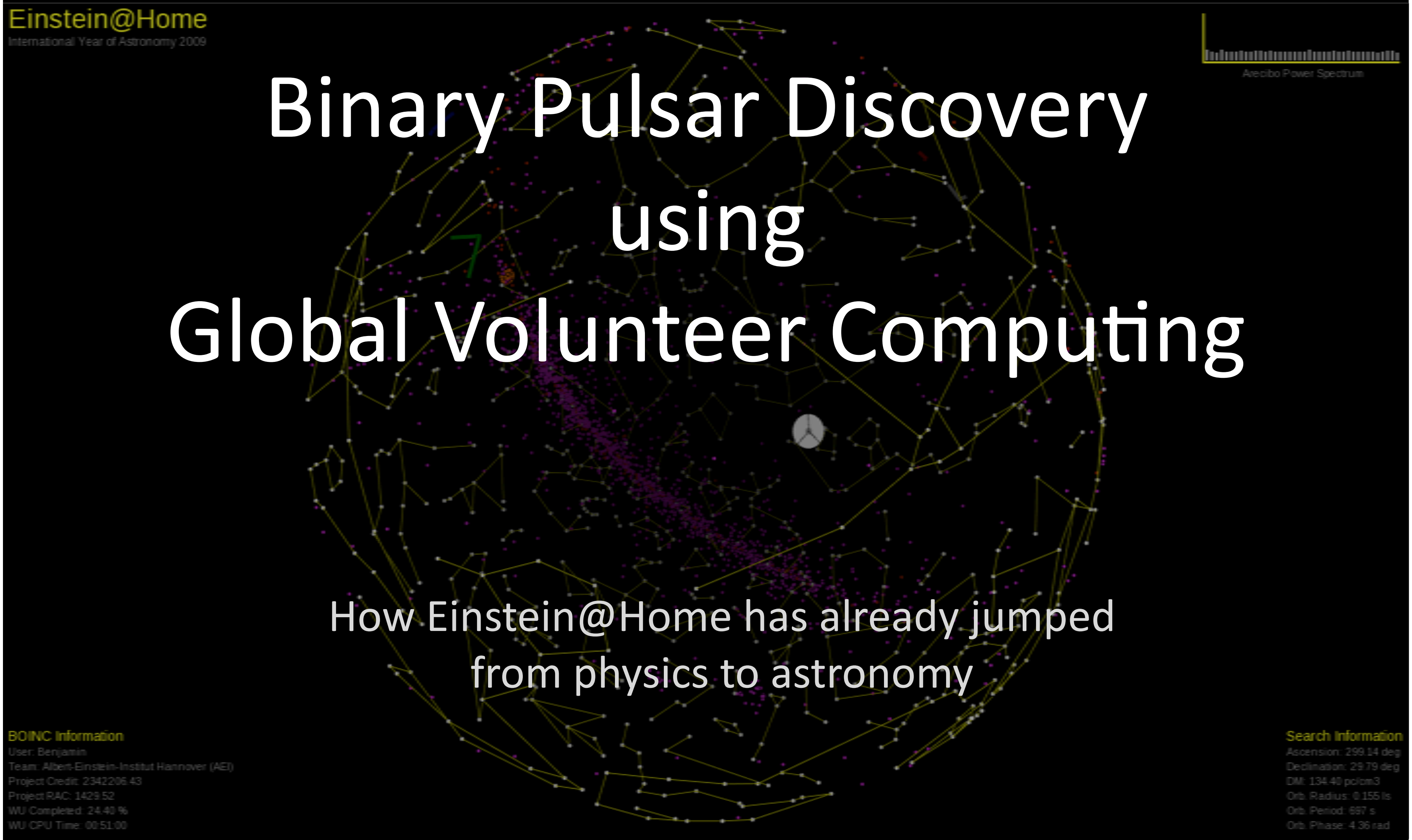
Binary Pulsar Discovery
using
Global Volunteer Computing

How Einstein@Home has already jumped
from physics to astronomy

Eric Myers
June 2012



BOINC Information
User: Benjamin
Team: Albert-Einstein-Institut Hannover (AEI)
Project Credit: 2342206.43
Project RAC: 1429.52
WU Completed: 24.40 %
WU CPU Time: 00:51:00

Search Information
Ascension: 299.14 deg
Declination: 29.79 deg
DM: 134.40 pc/cm3
Orb. Radius: 0.155 ls
Orb. Period: 697 s
Orb. Phase: 4.36 rad

Summary:

- LIGO is a physics experiment which is attempting to detect gravitational waves (which are predicted by the General theory of Relativity (GR) but have not yet been observed).

- Observation of gravitational waves will likely open up a new branch of Astronomy!

- Einstein@Home is a volunteer distributed computing project, dedicated primarily to searching through data from the LIGO (and Virgo) detectors for evidence of gravitational waves (GW's) from continuous wave (CW) sources.

  Results: No detections yet! (except injections)

- Since March 2009 about a third of Einstein@Home compute cycles have been dedicated to searching for pulsars in radio telescope data

  Results: Discovery of over 40 new pulsars!

What are Gravitational Waves?

Astronomy now is done via Electromagnetic Waves, which are time-varying oscillations of electro-magnetic fields: radio, infrared, visible, ultraviolet, X-rays, and γ rays

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

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

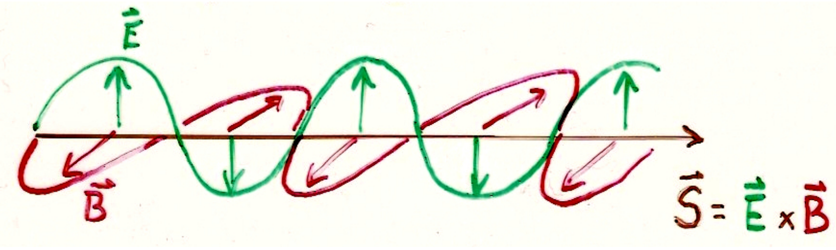
Rendering of space-time "stirred" by two orbiting black holes

"I sense a great disturbance in the Force…"

Comparison with EM waves

Electromagnetic Waves

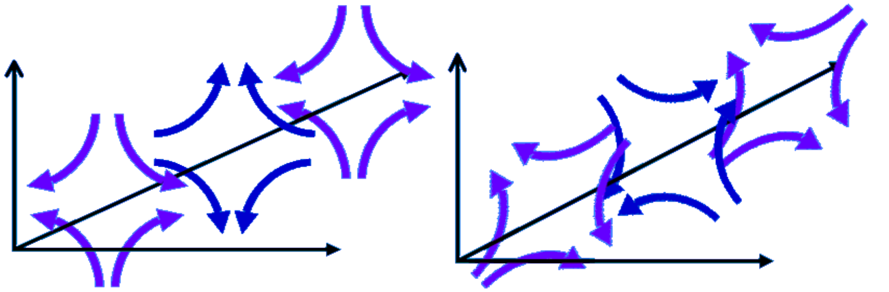
- Travel at the speed of light
- “transverse”
- Vector - dipole in both E and B
- Two polarizations: horizontal and vertical



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

Gravitational

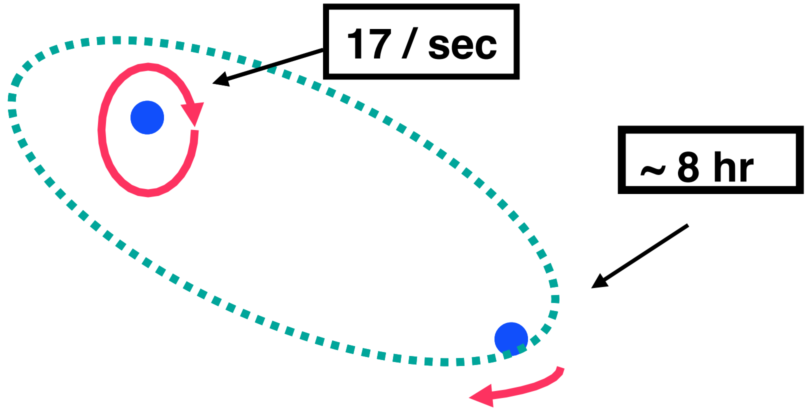
- Travel at the speed of light
- “transverse”
- Tensor - quadrupole distortions of space-time
- Two polarizations, “+” and “x”



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

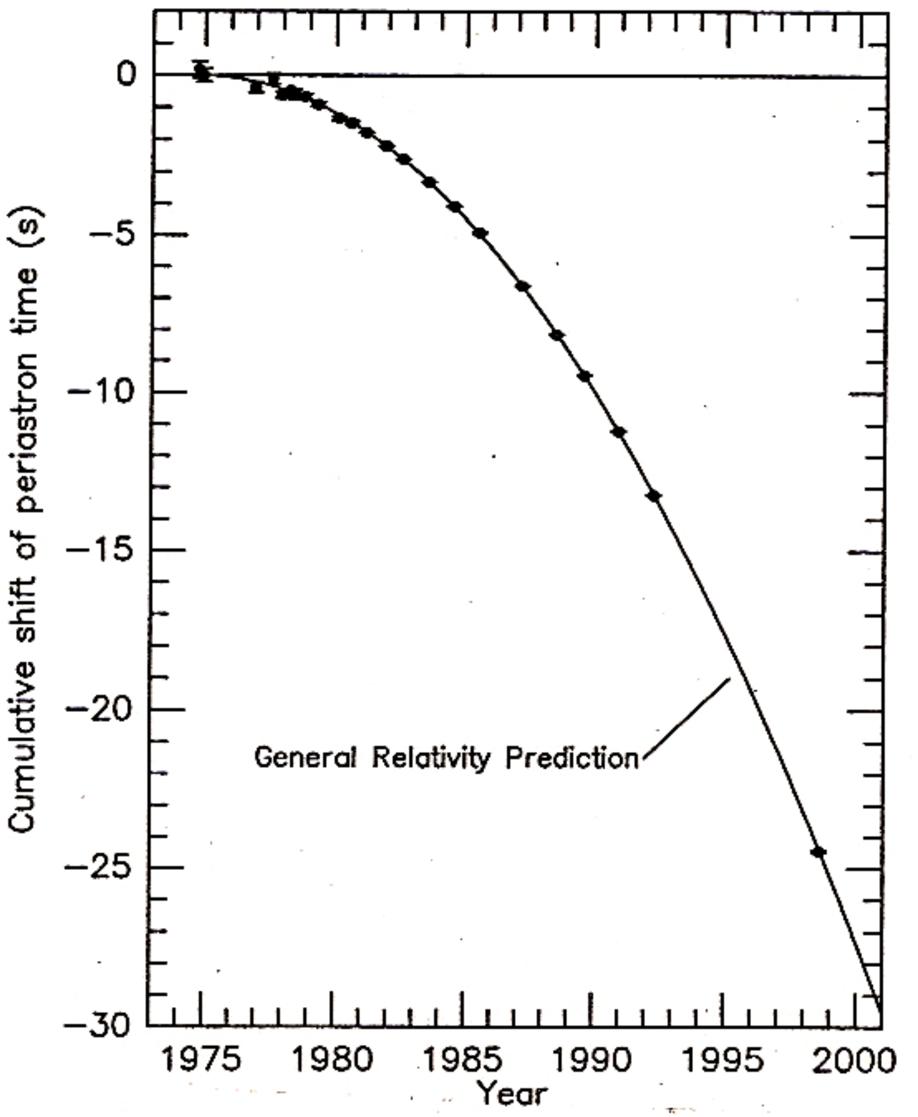
Indirect Evidence for Gravitational Waves

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

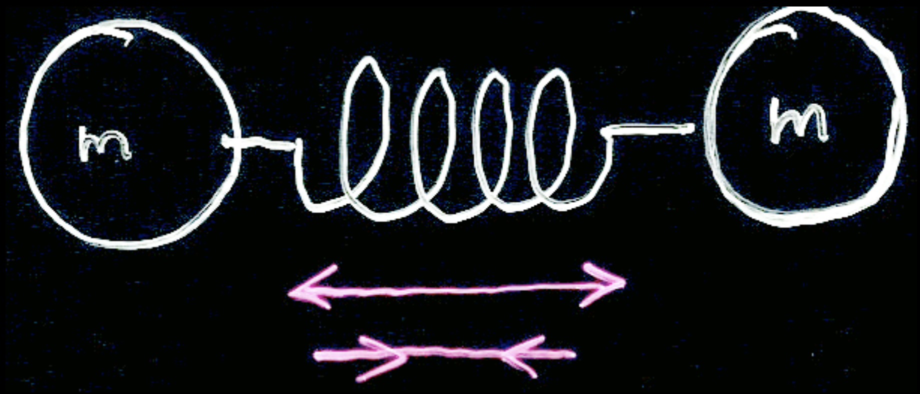


The measured precession of the orbit exactly matches the expected loss of energy due to gravitational radiation.

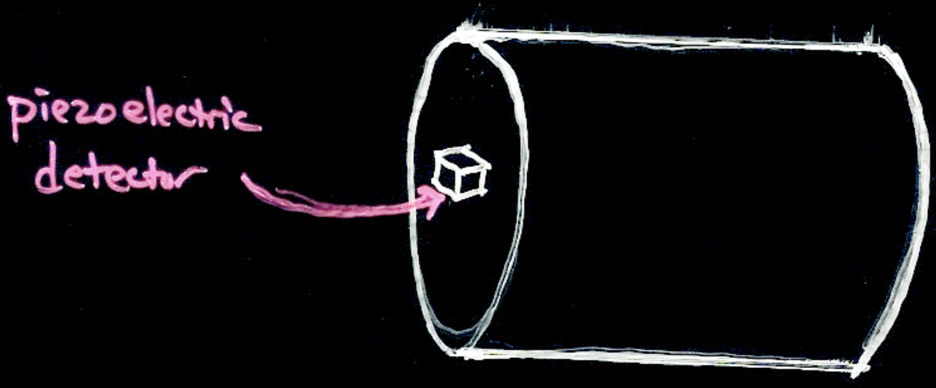
(Nobel Prize in Physics, 1993)

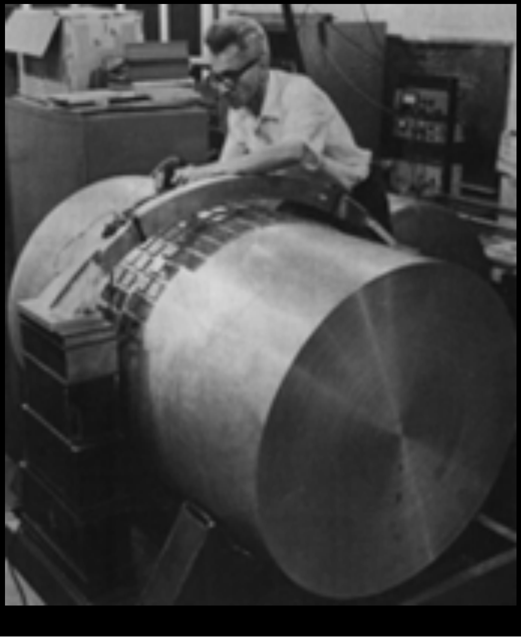


How might GW's be detected?



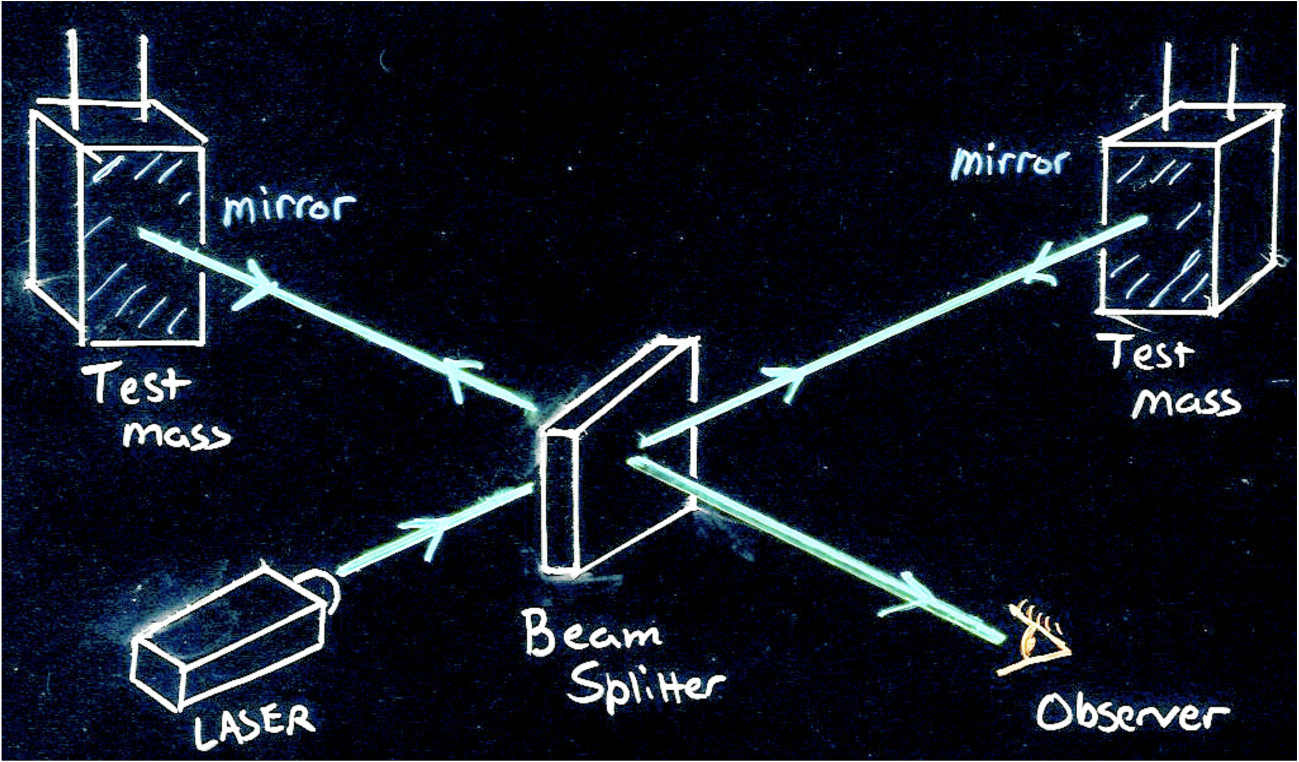
Pioneered by Joseph Weber at the University of Maryland in 1960's (no detection)





Michelson Interferometer method

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: **L**aser **I**nterferometer **G**ravitational wave **O**bservatory

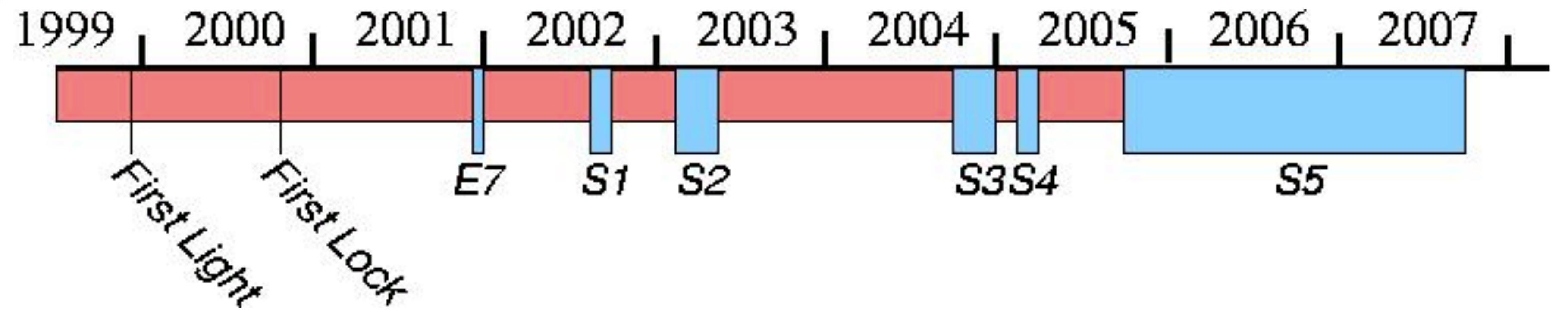
LIGO Livingston Observatory (LLO)
Livingston Parish, Louisiana
L1 (4km)

LIGO Hanford Observatory (LHO)
Hanford, Washington
H1 (4km) [and H2 (2km)]

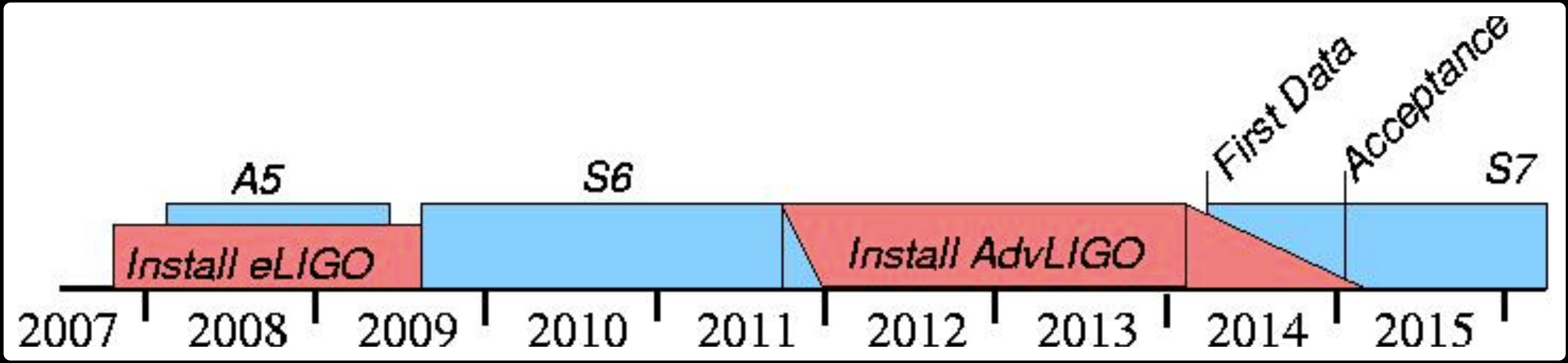
Funded by the National Science Foundation; operated by Caltech and MIT;
The research focus for 500+ members of the LIGO Scientific Collaboration worldwide.

LIGO Timeline

Construction began 1995



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



The most likely astronomical sources are:

Stochastic background from the early universe (Big Bang! Cosmic Strings,…) -- a “cosmic gravitational wave background”

Bursts from supernovae or other cataclysmic events

(requires changing *quadrupole*. Spherical symmetric ⇒ no GW!)

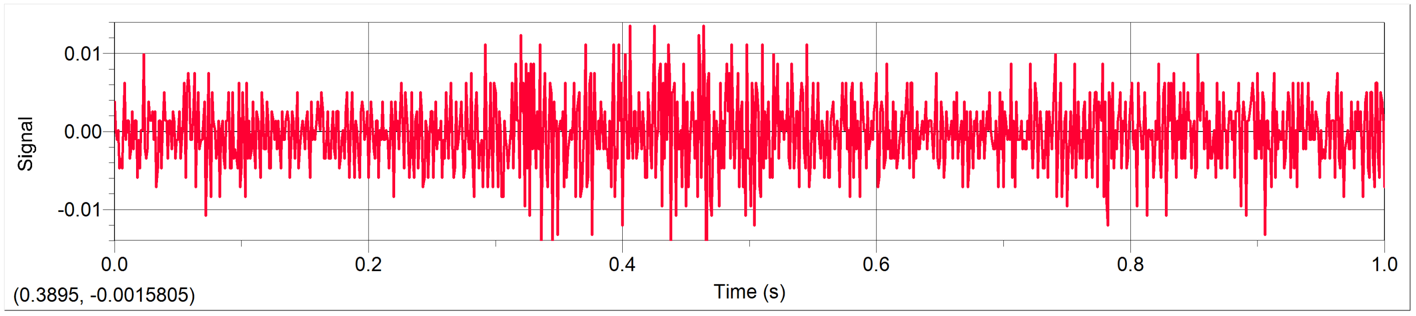
Coalescence of binary systems, inspiral of pairs of neutron stars and/or black holes (**NS-NS, NS-BH, BH-BH**) *CHIRP!*

Continuous Wave sources, such as spinning (and asymmetric!) or oscillating neutron stars (“gravitational pulsars”).

. . . or something unexpected!

How to search for modulated CW signals?

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



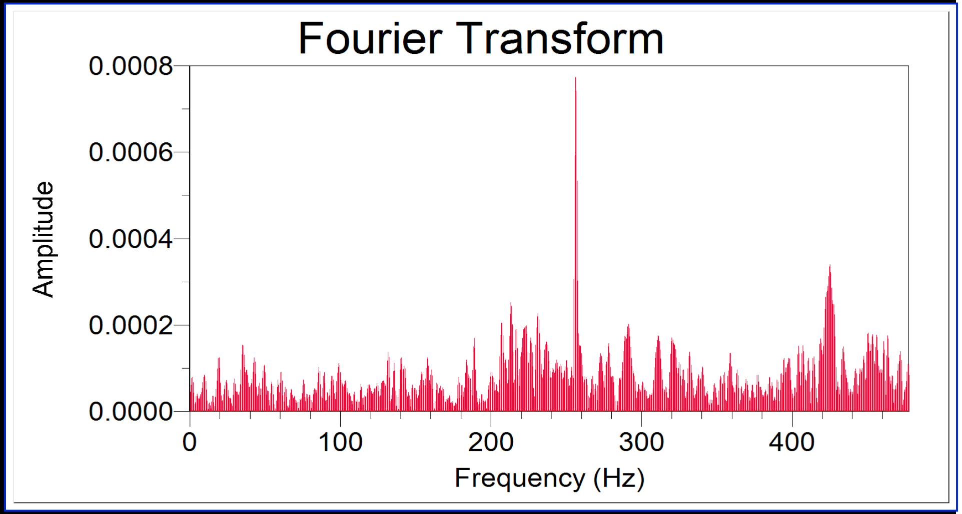
"time-series"

Take the Fourier Transform to obtain:

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

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

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



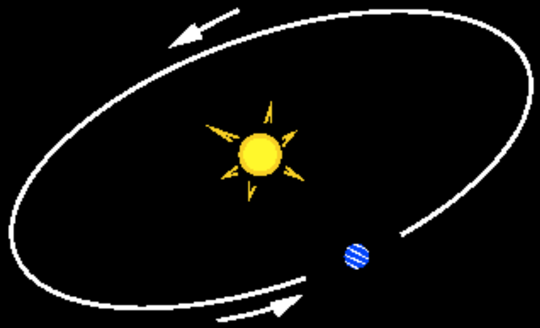
There is even a computationally fast algorithm for this, the Fast Fourier Transform (FFT).

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

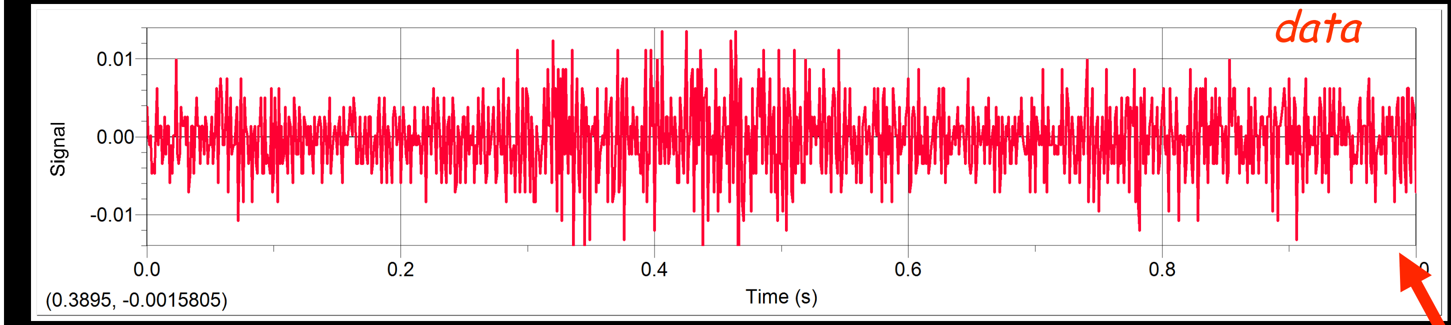
- The source losing energy due to "spin down"

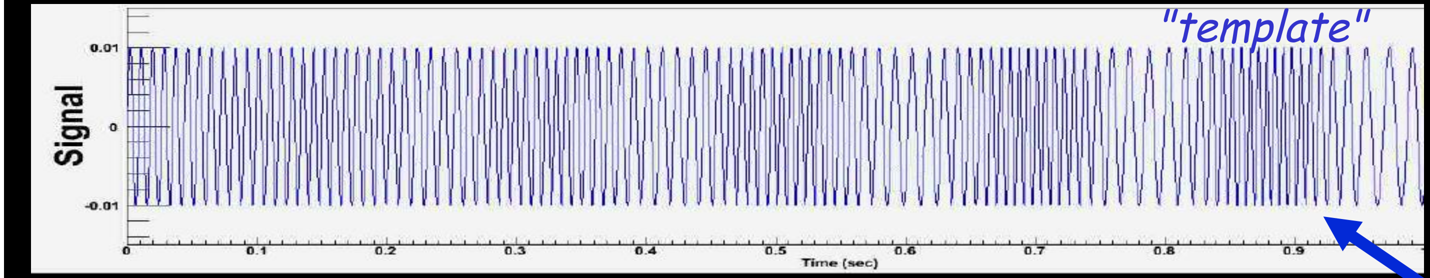
- Doppler shift due to Earth's motion around the Sun (one part in 10^4, with period of 1 year)
- Doppler shift due to Earth's rotation about its axis (one part in 10^6, with period 1 sidereal day)

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



Matched Filtering





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

"the F statistic"

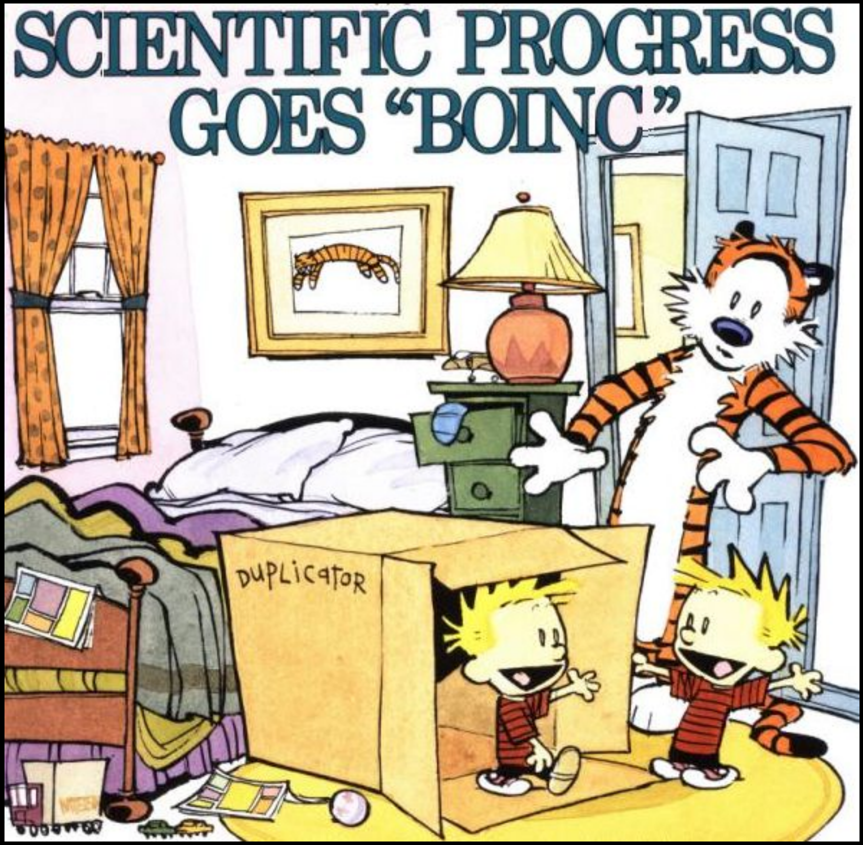
Assuming data is in the form $x(t) = h(t) + n(t)$

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



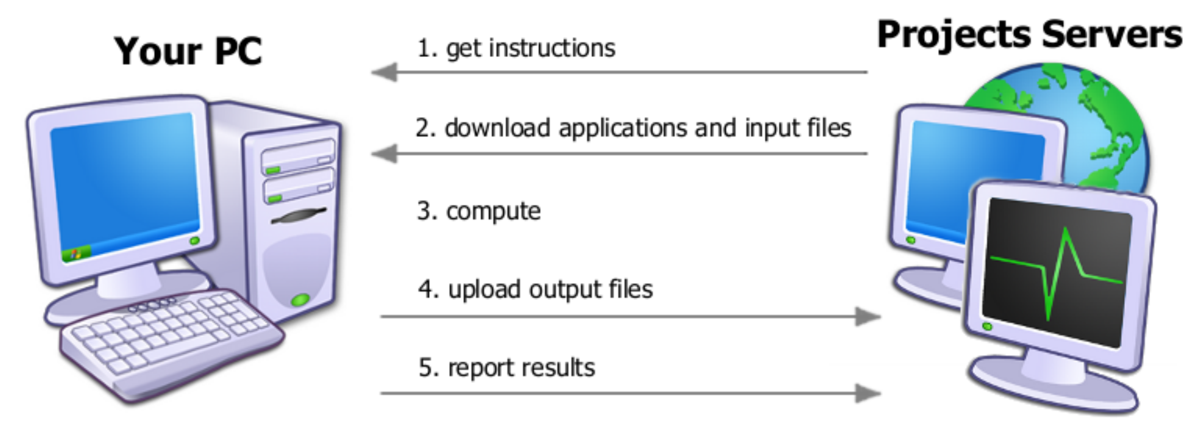
SETI@home is a distributed computing project searching for distinctive peaks in Arecibo radio data.
In 2004 they upgraded to BOINC:

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

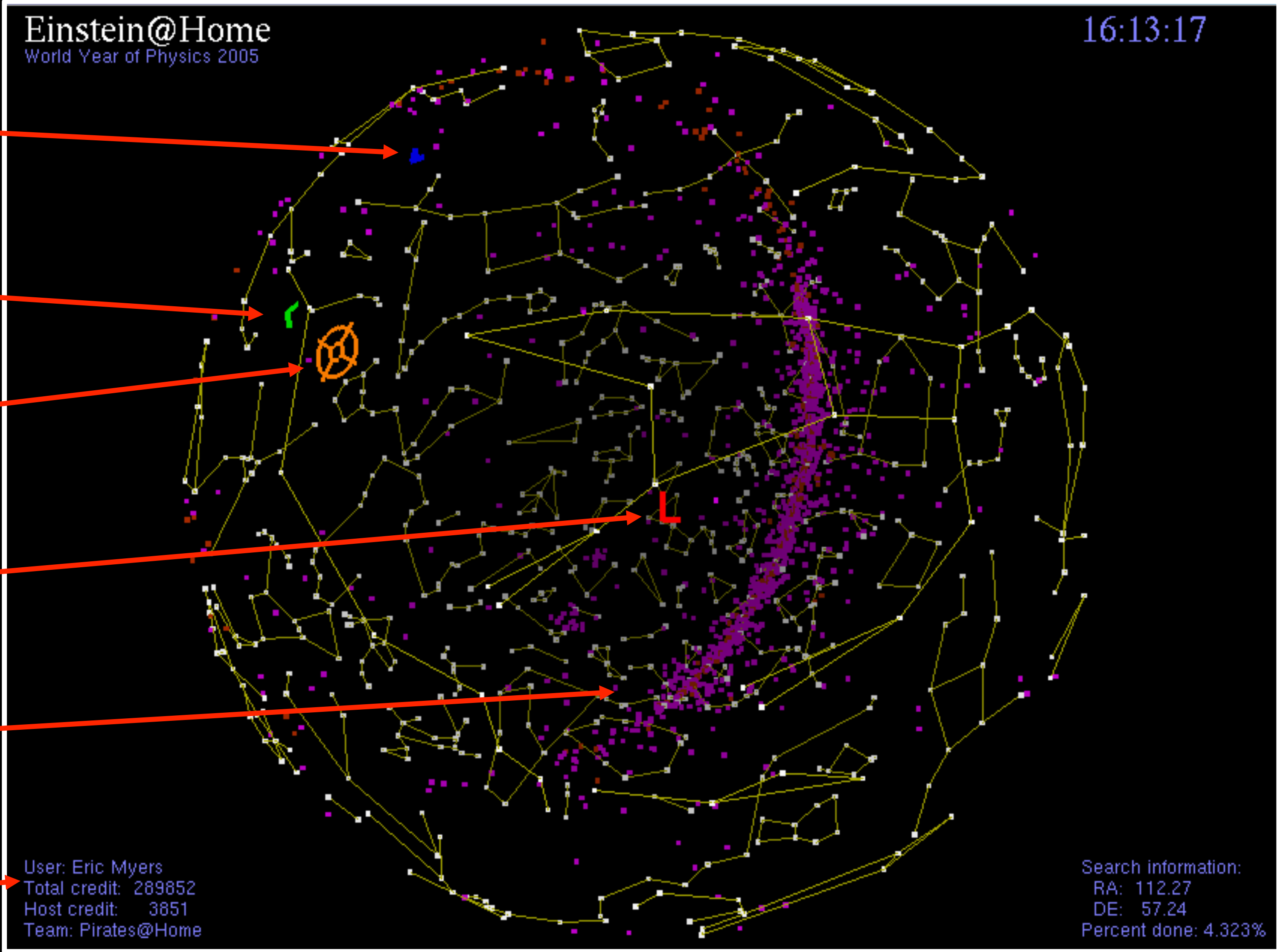
LLO azimuth position

Search marker

GEO600 azimuth position

Known pulsars (electromagnetic) and SNR's

User, team, host info



Einstein@Home
World Year of Physics 2005

16:13:17

User: Eric Myers
Total credit: 289852
Host credit: 3851
Team: Pirates@Home

Search information:
RA: 112.27
DE: 57.24
Percent done: 4.323%

Einstein@Home results

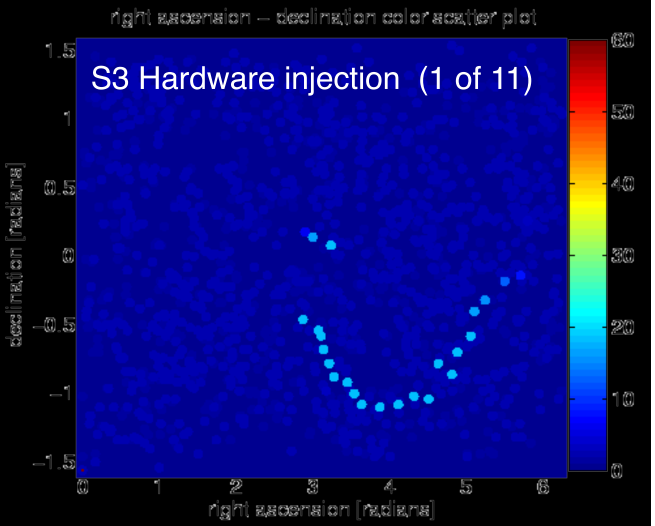
No detections! (except injections)

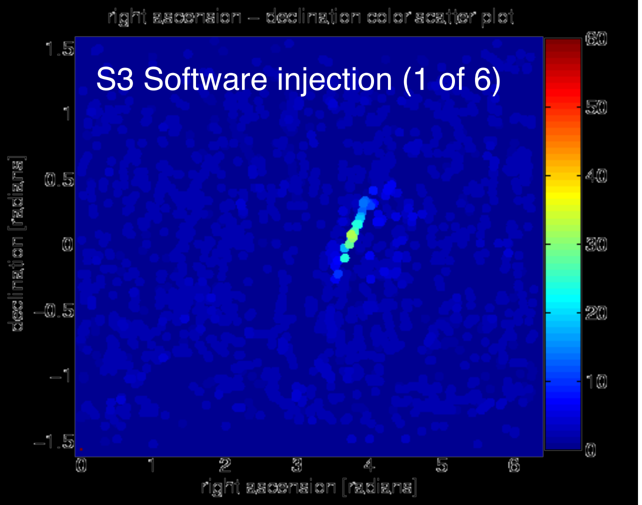
Analysis and results is described in these papers:

“The Einstein@Home search for periodic gravitational waves in LIGO S4 data”
by the LIGO Scientific Collaboration
Phys. Rev. D 79, 022001 (2009) [link]

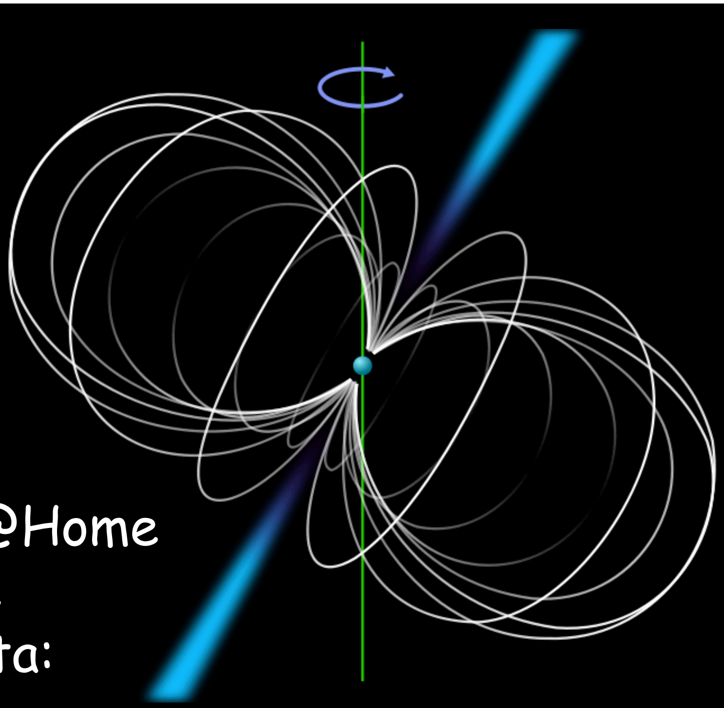
“Einstein@Home search for periodic gravitational waves in early S5 LIGO data”
by the LIGO Scientific Collaboration
Phys. Rev. D 80, 042003 (2009) [link]

Analysis of S5 and S6 data still in progress...





Radio Pulsar Searches



Since March 2009 about 35% of Einstein@Home compute cycles have been applied to three searches for pulsars in radio telescope data:

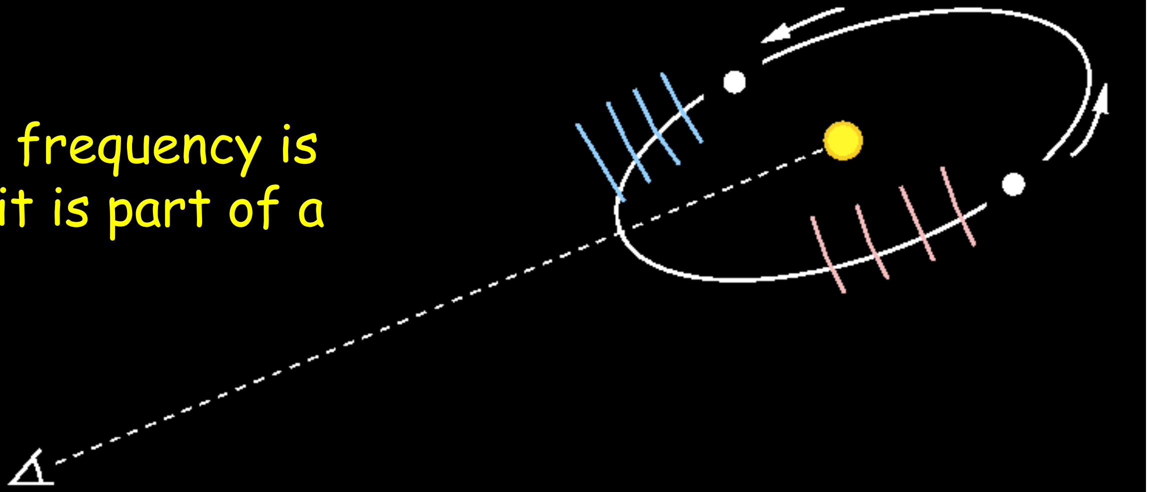
1. Arecibo Binary Pulsar search
2. Arecibo Mock Spectrometer Search
3. Parkes Multibeam Pulsar Survey data

Coherent Binary Search Method

Direction to the source is not an issue, because radio telescope uses highly directional "beams"

No Doppler shift due to Earth's motions, because observation times are short (5 to 35 minutes)

Instead, the source frequency is modulated because it is part of a binary system.



Search for the modulated signal using *Matched Filtering* with appropriate template functions.

Arecibo Binary Pulsar Search

Courtesy of the NAIC - Arecibo Observatory, a facility of the National Science Foundation

ALFA Receiver
(Arecibo L-Band Feed Array)
7 feed system around 1.4 GHz,
dual polarizations, cooled to 30K
5 minute observations
(same detector used by SETI@home)

↓

WAPP autocorrelation spectrometer
(Wideband Arecibo Pulsar Processor)
Generates spectra w/ 100 MHz bandwidth
into 256 channels every 64 μs

↓

Shipped on disks from Puerto Rico to Cornell

↓

Transferred to AEI, Hannover, Germany via Internet

↑

De-dispersed into time-series with 628 trial dispersion measure (DM) values, downsampled to 128μs for reduced bandwidth

↓

2MB Workunits with 4 DM values for one beam of duration 268 sec

↓

Arecibo Binary Pulsar Search

continued…

Same Workunit is processed by at least two different volunteer computers (approx 2 hr each)

↓

Client computer uploads 100 most significant candidates

↓

Candidates with S > 15 are identified "by eye" and processed with PRESTO

↓

Suspected detection followed up with additional radio telescope observations

Results:

270 re-detections of 134 known pulsars, including 8 known millisecond pulsars.

3 detections of 2 new millisecond pulsars!

Arecibo Binary Pulsar Search: Results

J2007+2722

Detected by 4 computers in 2 Workunits on 11 and 14 June 2010

f = 40.82 Hz distance of 5.3 kpc (from dispersion measure)

isolated, low magnetic field

J1952+2630

Detected by 2 computers in 1 Workunit on 2 and 6 July 2010

f = 48.24 Hz, distance of 9.4 kpc (from dispersion measure)

Circular orbit with period 9.4 hrs.
Companion is probably a white dwarf with mass > 0.95 $M_{\odot}$

Listen to the pulsar

Arecibo PALFA Mock Spectrometer Search

ALFA Receiver
(Arecibo L-Band Feed Array)

↓

Mock spectrometer (PDEV)
14 FPGA spectrometer boxes x 2 boards
172 MHz bandwidth each = 300 MHz
6 to 8192 channels (per freq band)
Choice of polarizations

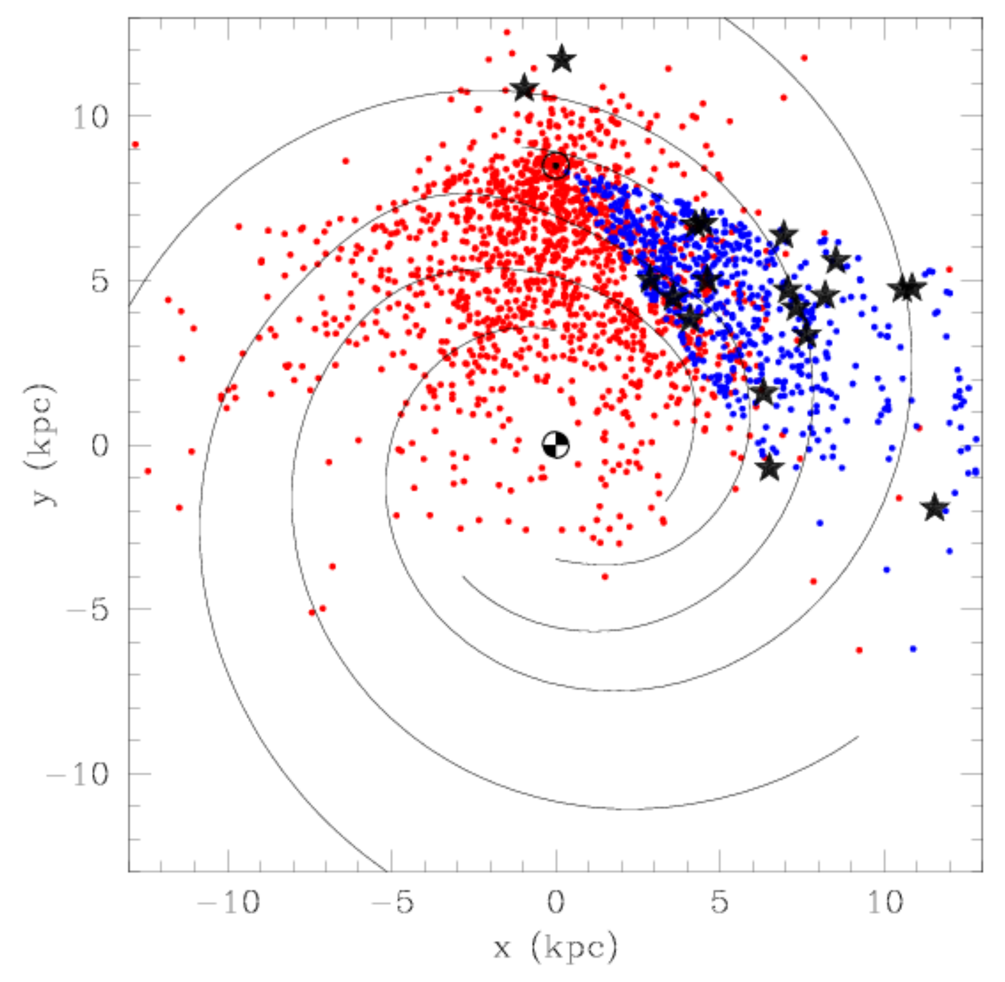
↓

Same analysis pipeline
as previous search

↓

Results:

18 new pulsars detected
as of 21 May 2012



Know Pulsars / Expected Pulsars / ★ recent discoveries

Parkes Multi-Beam Pulsar Survey

http://www.atnf.csiro.au/people/pulsar/pmsurv/

Data collected by the "The Dish" at the Parkes Observatory, in New South Wales, Australia, from around 1999 to 2006.

First search of this dataset using the coherent binary search methods over the full observation time of each beam

20 cm multibeam receiver system
Center frequency 1.374 GHz
288 MHz bandwidth -> 96 channels
13 beams per pointing, for 35 minutes

Results:

21 new pulsars detected
as of 21 May 2012

Total New Pulsars

- Arecibo Binary Pulsar Search

  2 new pulsars

- Arecibo Mock Spectrometer Search

  18 new pulsars

- Parkes Multi-Beam Pulsar Survey

  21 new pulsars

22 new pulsars discovered in 2012 alone!

Summary:

- LIGO is a physics experiment which is attempting to detect gravitational waves

- Observation of gravitational waves will ~~likely~~ open up a new branch of Astronomy!

- Einstein@Home is a volunteer distributed computing project searching for evidence of gravitational waves (GW's) from continuous wave (CW) sources.

  Results: No detections yet! (except injections)

- Since March 2009 about a third of Einstein@Home compute cycles have been dedicated to searching for pulsars in radio telescope data

  Results: Discovery of over 40 new pulsars!

Further reading…

1. *"The Einstein@Home Aricebo Radio Pulsar Search"*
   http://einstein.phys.uwm.edu/radiopulsar/html/index.php

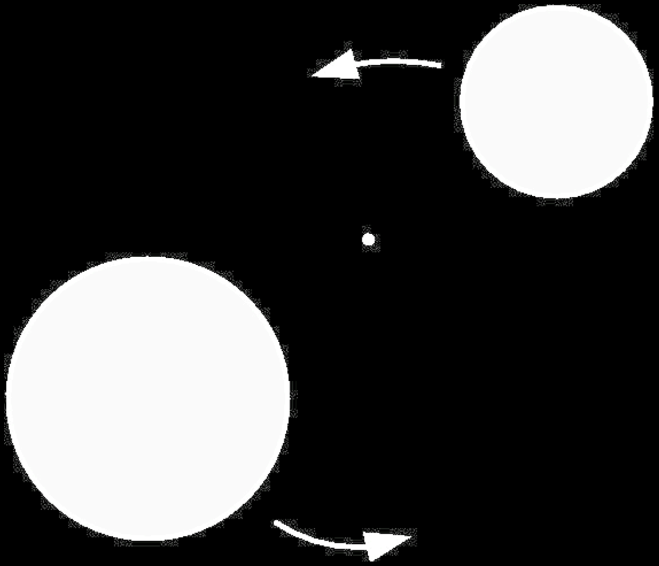
2. *"Pulsar Discovery by Global Volunteer Computing",* B. Knispel, *et. al*. Science vol 329, 10 Sept. 2010, pg 1305

3. *"Arecibo PALFA Survey and Einstein@Home: Binary Pulsar Discovery by Volunteer Computing",* B. Knispel, *et. al.,* ApJ Letters, 732:L1 (2011)

Extra slides for questions . . .

Example: Binary Inspiral

1.4M$_\odot$ binary inspiral provides a translation from dimensionless strain amplitude *h* to the “reach” of the instruments, measured in Mpc, much like a "standard candle".



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

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!

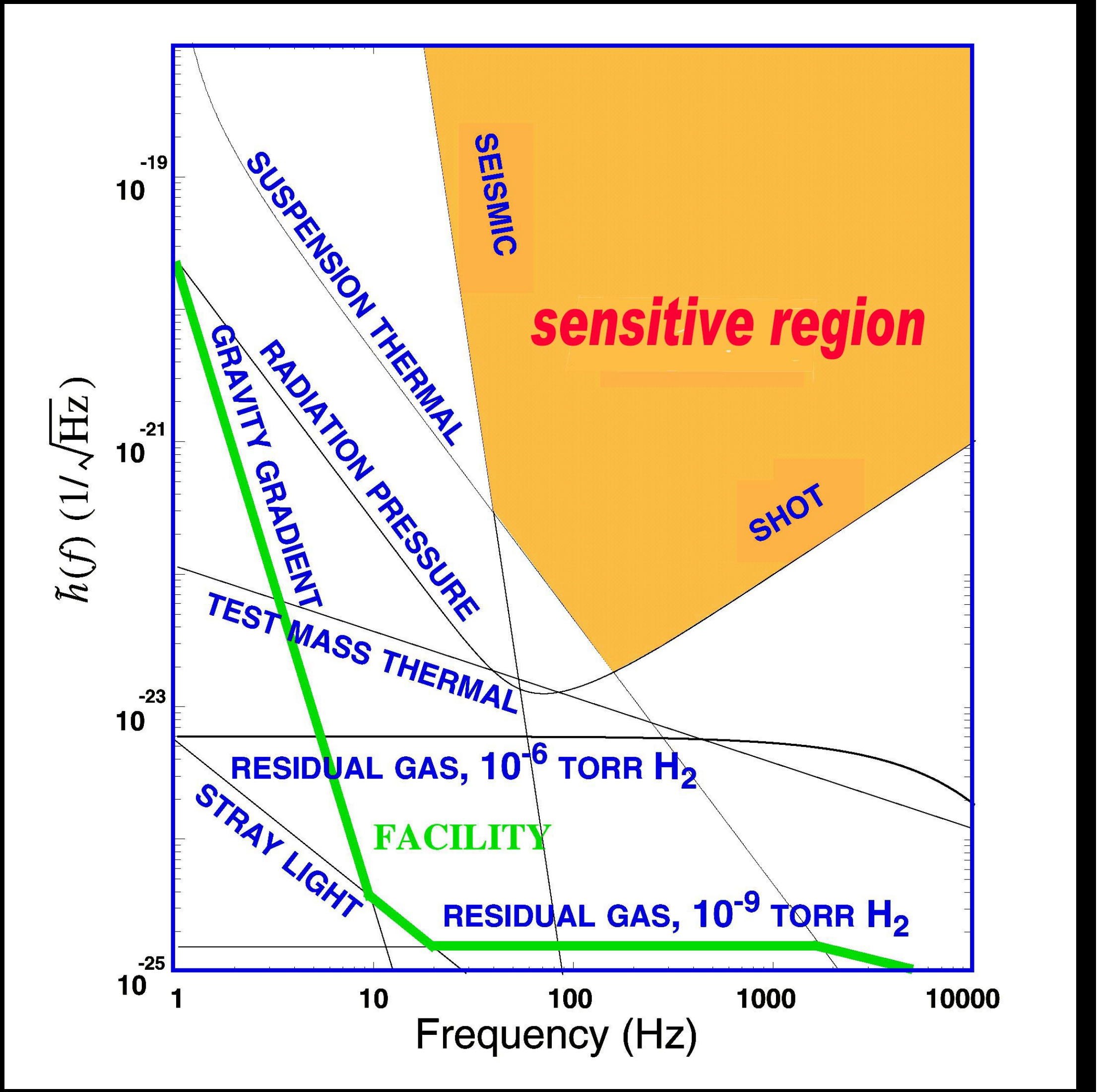
What Limits LIGO Sensitivity?

Seismic noise & vibration at low frequencies

Atomic vibrations (thermal noise) inside components at mid frequencies

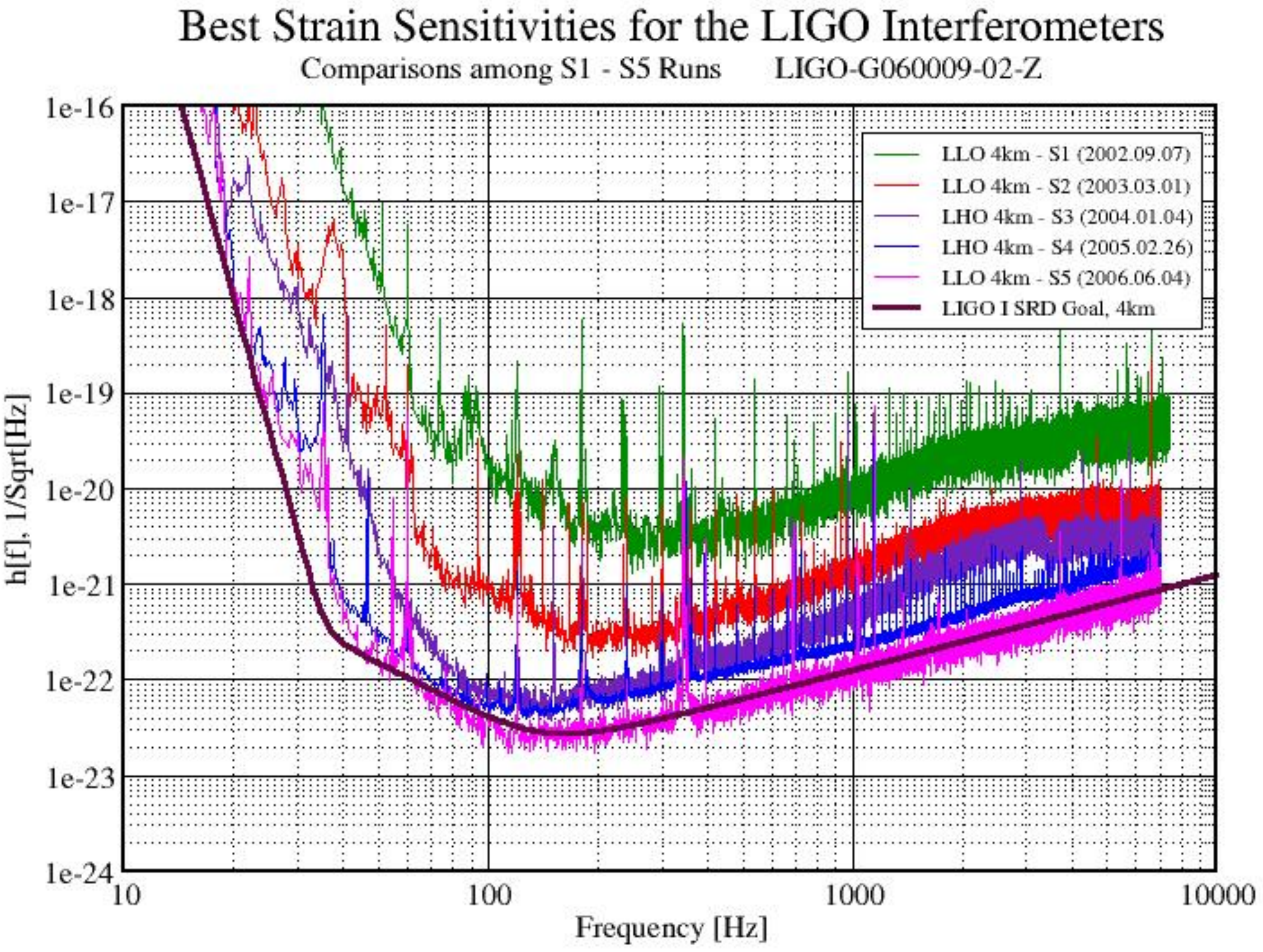
Quantum nature of light ("*shot noise*") at high frequencies

Myriad details of the lasers, electronics, etc., can make problems above these levels



LIGO Strain Sensitivity   S1 - S5

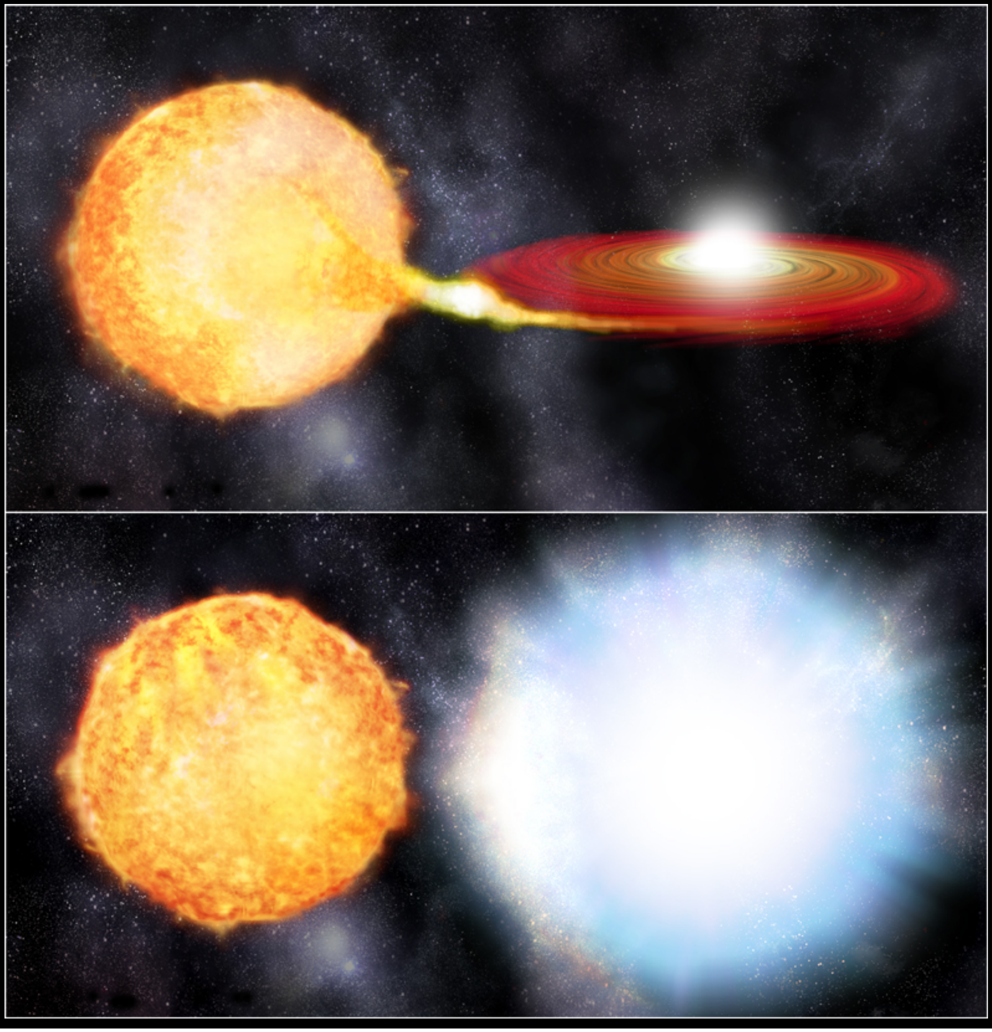
S5: 4 Nov 2005 to 30 Sept 2007


Best Strain Sensitivities for the LIGO Interferometers

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

Another type of Type Ia supernova?

Accretion onto White Dwarf



Binary White Dwarf merger