Searching for Ripples in Space-time

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- What are gravitational waves?
- How are they produced?
- How will they be detected?
- How will they be useful?
- How you can join the search!

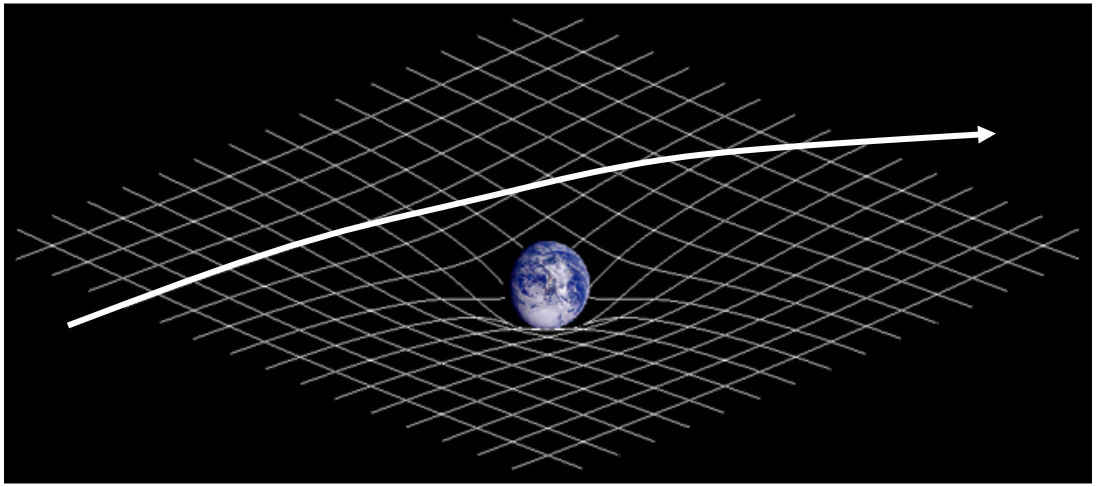
What are Gravitational Waves?

- 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>

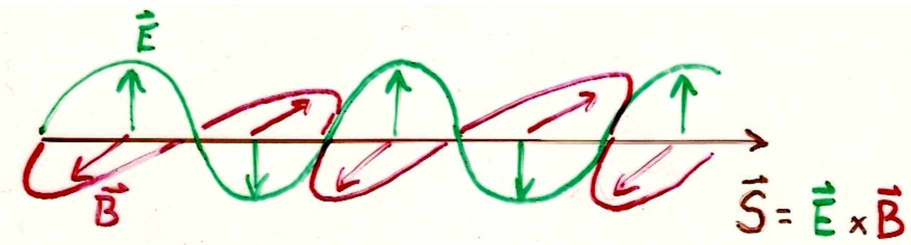
Matter curves spacetime,
and
Objects in "free-fall" travel in "straight" paths in the curved space.



Comparison with EM waves

Electromagnetic Waves

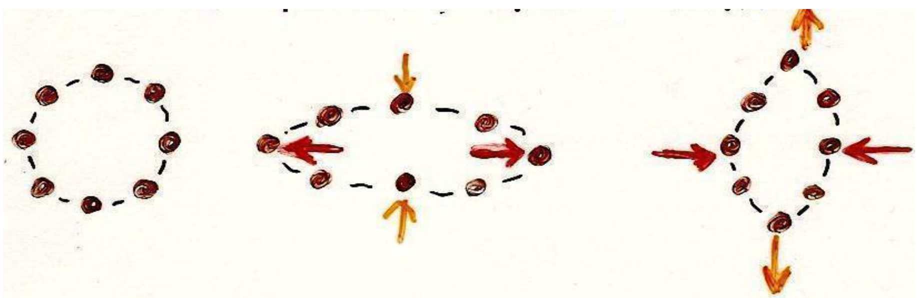
- Travel at the speed of light
- "transverse"
- Two polarizations: horizontal and vertical
- Dipole in both E and B



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

Gravitational Waves

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



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

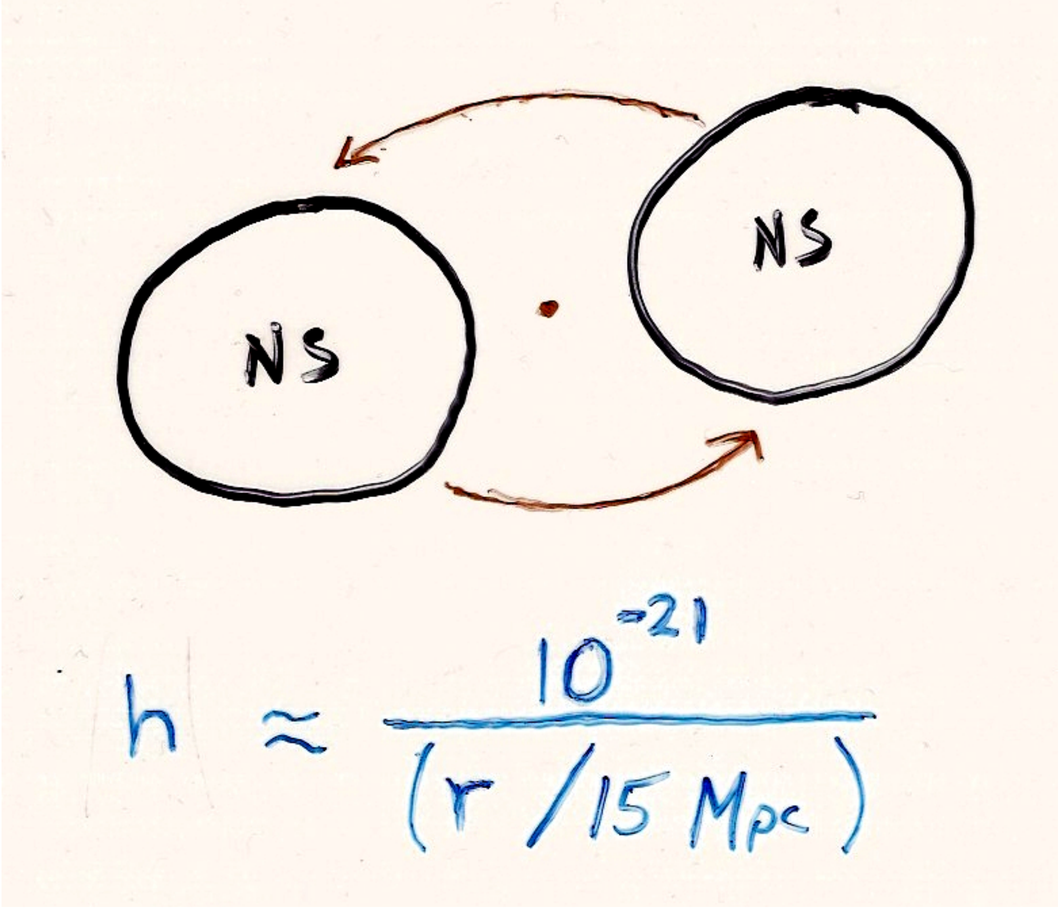
How might GW's be produced?

Producing significant gravitational radiation requires a large change in the quadrupole moment of a large mass distribution. The most likely astronomical sources are:

1. Coalesence of binary systems, such as the inspiral of pairs of neutron stars or black holes (NS-NS, NS-BH, BH-BH) CHIRP!
2. Continuous Wave sources, such as spinning (asymmetric!) neutron stars (gravitational pulsars), or body oscillations of large objects (neutron star "r"-modes).
3. Bursts from supernovae or other cataclysmic events (must be asymmetric!)
4. Stochastic background from the early universe (Big Bang! Cosmic Strings,…)

Example

A pair of $1.4M_{\odot}$ neutron stars in a circular orbit of radius 20 km, with orbital frequency 400 Hz produces a strain of amplitude $h = \Delta L/L$ at frequency 800 Hz.



(Due to Peter Saulson, Syracuse Univ.)

Importance of Gravitational Waves

- Gravitational Waves are predicted in Einstein's theory of general relativity (GR), but they have never been detected.
- Unlike the gravitational field of the Earth, or the Sun, or of a Black Hole, gravitational waves are "dynamic", not static.
- They are incredibly weak! *A great challenge!*
- They will provide us a new way to look at (or "listen" to) the universe -- a new branch of Astronomy.
- Theoretical Link: there is still no consistent mathematical theory of both gravitation and quantum theory: a "Quantum Gravity". Quantum physics is <u>Wave</u> physics, so understanding gravitational waves could be an important step toward understanding Quantum Gravity

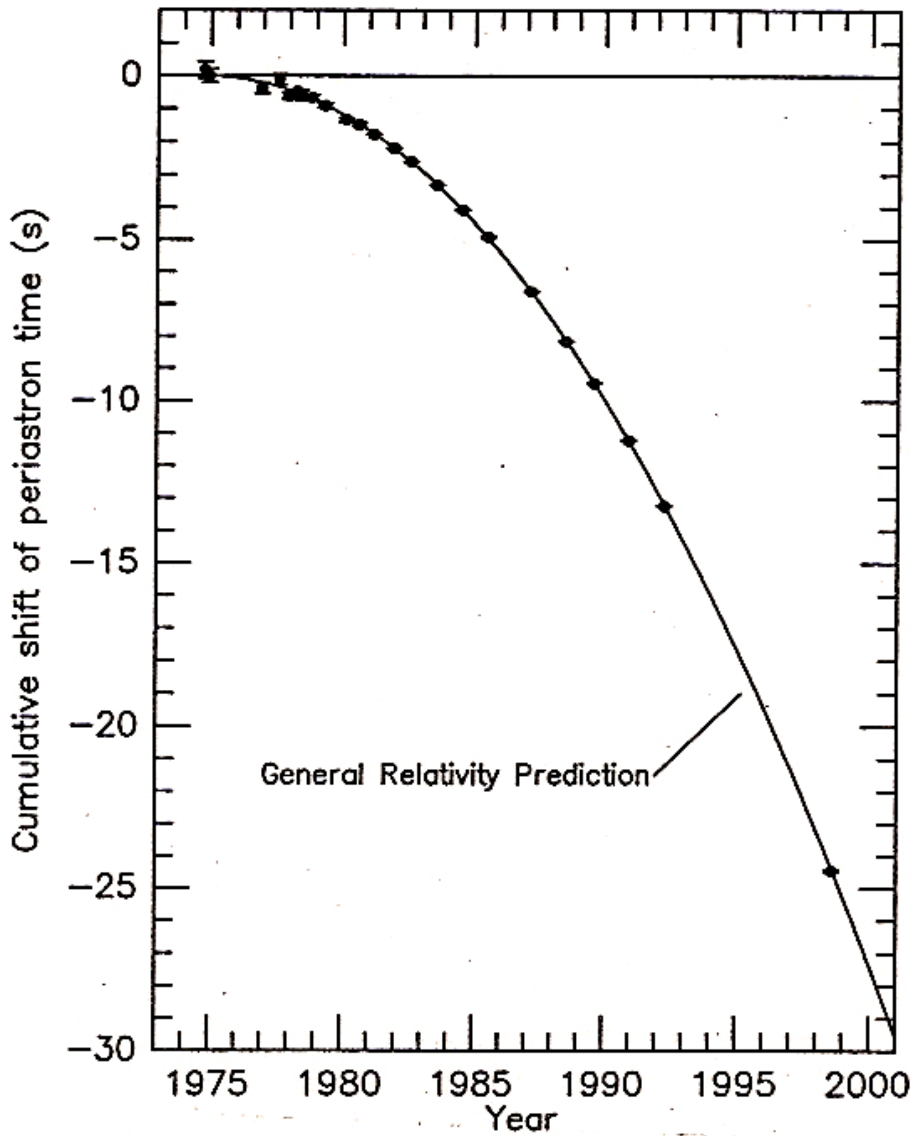
Indirect Evidence for GW's

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

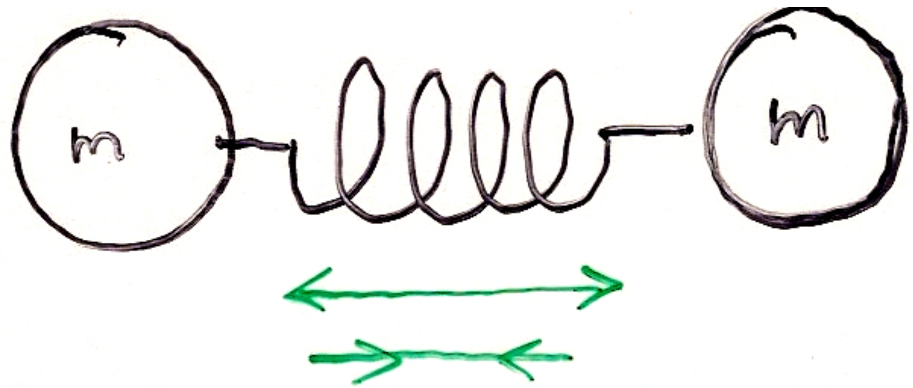
T ≈ 8 hrs
e ≈ 0.6

(Nobel Prize in Physics, 1993)

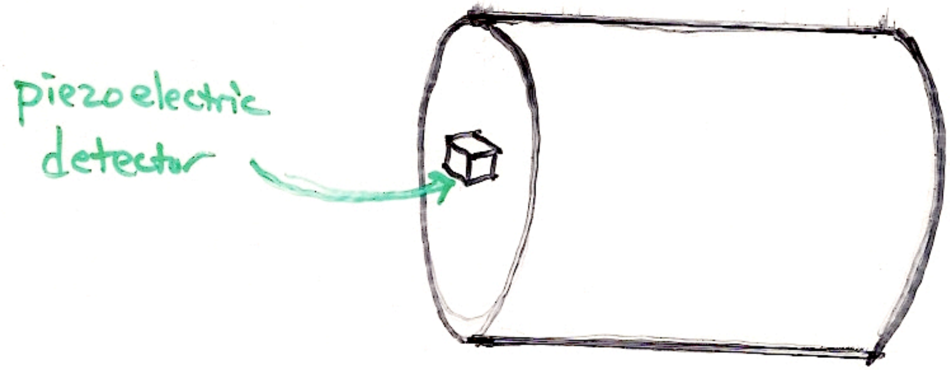


How might GW's be detected?

Simplest example:
the "bar-bell"
detector.

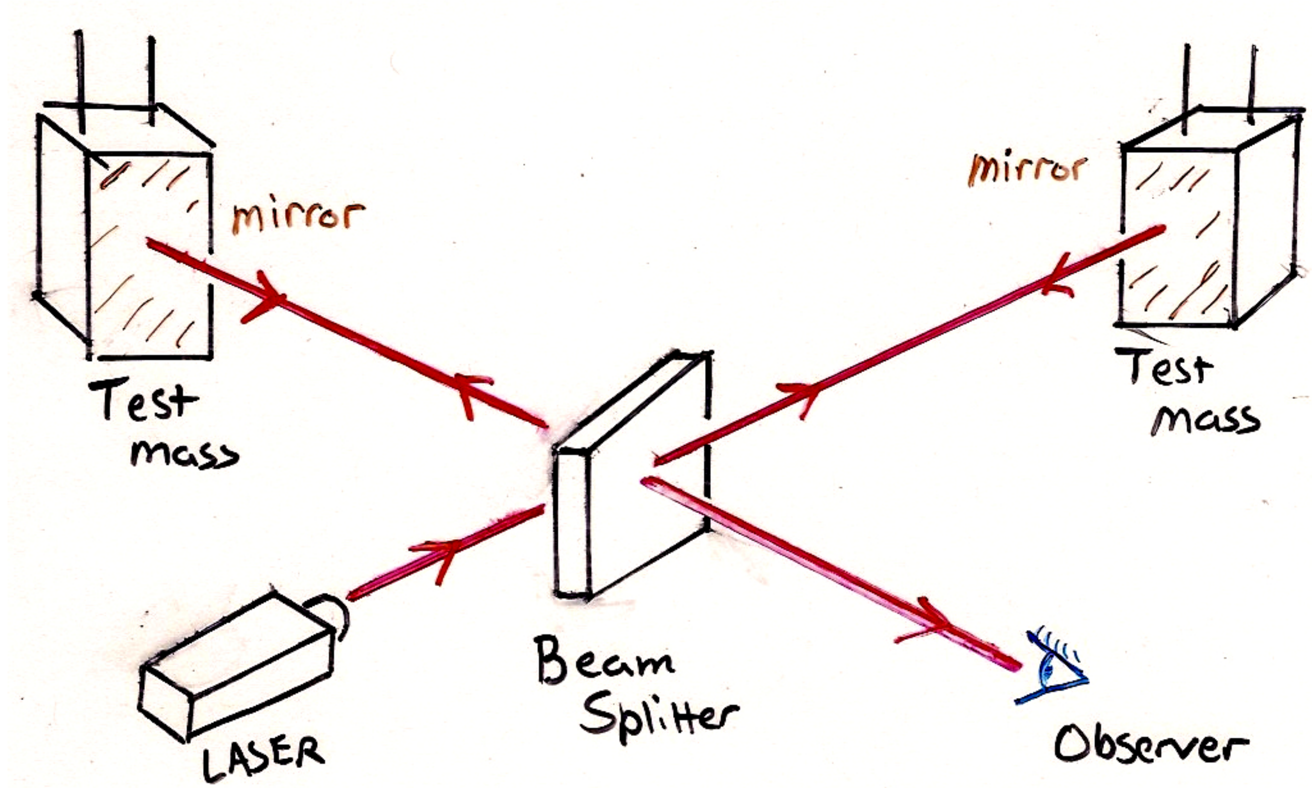


Practical implementation:
a "bar" detector



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

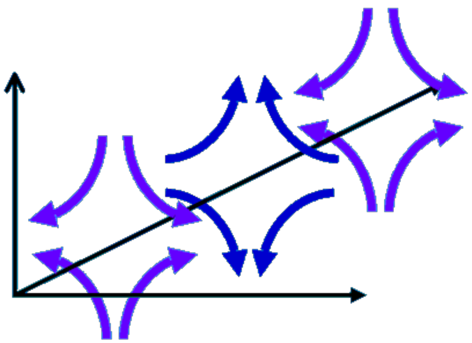
Michelson Interferometer

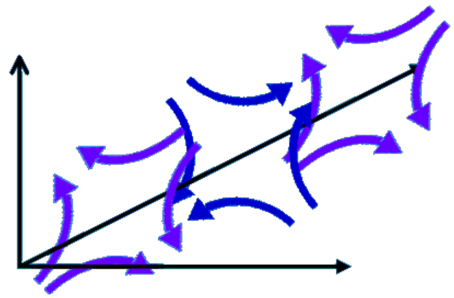


Measuring ΔL in arms allows the measurement of the strain $h = \Delta L/L$, which is proportional to the gravitational wave amplitude. (Multiple reflections increase effective length.)

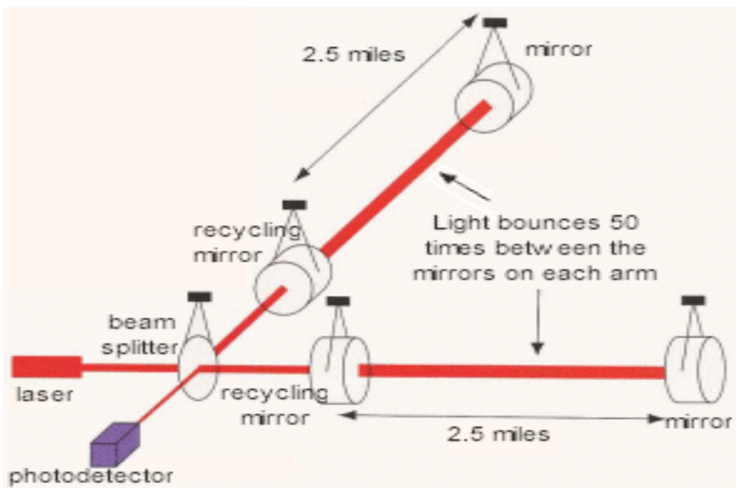
Detecting Gravitational Waves

Gravitational waves are time-varying quadrupole distortions of space-time:





These are detected as small changes in length in the arms of the Interferometers:



LIGO Observatories

LIGO Livingston Observatory (LLO)

Livingston Parish, Louisiana

L1 (4km)

LIGO Hanford Observatory (LHO)

Hanford, Washington

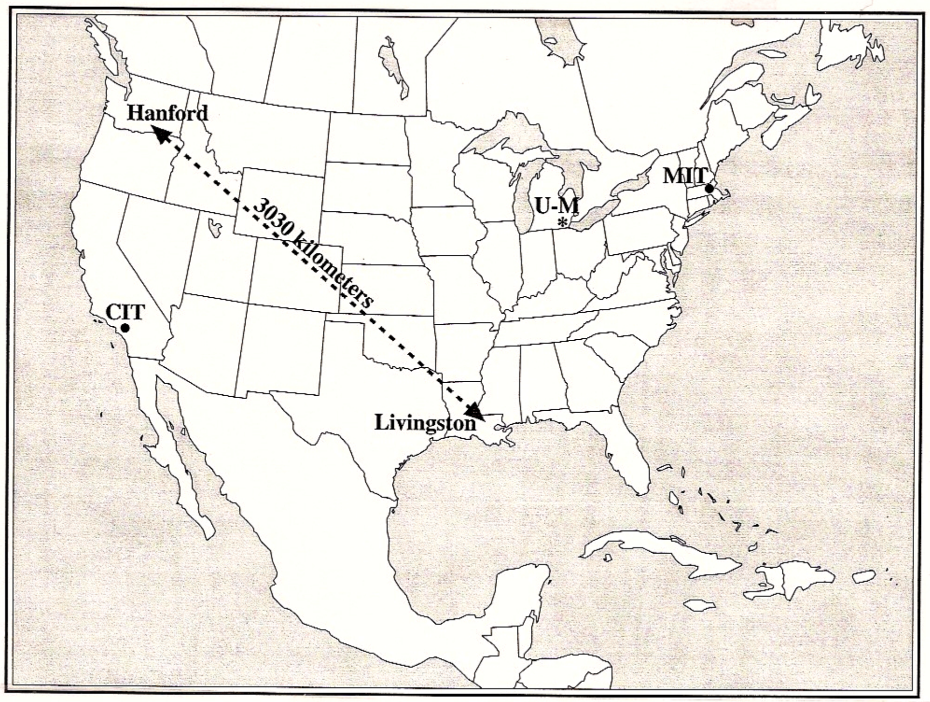
H1 (4km) and H2 (2km)

LIGO is…

- Laser Interferometer Gravitational wave Observatory
- An experiment to *detect* the gravitational waves (GW's) predicted by Einstein's general theory of relativity (GR).
- A facility for astronomical observation using GW's -- *opening a whole new branch of astronomy!*
- Jointly run by Caltech and MIT.
- LIGO Scientific Collaboration (LSC) consists of over 400 scientists from over 40 institutions
- No detections yet, but upper limits established and analysis methods developed and refined.
- Just began year-long science run (S5) in November 2005

Skip it

Baseline & Timeline



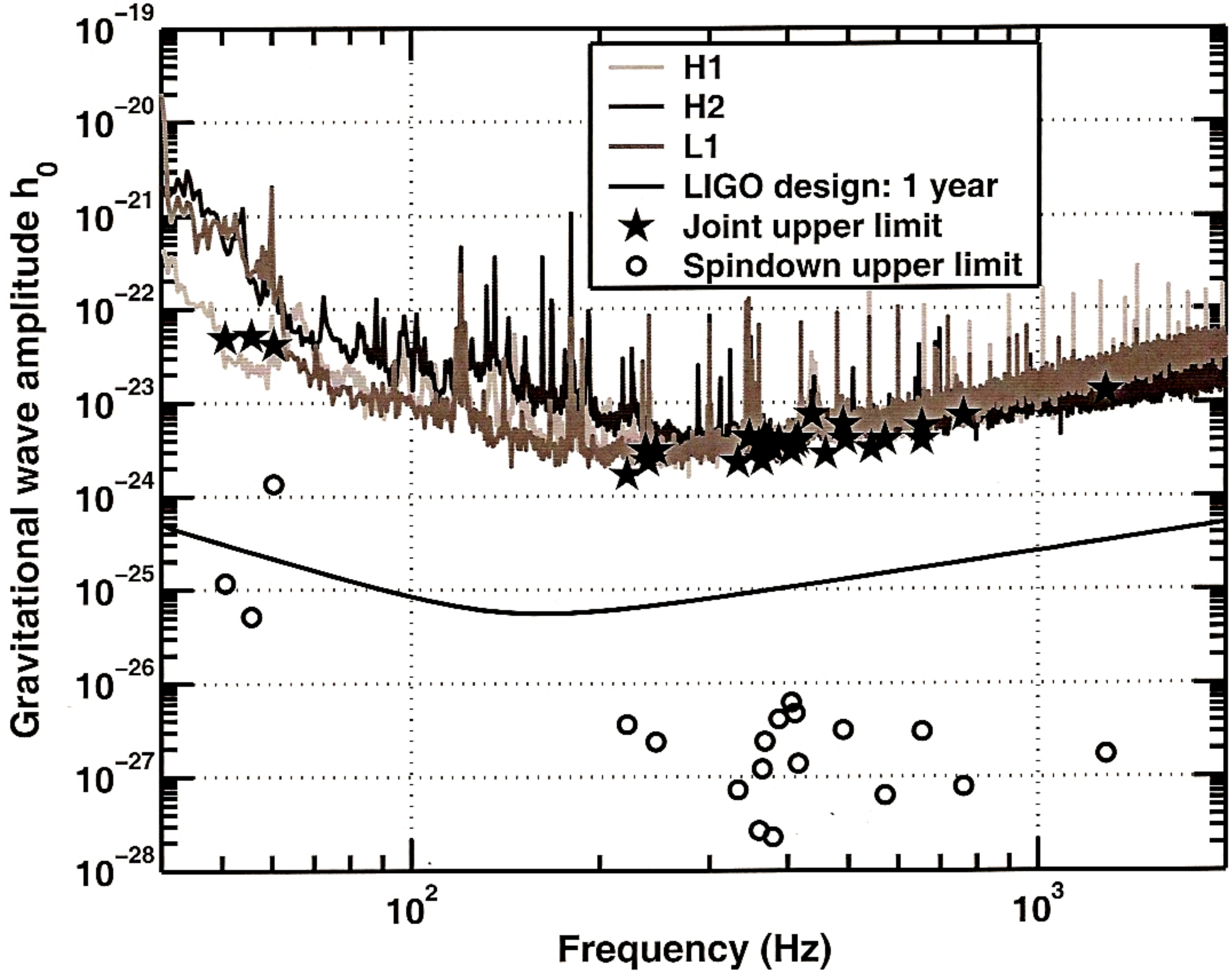
To veryify detection will require same signal at both sites.

- 1995: Construction begins
- ……
- Dec 1999: first light and lock
- April 2000: First Engineering Run (E1)
- Aug-Sept 2002: First Science run (S1)
- Feb-Apr 2003: S2 (6 weeks)
- Oct 31 2003-Jan 9 2004: S3
- Feb 22 2005- Mar 23 2005: S4
- Nov 2005 to present: S5 (one year run at full design sensitivity)

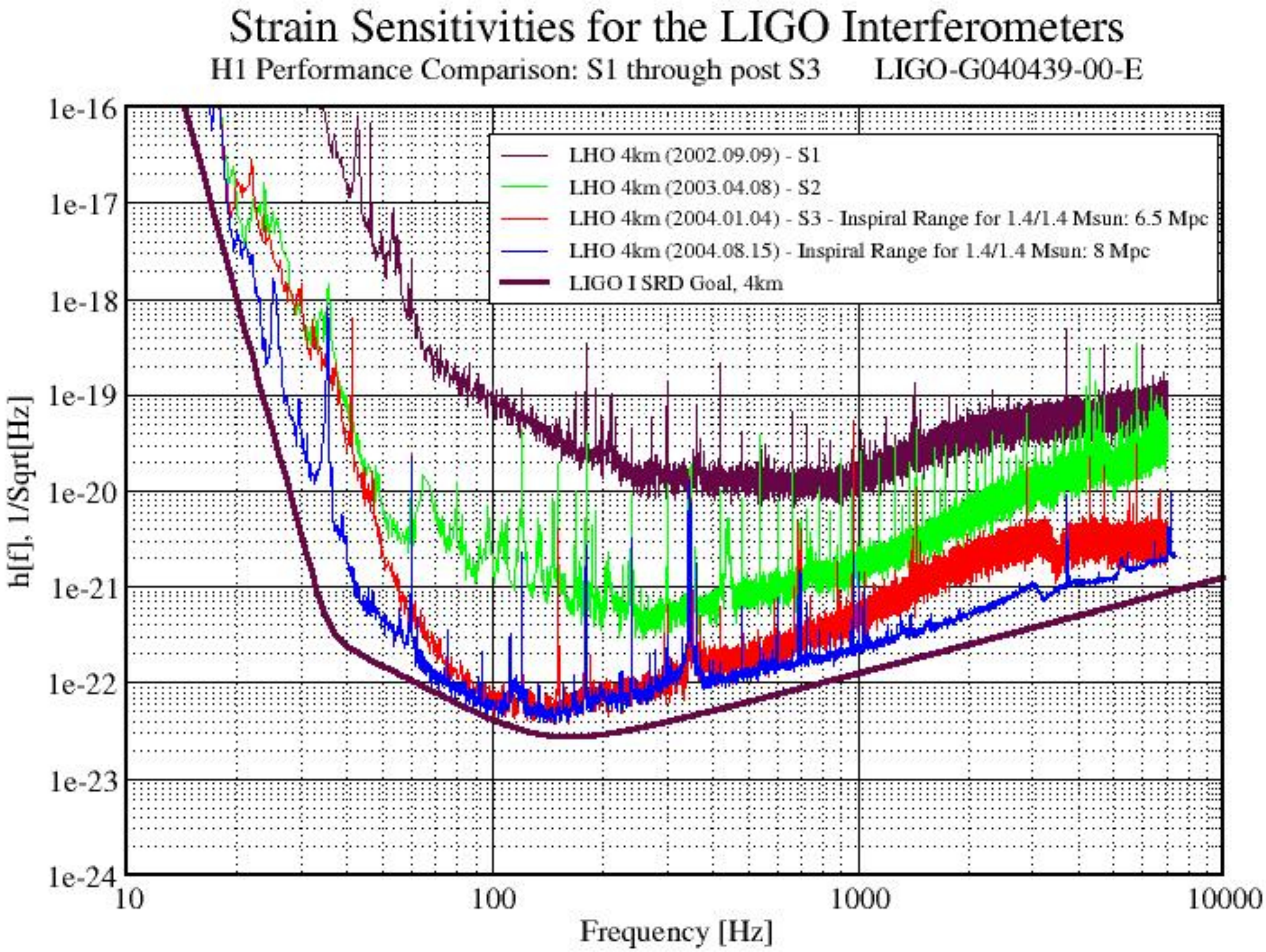
How to read a sensitivity curve

Requires the overhead projector…

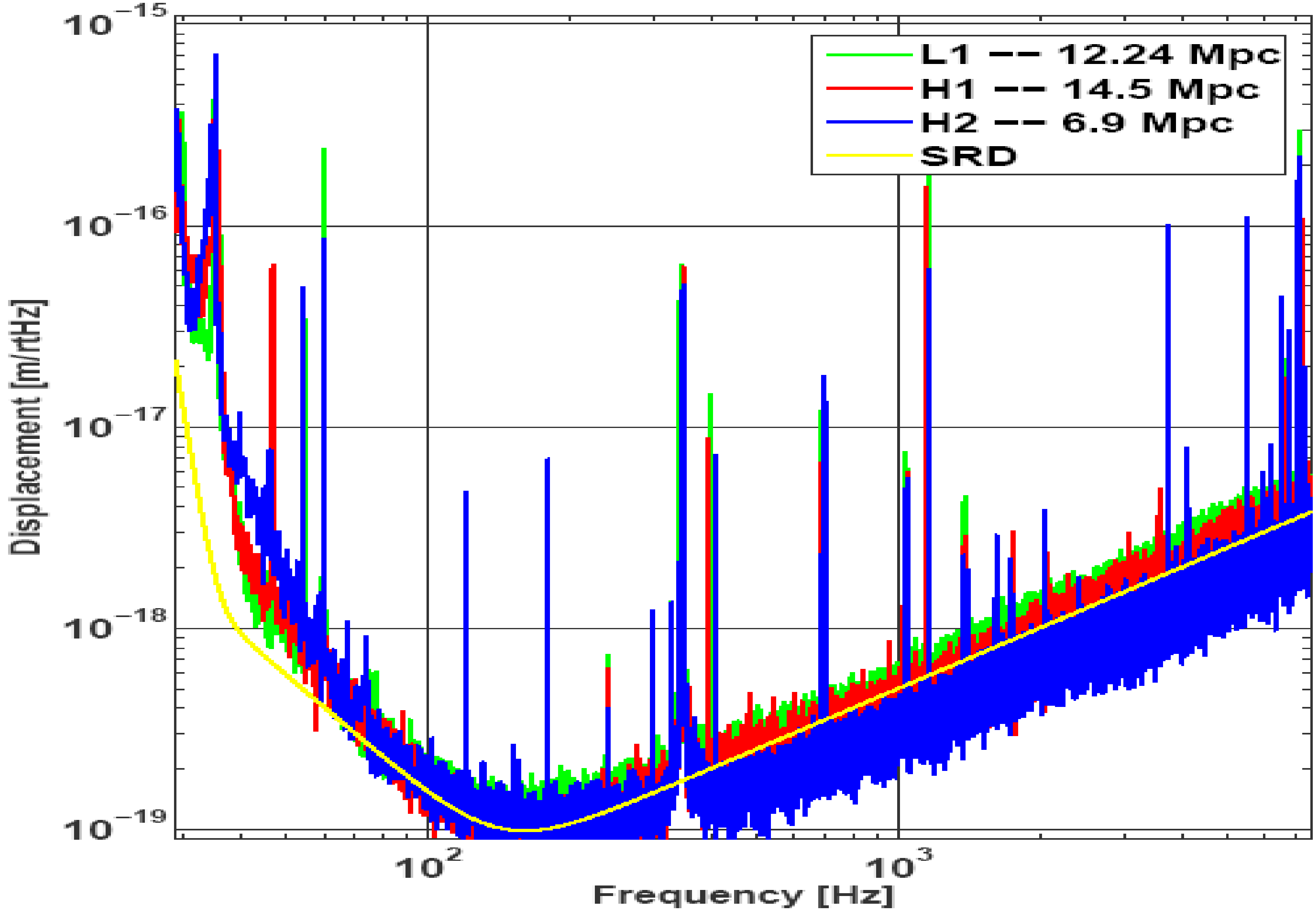
Pulsar Upper Limits (S2)



S3 Sensitivity



Current Sensitivity (S5)

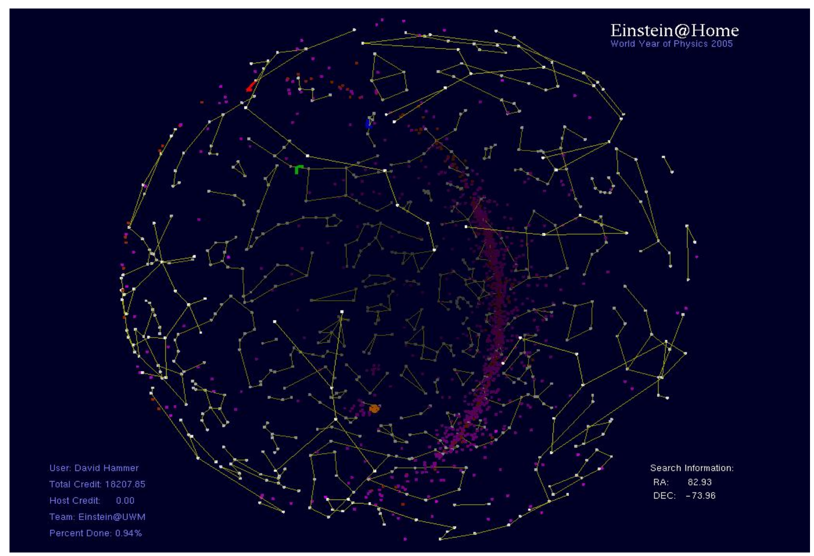


Einstein@Home

- Searching through the data streams for evidence of gravitational waves from a periodic source at an arbitrary sky position requires an extremely large amount of computing power - more than existing Beowulf clusters.
- Einstein@Home uses the Berkeley Open Infrastructure for Network Computing (BOINC) to perform the search on a "small" chunk of data on a volunteer's PC, all while displaying a nifty screensaver.

Anybody can join:

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



Einstein@Home Status

status

Host	Status
nstein	Running
nstein	Running
nstein	Running
nstein	Running
nstein	Running
nstein	Running
nstein	Running
nstein	Running
nstein	Running

Download mirror status

Site	Status	Last failure
Albert Einstein Institute	Running	382 h 16 m ago
University of Glasgow LSC group	Running	1513 h 21 m ago
MIT LSC group	Running	1513 h 21 m ago
Penn State LSC group	Running	266 h 56 m ago

Improved S4 search progress

Total needed	Already done	Work still remaining
6,731,410 units	3,990,101 units	2,741,309 units
100 %	59.276 %	40.724 %
195.2 days	115.7 days	79.5 days (estimated)

Users and Computers

USERS	Approximate #
in database	189,955
with credit	117,240
registered in past 24 hours	225
HOST COMPUTERS	**Approximate #**
in database	366,078
registered in past 24 hours	1,401
with credit	~~223,706~~
active in past 7 days	76,189
potential floating point speed[1)]	98.7 TFLOPS
floating point speed[2)]	42.4 TFLOPS

Work and Results

WORKUNITS	Approximate #
in database	464,148
with canonical result	288,868
RESULTS	**Approximate #**
in database	1,456,496
unsent	15,729
in progress	240,404
deleted	890,581
valid	866,571
valid last week	659,888
invalid	1,410
Oldest Unsent Result	4 d 16 h 3 m

Summary

- ✓ What are gravitational waves?
  - ✓ Quadrupole distortions of space-time that travel at the speed of light
- ✓ How are they produced?
  - ✓ Changes in quadrupole moment of a large mass distribution
- ✓ How will they be detected?
  - ✓ Laser Interferometers such as LIGO, GEO600, VIRGO, etc…
  - ✓ Bar detectors such as Allegro (LSU)
- ✓ How will they be useful?
  - ✓ A new way to look at (or "listen") to the Universe.
- ✓ How you can join the search!
  - ✓ Einstein@Home