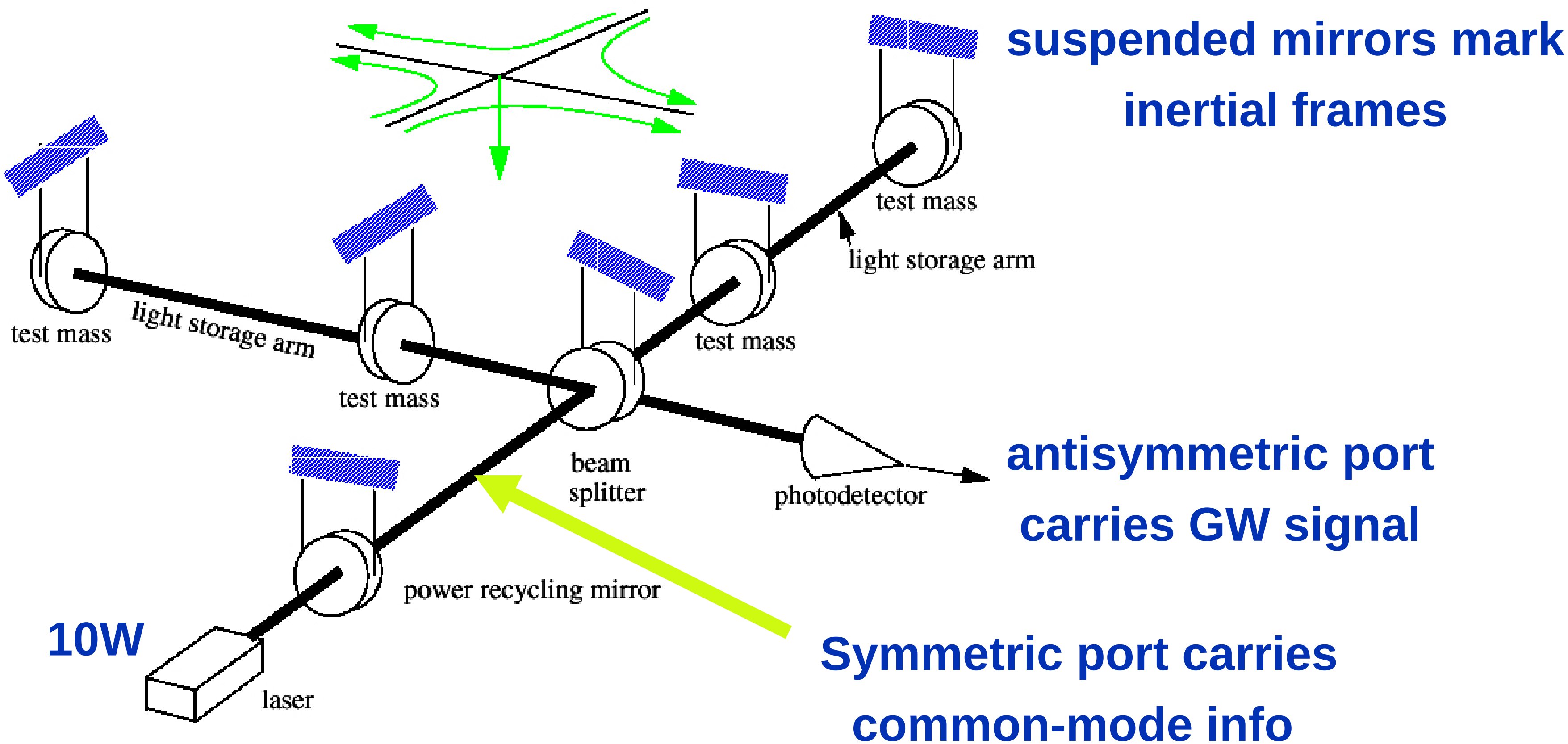


Measuring ΔL in arms allows the measurement of the *strain*

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

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

Power-recycled Fabry-Perot-Michelson



Laser Interferometer Gravitational wave Observatory

LIGO Livingston Observatory (LLO)

Livingston Parish, Louisiana

L1 (4km)

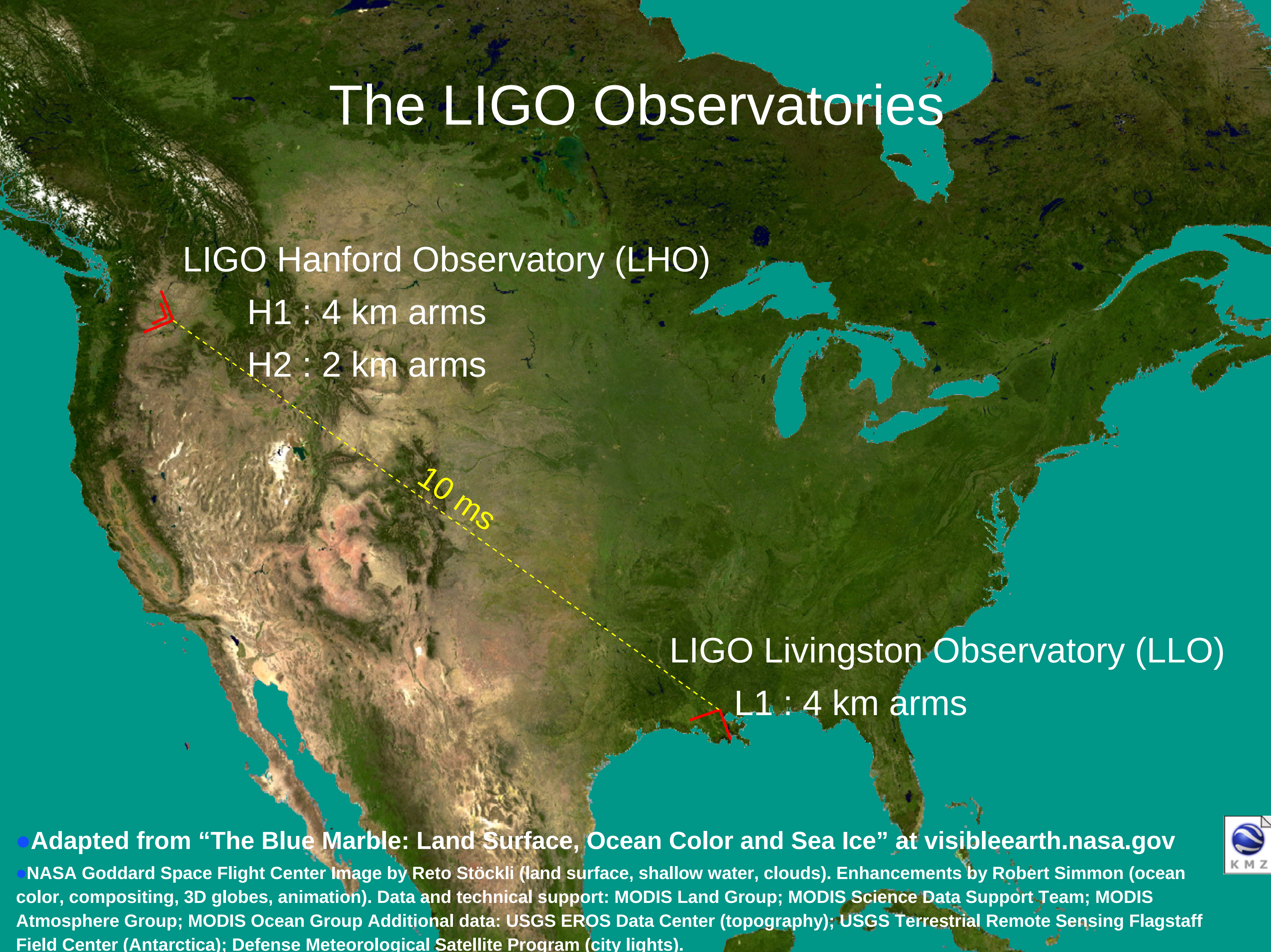
LIGO Hanford Observatory (LHO)

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.

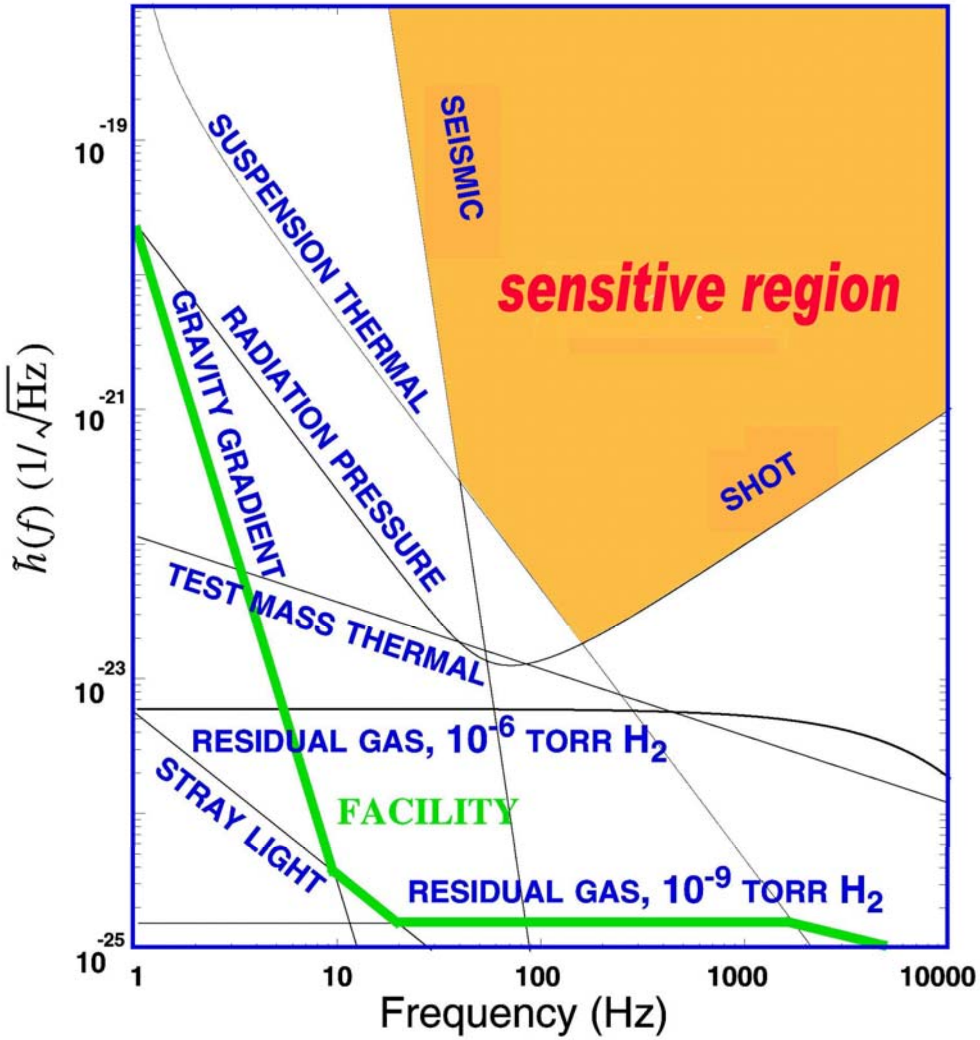
The LIGO Observatories



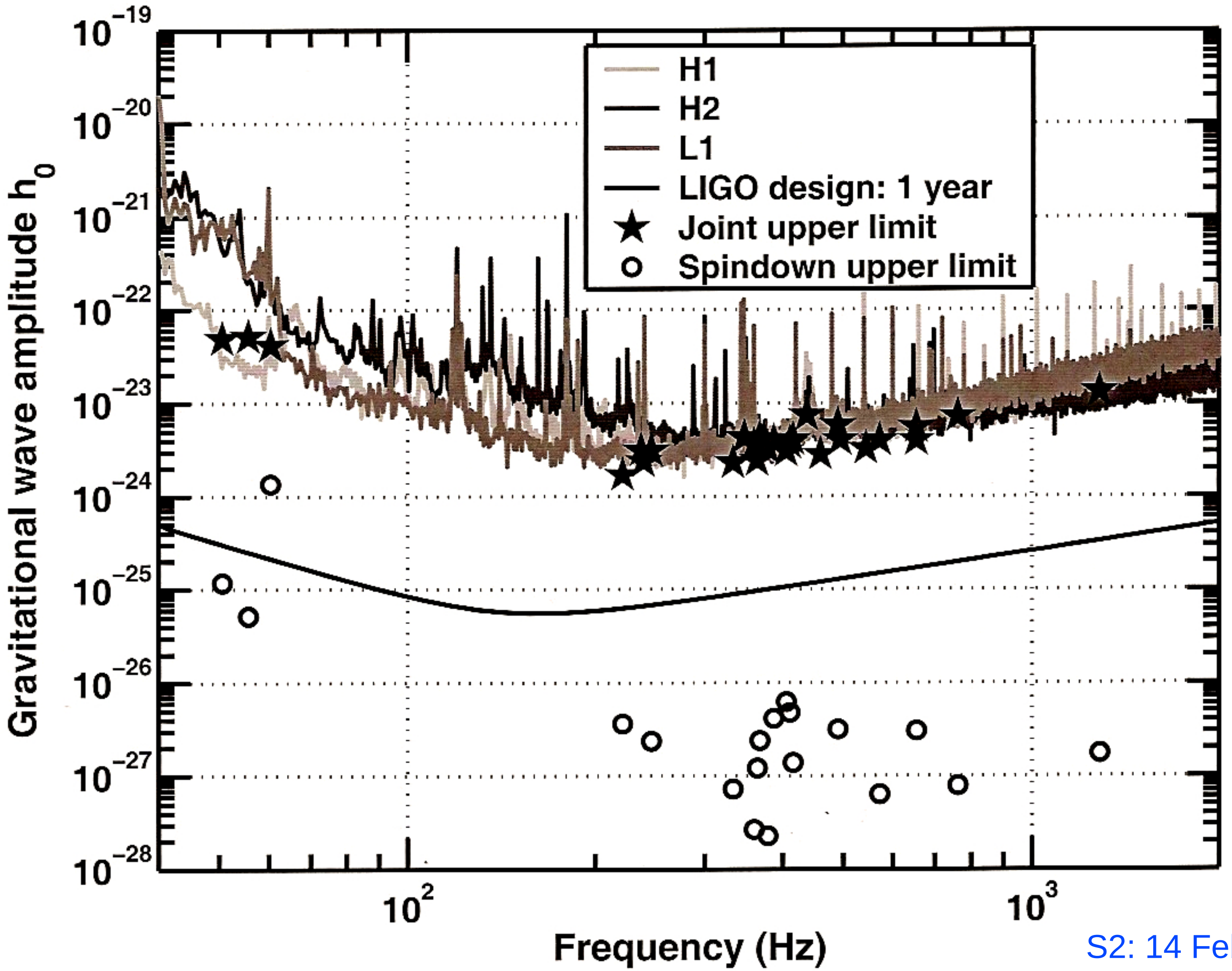
- **Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov**
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: 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

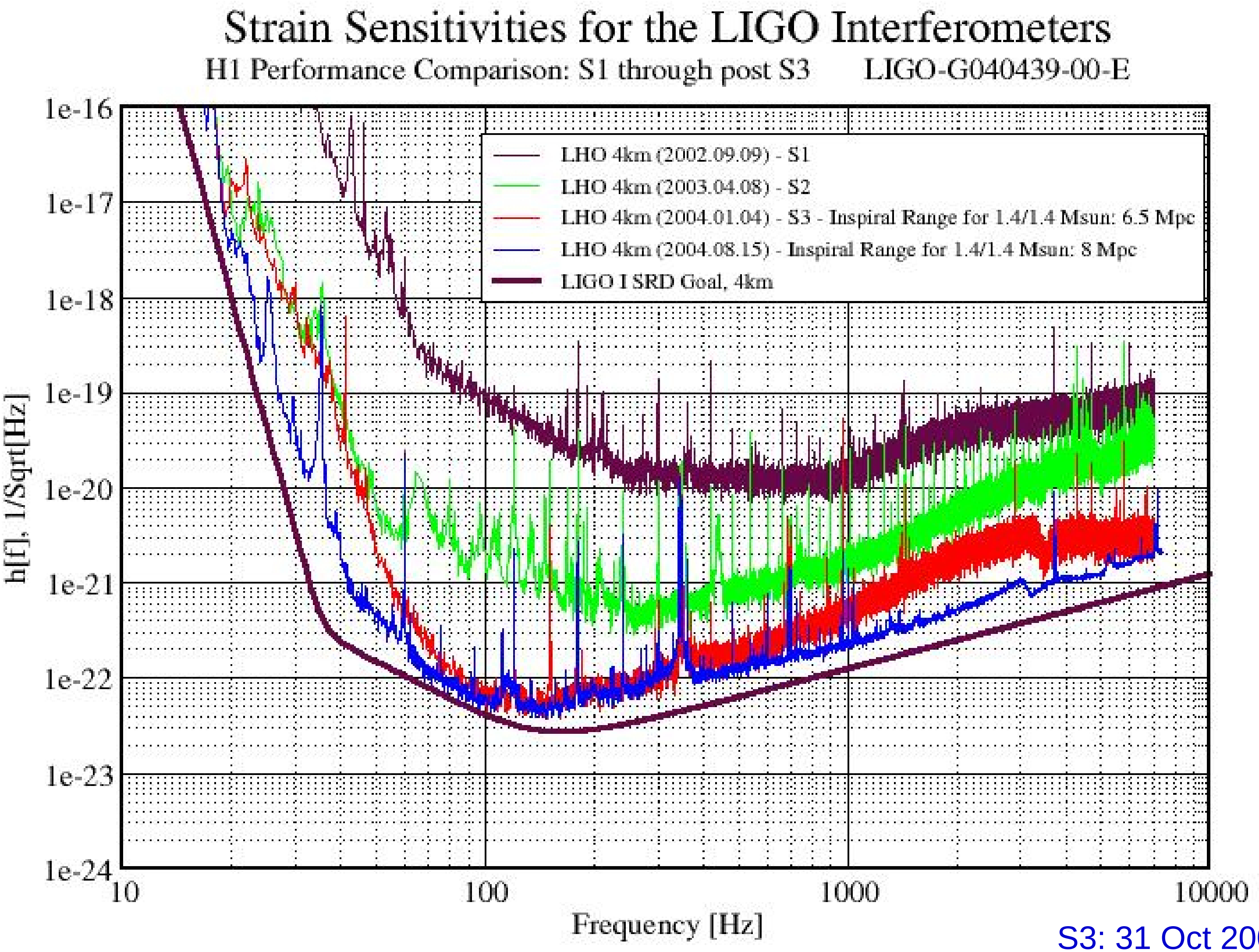


Pulsar Upper Limits (S2)



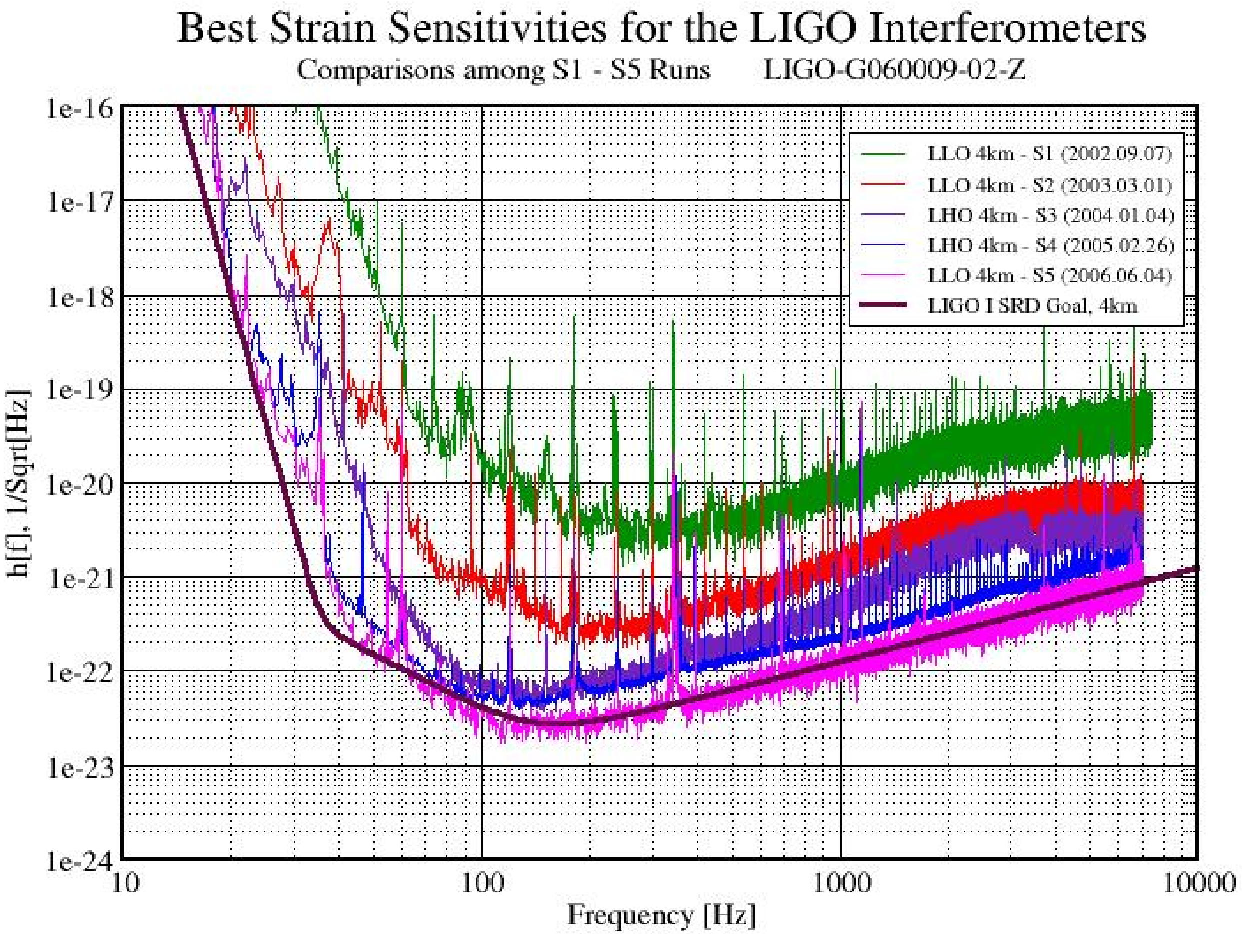
S2: 14 Feb to 14 April 2003

S3 Sensitivity



S3: 31 Oct 2004 to 9 Jan 2005

Strain Sensitivity S1 - S5



S5: 4 Nov 2005 to 30 Sept 2007

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"

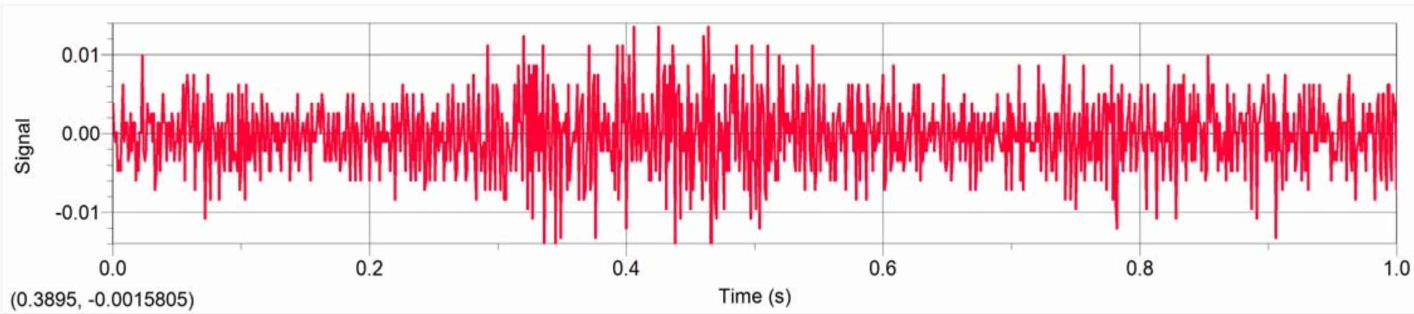
S6 run will start in late 2009, for about 3.5 years

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

LIGO

Searching for CW signals

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



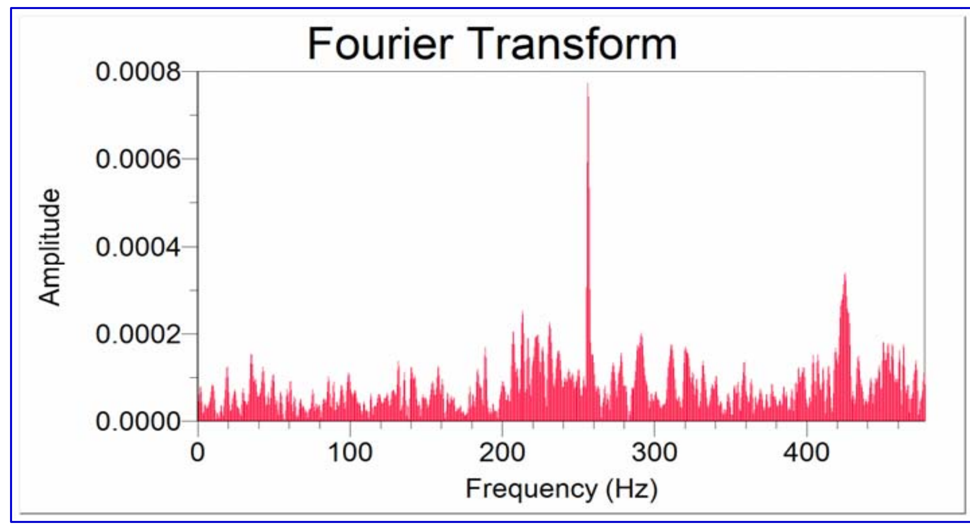
$\longrightarrow t$

Take the Fourier Transform to obtain:

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

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

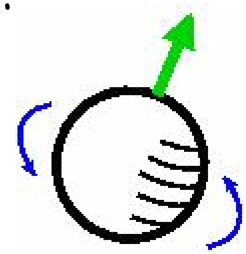
$$\tilde{B}_m = \frac{1}{\sqrt{2\pi}} \int_0^T f(x) \sin\left(\frac{2\pi m t}{T}\right) dt$$



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

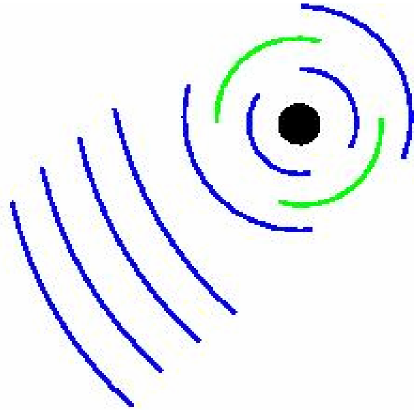
The frequency will change!

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



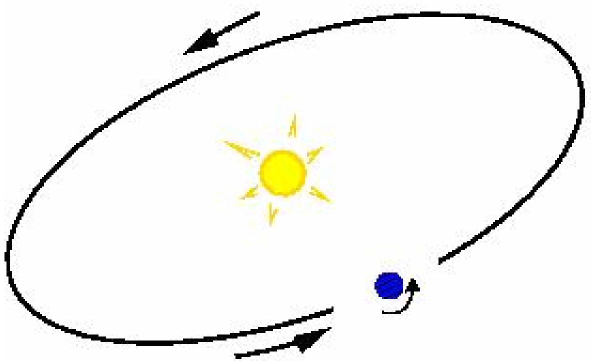
1. The source losing energy due to "spin down"

2. Doppler shift due to Earth's motion about the Sun (one part in 10^4, with period of 1 year)

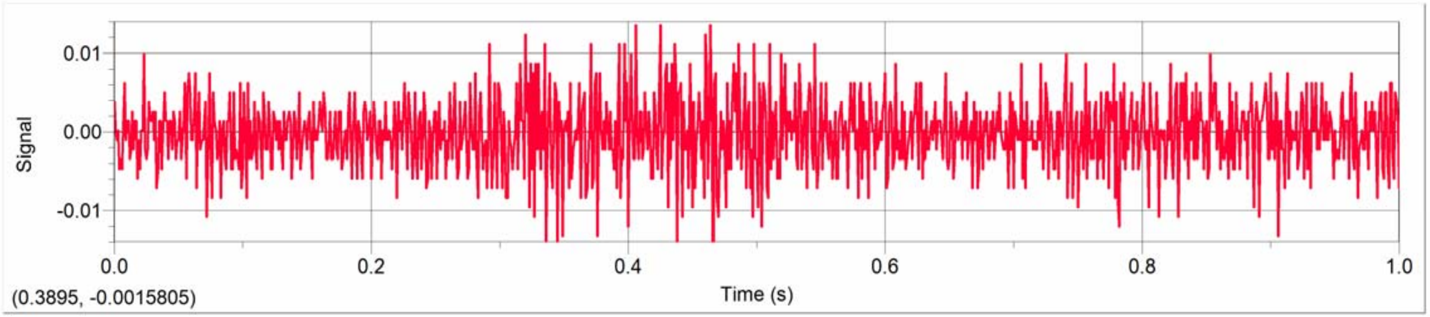


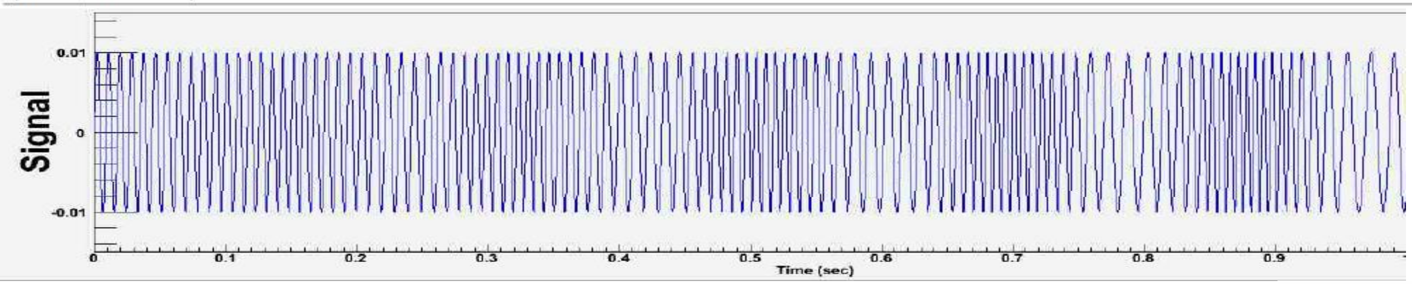
3. Doppler shift due to Earth's rotation about its axis (one part in 10^6, with period 1 sidereal day)

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



Matched Filtering





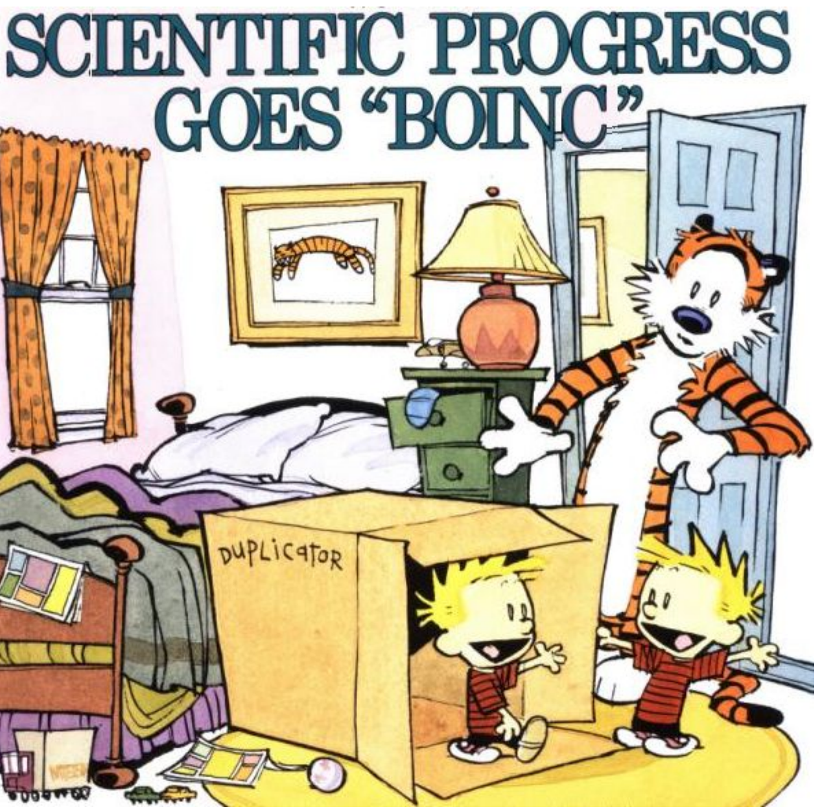
Assuming data $x(t) = h(t) + n(t)$ compute $\mathcal{F} \approx \int_0^T \frac{h(t)\,x(t)}{S_h(t)}\,dt$

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

And computational effort goes up like T^6 !

Looks like we're gonna need a bigger computer!

BOINC to the rescue



In 2004 SETI@home upgraded to BOINC:

Berkeley
Open
Infrastructure for
Network
Computing

Second generation of distributed computing software to search for distinctive peaks in Arecibo radio data.

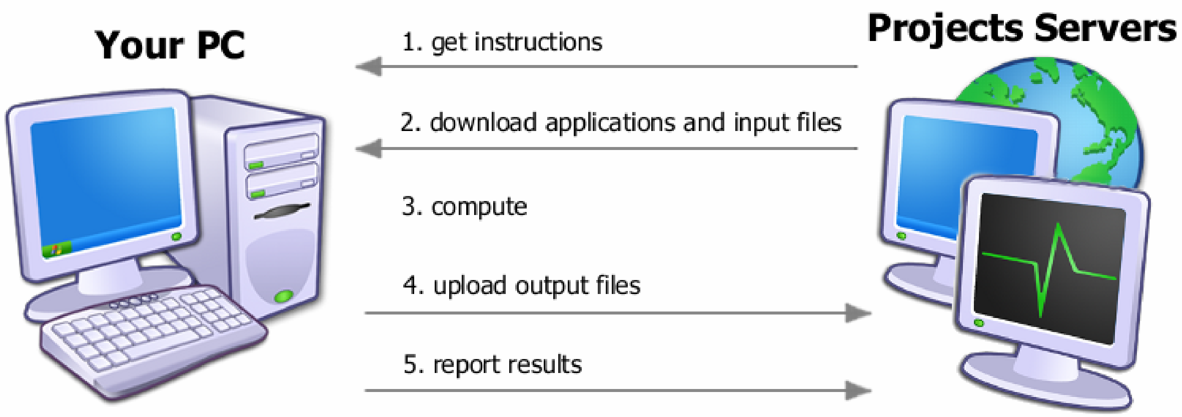
Modular, so that one can replace the "computation thread" and the "graphics thread".

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

3x redundancy protects against failures or cheating



Screensaver graphics

LHO azimuth position

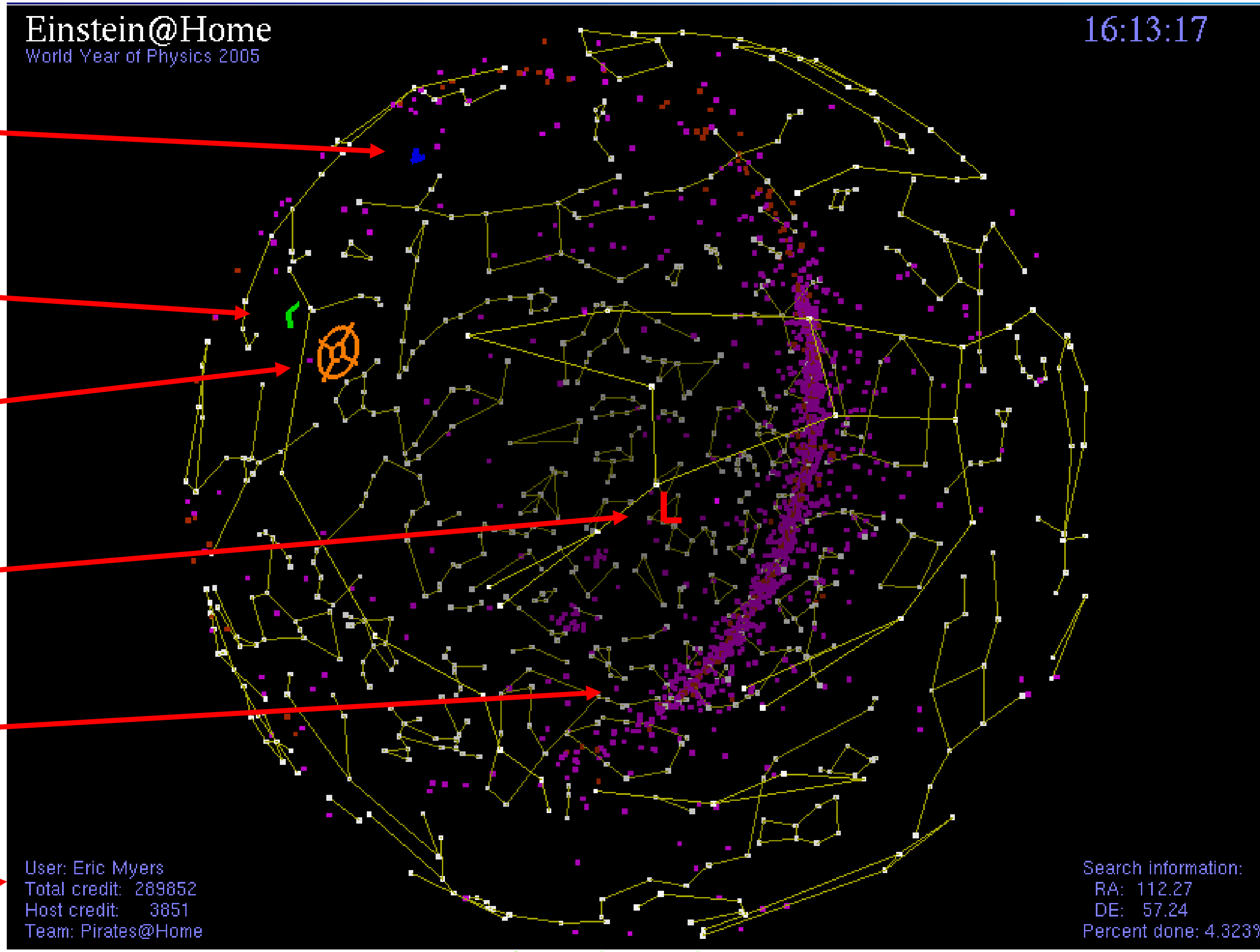
LLO azimuth position

Search marker

GEO600 azimuth position

Known pulsars (electromagnetic) and SNR's

User, team, host info



Einstein@Home status

As of 4 April 2008

Nexus Slashdot Prep Pirates@Home I2U2 RSS Feeds

Einstein@Home Message ... | Einstein@Home - Serv...

Einstein@Home - Server Status

Einstein@Home server status as of 3:15 PM UTC on Friday, 4 April 2008 (updated every 20 minutes).
The Einstein@Home main server has been continuously up for 661 days 18 hours 20 minutes.

Server status

Program	Host	Status
Web server	einstein	Running
Einstein S5R3 generator	einstein	Running
BOINC database feeder	einstein	Running
BOINC transitioner	einstein	Running
BOINC scheduler	einstein	Running
BOINC file uploads	einstein	Running
Einstein S5R3 validators	einstein	Running
Einstein S5R2 validators	einstein	Running
Einstein S5R3 assimilator	einstein	Running
Einstein S5R2 assimilator	einstein	Running
BOINC file deleter	einstein	Running
BOINC database purger	einstein	Running

Download mirror status

Site	Status	Last failure
Albert Einstein Institute	Running	31 h 45 m ago
University of Glasgow LSC group	Running	0 h 31 m ago
MIT LIGO Lab	Running	0 h 31 m ago
Penn State LSC group	Running	0 h 31 m ago
Caltech LIGO Lab	Running	None

S5R3 search progress

Total needed	Already done	Work still remaining
7,369,434 units	3,422,521 units	3,946,913 units
100 %	46.442 %	53.558 %
419.8 days	195.0 days	224.9 days (estimated)

Users and Computers

USERS	Approximate #
in database	[illegible]
with credit	194,611
registered in past 24 hours	184
HOST COMPUTERS	**Approximate #**
in database	952,264
registered in past 24 hours	3,950
with credit	484,088
active in past 7 days	[illegible]
floating point speed[1)]	120.8 TFLOPS

Work and Results

WORKUNITS	Approximate #
in database	337,993
with canonical result	180,503
no canonical result	157,490
RESULTS	**Approximate #**
in database	723,340
unsent	7,344
in progress	192,460
deleted	375,696
valid	361,650
valid last week	290,538
invalid	40
Oldest Unsent Result	4 d 15 h 12 m

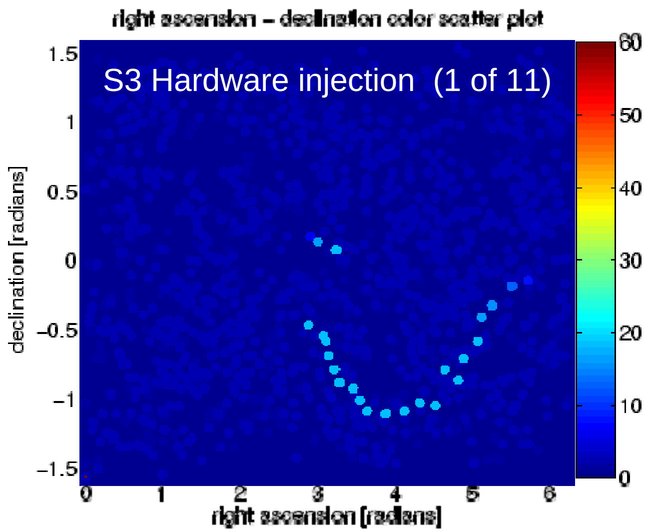
1) from the sum of the Recent Average Credit (RAC) for all users Graphical display of progress on S5.

Return to Einstein@Home main page

Einstein@Home results

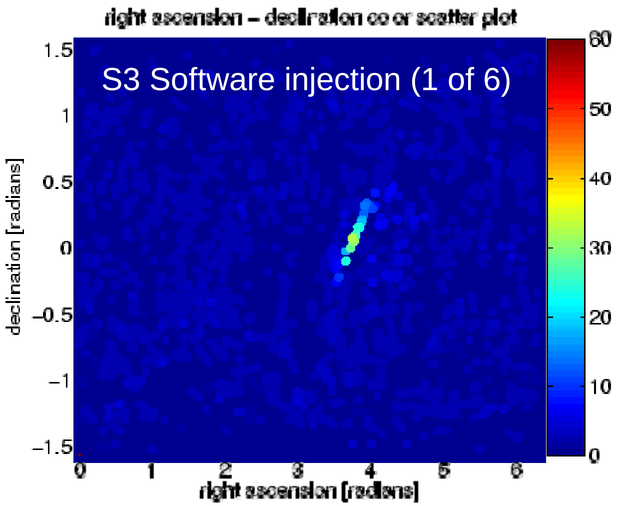
No detections! (except injections)

S3 final analysis is described on the project website [http://einstein.phys.uwm.edu/FinalS3Results]



S4 analysis is described in a paper being prepared for publication, to be released soon…

Paper posted to arXiv.org on 10 April !
Bruce Allen is presenting S4 results next week at the American Physical Society meeting in St. Louis



S5 analysis is still in progress….

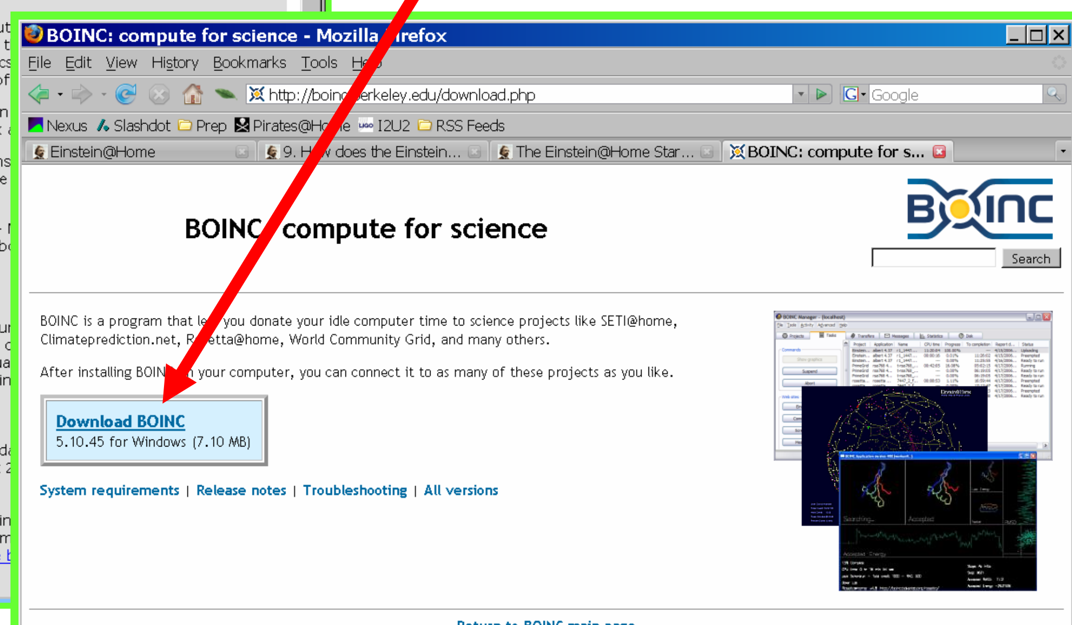
How you can join

1) Visit project web site at http://einstein.phys.uwm.edu

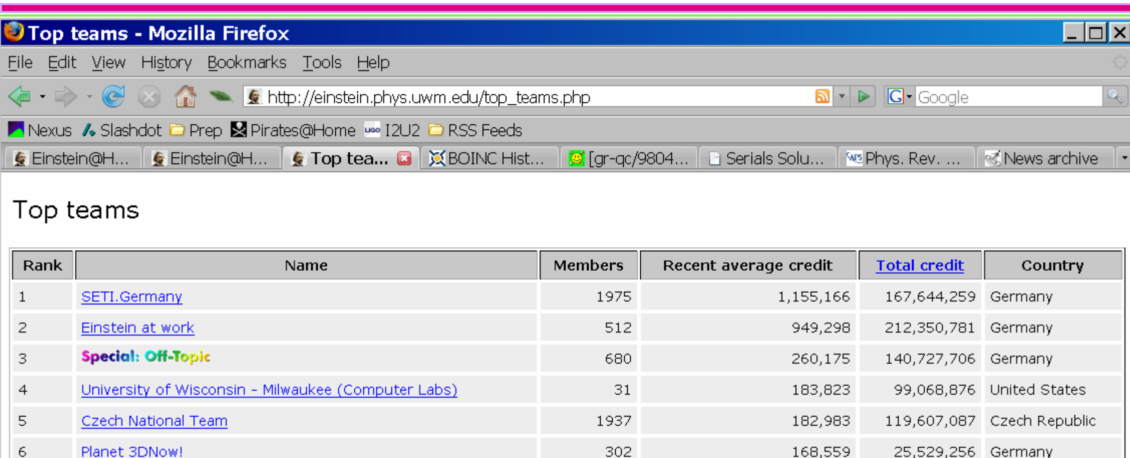
2) Follow download link to Berkeley BOINC site

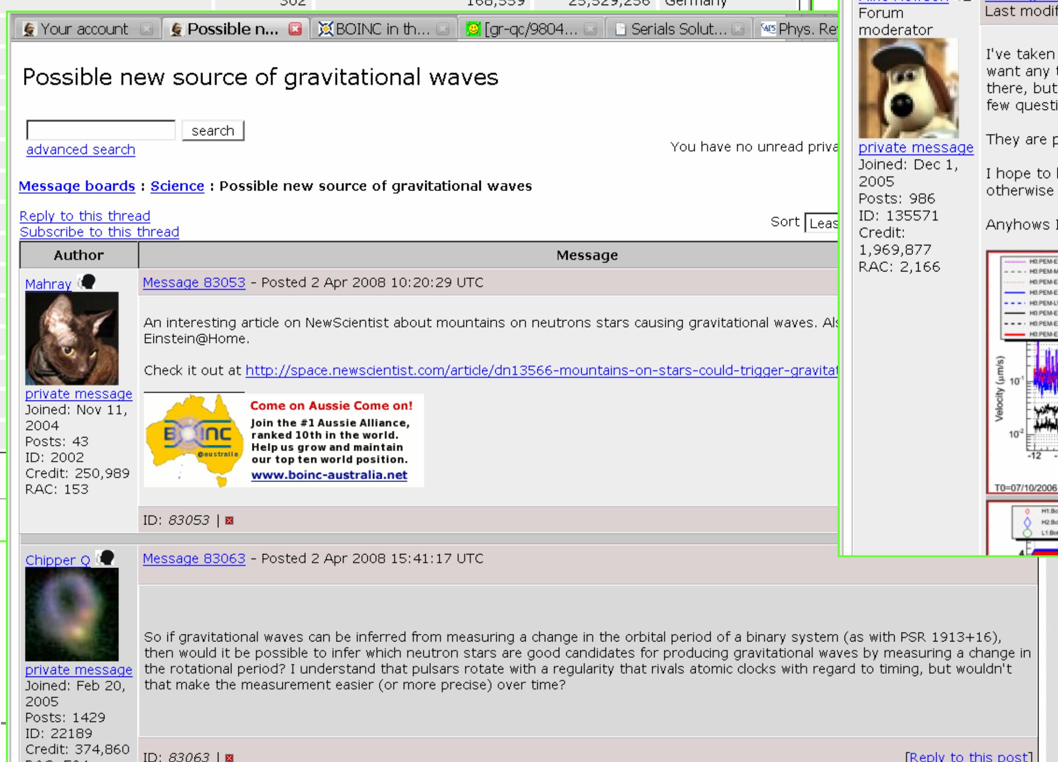
3) Download BOINC package

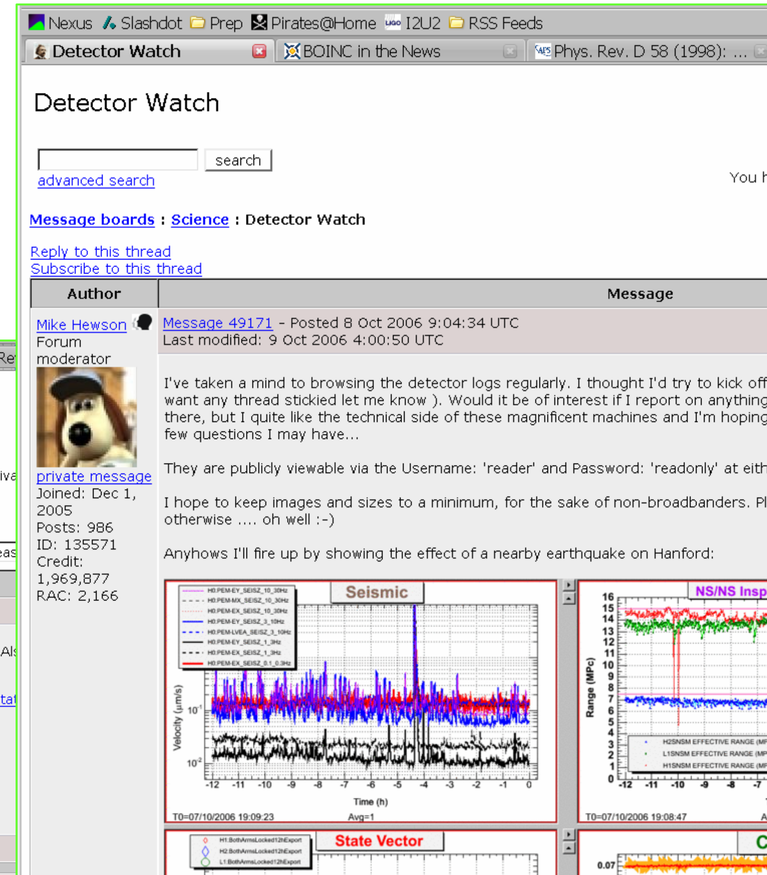
4) Double click to install and follow directions



Teams and Forums







- ❑ What are Gravitational Waves? ✓
- ❑ What is LIGO? ✓ How well does it work? ✓
- ❑ What is *Einstein@Home*? ✓ How does it work? ✓
- ❑ How <u>*you*</u> can join the effort !! ✓

$\Rightarrow$ http://einstein.phys.uwm.edu

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 200,000 volunteers!