Einstein@Home: Gravitational Wave Astronomy with Your Home Computer

Eric Myers

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

Summary

- **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!

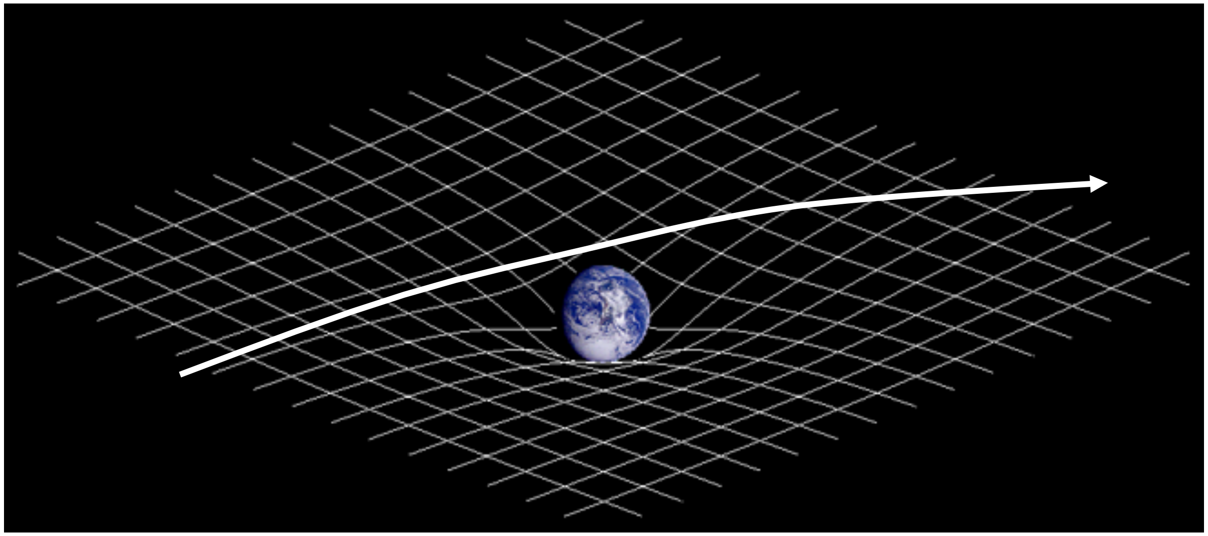
What are Gravitational Waves?

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

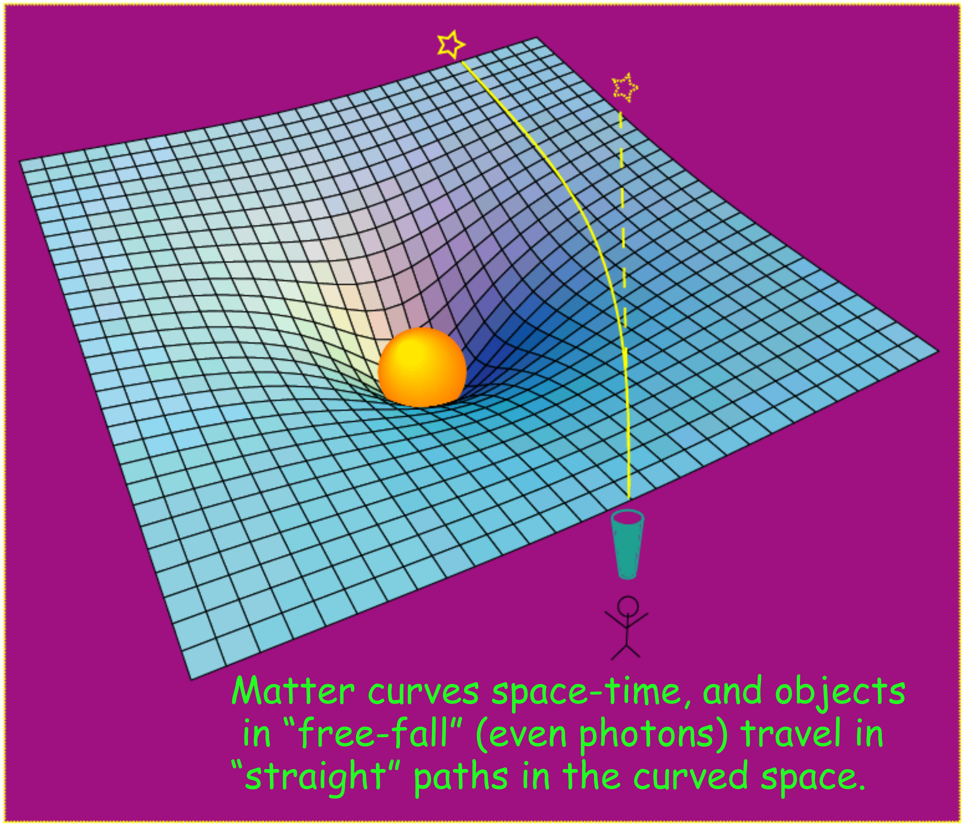
Gravitational Waves are time-varying oscillations of the *gravitational* field.

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

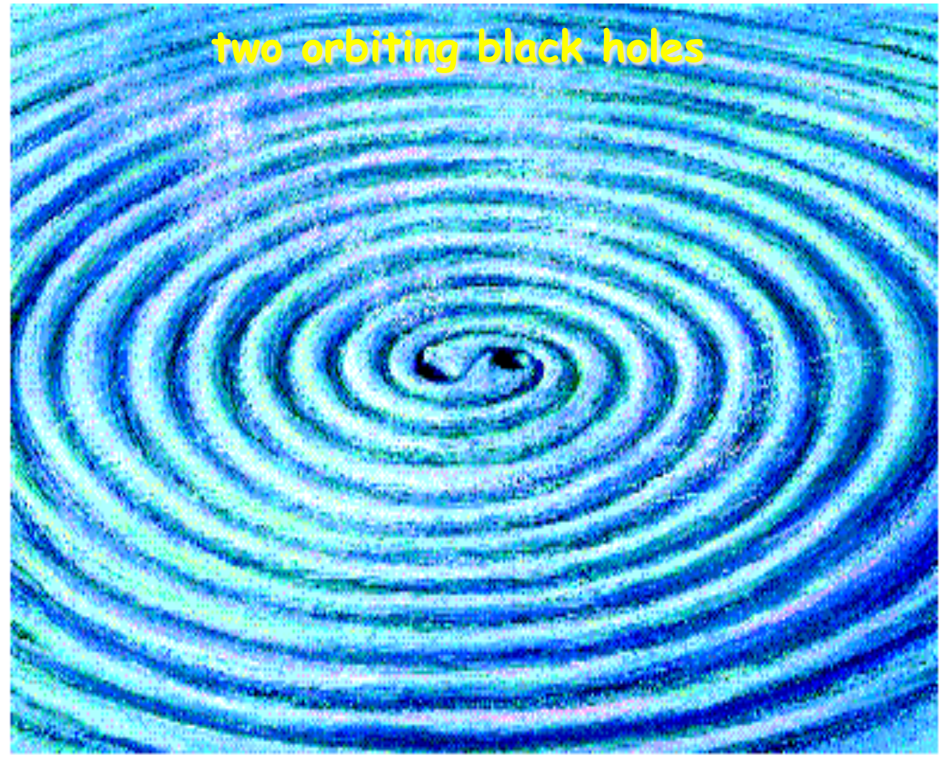
Principles:
Matter curves spacetime,
and
Objects in "free-fall" travel in "straight" paths in the curved space.



Gravitational Waves



Rendering of space-time stirred by

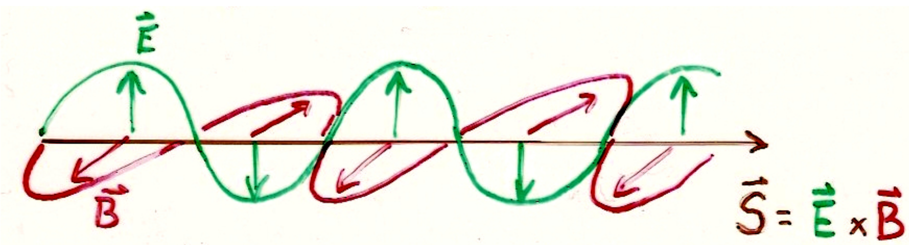


Changes in space-time produced by moving a mass are not felt instantaneously everywhere in space, but propagates as waves

Comparison with EM waves

Electromagnetic Waves

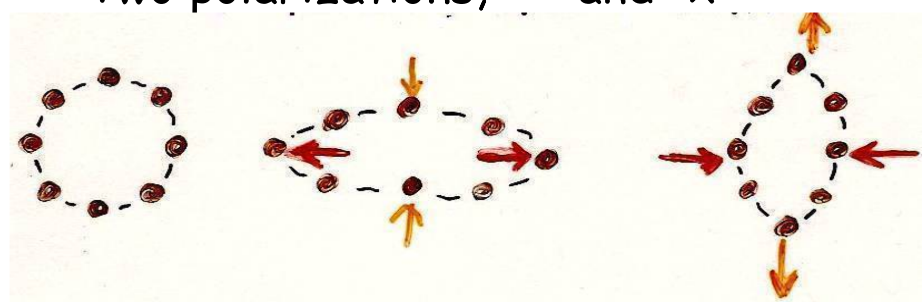
- Travel at the speed of light
- "transverse"
- Vector - dipole in both E and B
- Two polarizations: horizontal and vertical



- 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"

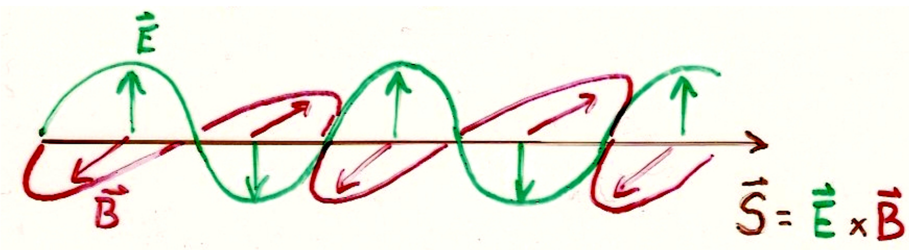


- Solutions to Einstein's Eqns.
- Gravitational waves require *changing* quadrupole mass distribution.

Comparison with EM waves

Electromagnetic Waves

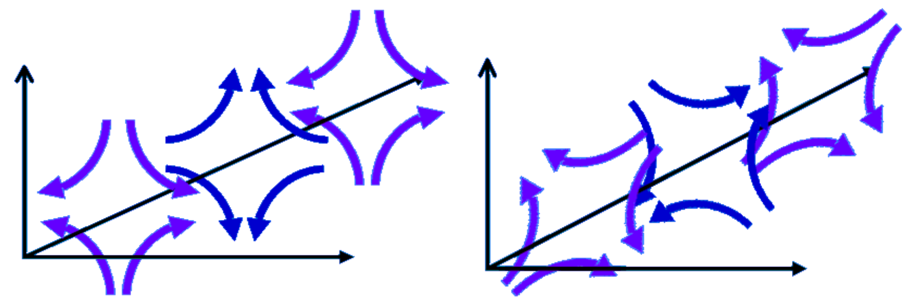
- Travel at the speed of light
- "transverse"
- Vector - dipole in both E and B
- Two polarizations: horizontal and vertical



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

Gravitational Waves

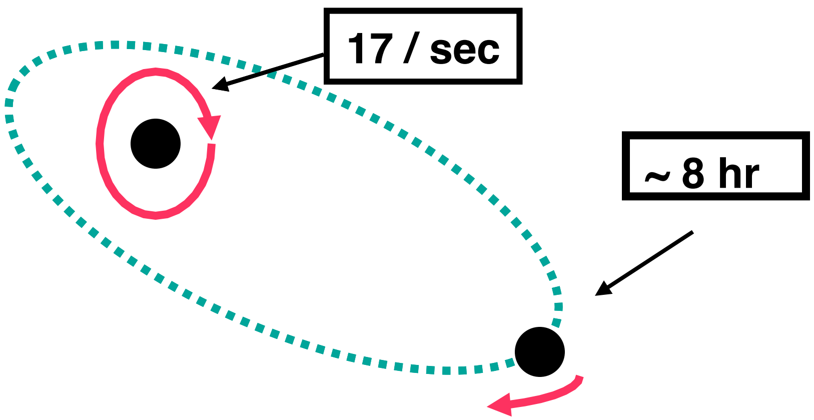
- Travel at the speed of light
- "transverse"
- Tensor - quadrupole distortions of space-time
- Two polarizations, "+" and "x"



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

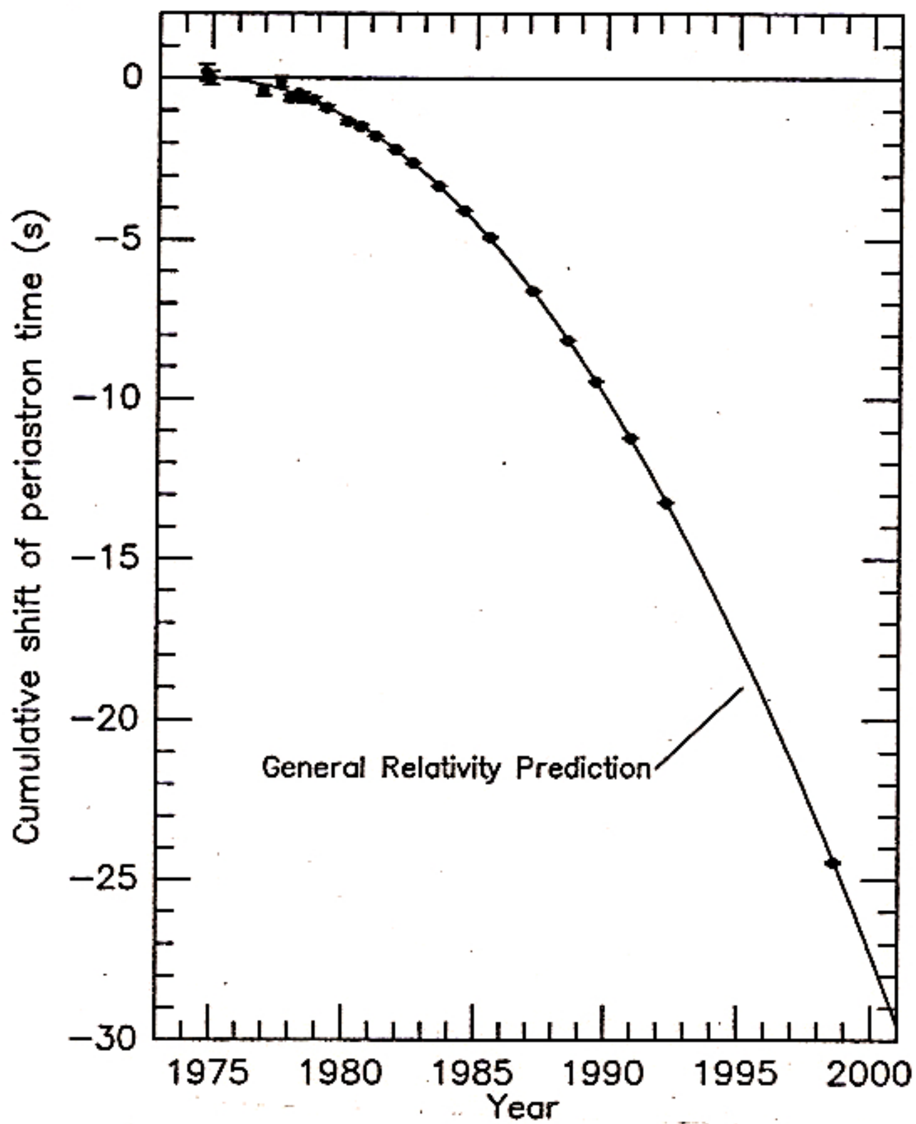
Indirect Evidence for GW's

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

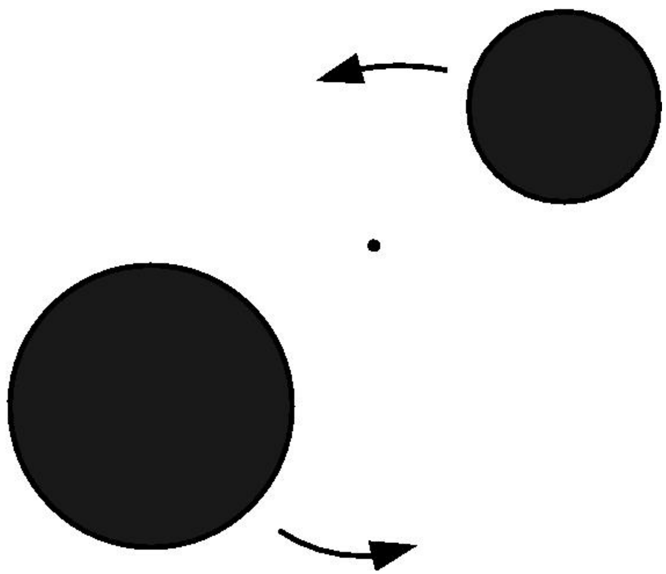


The measured precession of the orbit exactly matches the expected loss of energy due to gravitational radiation.

(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"

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

$1.4M_{\odot}$ 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?

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!)

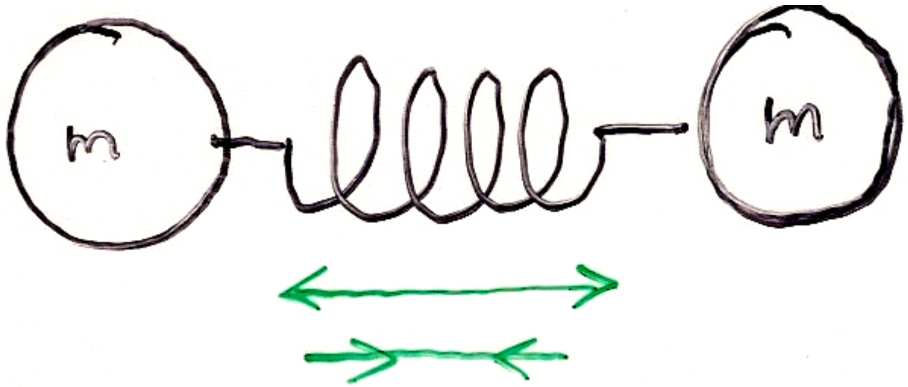
3) *Coalescence of binary systems*, inspiral of pairs of neutron stars and/or black holes (NS-NS, NS-BH, BH-BH) *CHIRP!*

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

5) Something unexpected…!

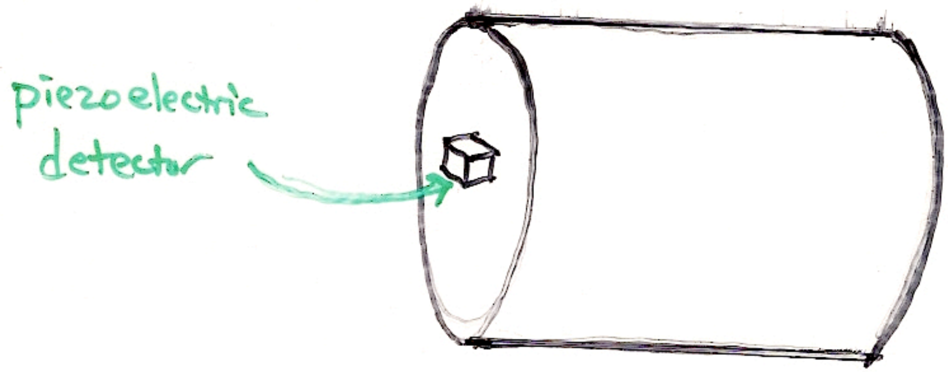
How might GW's be detected?

Simplest example: the "bar-bell" detector

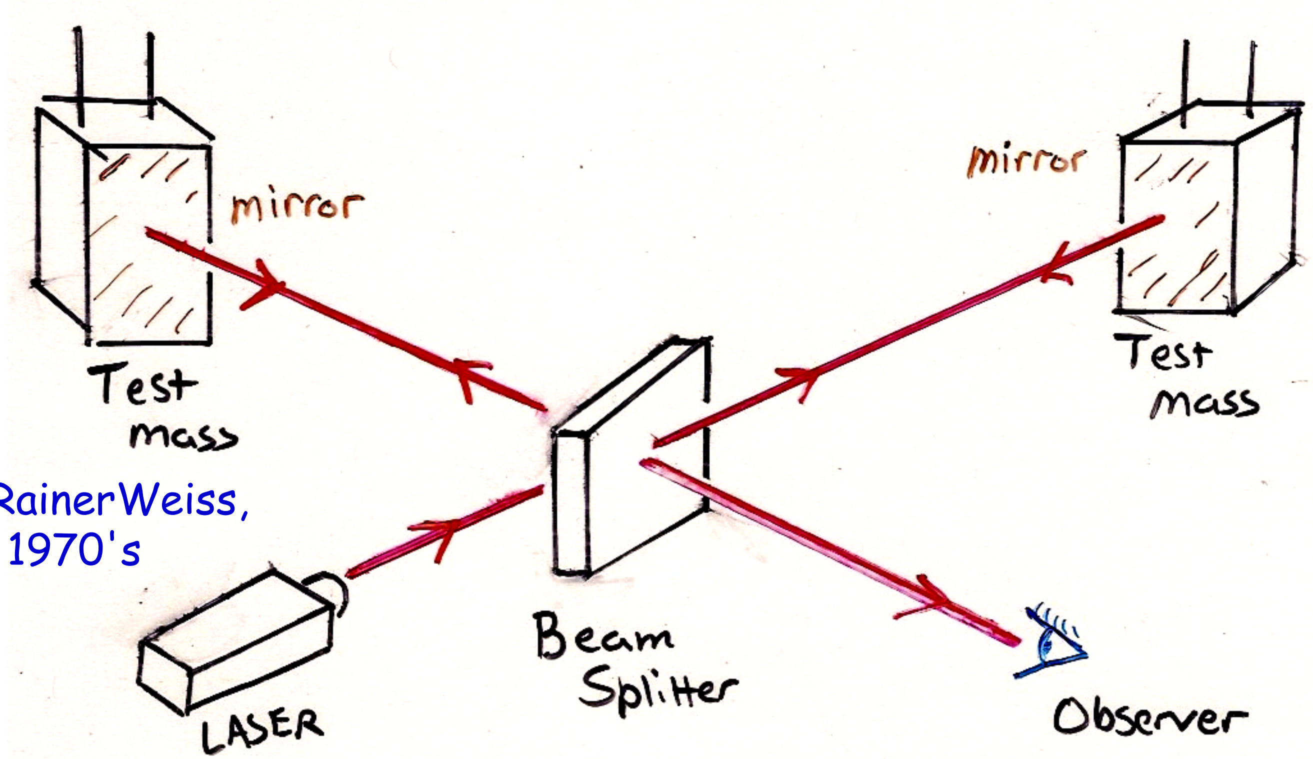


Pioneered by Joseph Weber at the University of Maryland in 1960's (no detection)

Practical implementation: a "bar" detector



Michelson Interferometer



Pioneered by RainerWeiss, at MIT in the 1970's

Measuring ΔL 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.)

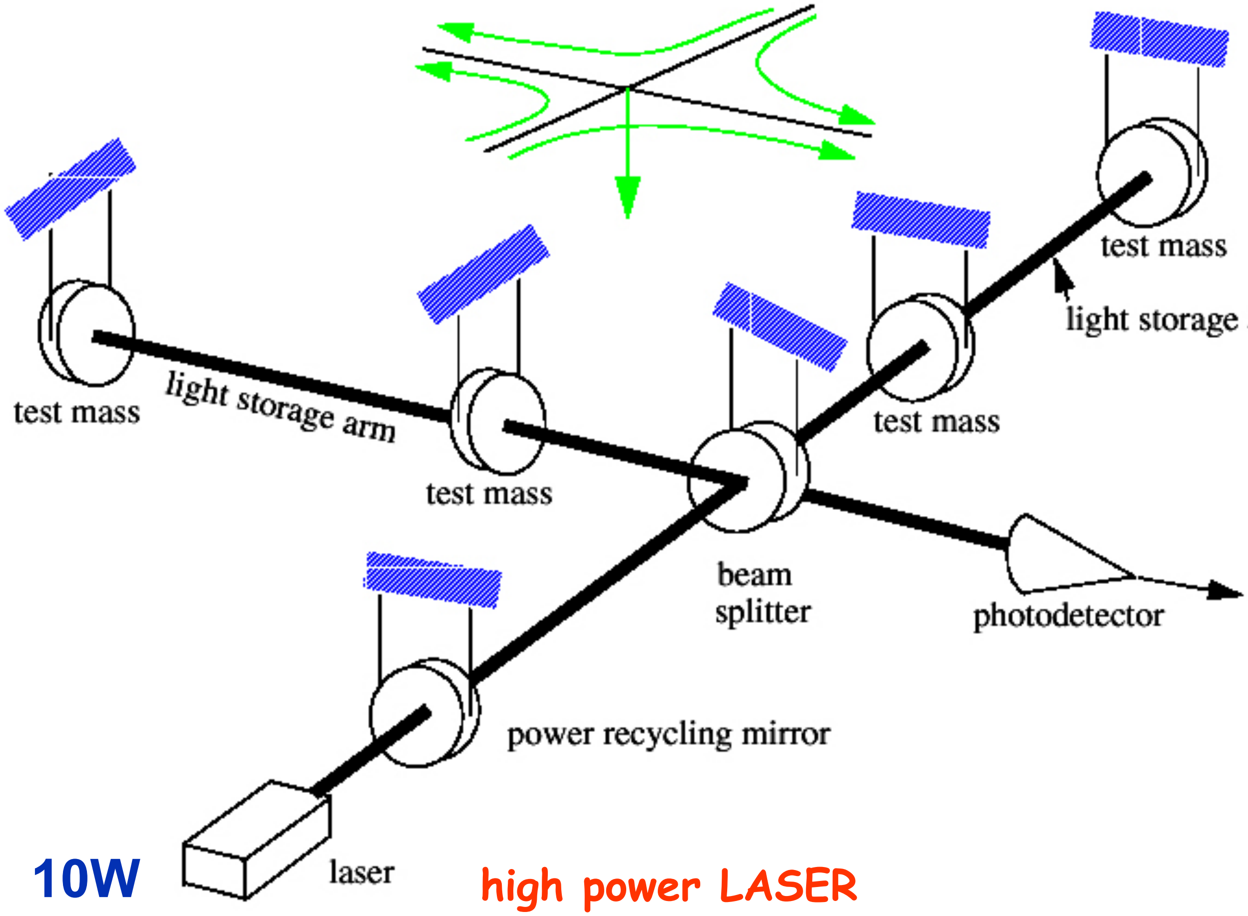
LIGO: Laser Interferometer Gravitational wave Observatory

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

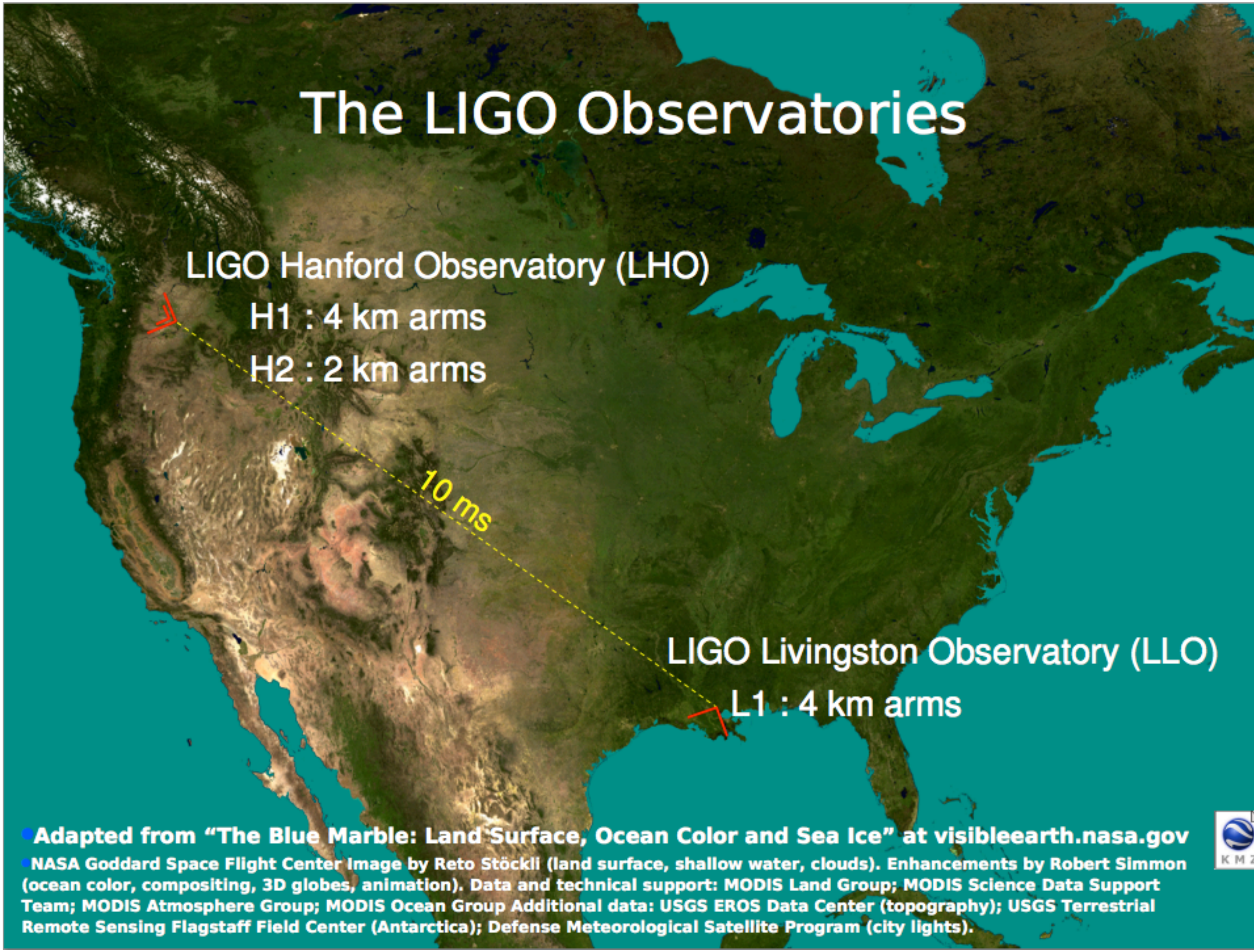


suspended mirrors mark inertial frames

antisymmetric port carries GW signal

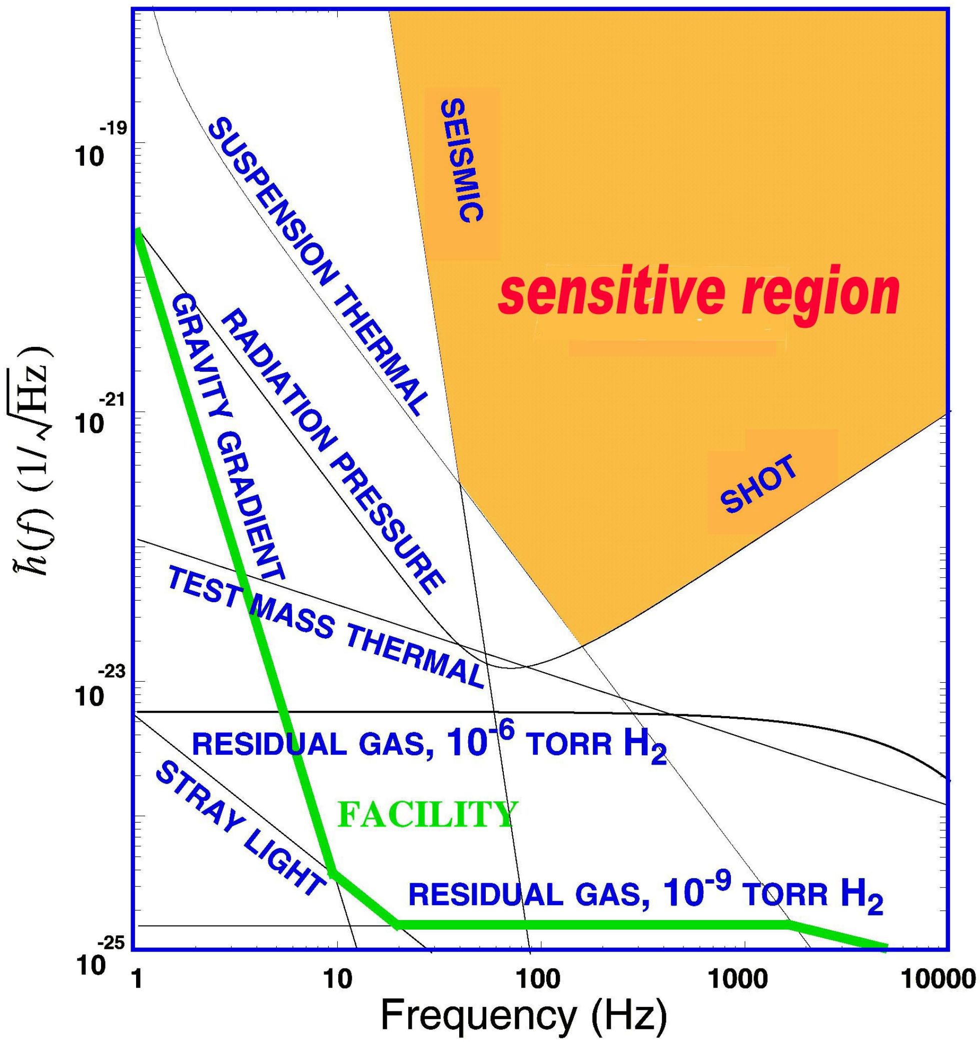
10W

high power LASER reduces signal noise


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 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).
KMZ

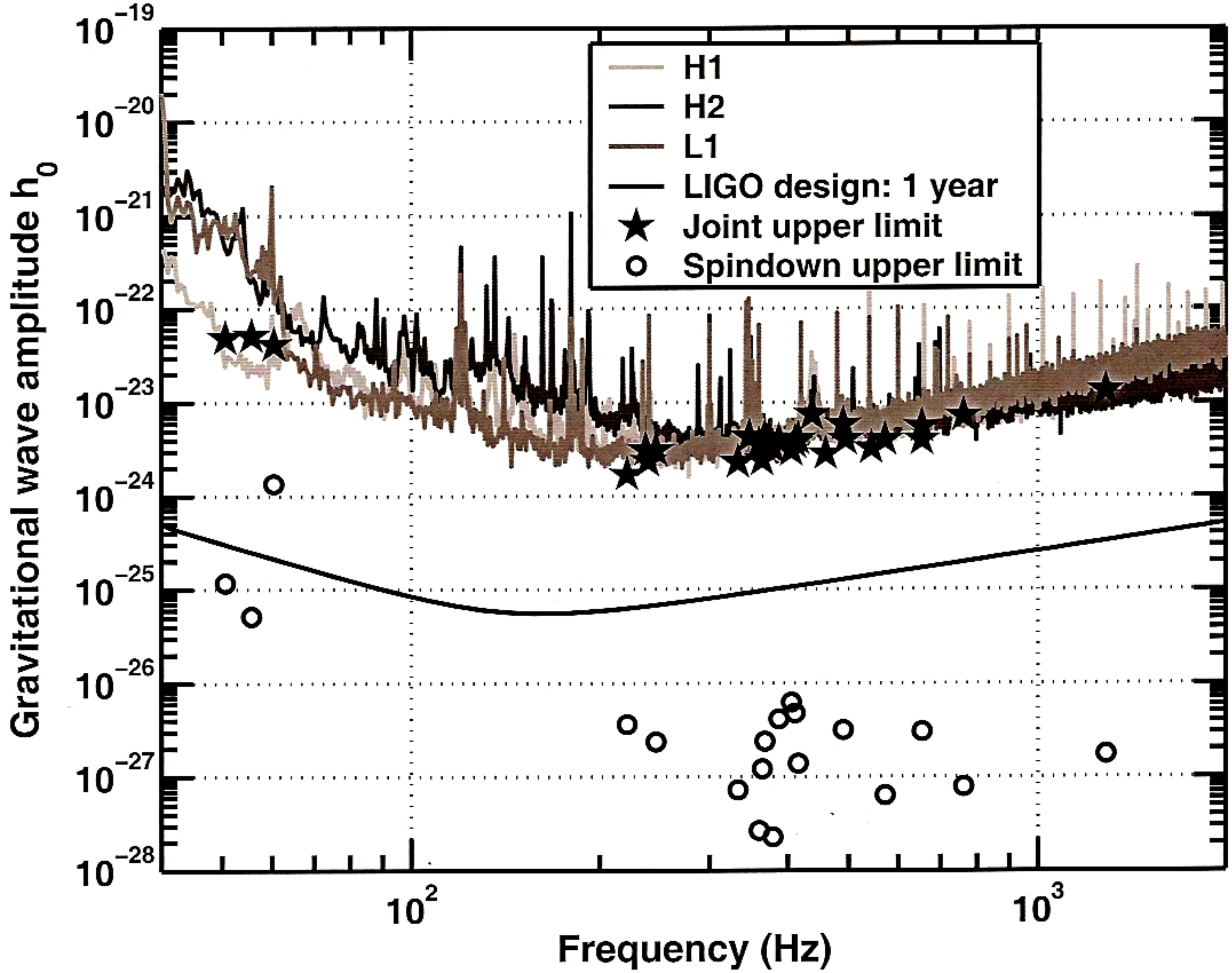
What Limits Sensitivity?

- 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



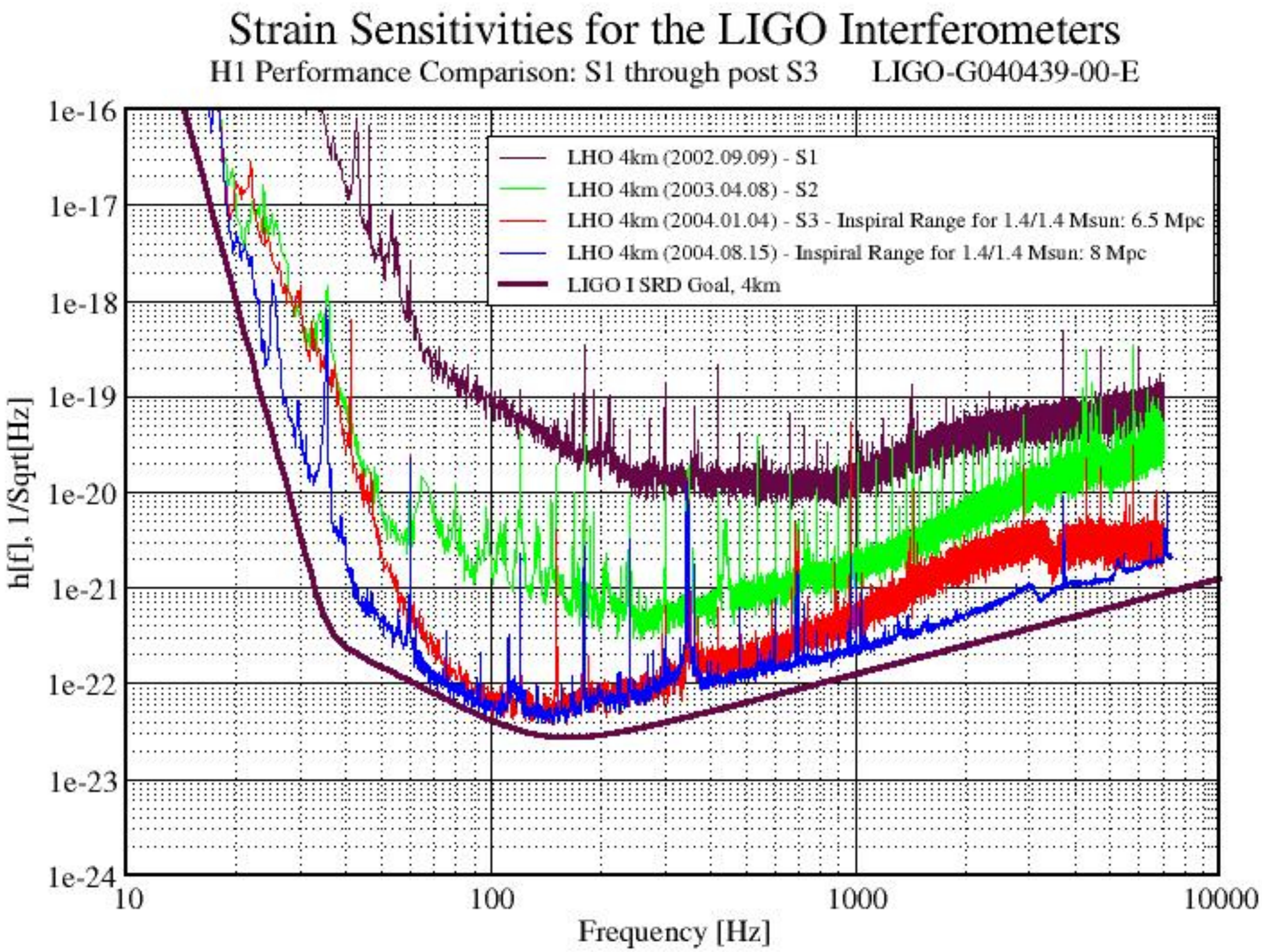
Pulsar Upper Limits (S2)

S2: 14 Feb to 14 April 2003



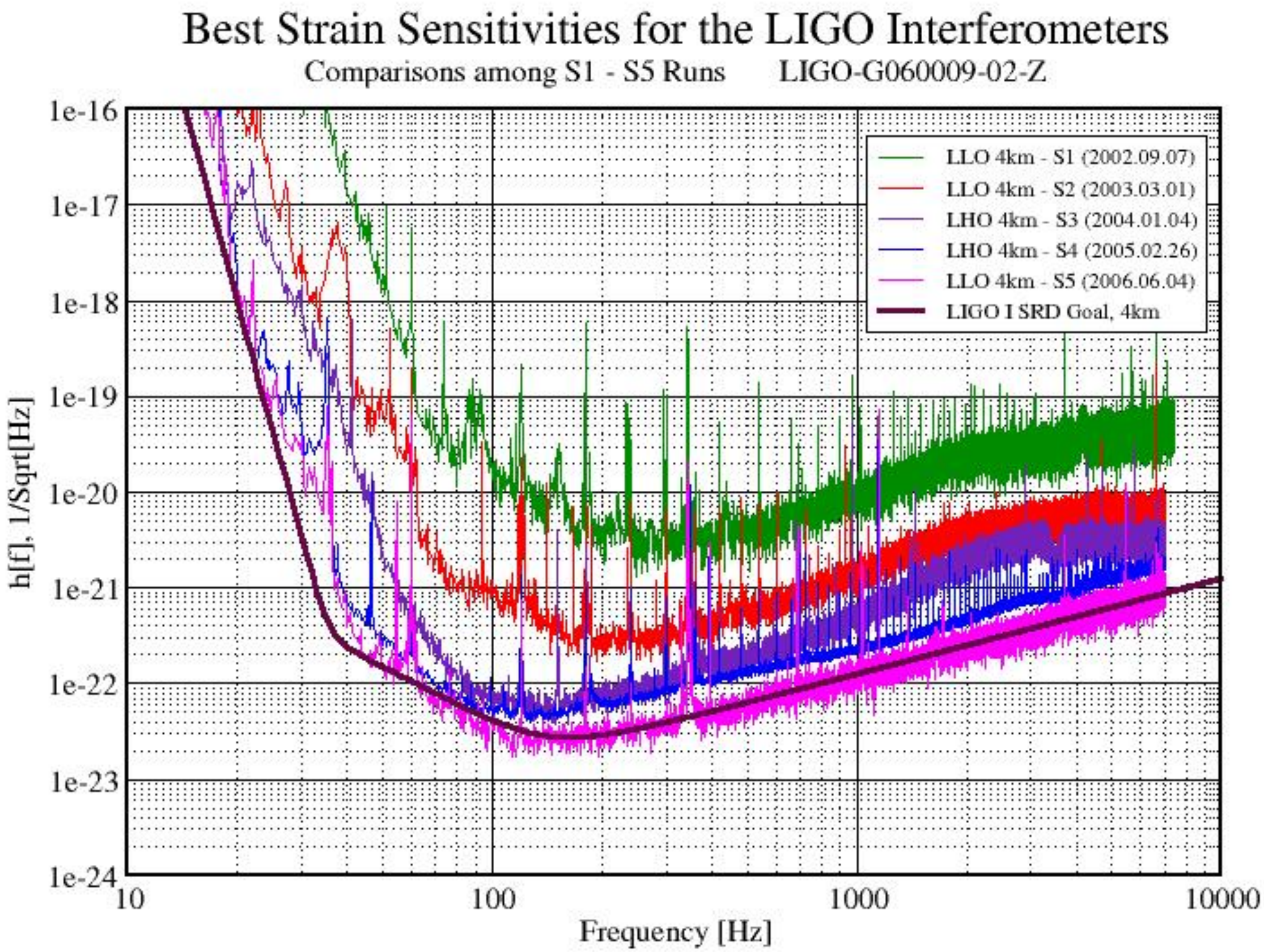
S3 Sensitivity

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!

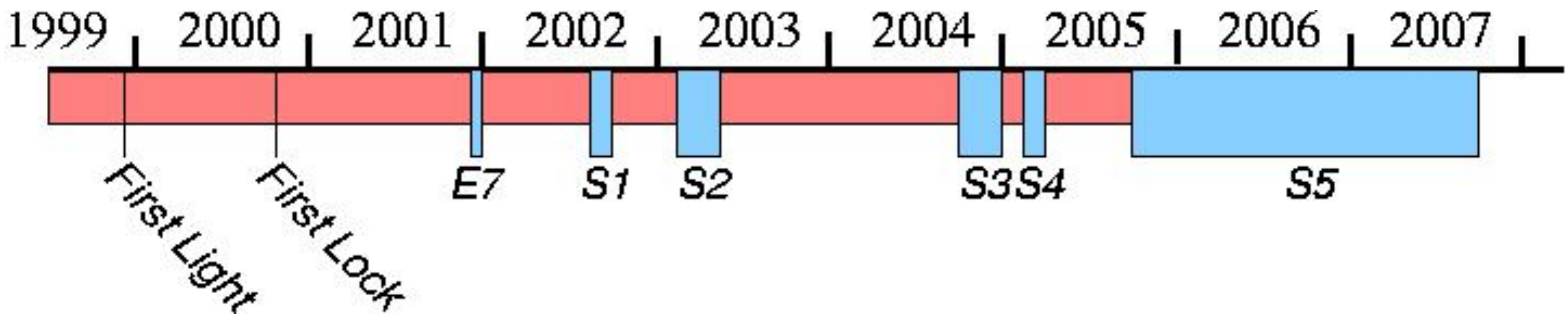
Now upgrading to "Enhanced LIGO"

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

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

LIGO Timelines

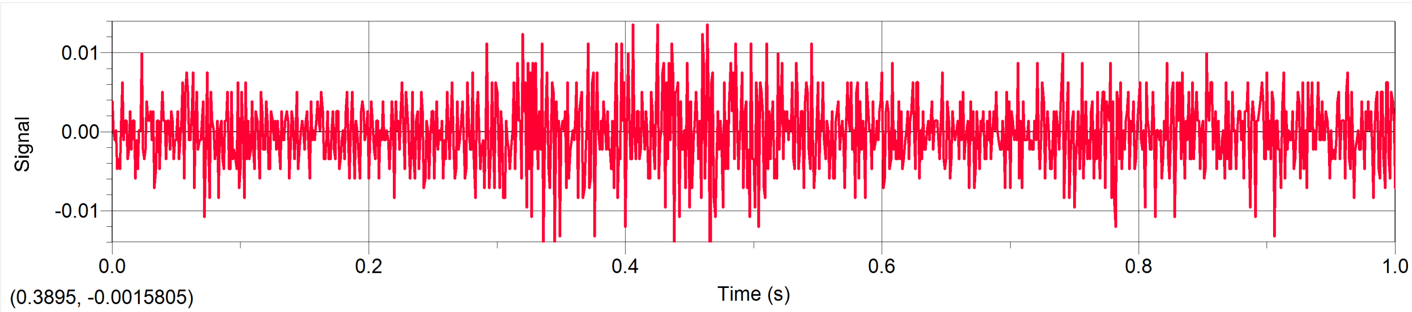
Construction began 1995



Enchance 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…



"time-series"

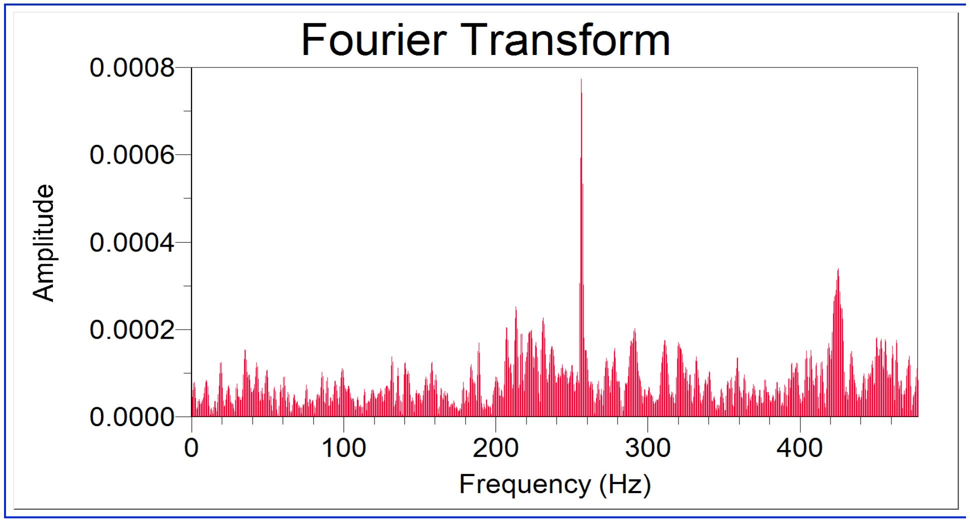
→ *t*

Take the Fourier Transform to obtain:

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

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

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

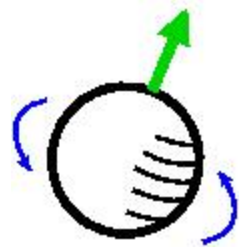


There is even a computationally fast algorithm for this, the Fast Fourier Transform (FFT).

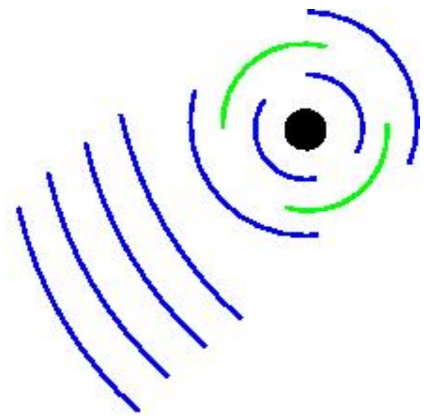
But the frequency will change!

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

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

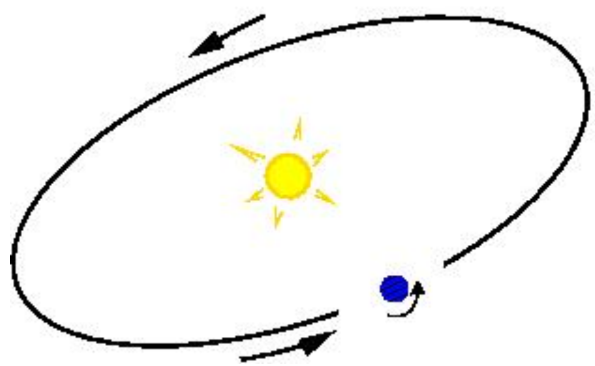


2. Doppler shift due to Earth's motion about the Sun (one part in 10^4, with period of 1 year)

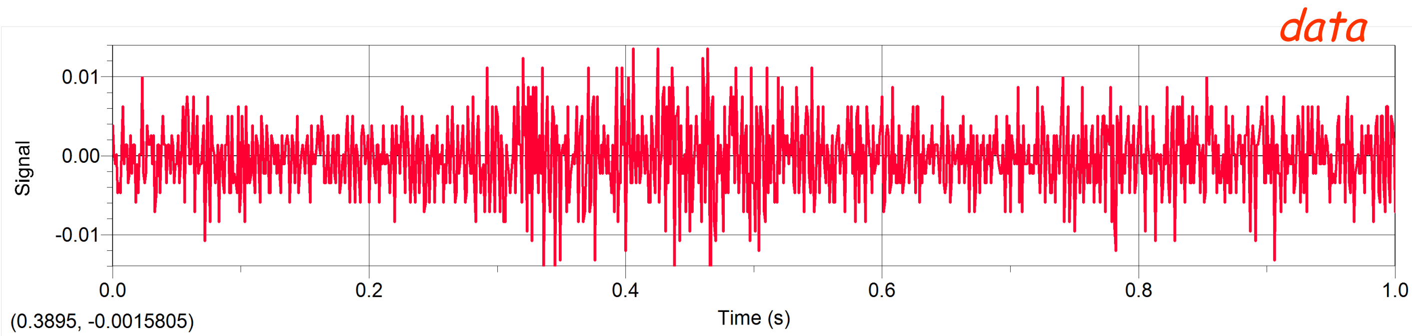


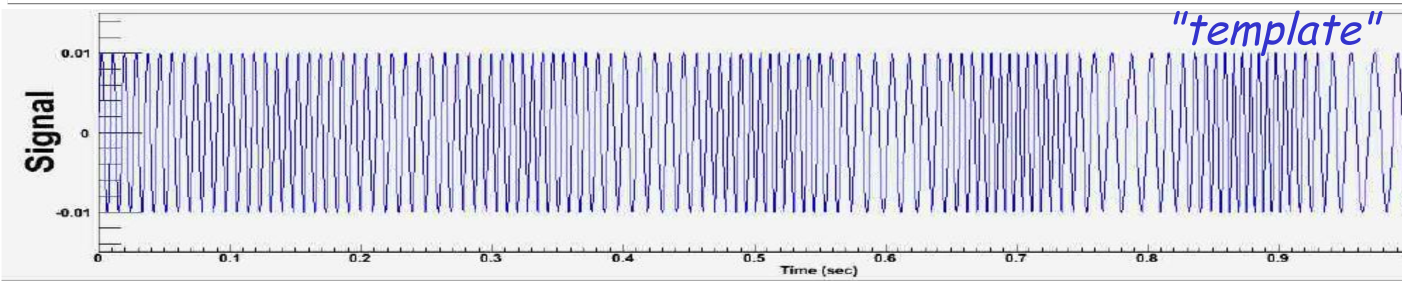
3. Doppler shift due to Earth's rotation about its axis (one part in 10^6, with period 1 sidereal day)

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



Matched Filtering





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

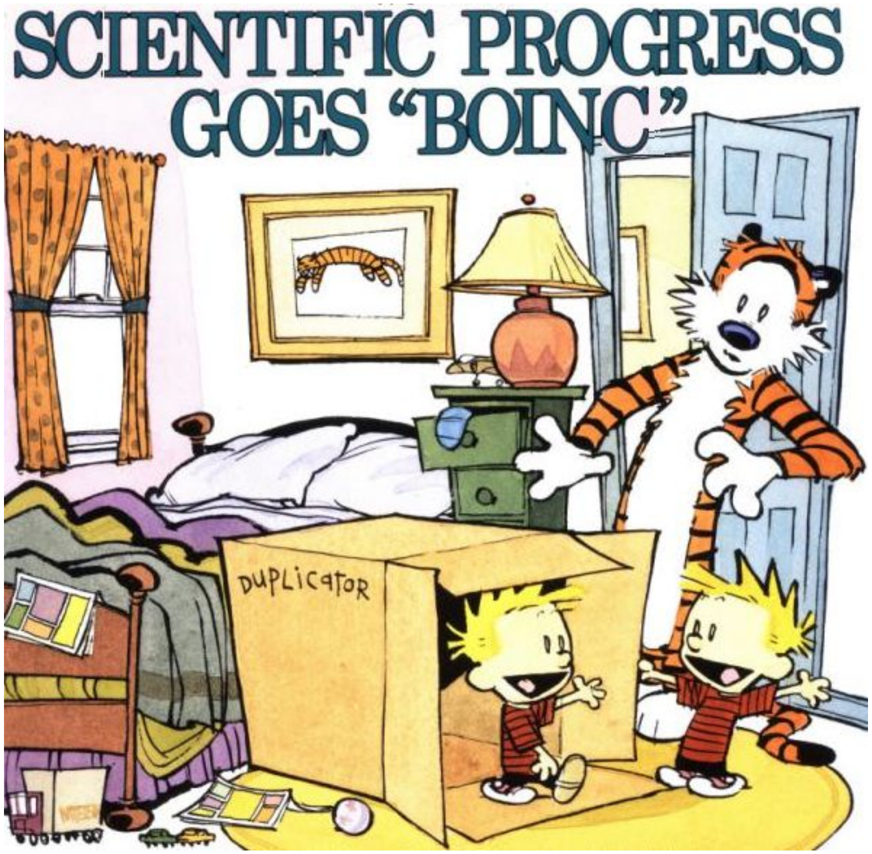
"the F statistic"

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



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

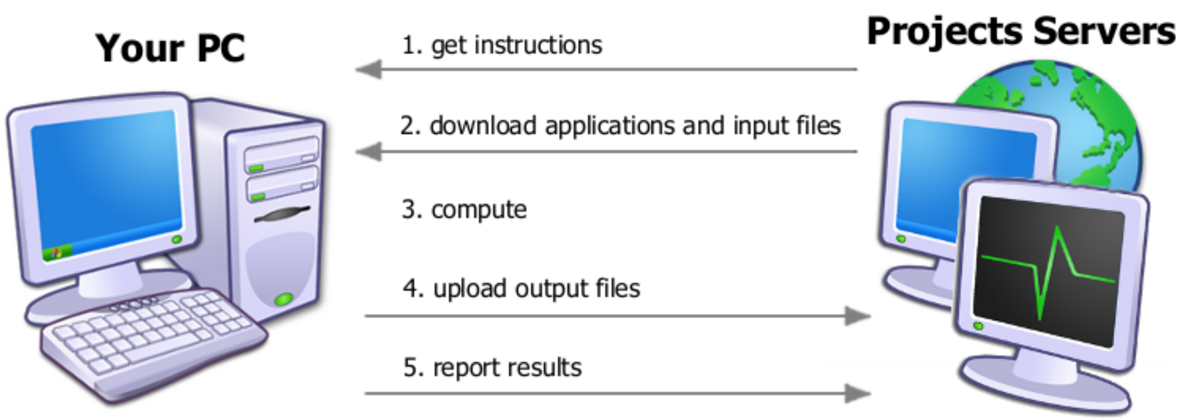
BOINC is modular, so that one can replace the "computation thread" and the "graphics thread".

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

LHO azimuth position

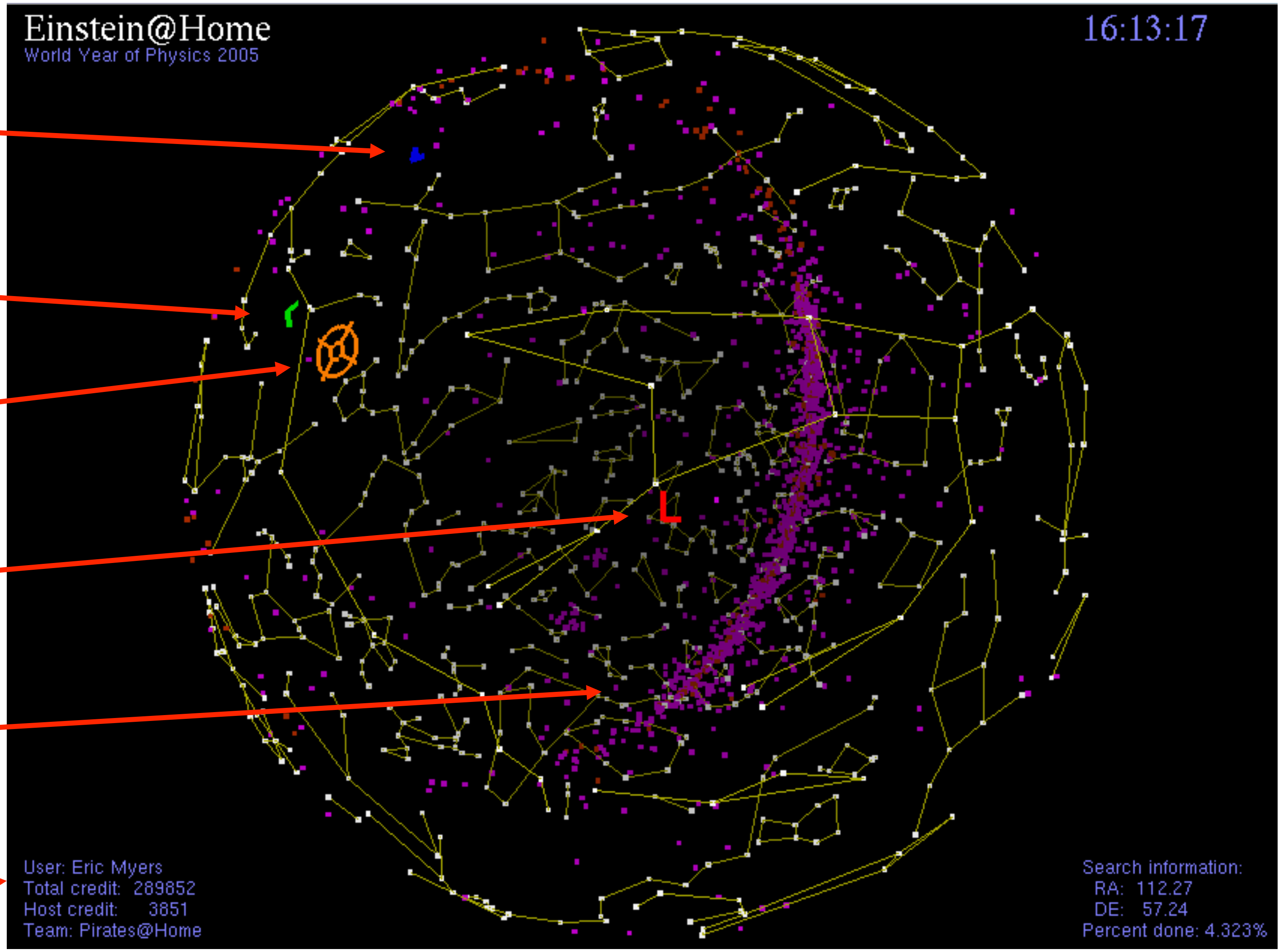
LLO azimuth position

Search marker

GEO600 azimuth position

Known pulsars (electromagnetic) and SNR's

User, team, host info



Einstein@Home status

As of 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

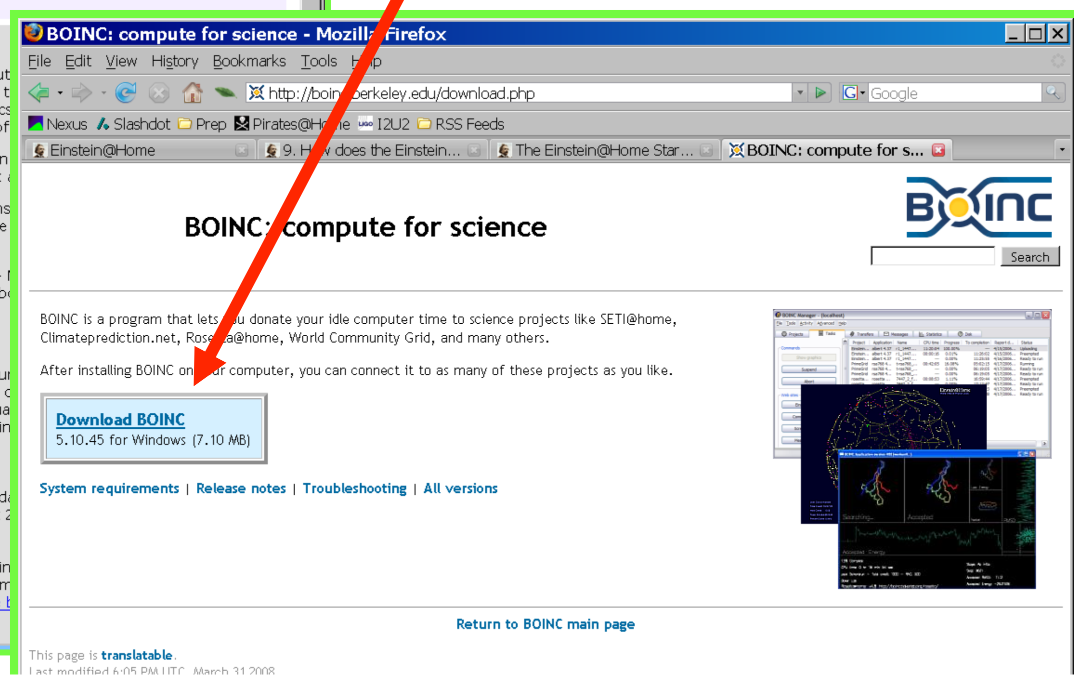
USERS	Approximate #
in database	439,762
with credit	218,958
registered in past 24 hours	[illegible]
HOST COMPUTERS	**Approximate #**
in database	1,547,449
registered in past 24 hours	1,825
with credit	788,393
active in past 7 days	[illegible]
floating point speed[1]	159.1 TFLOPS

Work and Results

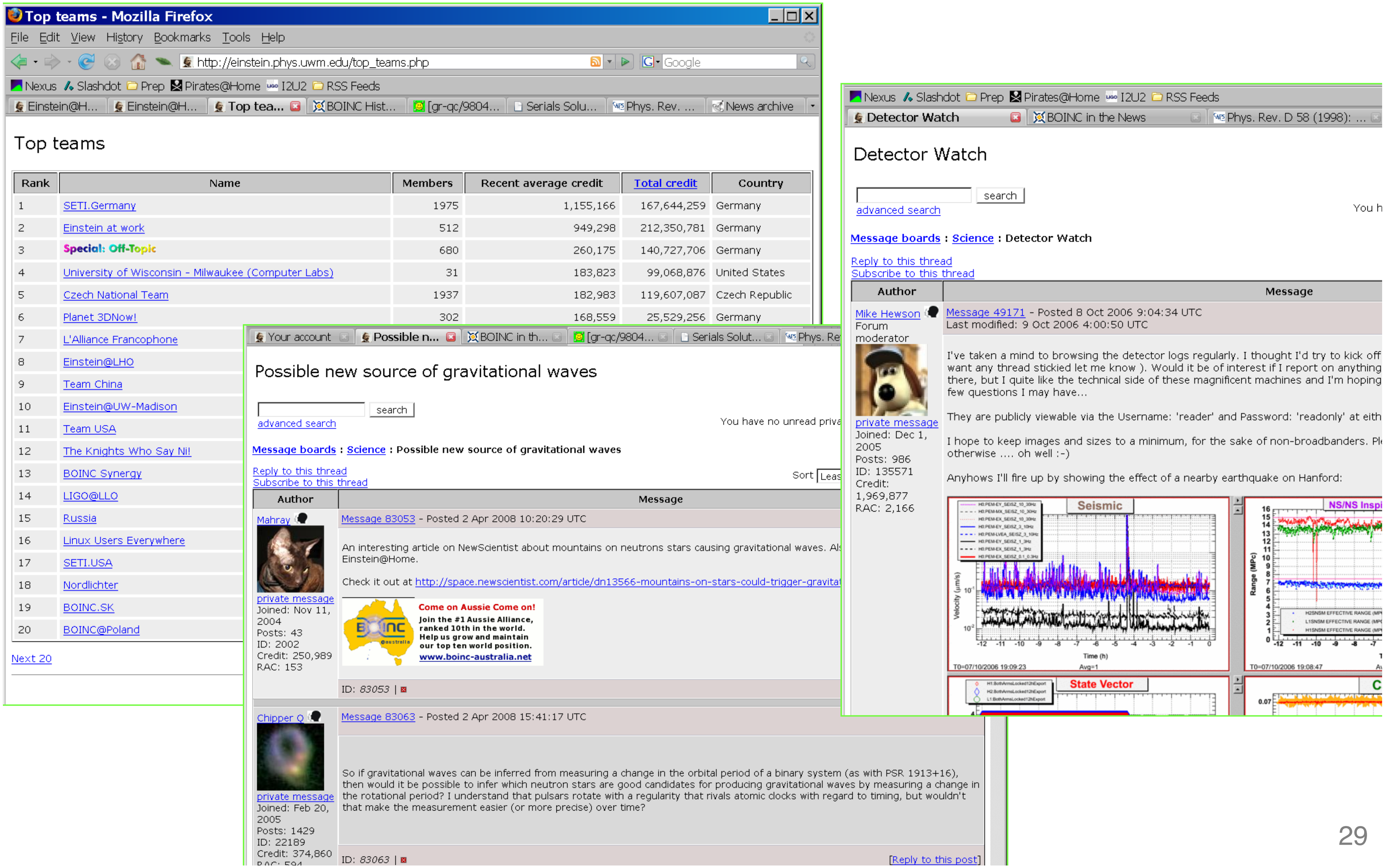
WORKUNITS	Approximate #
in database	514,250
with canonical result	282,783
no canonical result	231,467
RESULTS	**Approximate #**
in database	1,168,243
unsent	68,703
in progress	242,368
deleted	596,853
valid	567,003
valid last week	433,299
invalid	88
Oldest Unsent Result	6 d 23 h 59 m

How you can join

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



Join others: Teams and Forums



Einstein@Home results

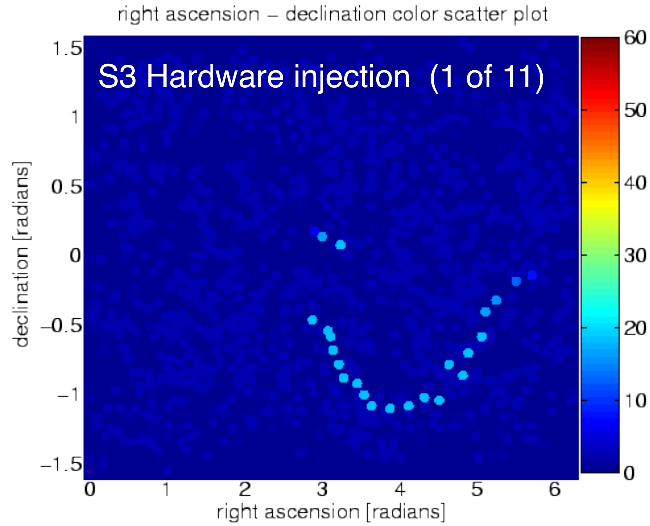
No detections! (except injections)

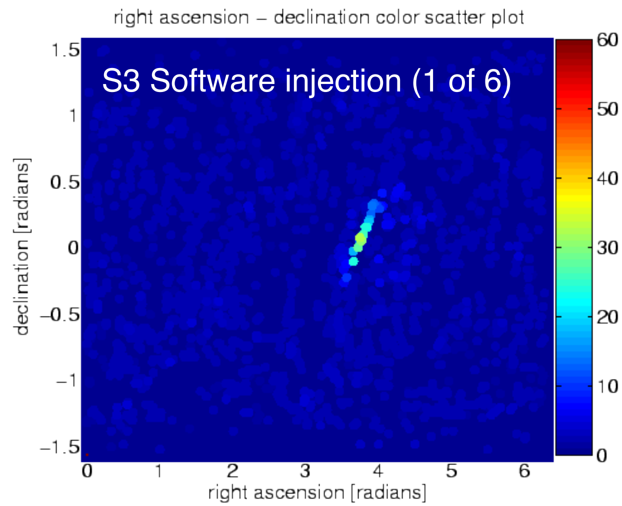
S3 final analysis is described on the project website: See http://einstein.phys.uwm.edu/FinalS3Results

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

- **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!