

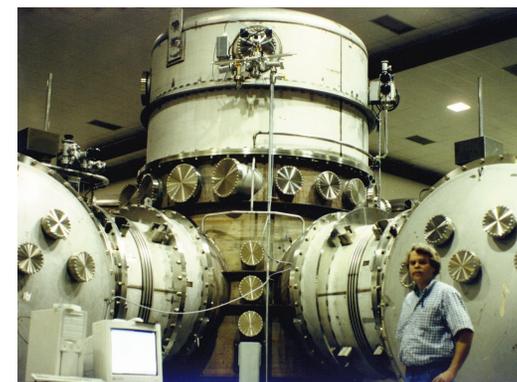
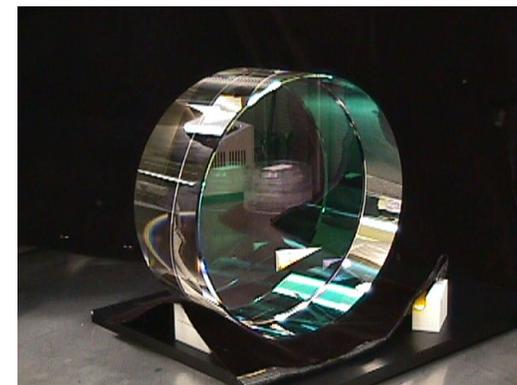


Einstein@Home: Searching for Ripples in Space-Time with Your Home Computer

Eric Myers

LIGO Hanford Observatory
Hanford, Washington

*Amateur Astronomers Association
of New York
11 April 2008*





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?

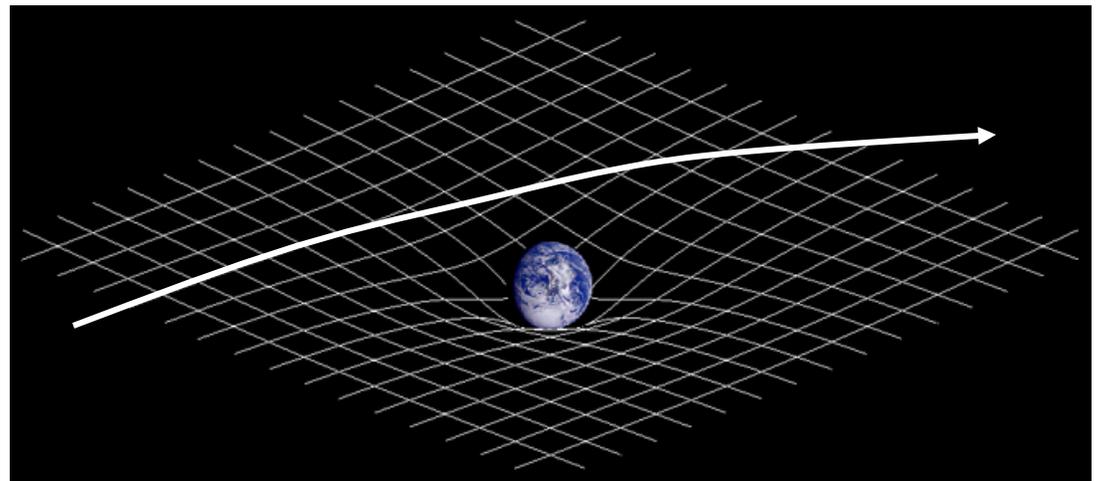
Just as **Electromagnetic Waves** (radio, infrared, visible, ultraviolet) are time-varying oscillations of electric and magnetic fields, **Gravitational Waves** are time-varying oscillations in the gravitational field. But...

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

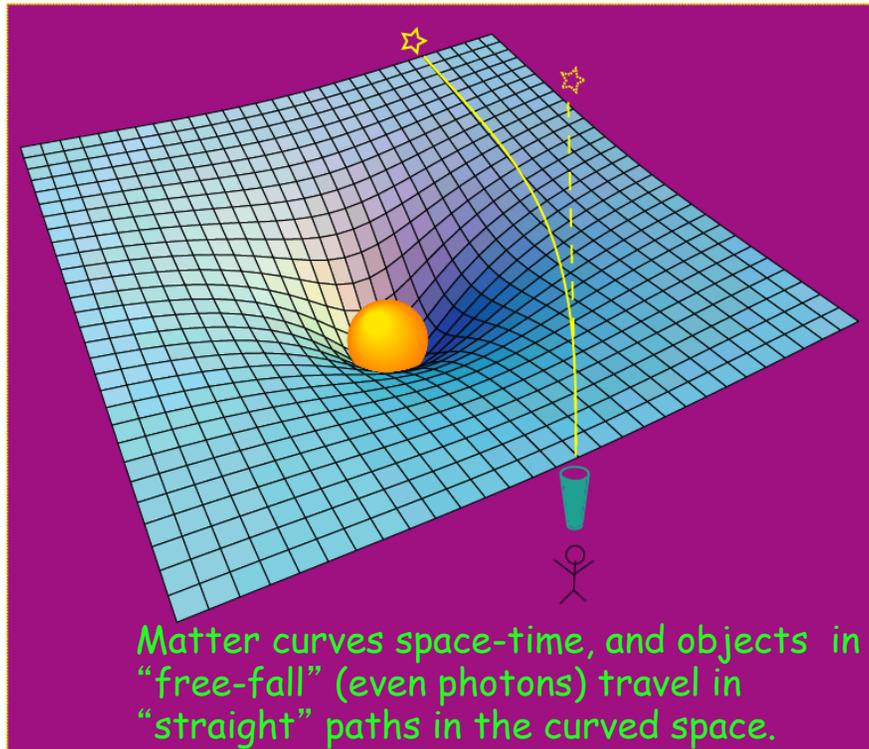
Principles:

Matter curves spacetime,
and

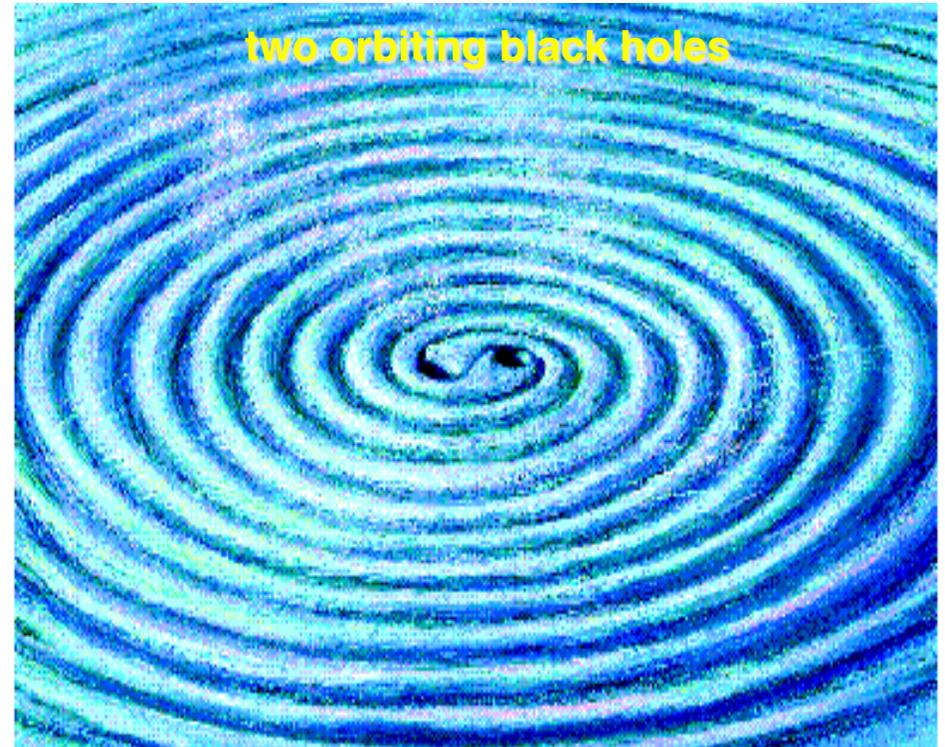
Objects in "free-fall"
travel in "straight"
paths in the curved space.



Gravitational Waves



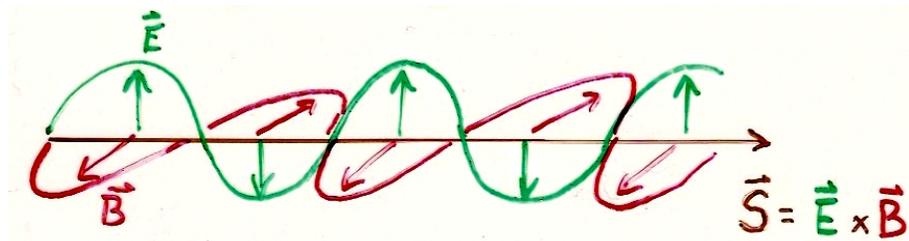
Rendering of space-time stirred by



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

Electromagnetic Waves

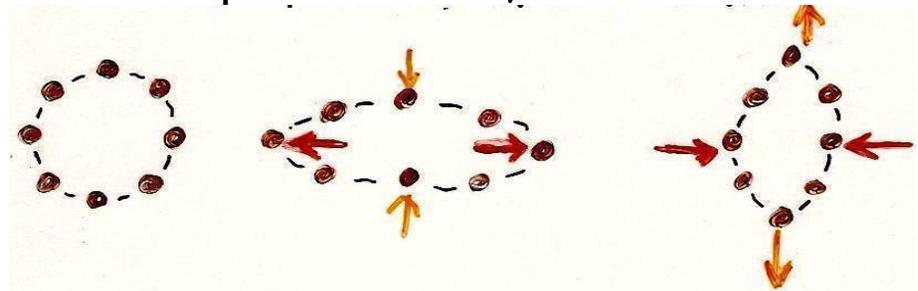
- Travel at the speed of light
- “transverse”
- Vector - dipole in both E and B
- Two polarizations: horizontal and vertical



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

Gravitational Waves

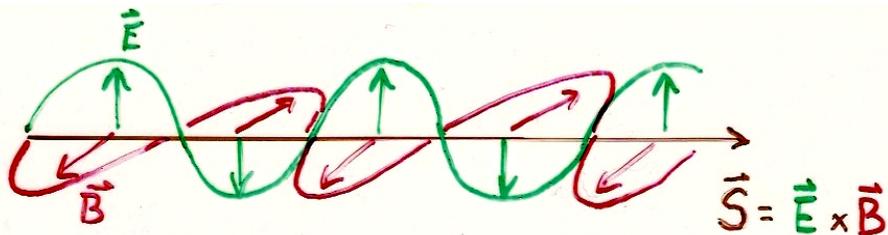
- Travel at the speed of light
- “transverse”
- Tensor - quadrupole distortions of space-time
- Two polarizations, “+” and “x”



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

Electromagnetic Waves

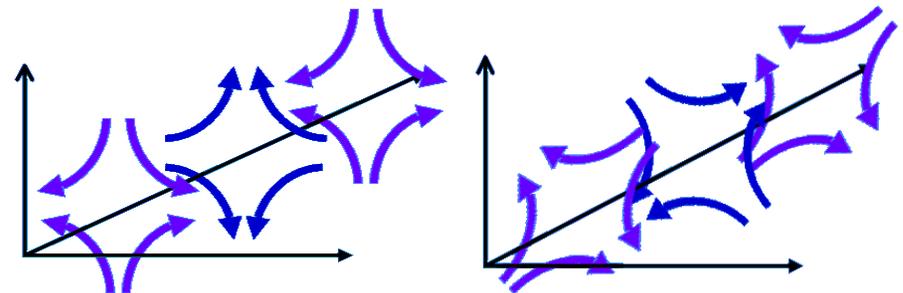
- Travel at the speed of light
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- Solutions to Maxwell's Eqns.
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Gravitational Waves

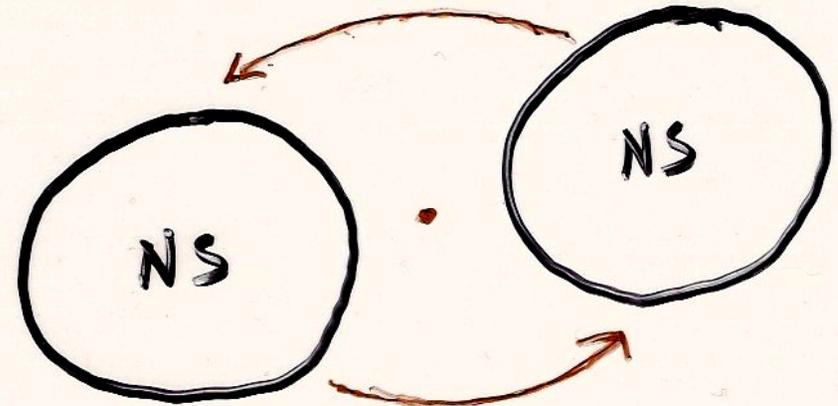
- Travel at the speed of light
- “transverse”
- Tensor - quadrupole distortions of space-time
- Two polarizations, “+” and “x”



- Solutions to Einstein's Eqns.
- Gravitational waves require 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 strain of amplitude $h = \frac{4}{r} L/L$ at frequency 800 Hz. (a)

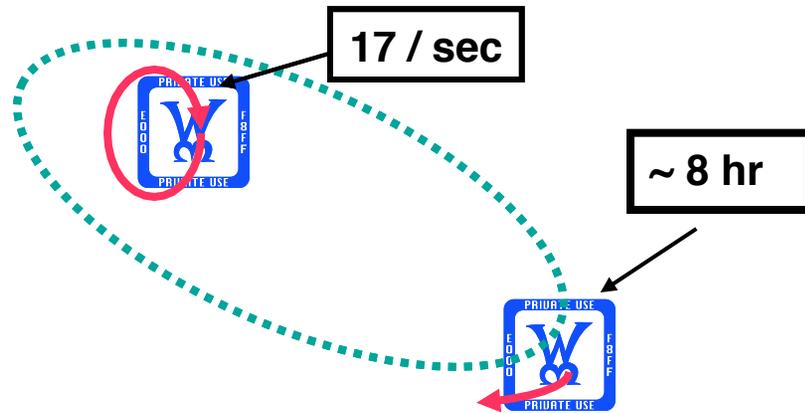
Wave frequency is twice the rotation frequency of binary!



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

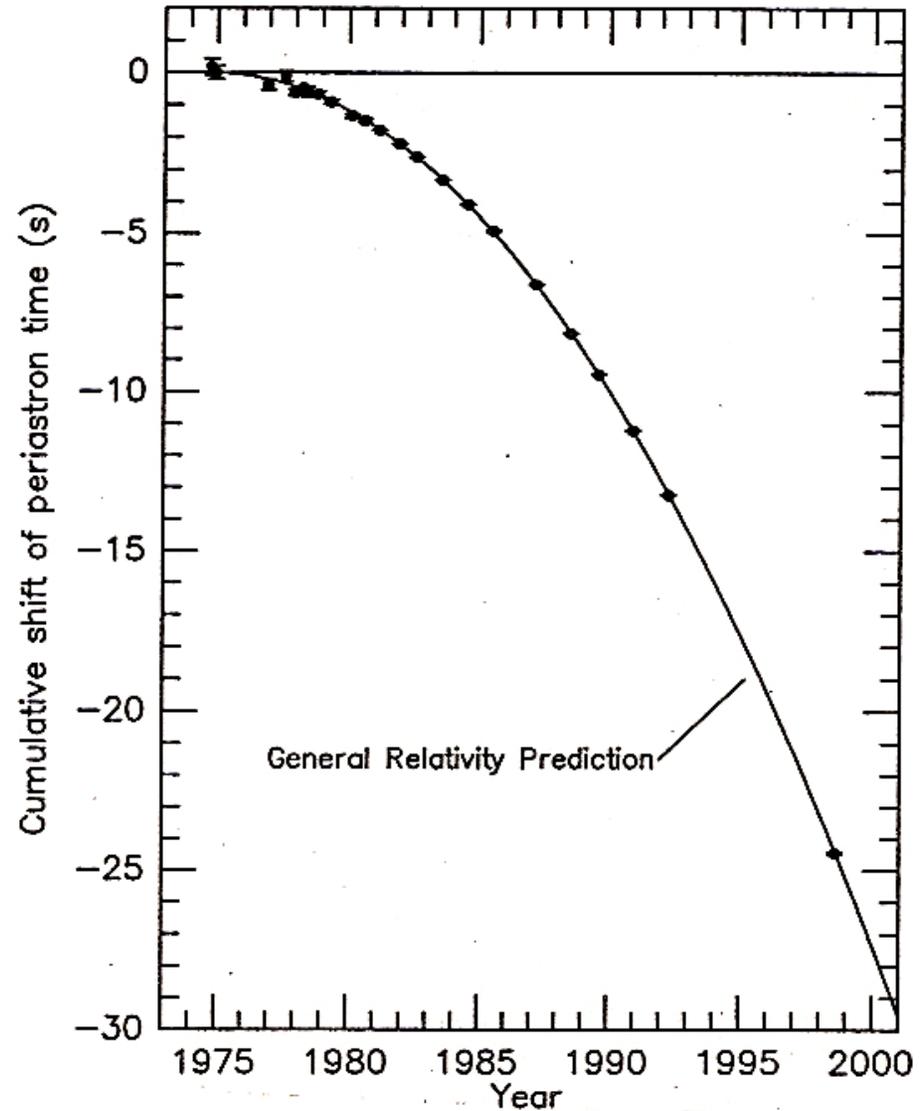
($1.4M_{\odot}$ binary inspiral provides a useful translation from dimensionless strain h to the “reach” of the instruments, in Mpc)

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?

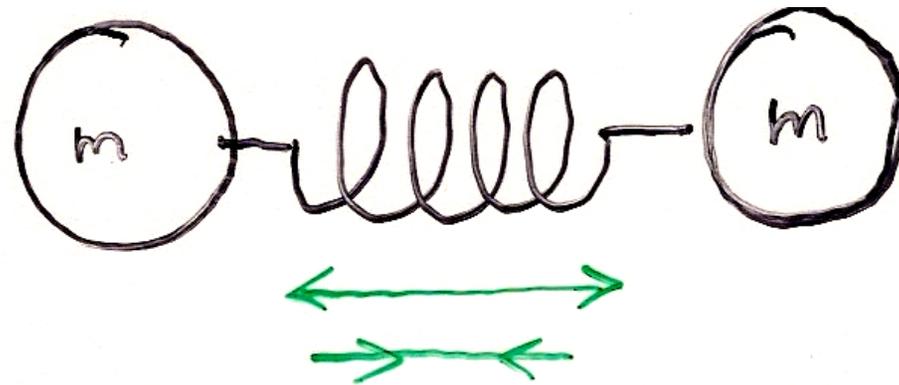


The most likely astronomical sources are:

- 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 \square 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...!**

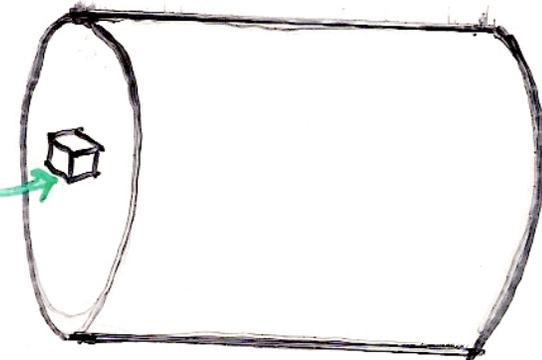
How might GW's be detected?

Simplest example: the "bar-bell" detector.

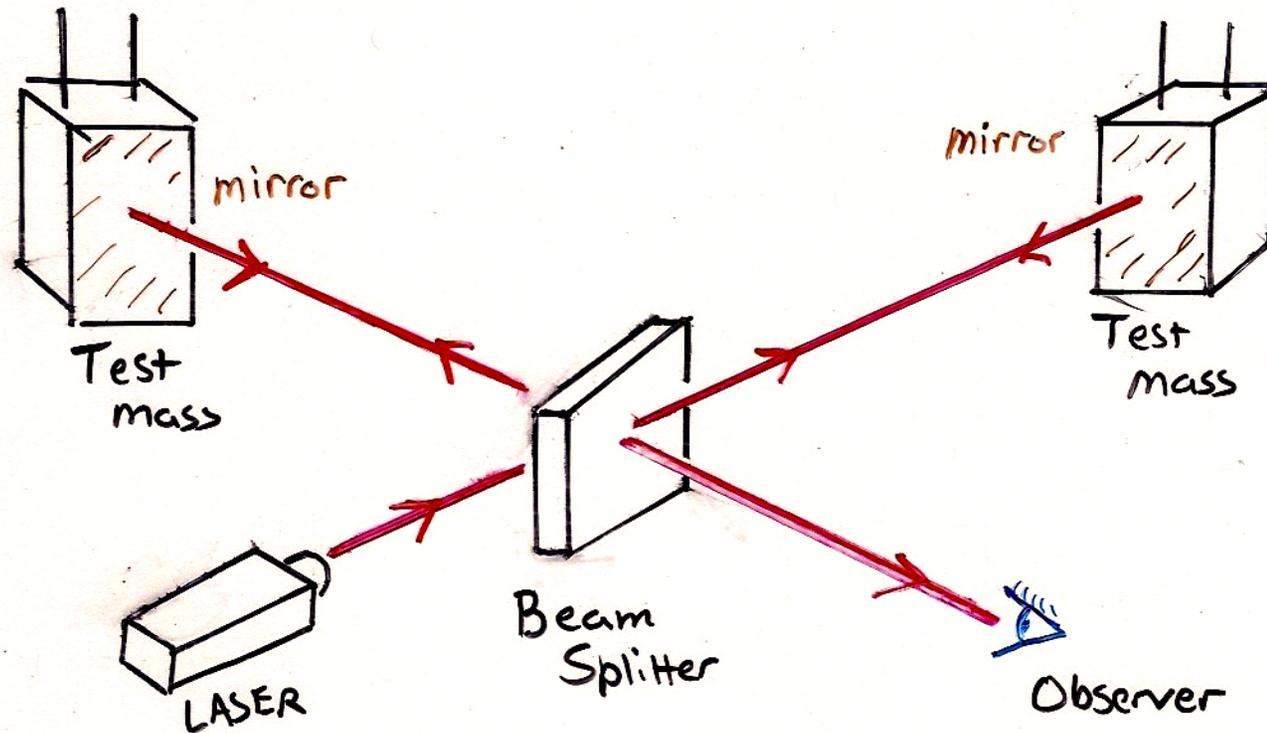


Practical implementation: a "bar" detector

piezoelectric detector



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

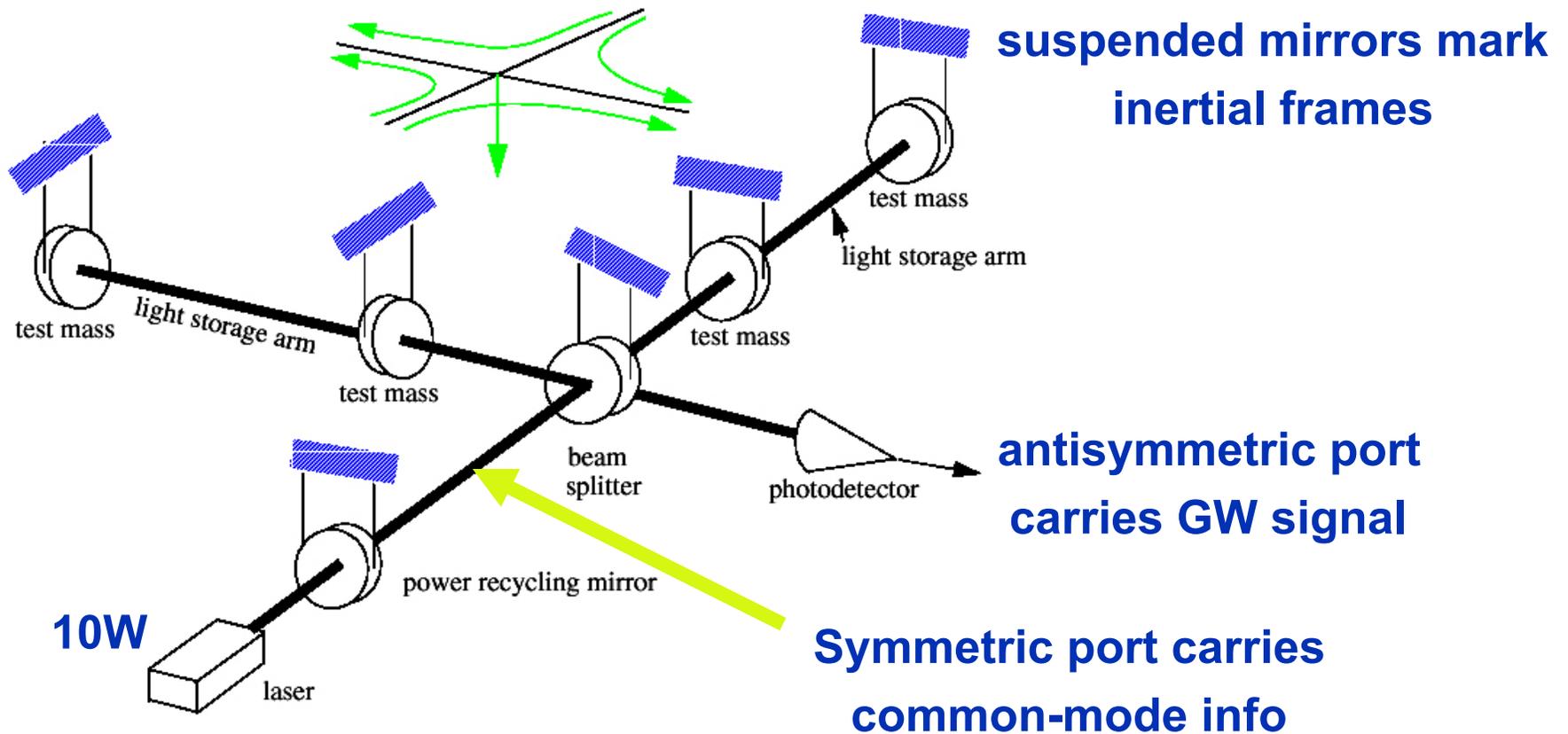


Measuring ΔL in arms allows the measurement of the strain

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

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

LIGO Hanford Observatory (LHO)

H1 : 4 km arms

H2 : 2 km arms

10 ms

LIGO Livingston Observatory (LLO)

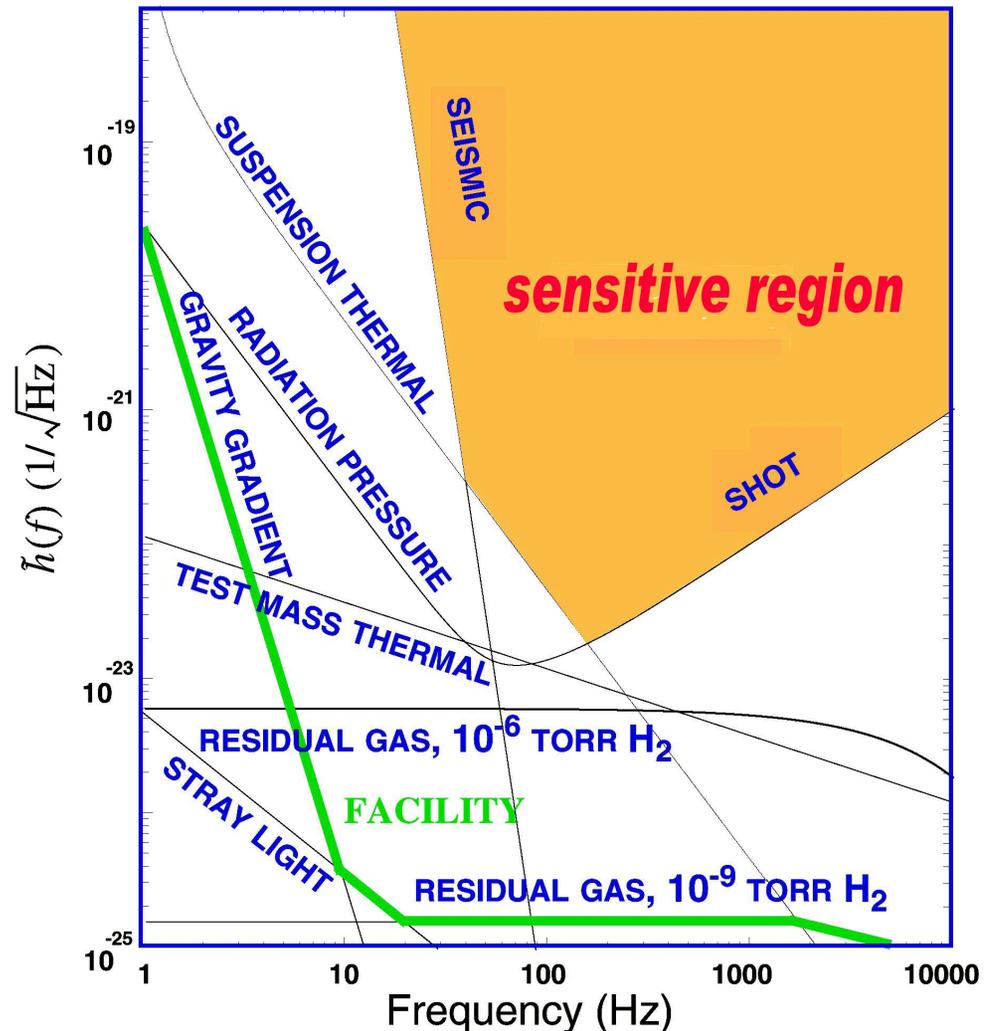
L1 : 4 km arms

● Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov

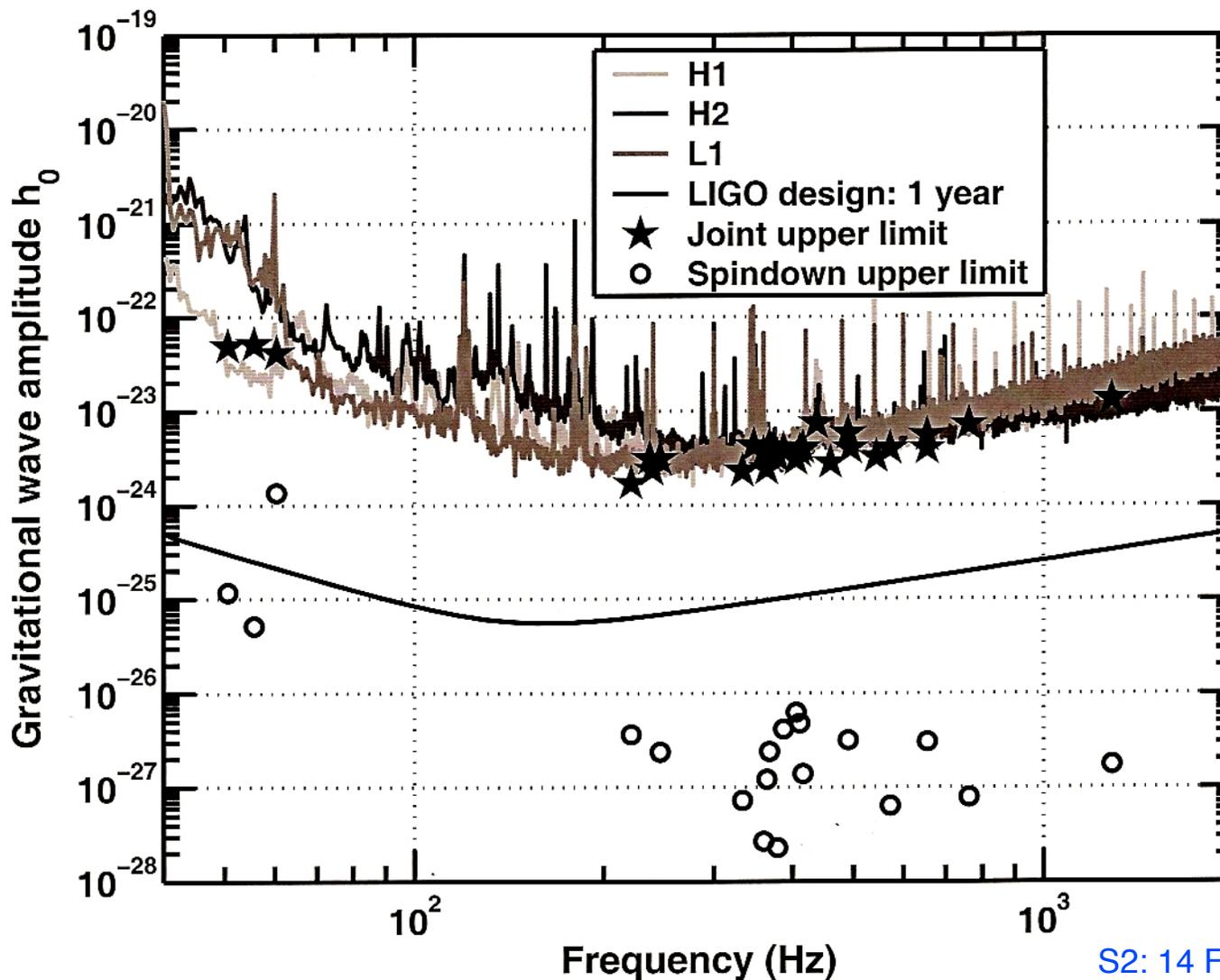
● NASA Goddard Space Flight Center Image by Reto Stockli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).



- ❑ 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



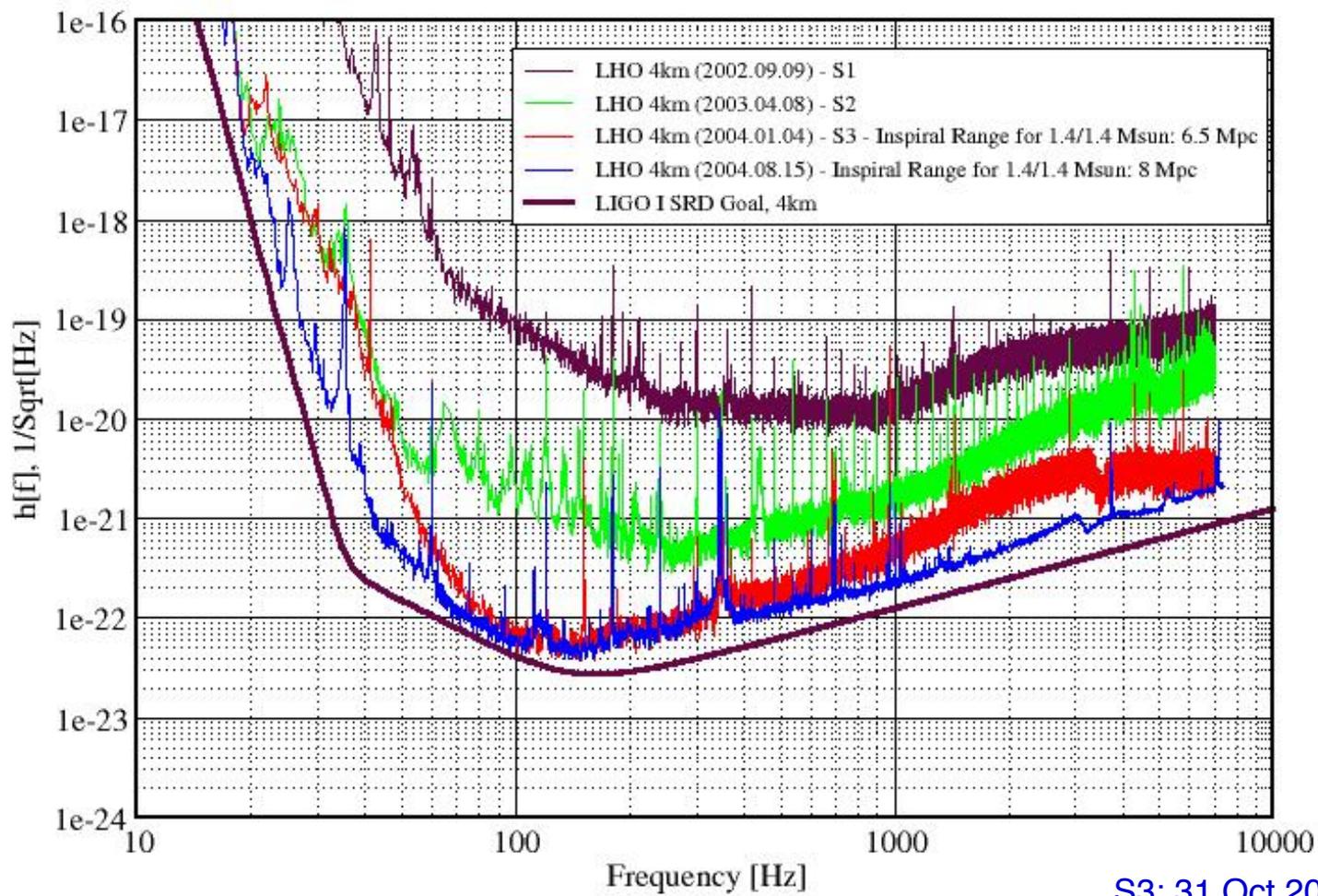
Pulsar Upper Limits (S2)



S2: 14 Feb to 14 April 2003

S3 Sensitivity

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



S3: 31 Oct 2004 to 9 Jan 2005

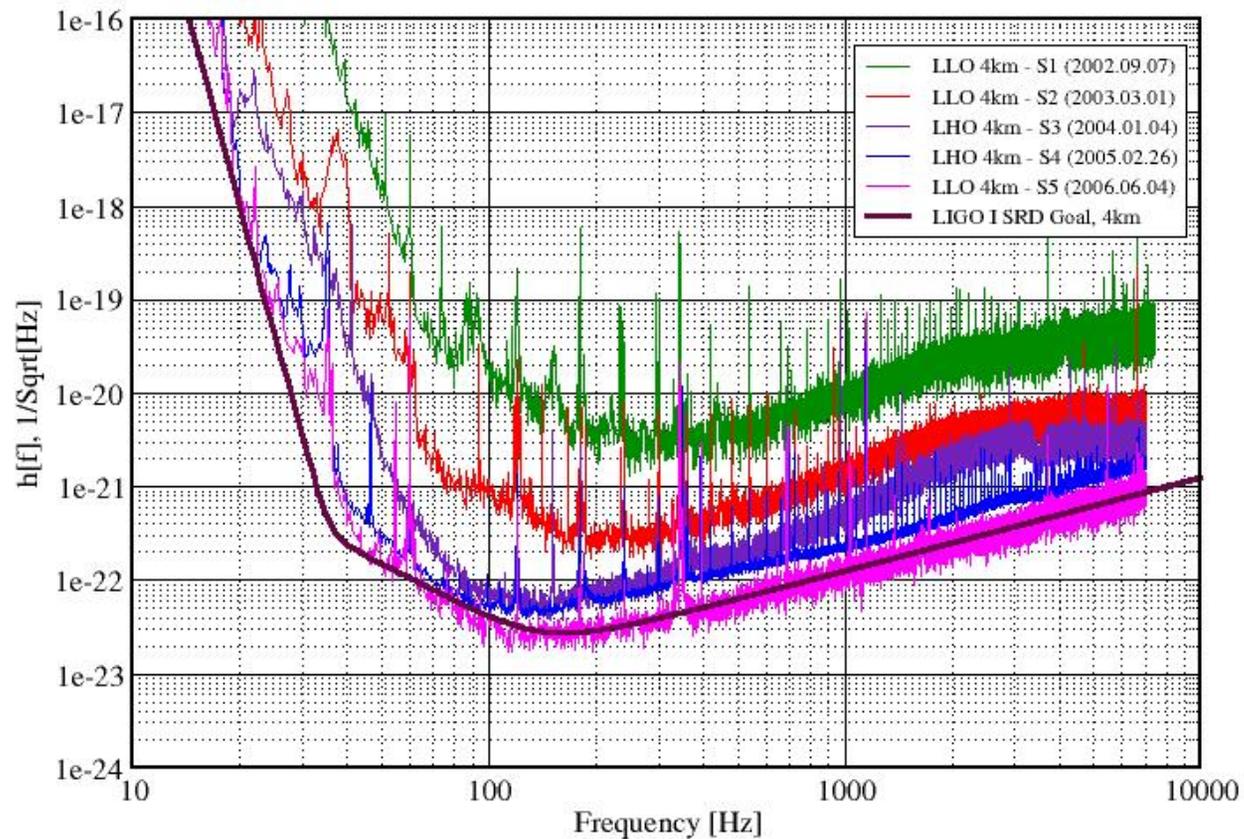


Strain Sensitivity S1 - S5



Best Strain Sensivities for the LIGO Interferometers

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



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!

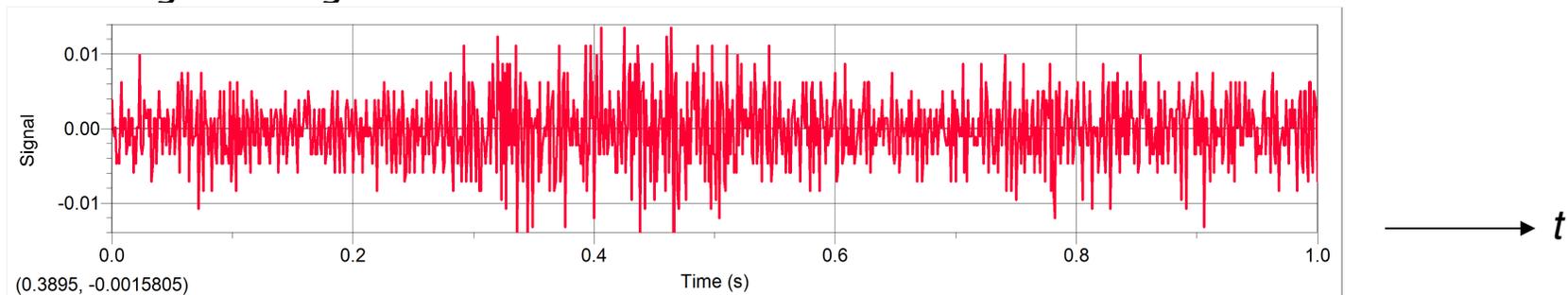
Now upgrading to "Enhanced LIGO"

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

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

Searching for CW signals

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

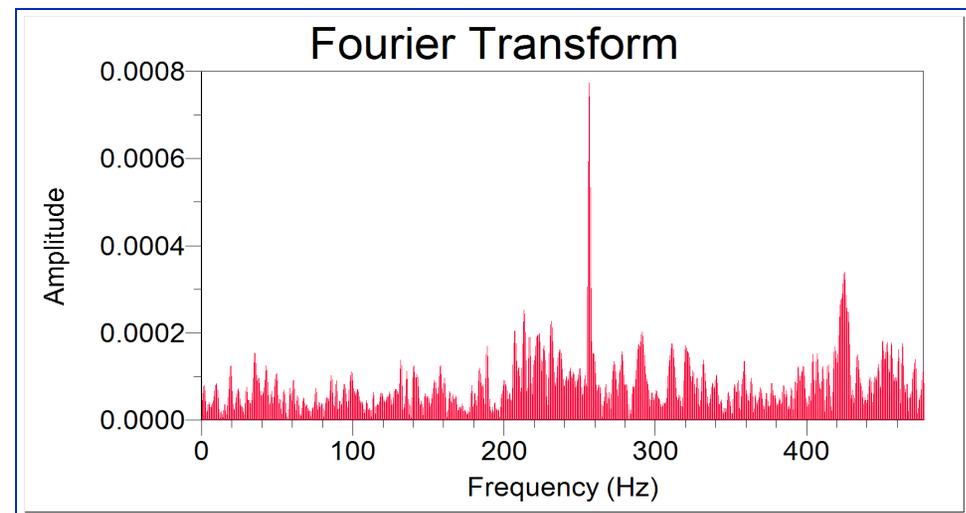


Take the **Fourier Transform** to obtain:

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

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

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

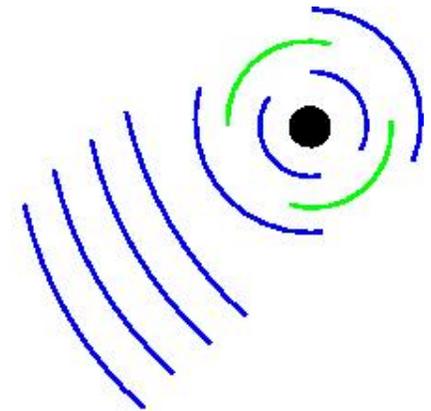
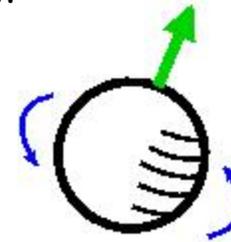


There is even a computationally fast algorithm for this, the **Fast Fourier Transform (FFT)**.

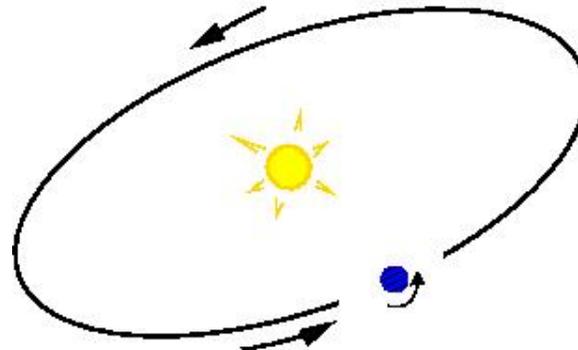
The frequency will change!

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

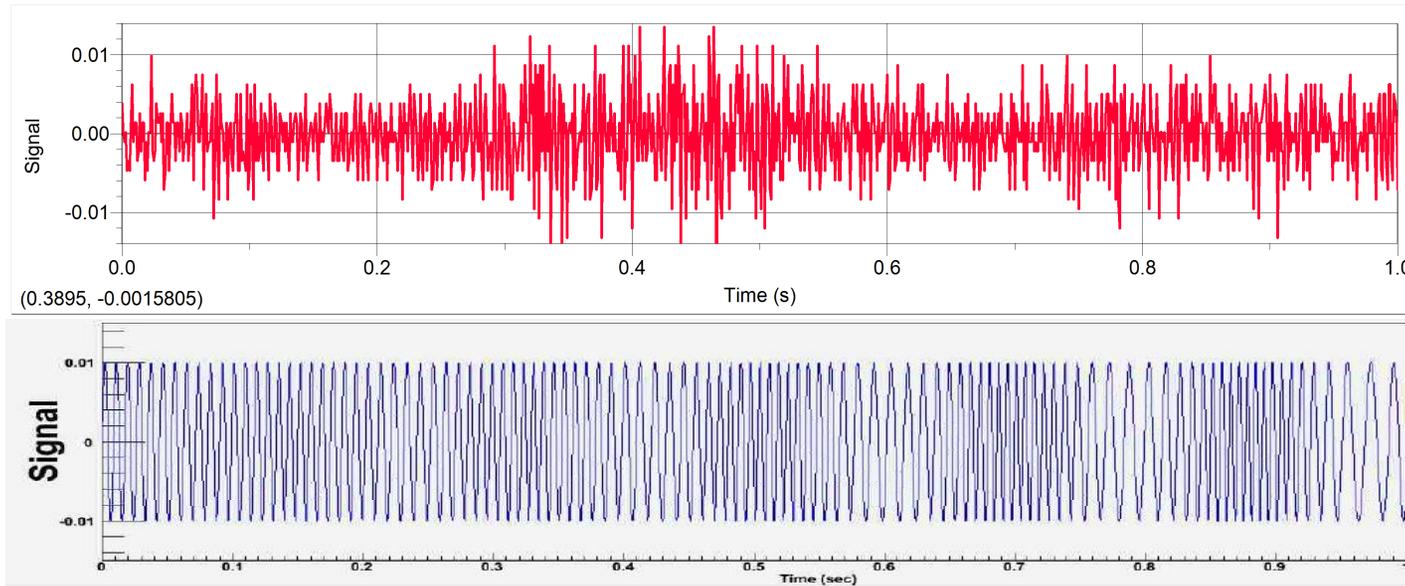
1. The source losing energy due to "spin down"
2. Doppler shift due to Earth's motion about the Sun (one part in 10^4 , with period of 1 year)
3. Doppler shift due to Earth's rotation about its axis (one part in 10^6 , with period 1 sidereal day)



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!

Looks like we're gonna need a bigger computer!

And computational effort goes up like T^6 !

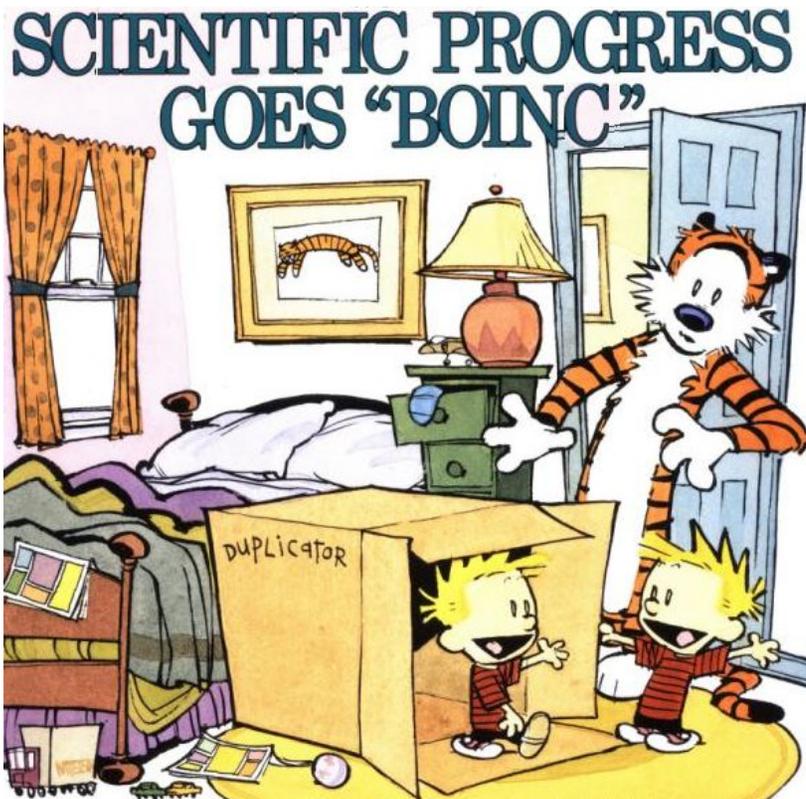
BOINC to the rescue

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".

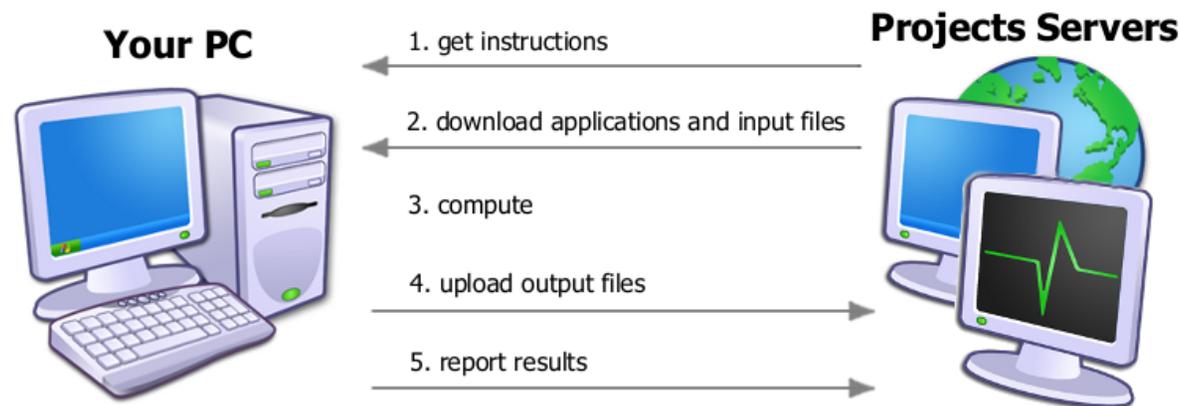


Einstein@Home

How to use BOINC to search for a CW signal:

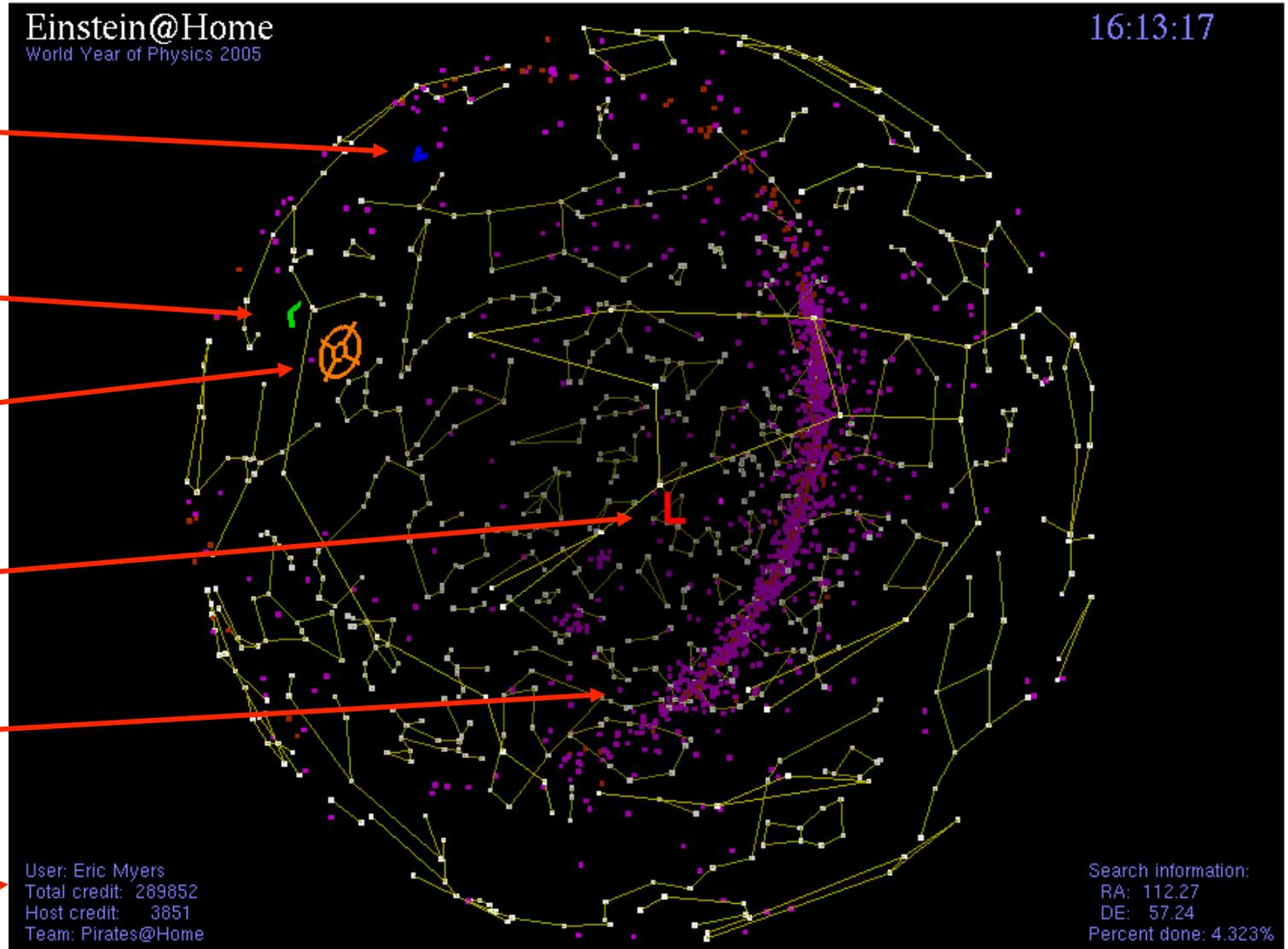
1. Break the computations up into smaller "workunits"
2. Send these workunits (WU's) to participating "clients"
3. Each WU searches the entire sky (~30,000 points!) for a narrow band of frequencies and the full range of spin-downs, computing the F -statistic.
4. Client returns top 13,000 candidates to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



Amateur Astronomers Association of New York, 11 April 2008



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	210,252
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	1,917
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

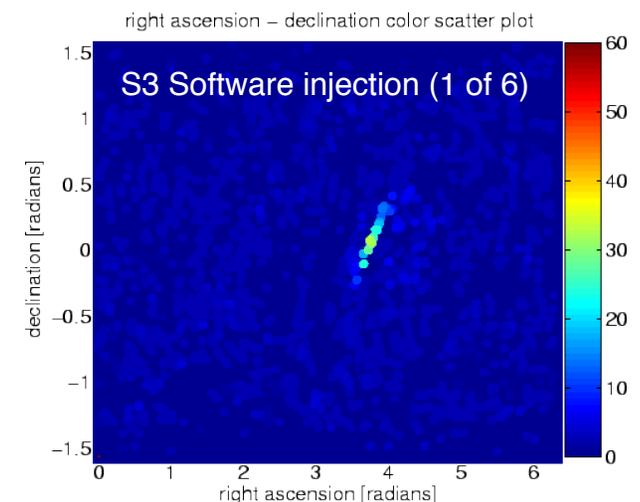
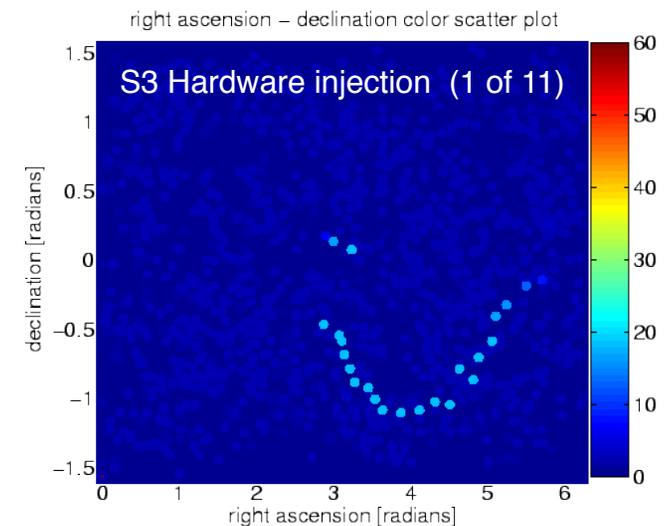
No detections! (except injections)

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

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 Berkeley BOINC site
- 3) Download BOINC package
- 4) Double click to install and follow directions

BOINC: compute for science

Download BOINC
5.10.45 for Windows (7.10 MB)

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

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	SETI.Germany	1975	1,155,166	167,644,259	Germany
2	Einstein at work	512	949,298	212,350,781	Germany
3	Special: Off-Topic	680	260,175	140,727,706	Germany
4	University of Wisconsin - Milwaukee (Computer Labs)	31	183,823	99,068,876	United States
5	Czech National Team	1937	182,983	119,607,087	Czech Republic
6	Planet 3DNow!	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
 Mahray 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 http://space.newscientist.com/article/dh13566-mountains-on-stars-could-trigger-gravitational-waves Come on Aussie Come on! Join the #1 Aussie Alliance, ranked 10th in the world. Help us grow and maintain our top ten world position. www.boinc-australia.net
 Chipper O 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
 Mike Hewson 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 stickled 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 http://www.ligo.caltech.edu/~LIGO/ or http://www.ligo.caltech.edu/~LIGO/ 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: <div style="display: flex; justify-content: space-around;"> <div> <p>Seismic</p> </div> <div> <p>NS/NS Inspi</p> </div> </div>

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



<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!