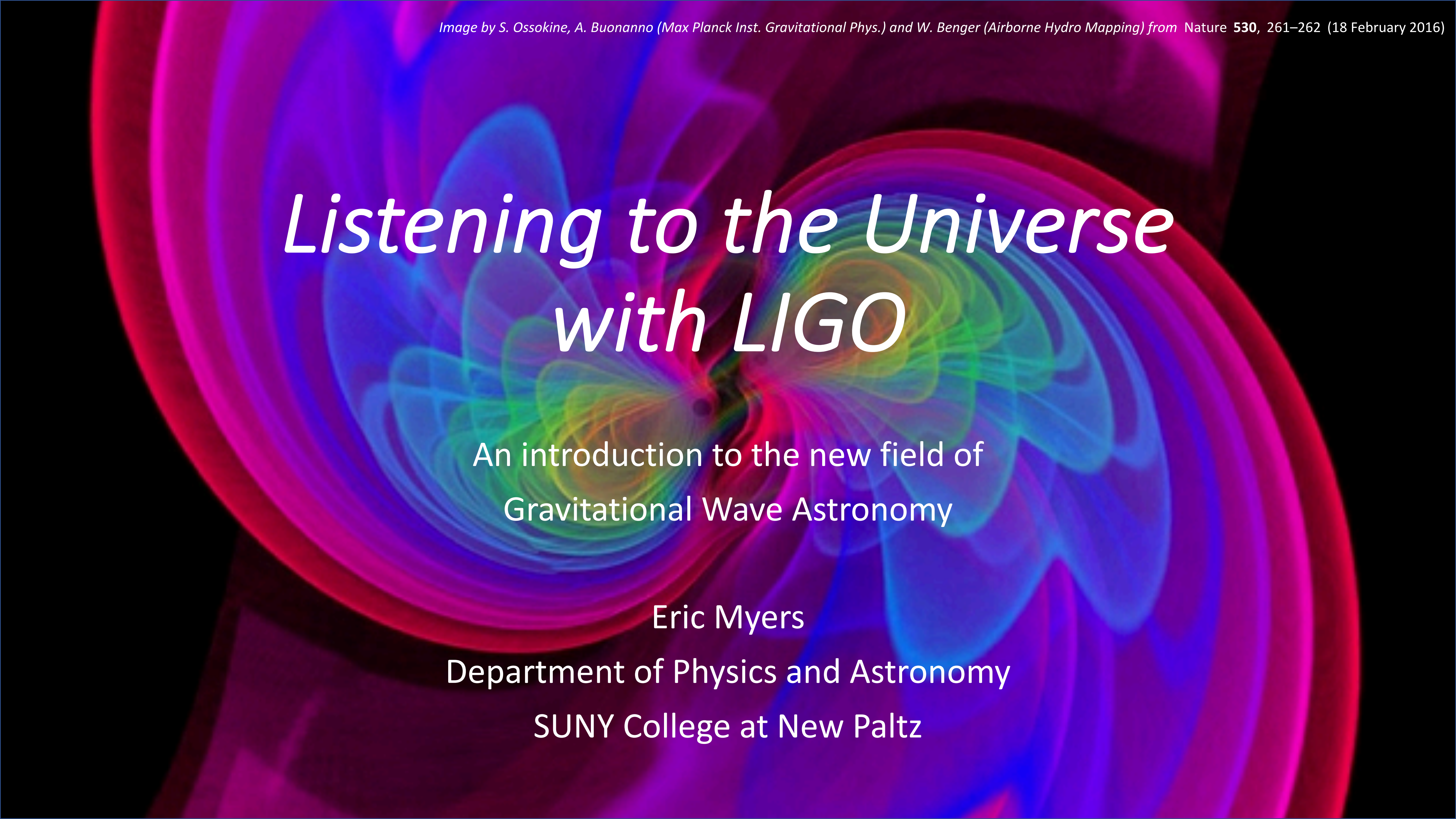


Image by S. Ossokine, A. Buonanno (Max Planck Inst. Gravitational Phys.) and W. Benger (Airborne Hydro Mapping) from Nature **530**, 261–262 (18 February 2016)

Listening to the Universe with LIGO

An introduction to the new field of Gravitational Wave Astronomy

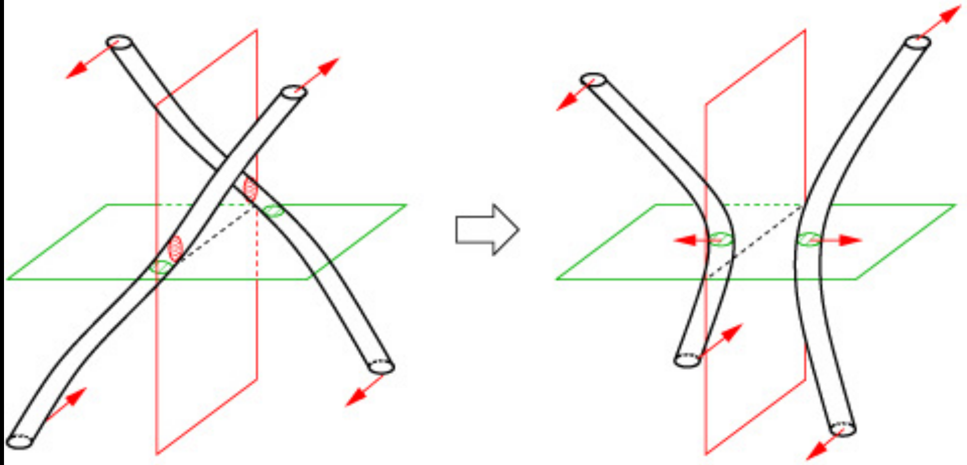
Eric Myers
Department of Physics and Astronomy
SUNY College at New Paltz

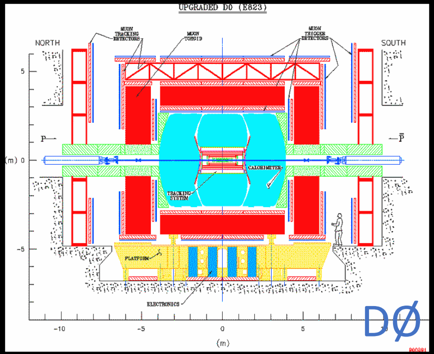
Eric Myers (Professional)

B.A. Pomona College, Claremont, CA
double major in math & physics

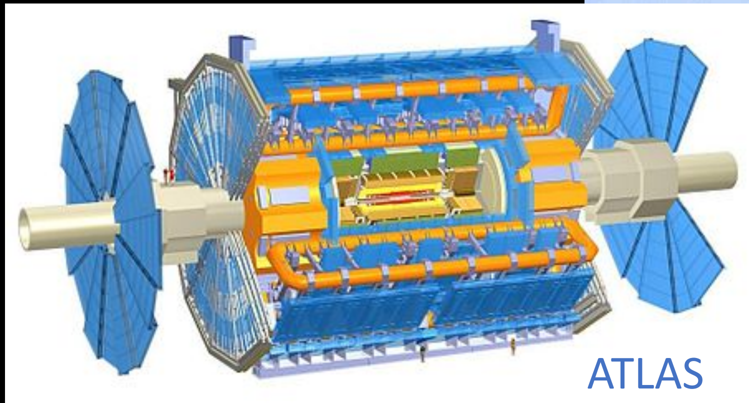
M.Phil & Ph.D., Yale University,
in high-energy theoretical physics

Post-doctoral research fellowships:
- Brookhaven National Laboratory, Upton, NY
- Dalhousie University, Halifax, Nova Scotia & Boston University
- Center for Relativity, at the University of Texas at Austin





Research Physicist, University of Michigan:
Worked on the DØ experiment at Fermilab
and the ATLAS experiment at CERN.



Physics Teaching Faculty at:
- Parks College of St. Louis University
- University of Michigan, Ann Arbor
- Vassar College (×2)
- SUNY New Paltz (×2)
- United States Military Academy

Two projects for LIGO: Einstein@Home & I2U2

Eric Myers
(Personal)


Projectile Motion!

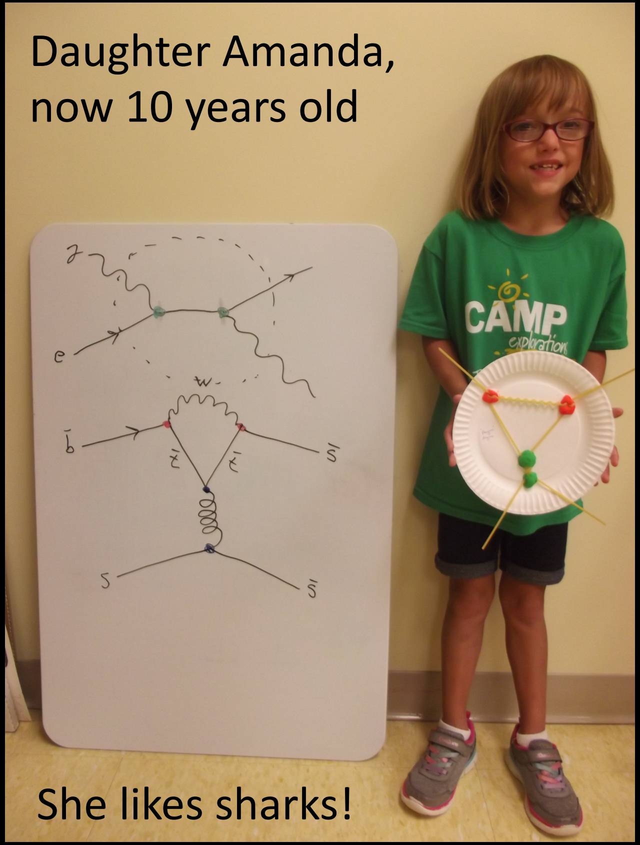
Married Nancy in 2003

Past Positions

- Maintenance Officer, University of Texas Flying Club
- Vice-Commodore, University of Michigan Sailing Club (and invented Ultimate Frisbee for Sailing)
- Treasurer, Mid-Hudson Astronomical Association

Hometown:
Salem, OR

Lived in:
Claremont, CA
Salt Lake City, UT
New Haven, CT
Long Island, NY
Halifax, Nova Scotia
Boston, MA
Austin, TX
Poughkeepsie, NY
Ann Arbor, MI
Poughkeepsie, NY

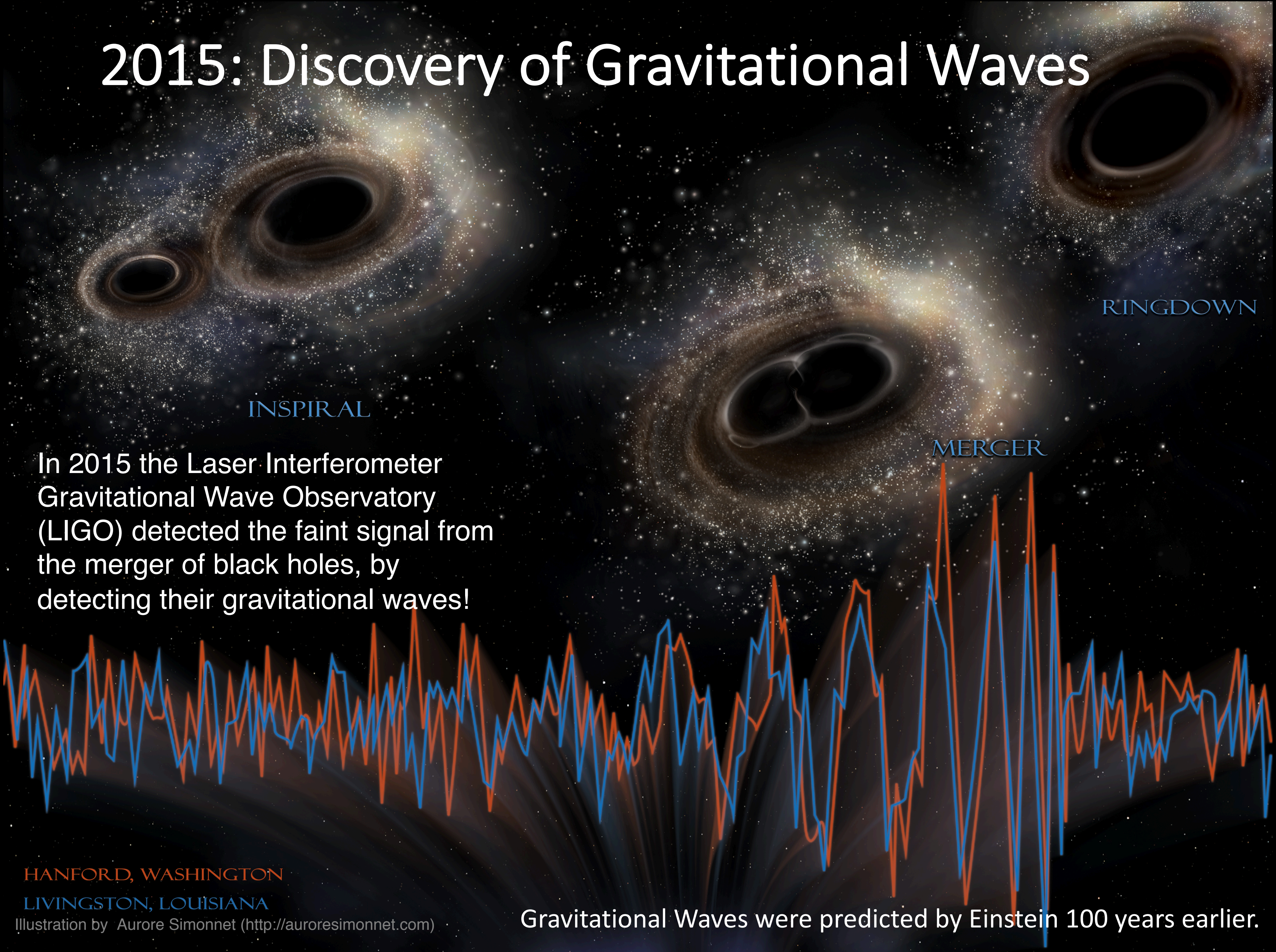


Daughter Amanda, now 10 years old

She likes sharks!

Private Pilot, Airplane, Single Engine Land
Rated for Instrument, Airplane & "conventional" gear
About 500 hrs total flight time (but no recent activity)

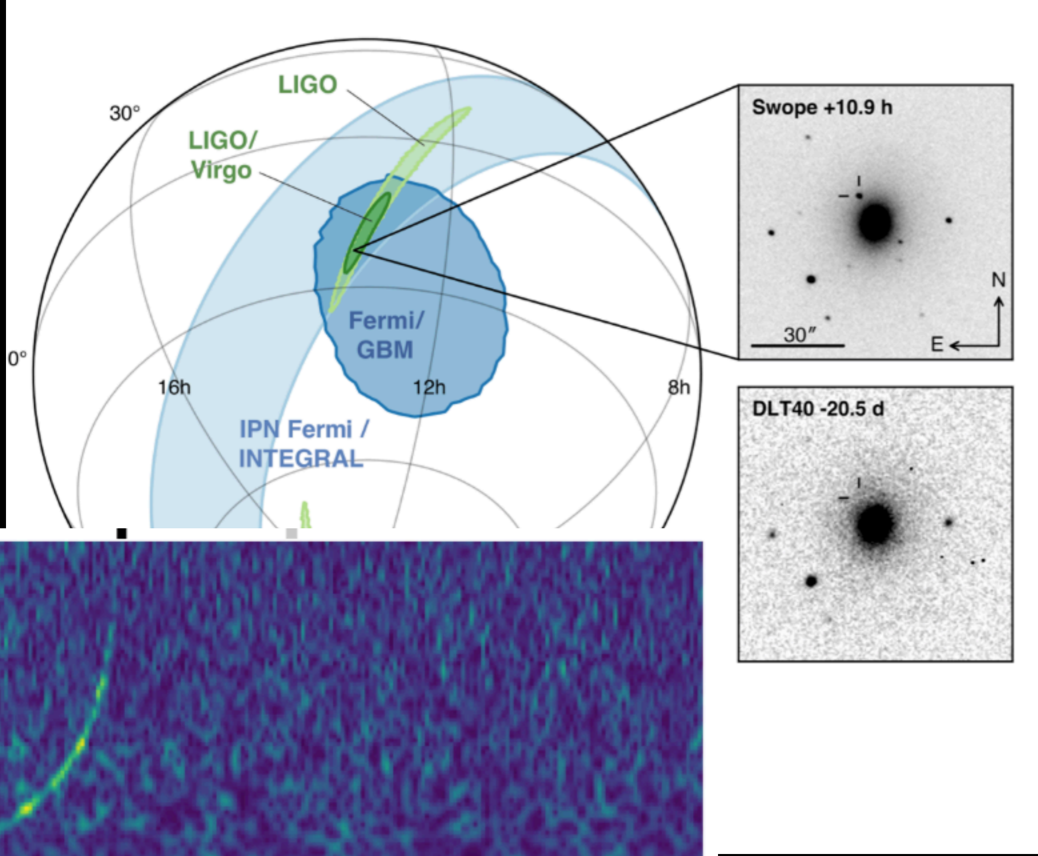
2015: Discovery of Gravitational Waves

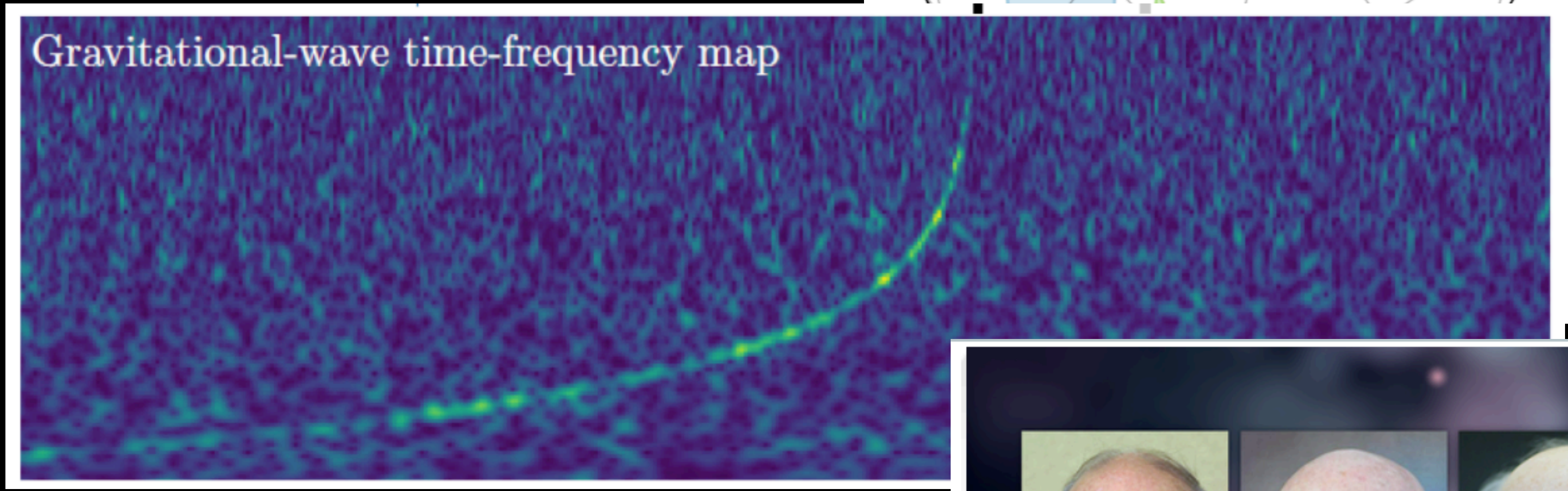


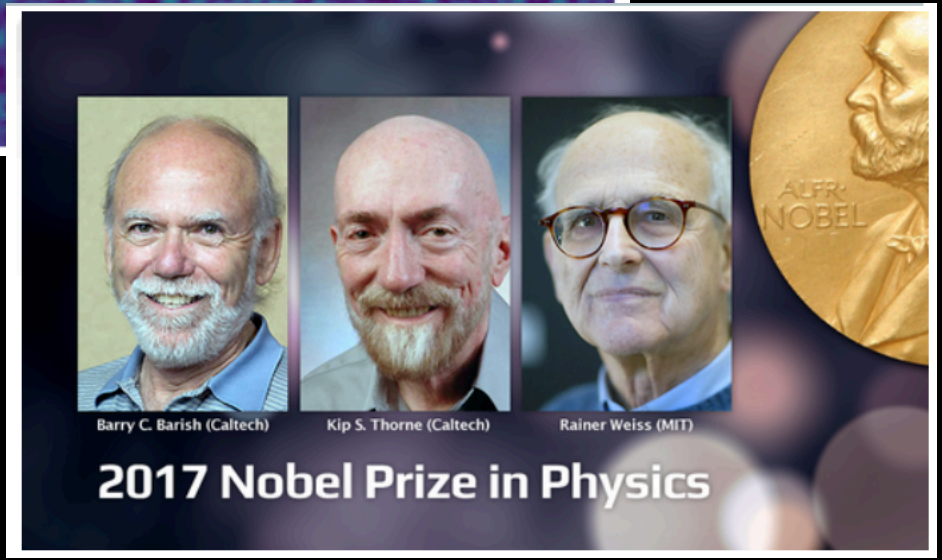
In 2015 the Laser Interferometer Gravitational Wave Observatory (LIGO) detected the faint signal from the merger of black holes, by detecting their gravitational waves!

Gravitational Waves were predicted by Einstein 100 years earlier.

2017: Neutron star coalescence!







Event GW170817 (2017 August 17)
was first with E-M counterparts.

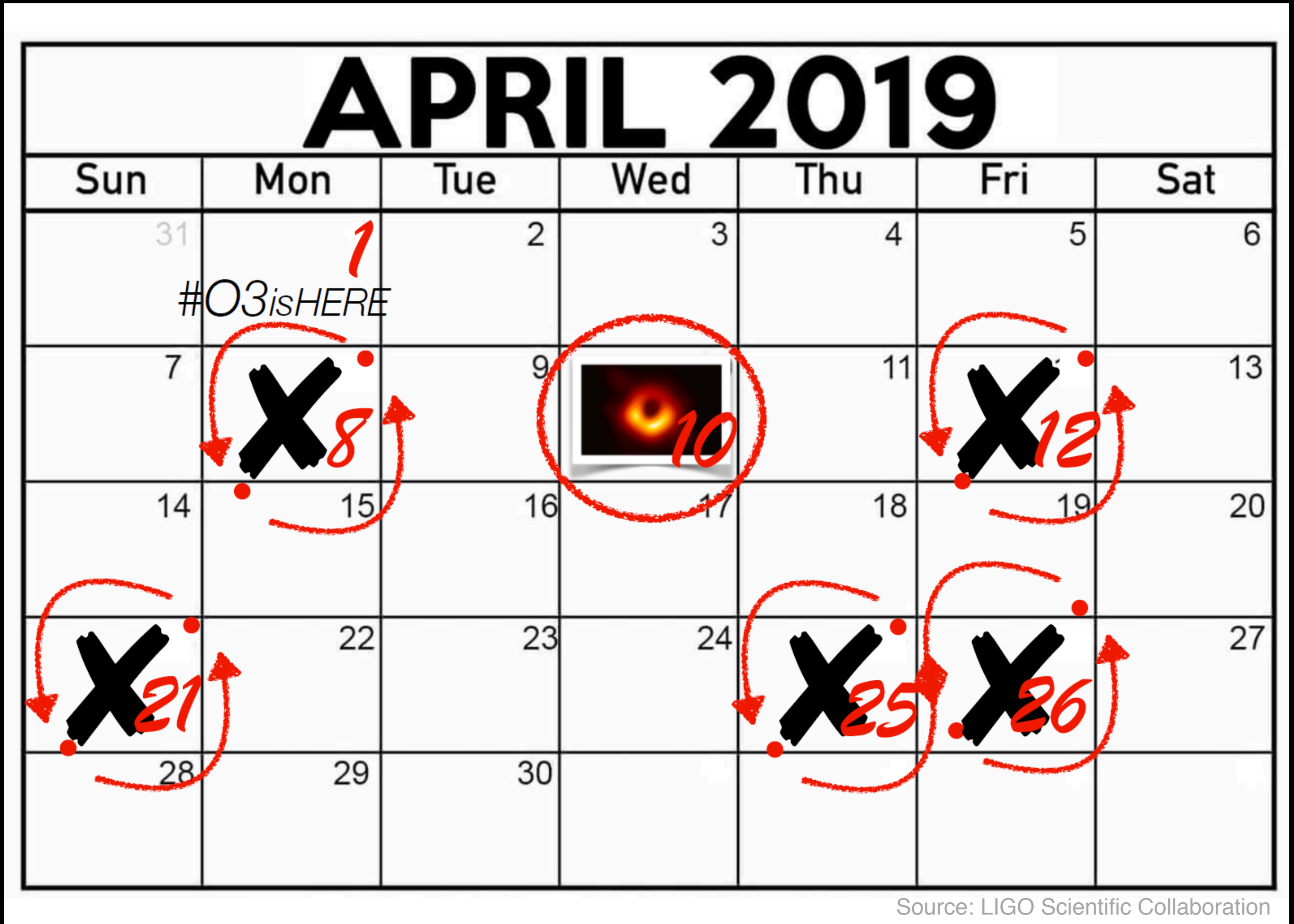
This is “multi-messenger” astronomy.

Images: https://www.ligo.org/

2019: Five new candidates in first month

Since Observation Run 3 (O3) began on 1 APRIL 2019, there have been 5 candidates events detected (and one false-alarm)

Event #S190426c may be a neutron star being swallowed by a black hole.



Questions?

- What are Gravitational Waves?
- How have they been detected?
- What is LIGO?
- Why has this been so difficult?
- What has LIGO found so far?
- What's next?

- Can I play too?

General Relativity: space-time is curved!

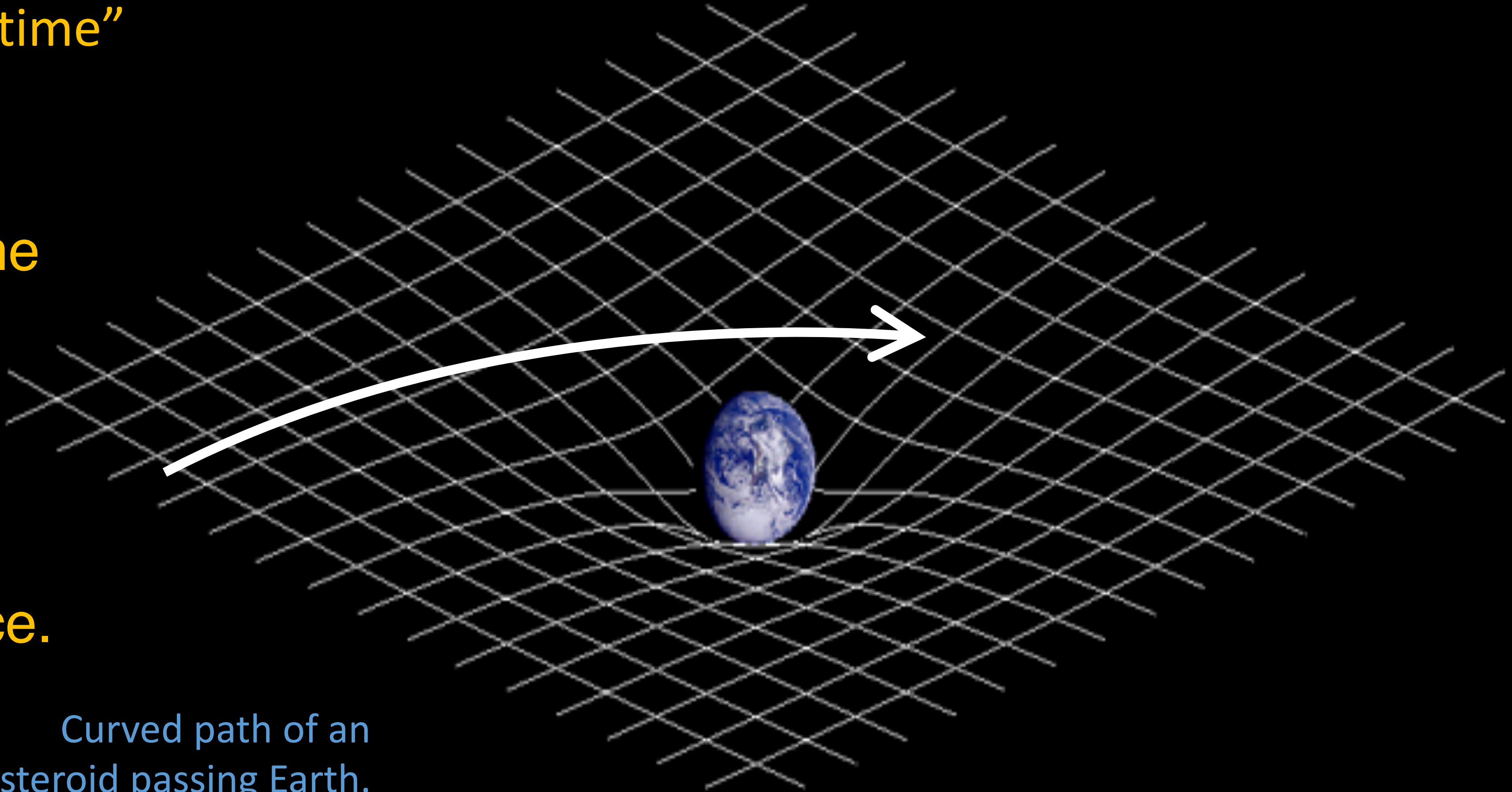
In *General Relativity* (Einstein, 1916), gravitation is described as being a property of the geometry of space + time = ”space-time”

<u>Two Principles:</u>

Matter curves space-time

and

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



Curved path of an asteroid passing Earth.

General Relativity: space-time is curved!

In *General Relativity* (Einstein, 1916), gravitation is described as being a property of the geometry of space + time = ”space-time”

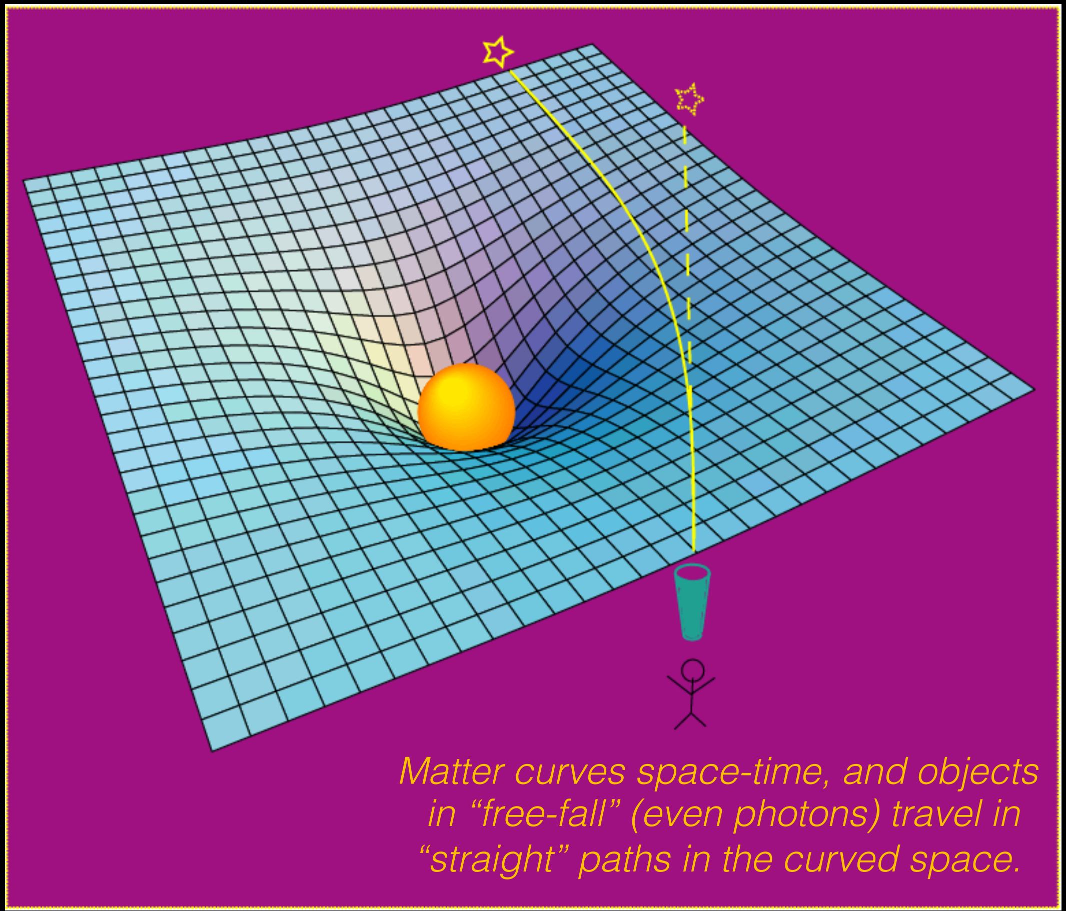
<u>Two Principles:</u>

Matter curves space-time

and

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

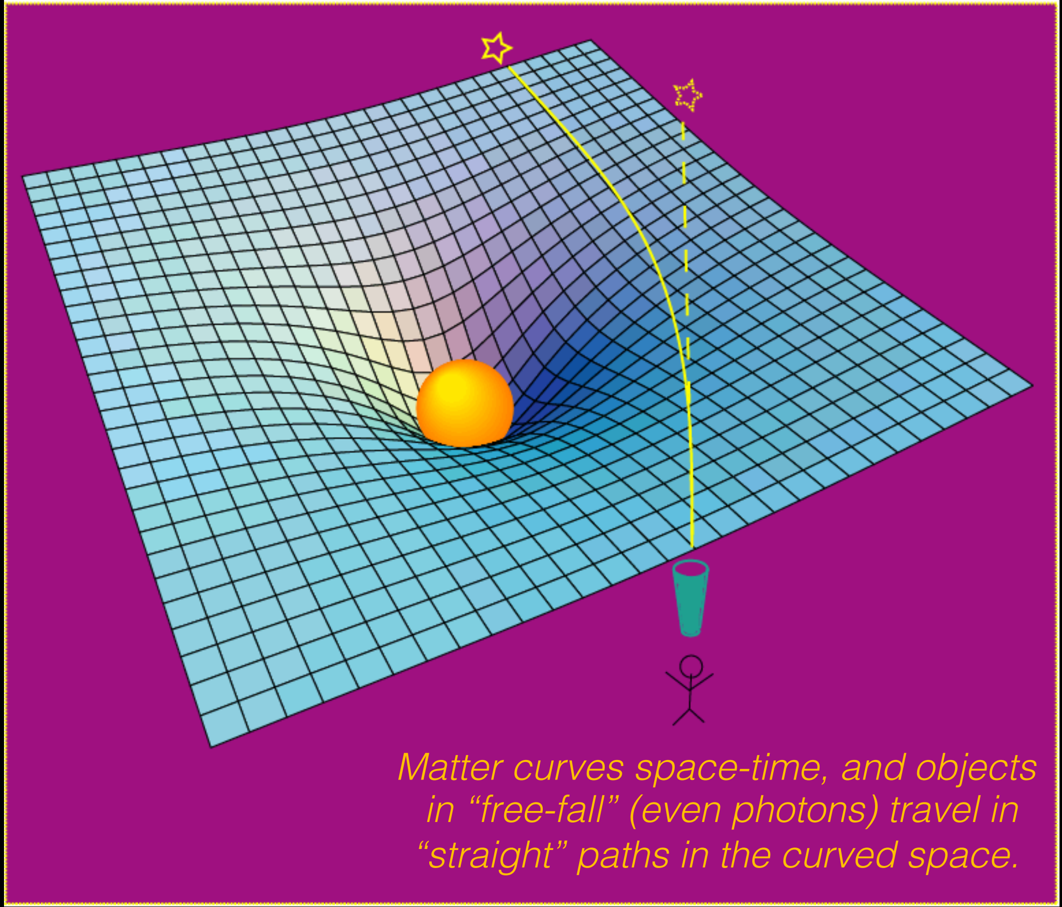
Deflection of starlight by the Sun.



What are gravitational waves?

Astronomy until now has been done using *Electromagnetic Waves*
(which include radio, infrared, visible light, ultraviolet, x-rays, and gamma rays).

These are all time-varying oscillations of electromagnetic fields.



Deflection of starlight by the Sun.

Image *Credit: R. Hurt/Caltech-JPL*

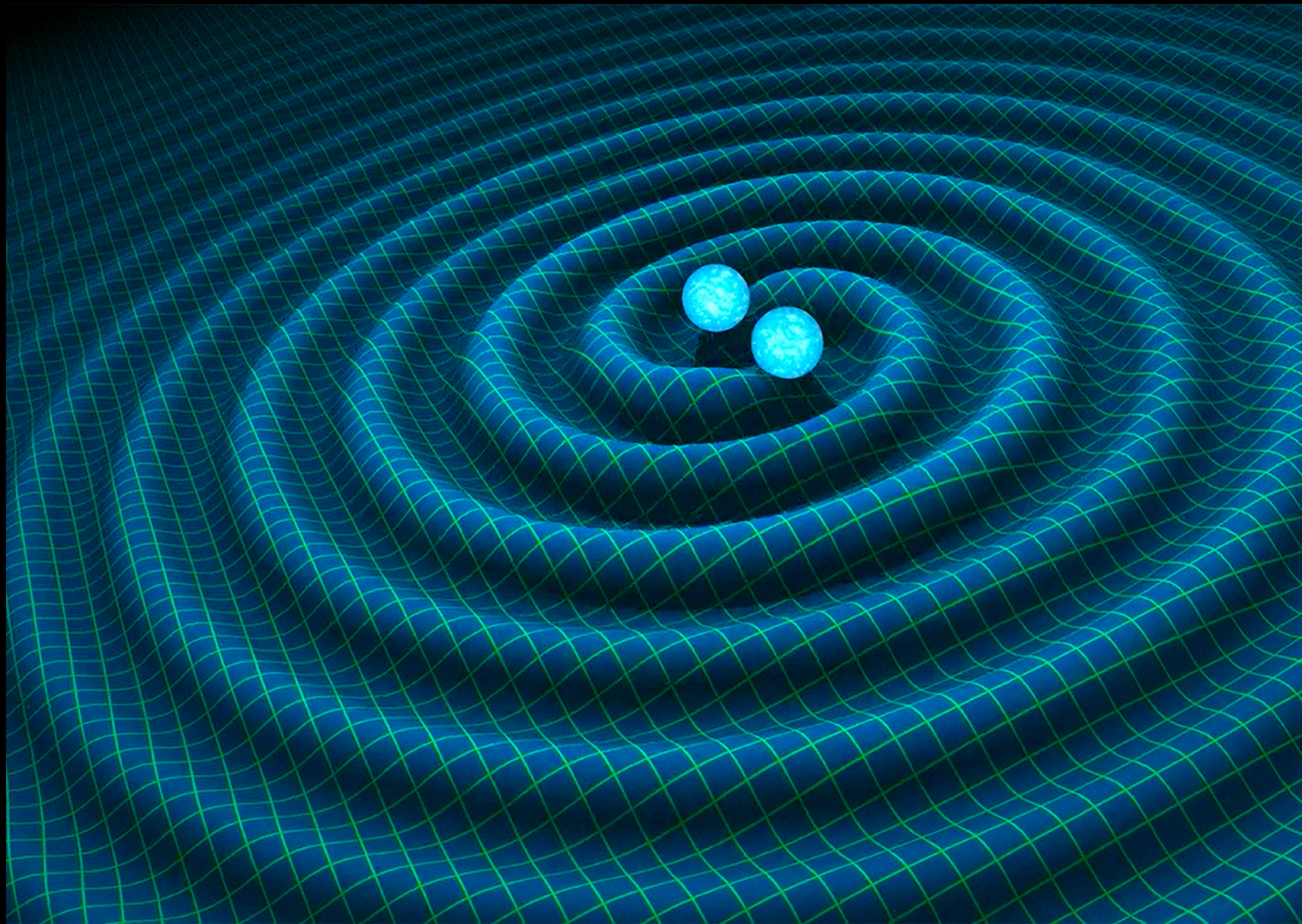
What are gravitational waves?

Astronomy until now has all been done with *Electromagnetic Waves* (which include radio, infrared, visible light, ultraviolet, x-rays, and gamma rays).

These are all time-varying oscillations of electromagnetic fields.

Gravitational Waves are time-varying oscillations of the curvature of space-time, caused by a changing mass distribution.

These oscillations are not instantaneous: they travel at the speed of light.

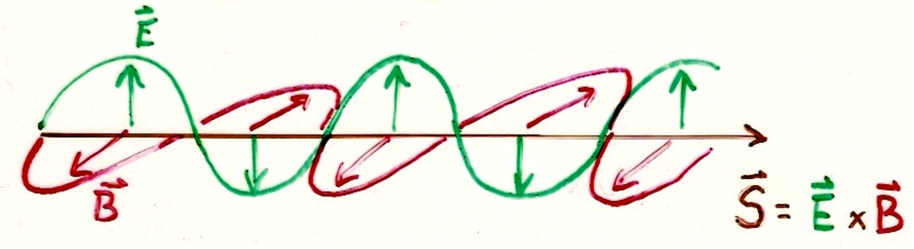


Oscillations due to orbiting stars

Comparison with EM waves

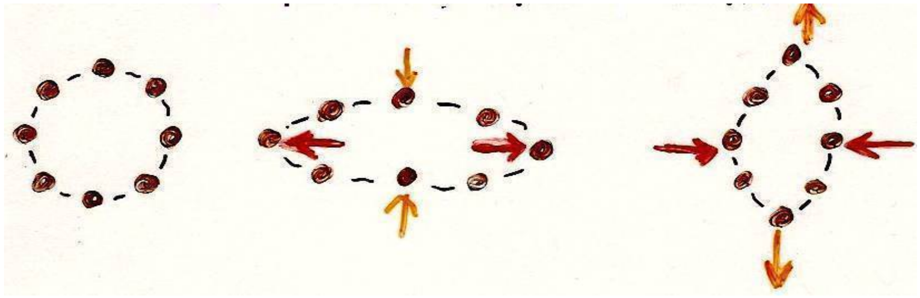
Electromagnetic Waves

- ✓ 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

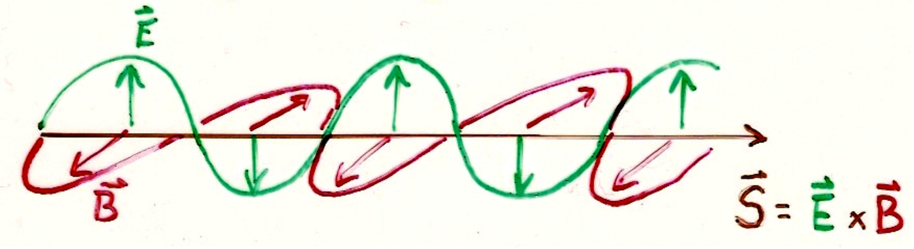
- ✓ Travel at the speed of light
- ✓ "transverse"
- ✓ *Tensor* - quadrupole distortions of space-time
- ✓ Two polarization: "+" and "×"
- ✓ Solutions to Einstein's Eqns.
- ✓ Gravitational waves require *changing* *quadrupole* mass distribution.



Comparison with EM waves

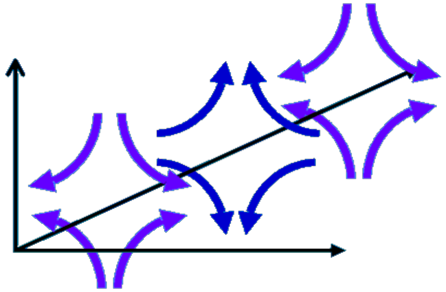
Electromagnetic Waves

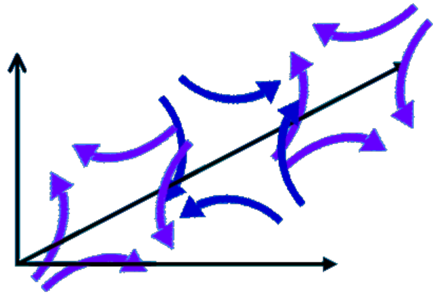
- ✓ Travel at the speed of light
- ✓ "transverse"
- ✓ *Vector* - dipole in both E and B
- ✓ Two polarizations: horizontal and vertical
- ✓ Solutions to Maxwell's Eqns.
- ✓ EM waves can be generated by a *changing* *dipole* charge distribution



Gravitational Waves

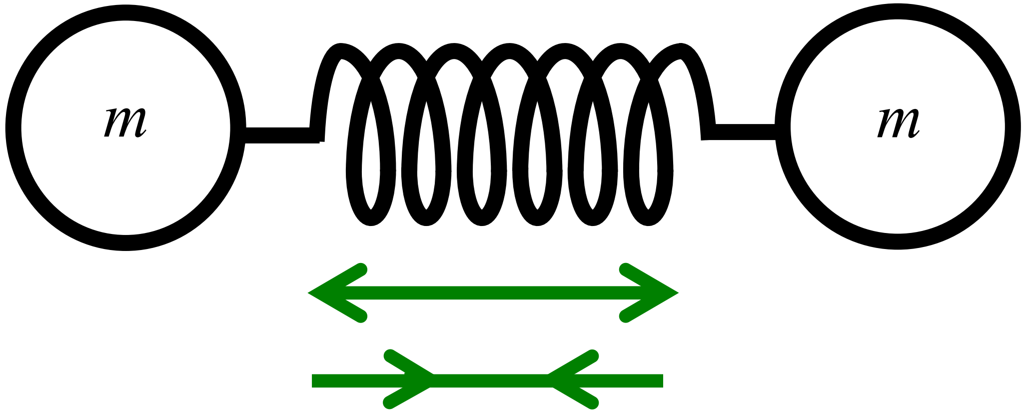
- ✓ Travel at the speed of light
- ✓ "transverse"
- ✓ *Tensor* - quadrupole distortions of space-time
- ✓ Two polarization: "+" and "×"
- ✓ Solutions to Einstein's Eqns.
- ✓ Gravitational waves require *changing* *quadrupole* mass distribution.



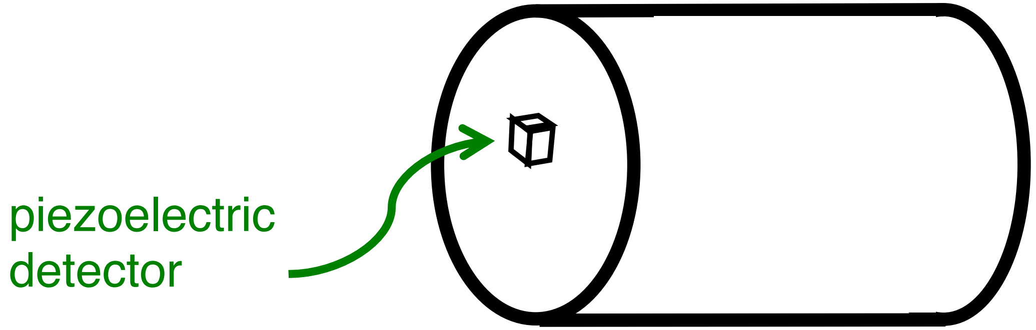


How to detect gravitational waves?

Simplest example: the “bar-bell” detector



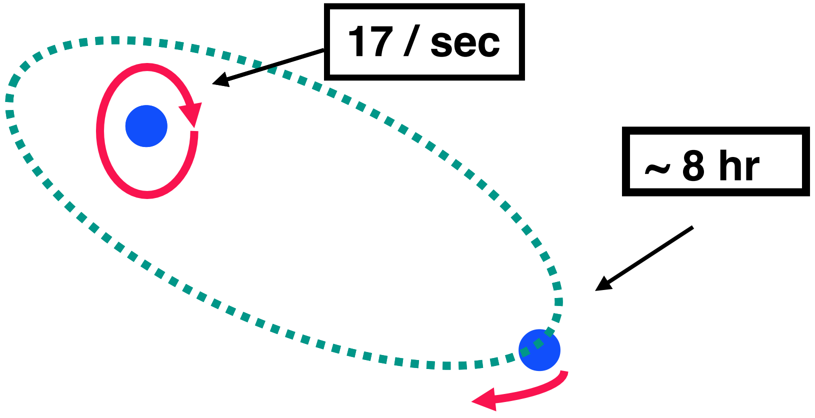
Practical implementation: a “bar” detector



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

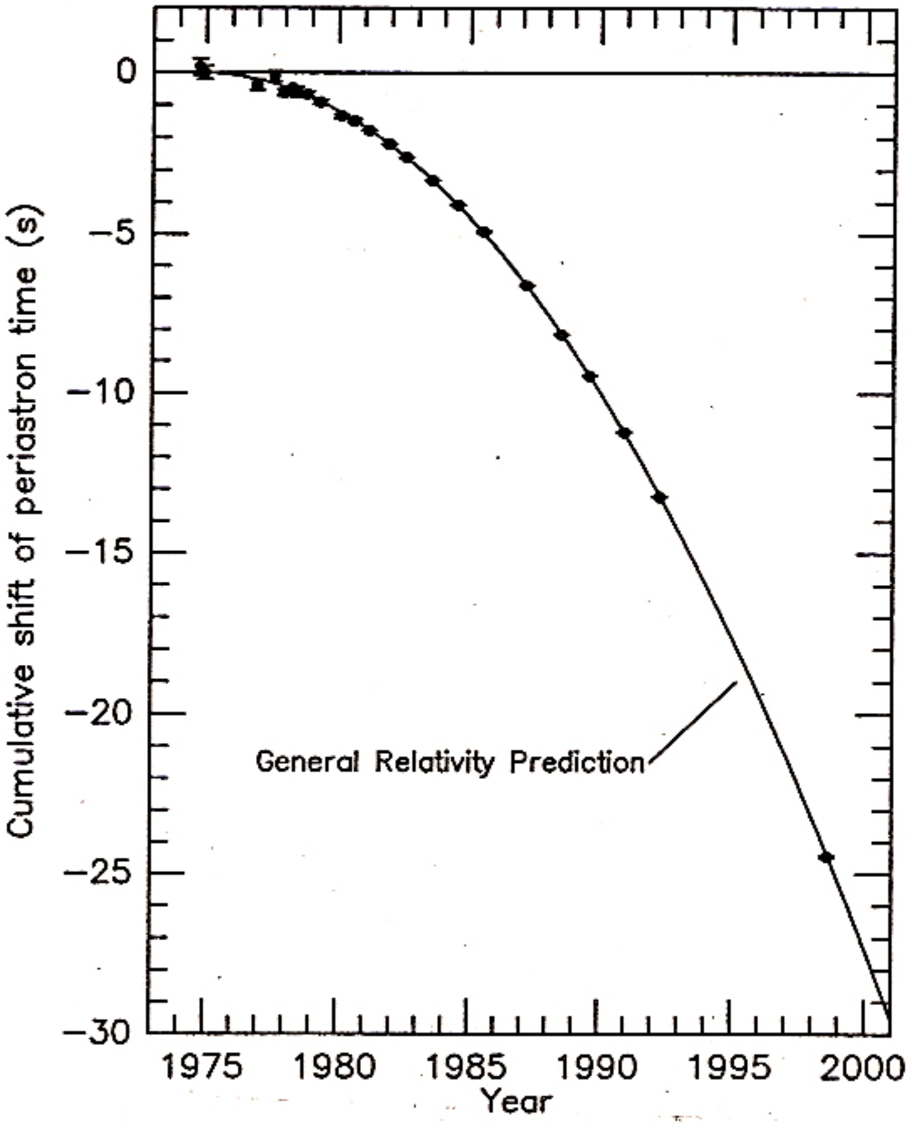
Indirect Evidence

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

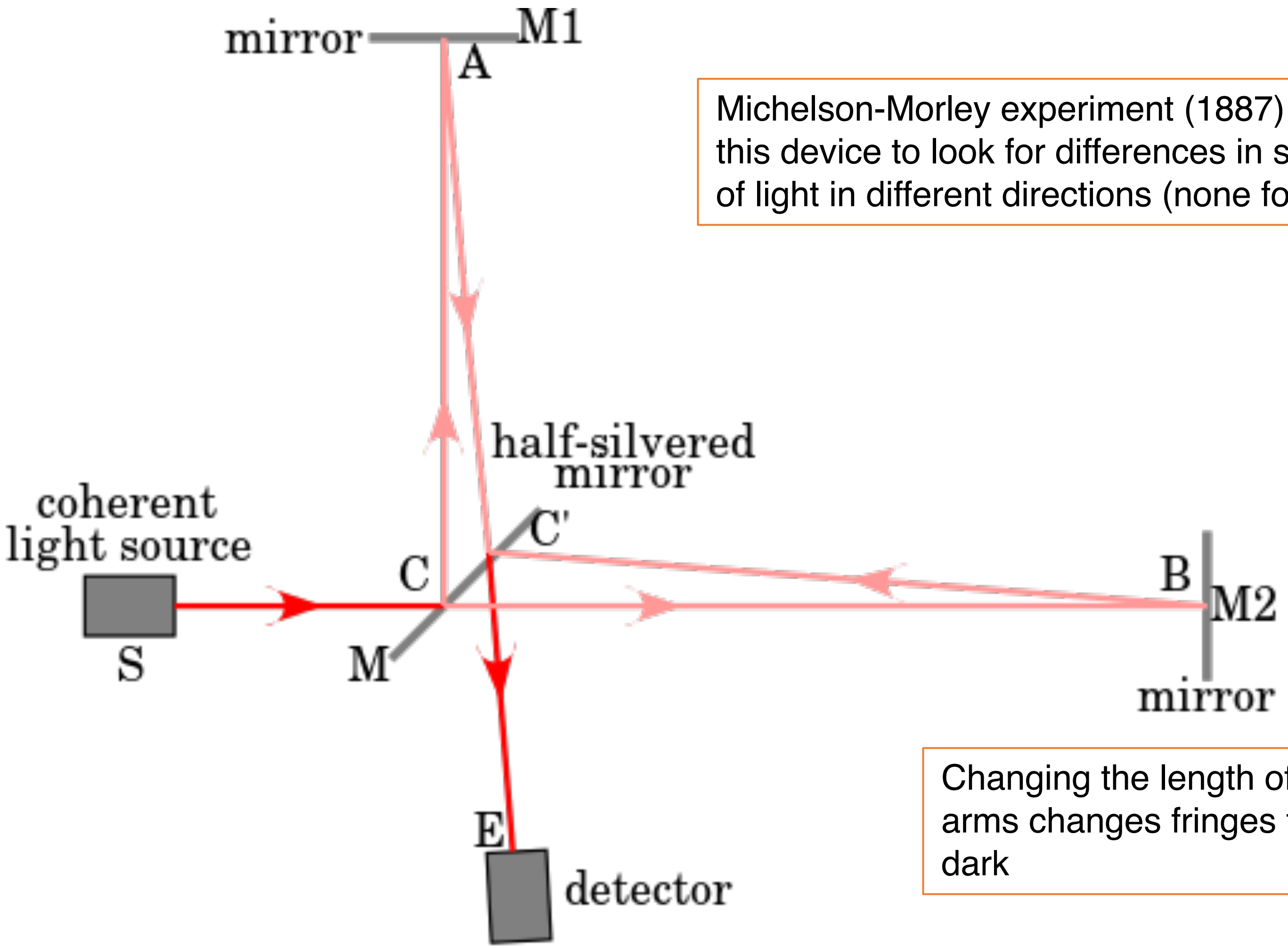


The measured precession of the orbit exactly matches the expected loss of energy due to gravitational radiation.

(Nobel Prize in Physics, 1993)



Michelson Interferometer



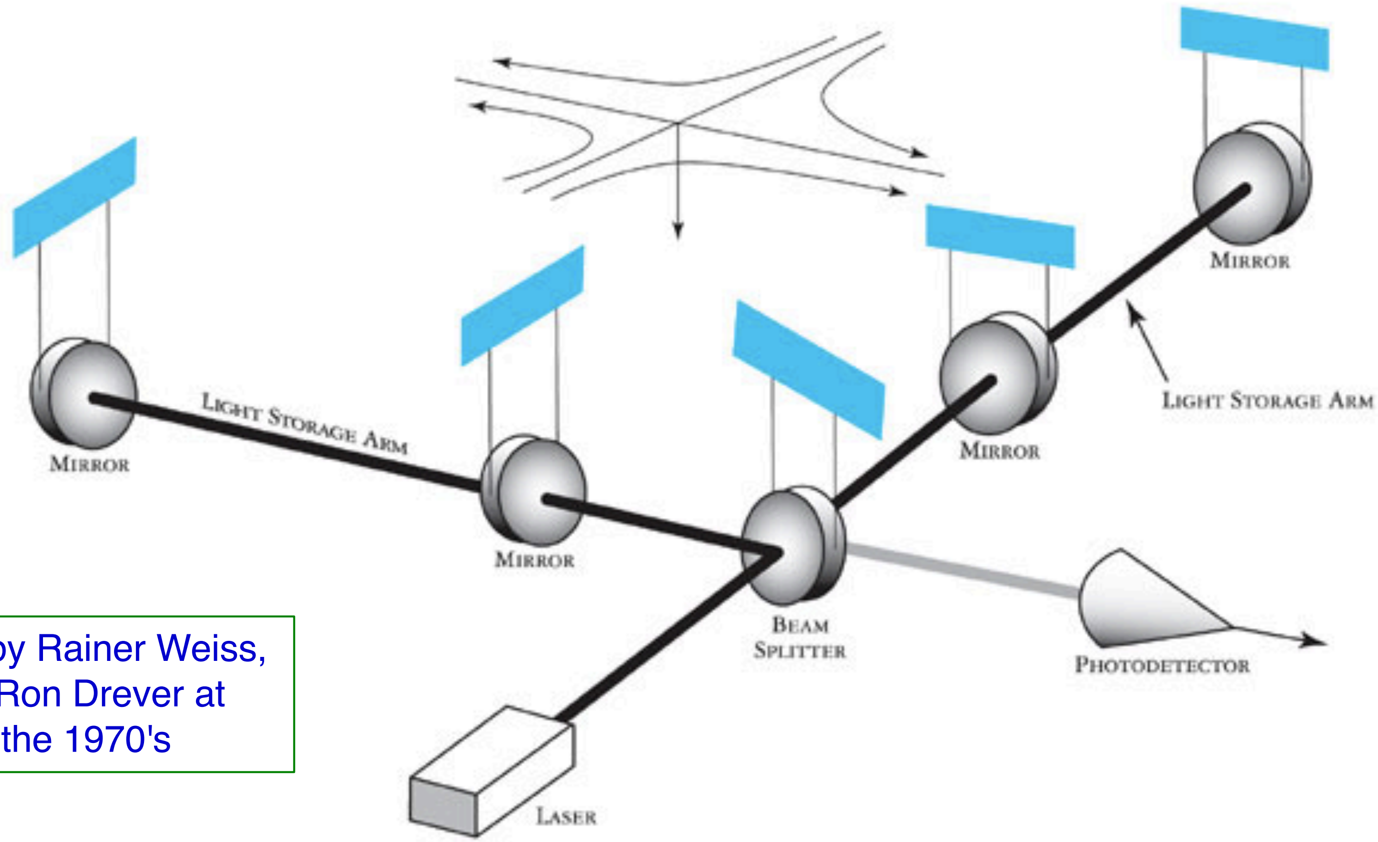
Michelson-Morley experiment (1887) used this device to look for differences in speed of light in different directions (none found!).

Changing the length of one or both arms changes fringes from bright to dark

Wave interference creates either bright or dark “fringes”

https://en.wikipedia.org/wiki/Michelson_interferometer

Michelson Fabry-Perot Interferometer



Pioneered by Rainer Weiss, at MIT and Ron Drever at Glasgow 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.)

Laser Interferometer Gravitational wave Observatory

LIGO Livingston Observatory (LLO)

Livingston Parish, Louisiana

L1 (4km)

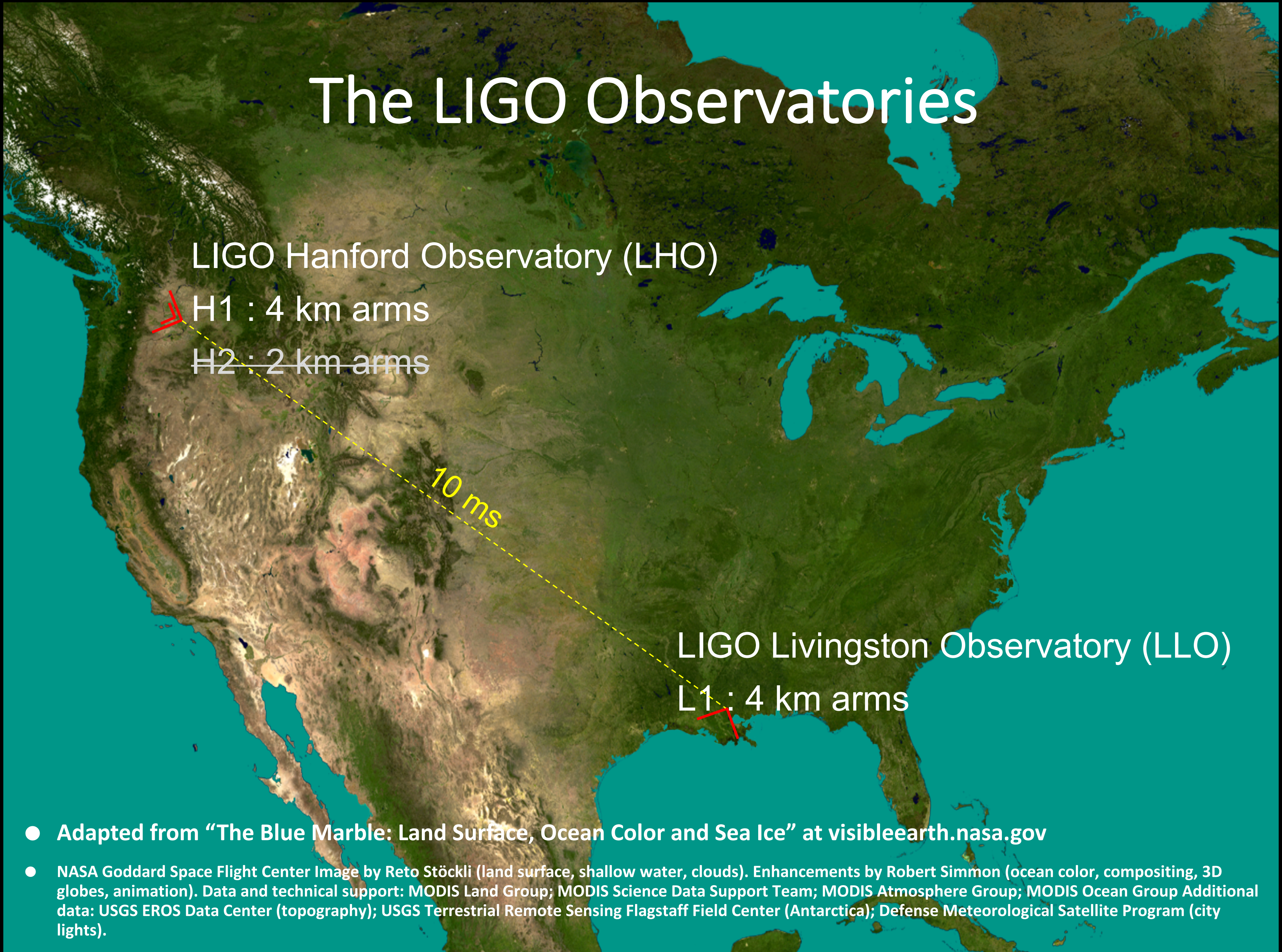
LIGO Hanford Observatory (LHO)

Hanford, Washington

H1 (4km) ~~and H2 (2km)~~

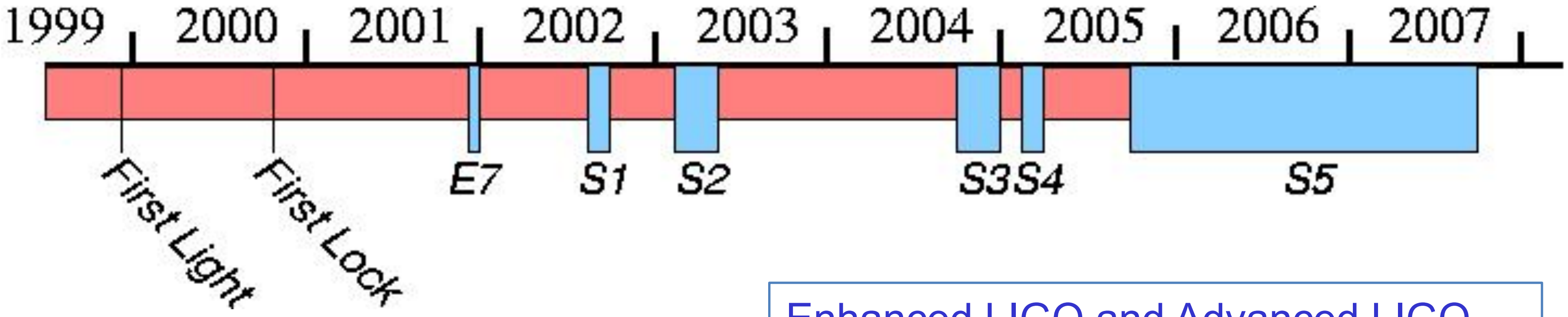
Funded by the National Science Foundation; operated by Caltech and MIT;
the research focus for ~ 1000 *LIGO Scientific Collaboration* (LSC) members worldwide.

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).**

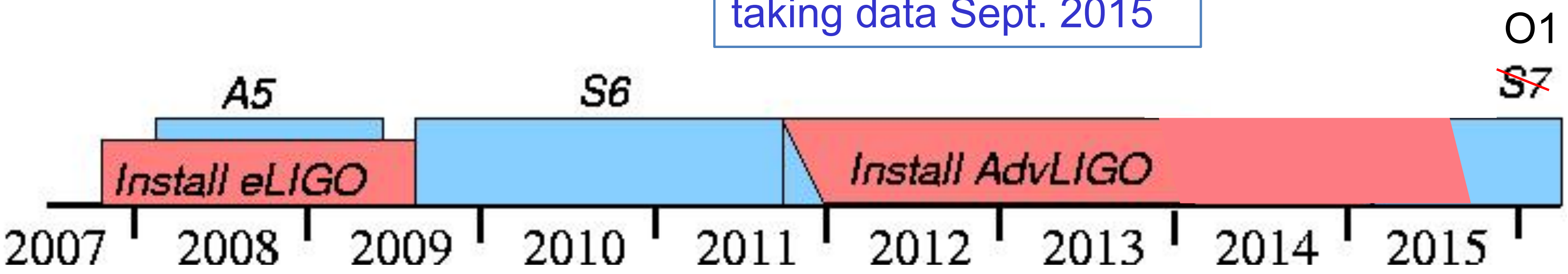
LIGO Timeline



Enhanced LIGO and Advanced LIGO approved in principle by NSB in 2005.

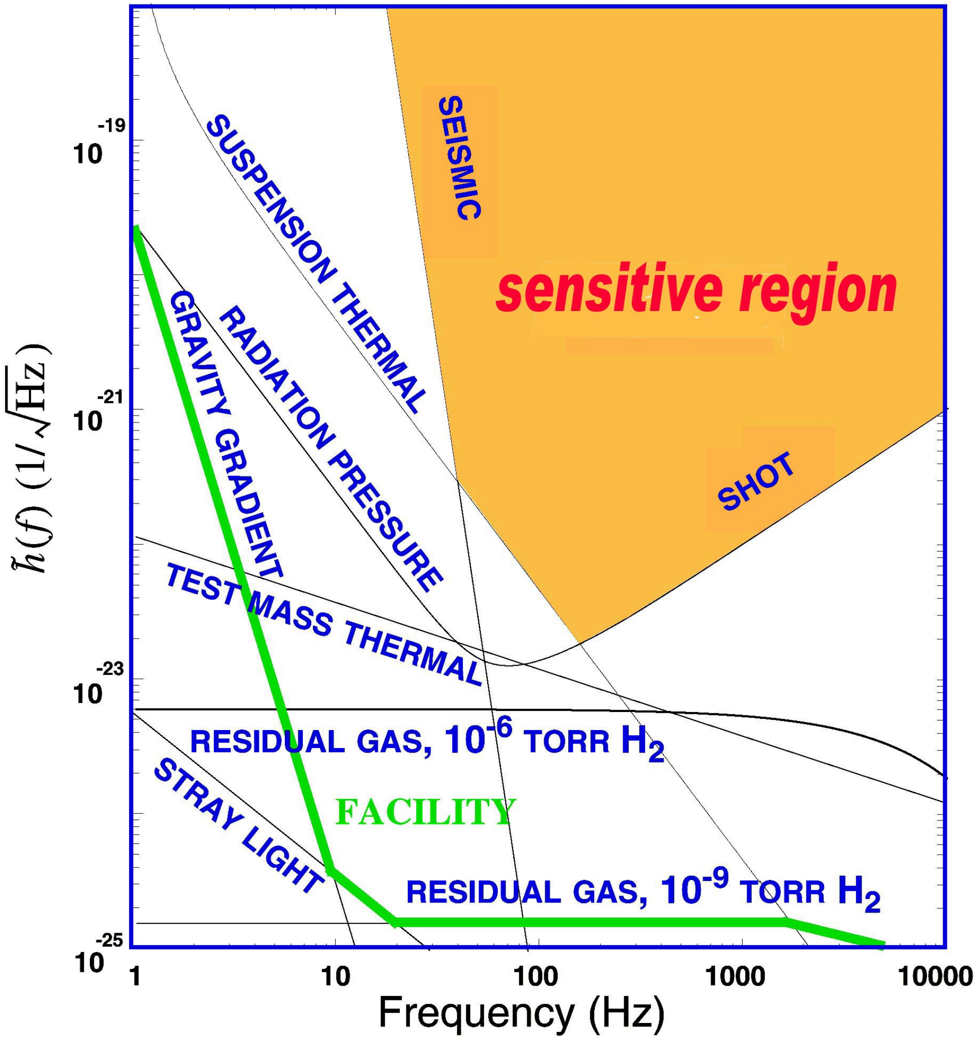
Construction began 1995

Advanced LIGO began taking data Sept. 2015



What Limits LIGO 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



Expert Service. Unbeatable Price. Weekly Ad | Credit Cards | Gift Cards | Gift Ideas | Registry | Order Status | Store Locator

PRODUCTS | SERVICES | DEALS | Search Best Buy | Sign In | Create Account

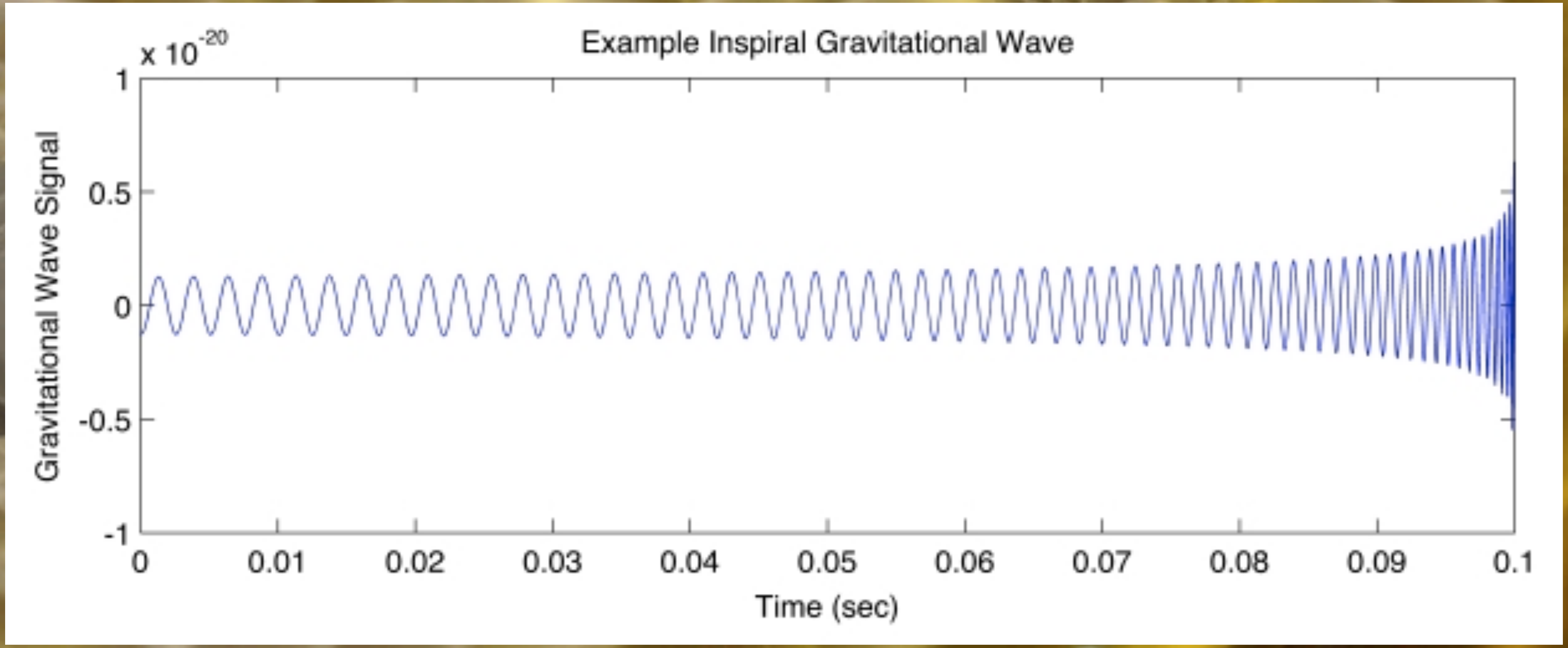
Compare Products

LIGO-T060156-01-I, LIGO–T060091-00-I, https://www.advancedligo.mit.edu/daq.html

Product Specifications	Initial LIGO	Enhanced LIGO	Advanced LIGO
Construction:	1995 - 2002	2007 - 2009	2011 - 2015
Data Collection:	2002 - 2007	2009- 2010	2015 -
Laser Power:	10 W	30-35 W	200 W
Output mode cleaner:	NO	YES	YES
In-vacuum readout HW:	NO	YES	YES
Active Seismic Isolation:	LHO: NO LLO: NO	LHO: NO LLO: YES	LHO: YES LLO: YES
Seismic cutoff freq:	40 Hz	40 Hz / 10 Hz	10 Hz
Data Channels:	12,733	~ 10,000	~ 300,000
Strain Sensitivity (@100Hz):	3×10^{-22}	~ 1.5×10^{-22}	3×10^{-23}
Relative Sensitivity:	× 1	× 2	× 3 to 5 (eventually ×10)
Maximum Reach:	10 Mpc	20 Mpc	40-80 Mpc (eventually 200 Mpc)
Cost:	420 M$	add 2.04 M$	620 M$ (add 200 M$)
	Add to Cart	Add to Cart	Add to Cart

What is the sound of two black holes colliding?

Gravitational waves are not sound waves, but the frequencies can be comparable to the audio range, so we can listen to them.



http://www.ligo.org/science/GW-Inspiral.php

LISTEN TO IT!

Binary neutron stars, 1.5 solar masses each

Binary black holes, 50 solar masses each

http://gmunu.mit.edu/sounds/comparable_sounds/comparable_sounds.html

Image Source: New Scientist

Success! Event GW150914

PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

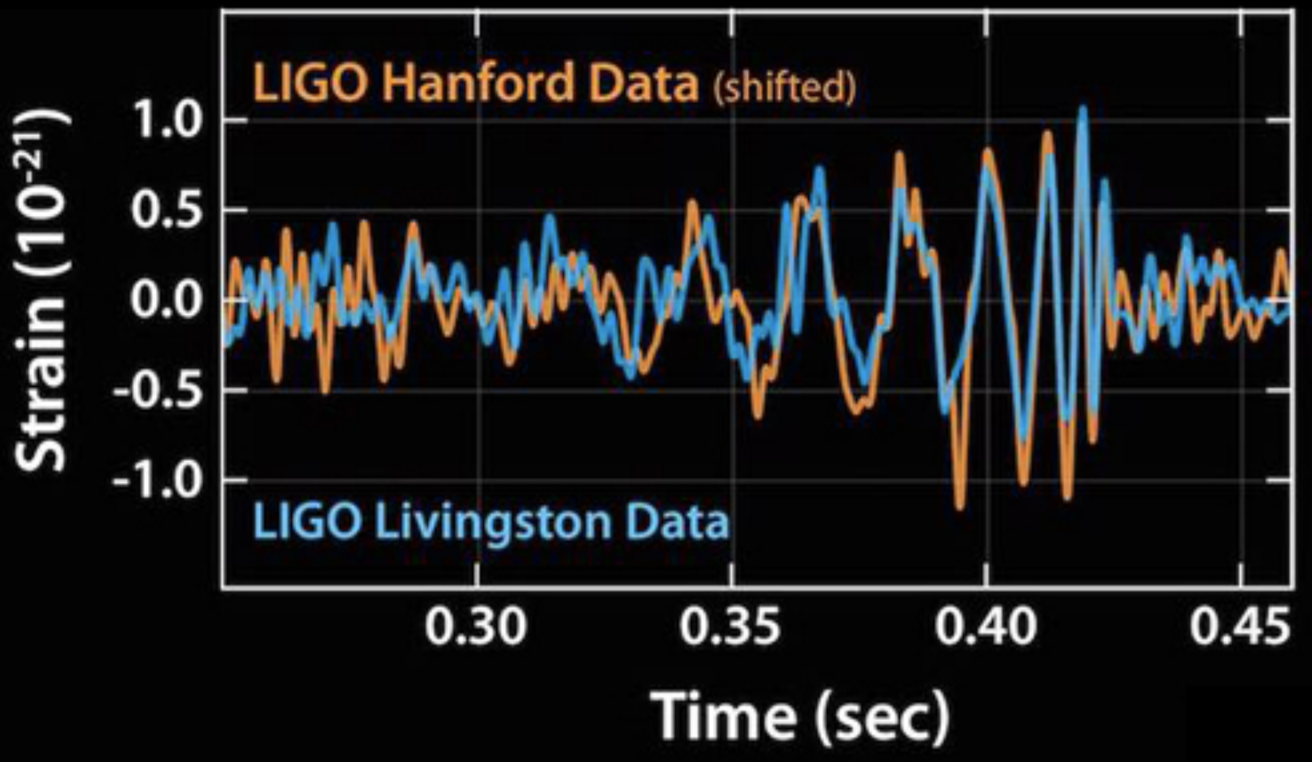
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

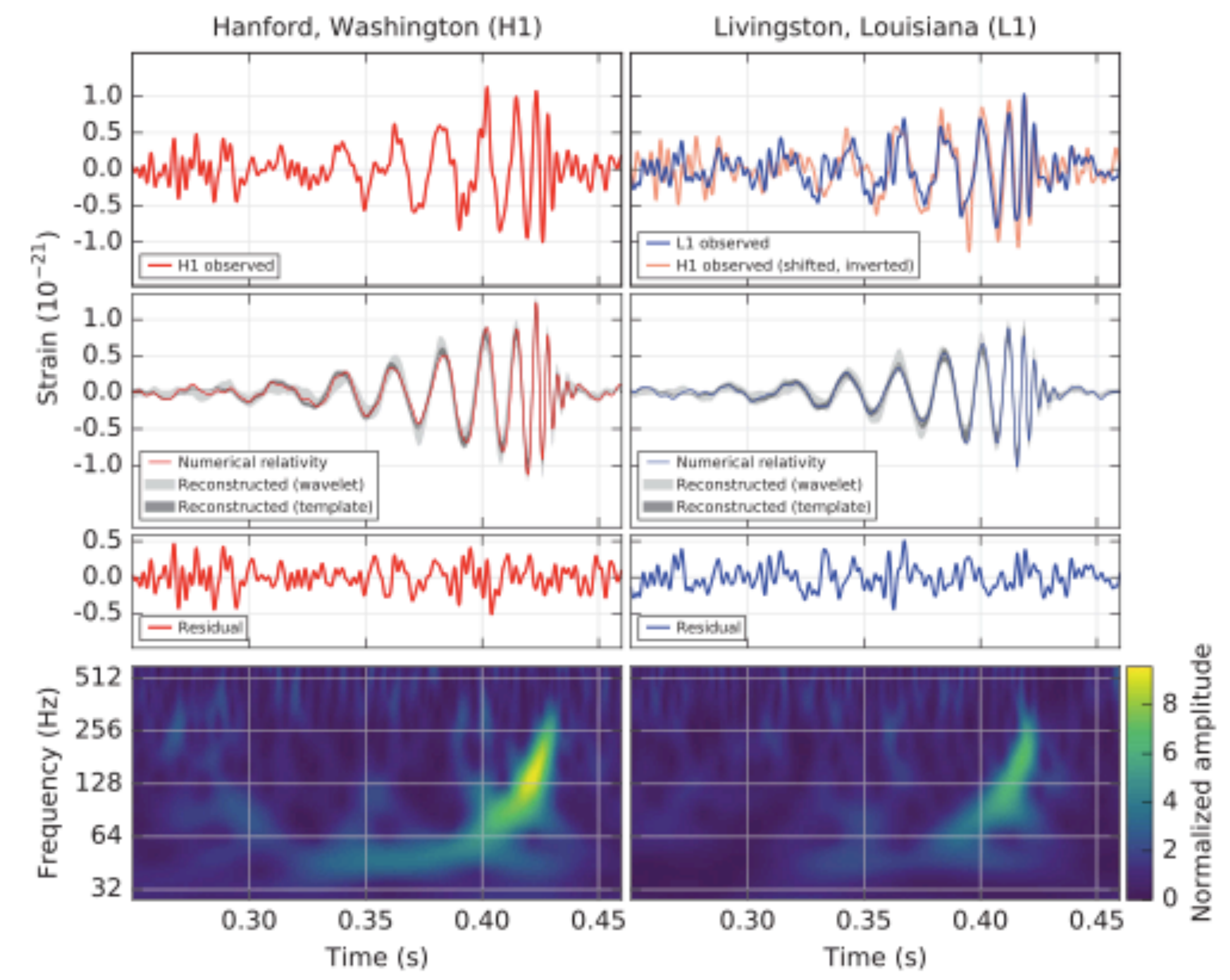
First Detection!

GW150914, recorded at 09:50:45 UTC on 14 Sept 2015



LISTEN TO IT!

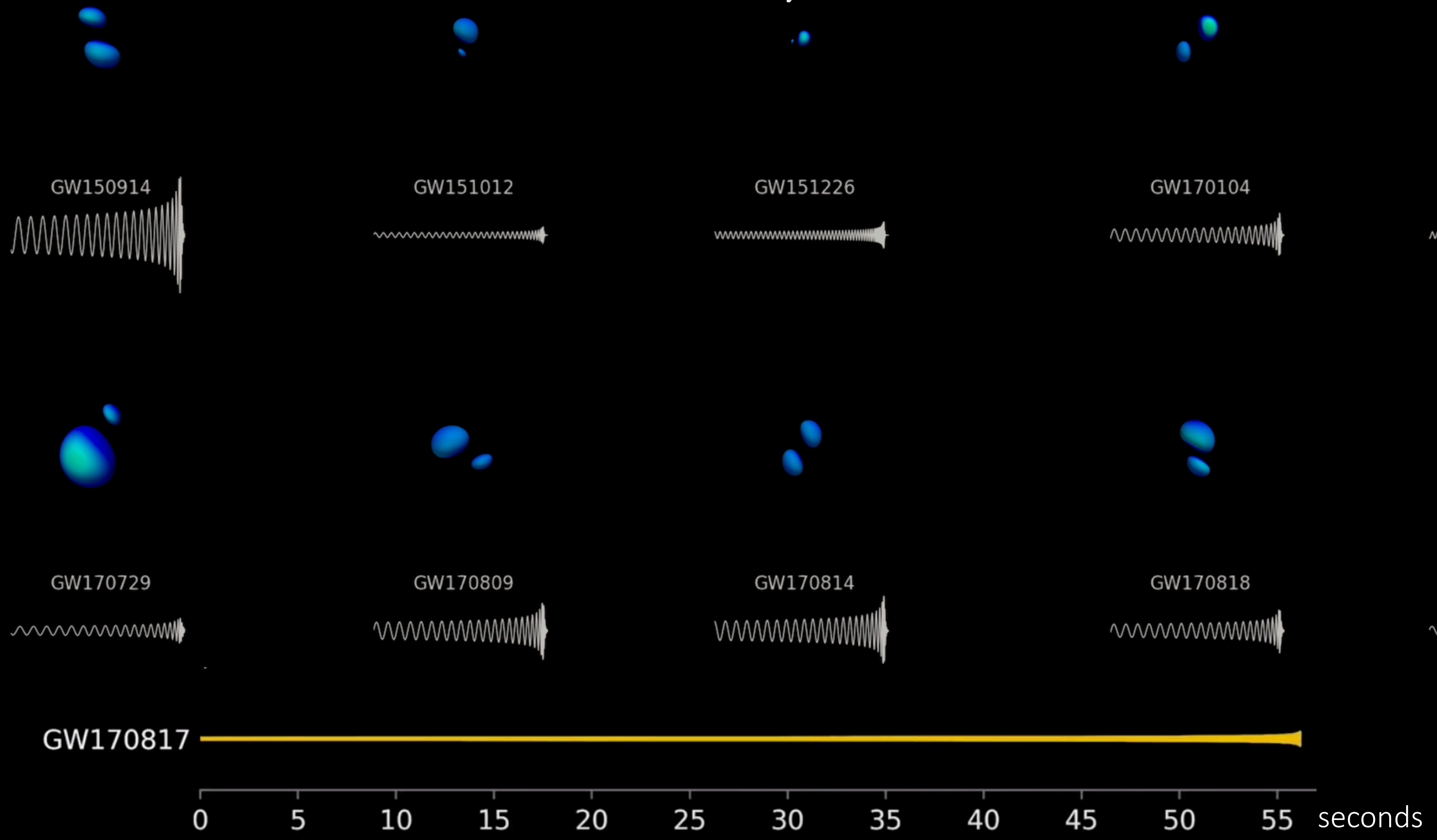
Event GW150914



Abbott, et. al., Physical Review Letters 116, 061102 (2016) - Figure 1

LIGO/Virgo release first catalog of gravitational-wave events

22 February 2019



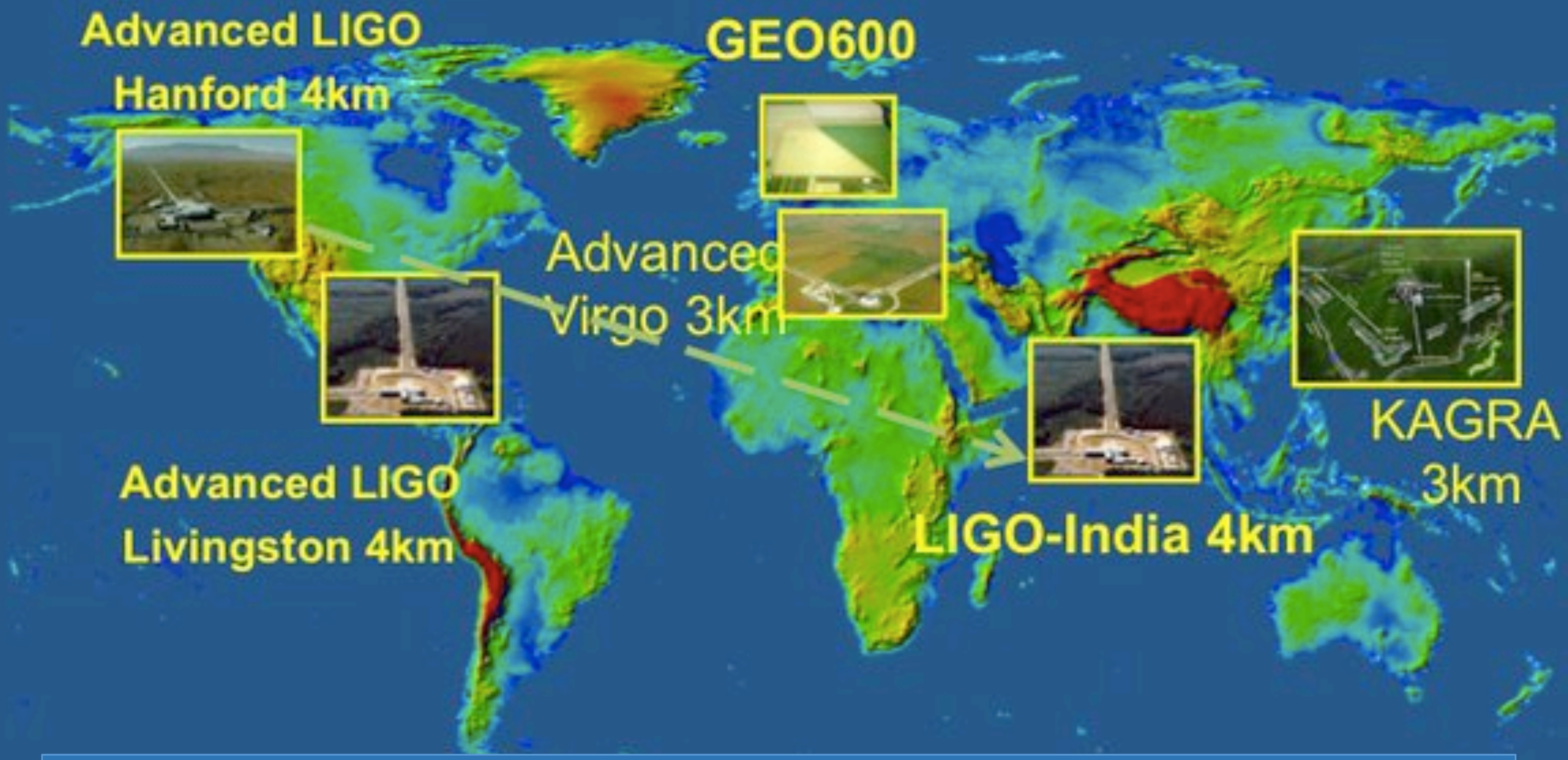
Questions?

- ✓What are Gravitational Waves?
- ✓How have they been detected?
- ✓What is LIGO?
- ✓Why has this been so difficult?
- ✓What has LIGO found so far?

- What’s next?
- Can I play too?

KAGRA and LIGO–India

(2019) (2024)



"We have built an exact copy of that instrument that can be used in the LIGO-India Observatory," says David Shoemaker, leader of the Advanced LIGO Project and director of the MIT LIGO Lab, "ensuring that the new detector can both quickly come up to speed and match the U.S. detector performance."

Image © Tarun Souradeep, from http://www.natureasia.com/en/nindia/article/10.1038/nindia.2016.20

Squeezed Light for “ALIGO+”

ScienceNews
MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

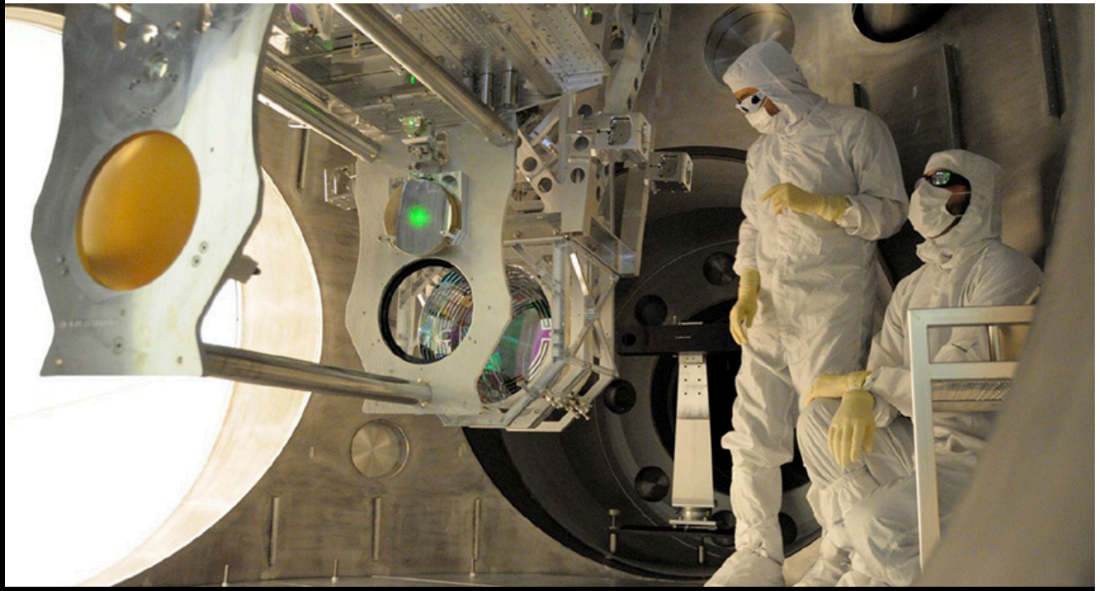
NEWS QUANTUM PHYSICS, ASTRONOMY, GRAVITATIONAL WAVES

LIGO will be getting a quantum upgrade

Quantum ‘squeezing’ light could lead to daily gravitational wave detections

BY EMILY CONOVER 2:54PM, FEBRUARY 15, 2019

AddThis



BETTER DETECTOR Scientists have been working on upgrades to LIGO (shown). Soon, the gravitational wave detector will begin using quantum techniques.

www.sciencenews.org/article/ligo-gravitational-wave-detector-quantum-upgrade

LIGO LAB/MIT/CALTECH

“LIGO scientists announced February 14 [that the] $35 million upgrade could let scientists catch a gravitational wave every day, on average. ”

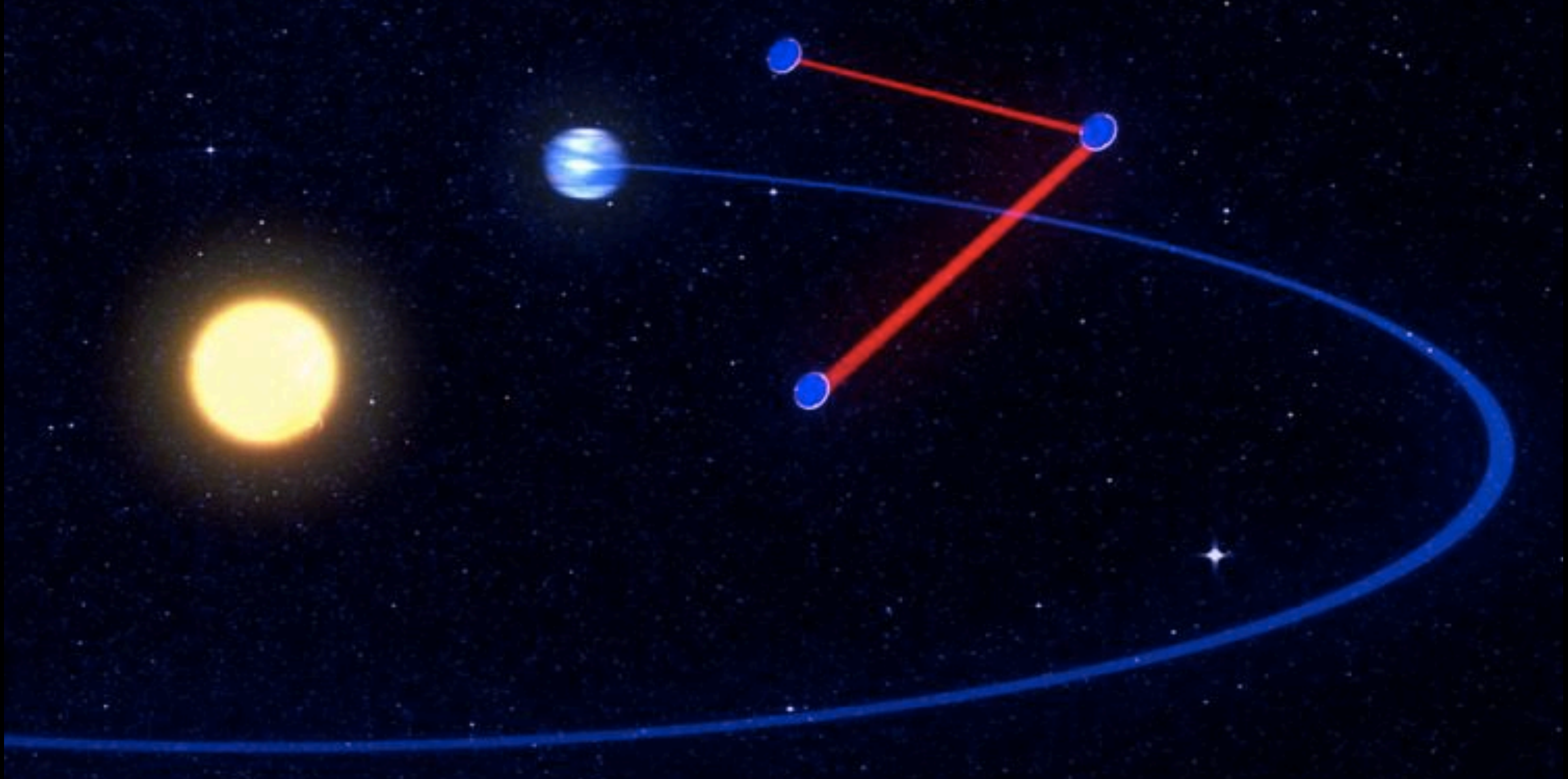
“Advanced LIGO Plus,” expected to start up in 2024, will make use of “squeezed light”

(LIGO-India will also make use of squeezed light.)

This upgrade will “almost double” the sensitivity of the detectors
-UK Research and Innovation

LISA

Laser Interferometer Space Antenna



The LISA mission originally consisted of one “Mother” and two “Daughter” spacecraft orbiting the Sun in a triangular configuration, connected by the two arms of a laser interferometer.

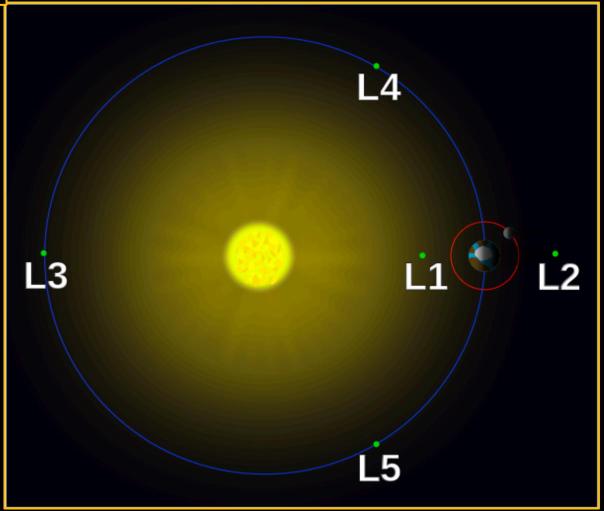
The formation trails Earth in its orbit by 20° and the plane of the triangle is 60° from the plane of the ecliptic.

Latest LISA Mission

https://lisa.nasa.gov/

Each of three spacecraft carry two test masses, two lasers, and two telescopes, forming 3 interferometers with 2.5×10^{9}m arms.

Lagrange Points:



https://en.wikipedia.org/wiki/Lagrangian_point

Learn more at

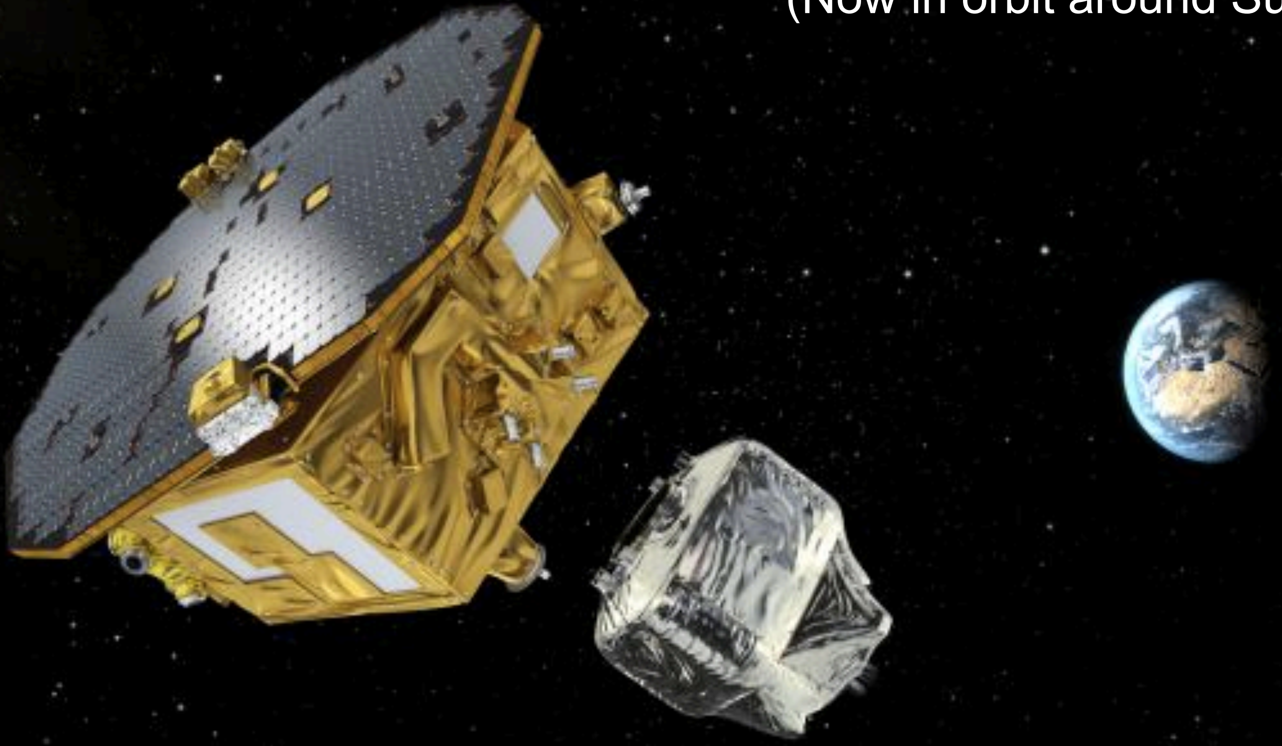
https://www.lisamission.org/

and

https://lisa.nasa.gov/

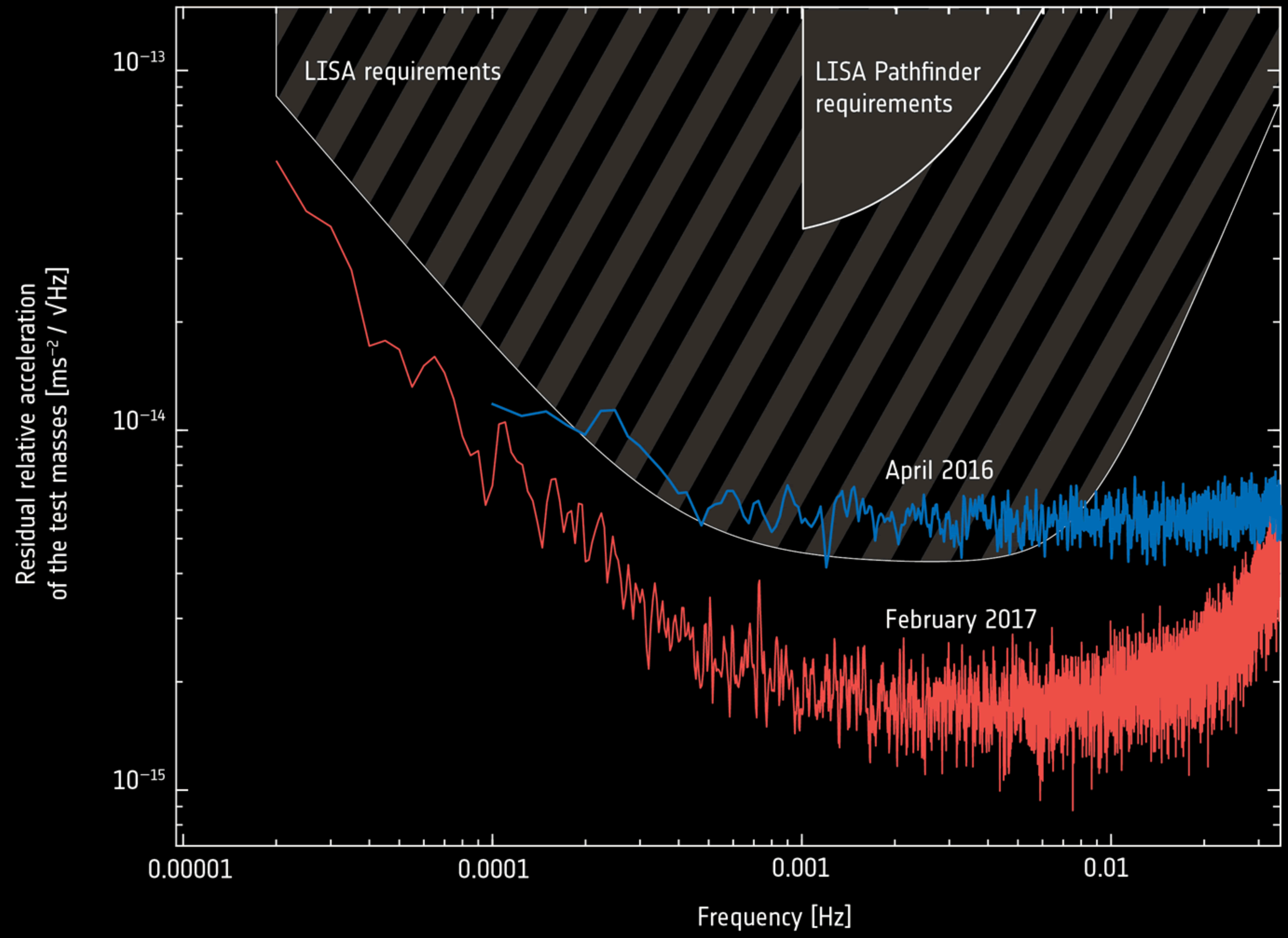
LISA Pathfinder

LISA Pathfinder was in a Lissajous orbit around L1 until April 2017.
(Now in orbit around Sun.)



3 DEC 2015 Launched
22 JAN 2016 Arrived at Lagrange point L1
16 FEB 2016 Test masses released
8 MAR 2016 Began science mode
30 JUN 2017 Mission Completion
18 JUL 2017 Last command

LISA Pathfinder Results



Questions?

✓What are Gravitational Waves?

✓How have they been detected?

✓What is LIGO?

✓Why has this been so difficult?

✓What has LIGO found so far?

✓What's next?

- Can I play too?
  - GWOSC & Pioneer Academics
  - Einstein@Home
  - Gravity Spy

Gravitational Wave Open Science Center

and

Pioneer Academics Research Programs

Gravitational Wave Open Science Center

Data ▾ Software ▾ Online Status ▾ About GWOSC ▾

Projects with GWOSC data

Some examples of projects using GWOSC data are shown on this page.

Listing a project here does not imply endorsement by LIGO Laboratory, the LIGO Scientific Collaboration or the Virgo Collaboration.

If you have completed a project with GWOSC data, please let us know!

Scientific Publications

Below are the fifty most recent publications citing GWOSC, as listed by INSPIRE HEP.
For a complete list, please query INSPIRE HEP.

1) Testing the no-hair theorem with GW150914
Maximiliano Isi, Matthew Giesler, Will M. Farr, et al.
arxiv:1905.00869 | INSPIRE

2) Gravitational-Wave Asteroseismology with Fundamental Modes from Compact Binary Inspirals
Geraint Pratten, Patricia Schmidt, Tanja Hinderer
arxiv:1905.00817 | INSPIRE

3) New Binary Black Hole Mergers in the Second Observing Run of Advanced LIGO and Advanced Virgo

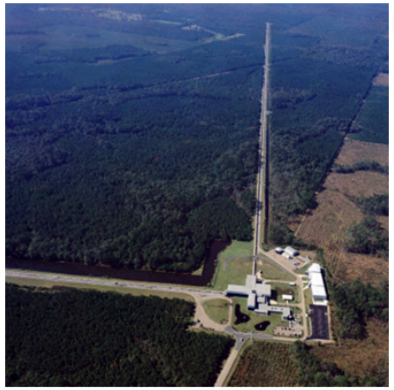
Student Ashley Disbrow presents her work at the 2014 American Astronomical Society meeting in Washington, DC.

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology
and supported by the U.S. National Science Foundation.

- Getting Started
- Data
  - Events
  - Bulk Data
- Tutorials
- Software
- Detector Status
- Timelines
- My Sources
- GPS ↔ UTC
- About the detectors
- Projects
- Acknowledge LOSC

LIGO Hanford Observatory, Washington
(image: C. Gray)



LIGO Livingston Observatory, Louisiana
(image: J. Giaime)

Virgo detector, Italy
(image: Virgo Collaboration)

The LIGO Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

Get started!

Download data

See parameter estimation samples NEW

Join the email list

After primary analysis has been completed, LIGO shares their data openly, along with tutorials and sample code.

Pioneer Research Program

For the past 4 summers, I have been working with capable high school students to use the data from LIGO to perform individual research projects.

http://PioneeracAdemics.com/

Initially, students obtained experience with scientific research, which they could list on their college applications.

Starting in 2016, Oberlin College grants course credit and provides an Oberlin transcript to Pioneer students upon their completion of the Pioneer Research Program.

https://www.gw-openscience.org/projects/

Pioneer Academics student projects
Projects mentored by Eric Myers
Final papers: Zhehao Lu | Minqi Fu

Art Installation: Void
Emma Wadley
See photo at right

Possible associated signal with GW150914 in the LIGO data
Hao Liu, Andrew D. Jackson
arXiv:1609.08346

Echoes from the Abyss: Evidence for Planck-scale structure at black hole horizons
Jahed Abedi, Hannah Dykaar, Niayesh Afshordi
arXiv:1612.00266

Modified LIGO data analysis notebook
Valentin Baillard
Azure | mybinder | github

Physics From Planet Earth homework problems
Joe Amato and Enrique (Kiko) Galvez
See Gravitational Radiation 2 and Gravitational Radiation 3

Non-Gaussian noise and data analysis of laser interferometric gravitational wave detectors
Takahiro Yamamoto, Ph.D. Thesis
See JGW-P1605355

Understanding the LIGO GW150914 event
P. Naselsky, A. D. Jackson, Hao Liu
See arxiv:1604.06211

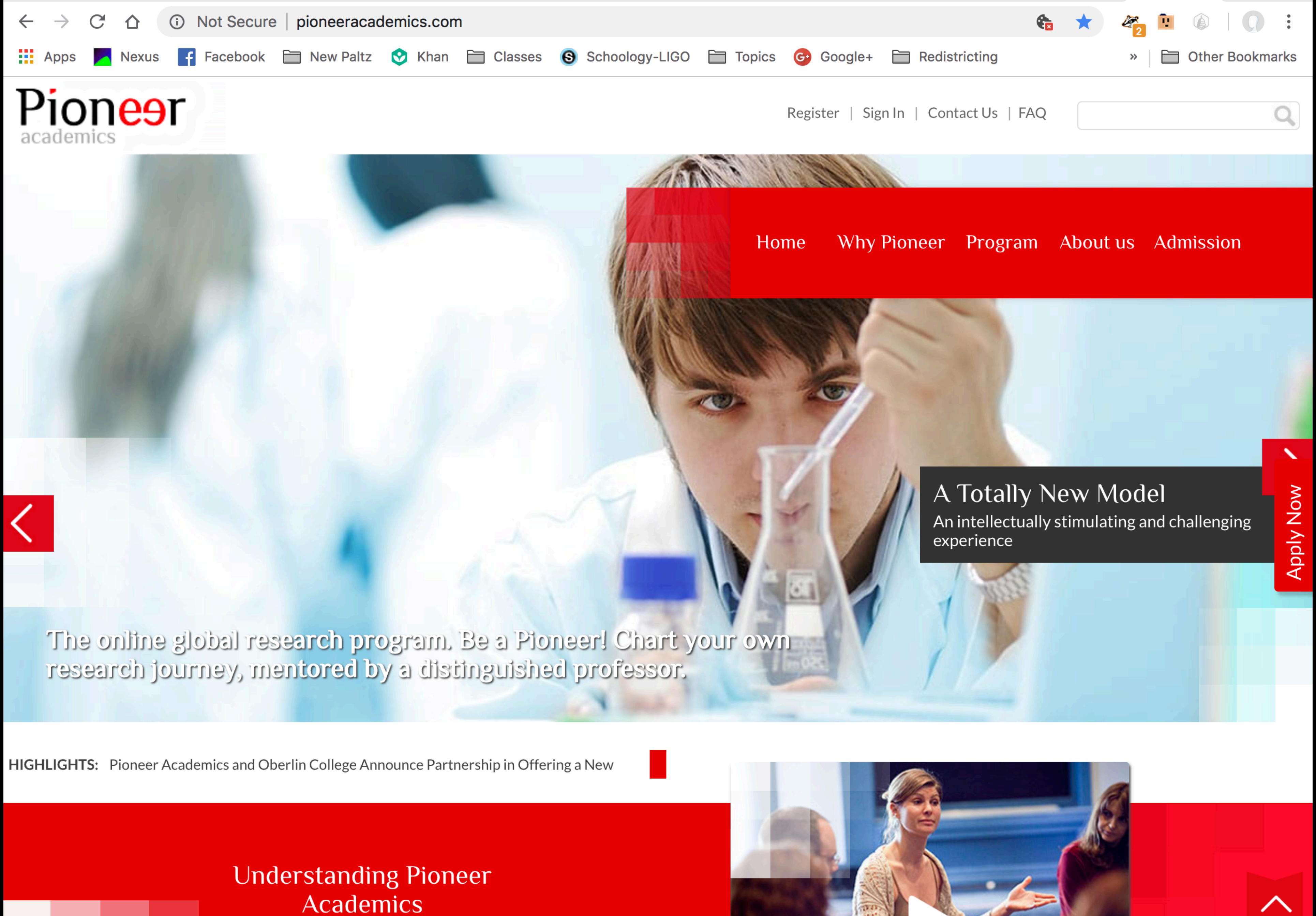
Gravitational Wave Detection in the Introductory Lab
Lior M. Burko
Georgia Gwinnett College,
See arxiv:1602.04666

2015

Pioneer Academics student projects
Projects mentored by Eric Myers
Final papers: Jinghong Liang | William Li

2014

Pioneer Academics: http://www.PioneerAcademics.com



Structure of the ``Program'' for LIGO

Group Meetings:

5 × 90 minutes, via Zoom.com

1. Introduction to LIGO
2. LIGO Technical Briefing
3. Scientific Research, E@H
4. LIGO data and LOSC
5. Plots & Events Tutorials

LIGO Links:

5 × articles, videos, news, etc…

(at least 2 different kinds) posted to Schoology.com

Individual Meetings

5+ × 60 minutes, via Zoom.com

Specific to each project

Python Programming:

0. Installing Python - from python.org
1. "Hello, World!" - print()
2. Aircraft Weight & Balance - assignment
3. Conditional Execution - if/then/else, input()
4. Iteration I - for, map(), float()
5. Iteration II - while, lists, modules, graphing
6. Nested Loops - functions & formatted output
7. Flour Bomb - plotting curves, recapitulation

Paper(s):

1. GW & LIGO Background (10%)
2. Research Proposal (10%)
3. Draft of Final Paper (10%)
4. Final Paper (50%)

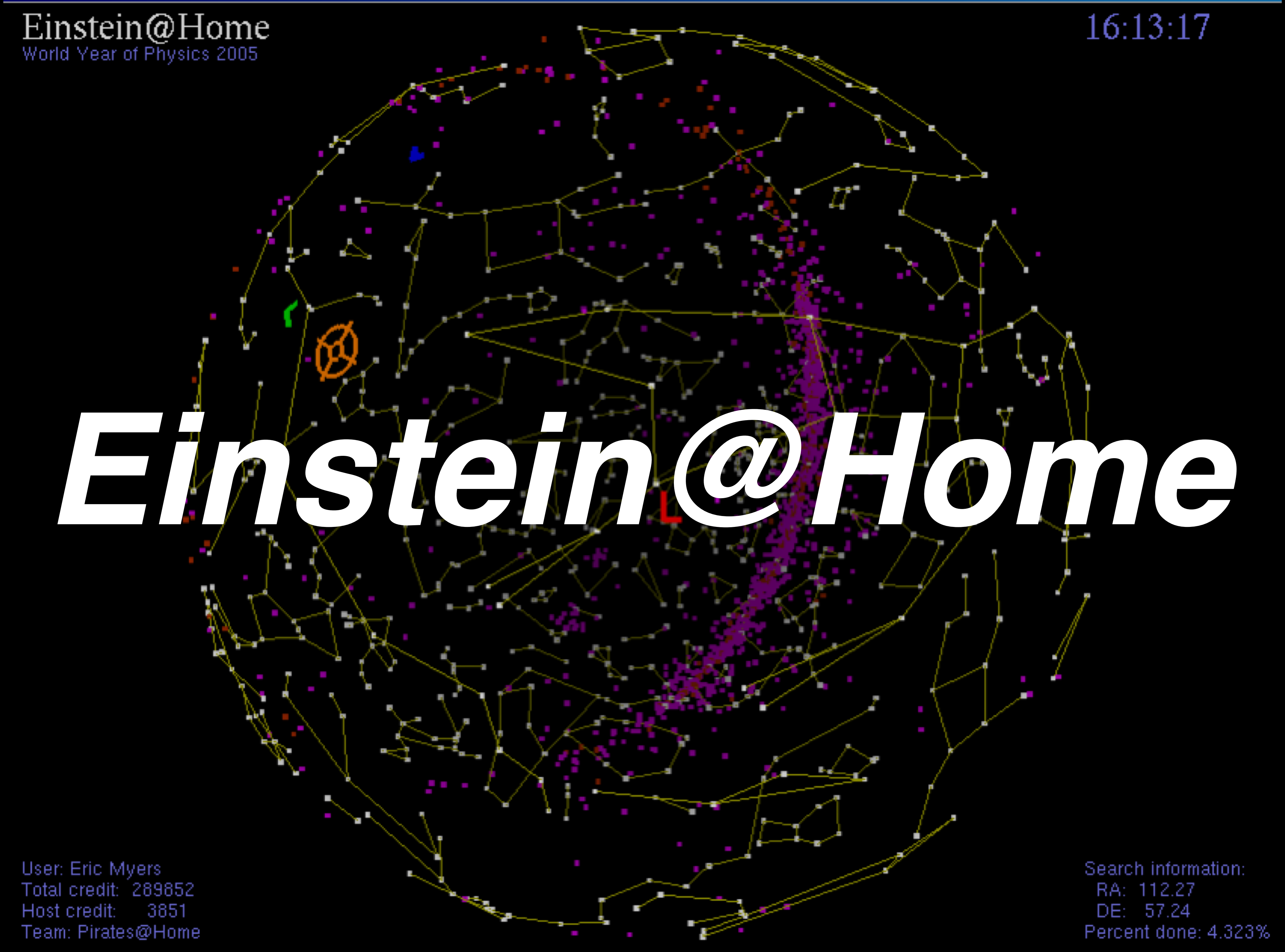
Desktop Setup

Questions?

- ✓What are Gravitational Waves?
- ✓How have they been detected?
- ✓What is LIGO?
- ✓Why has this been so difficult?
- ✓What has LIGO found so far?
- ✓What's next?

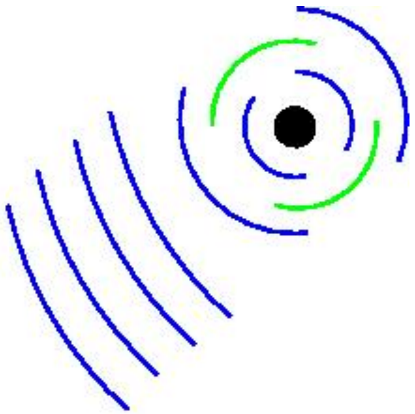
- Can I play too?
    - GWOSC & Pioneer Academics
    - Einstein@Home
    - Gravity Spy

Einstein@Home

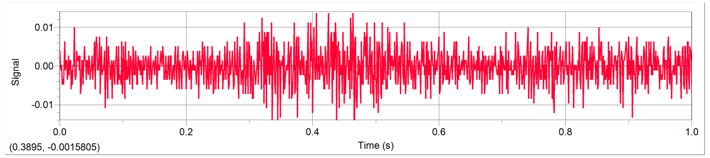


How might GW's be produced?

The most likely astronomical sources are:



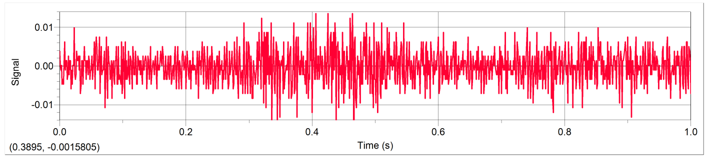
__Stochastic background__
from the early universe (the Big Bang! Cosmic Strings,…)
a "cosmic gravitational wave background"

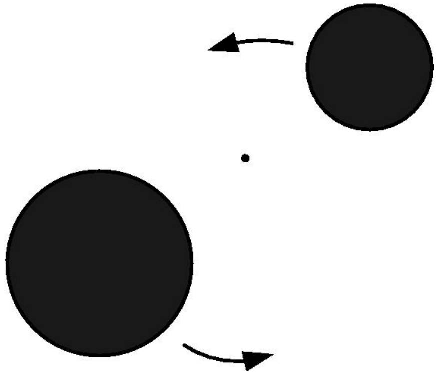


__Continuous Wave sources__,
such as spinning (and asymmetric!) or oscillating neutron stars ("gravitational pulsars").

__Coalescence of binary systems__,
inspiral of pairs of neutron stars and/or black holes

(NS-NS, NS-BH, BH-BH) *CHIRP!*



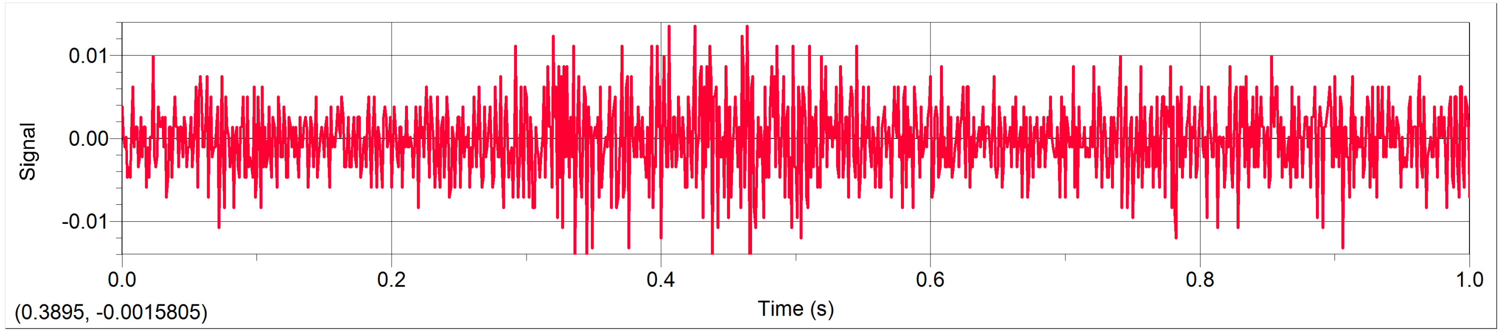


__Bursts__
from supernovae or other cataclysmic events
Requires changing *__quadrupole__*.
Spherical symmetric $\Longrightarrow$ no GW!

or..... something unexpected!

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"

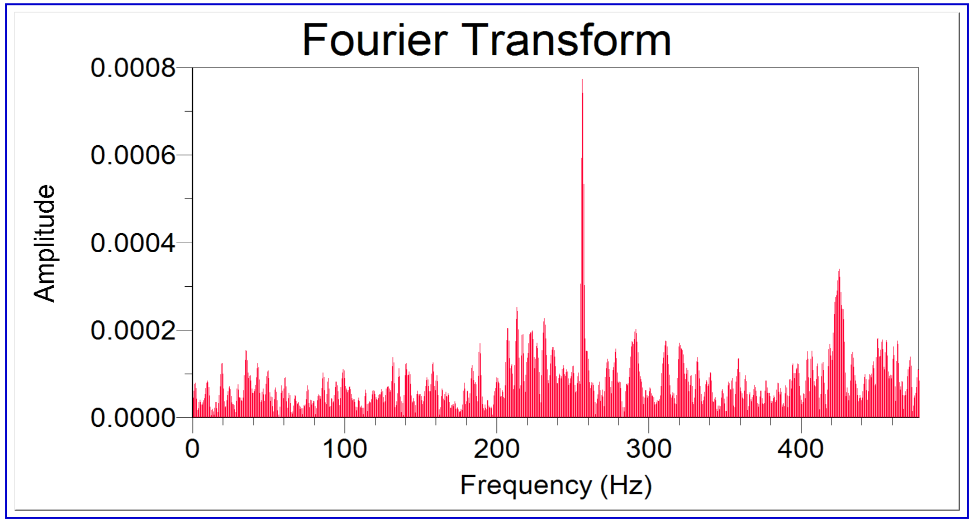
$\longrightarrow t$

Take the Fourier Transform to obtain:

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

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

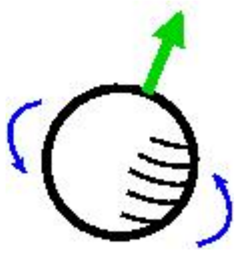
$$\tilde{B}_m = \frac{1}{\sqrt{2\pi}} \int_0^T f(x) \sin\left(\frac{2\pi mt}{T}\right) dt$$



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

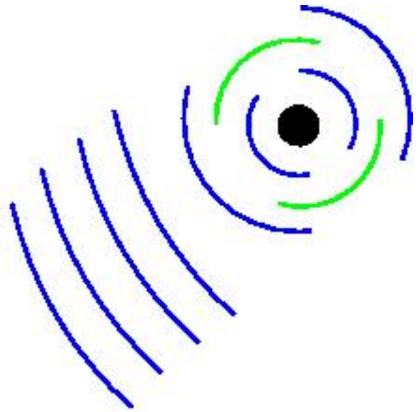
But the frequency will change!

The frequency is not expected to be constant, due to:



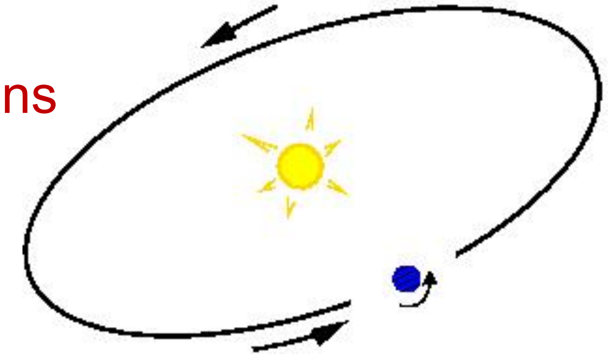
1. The source losing energy due to "spin down"

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



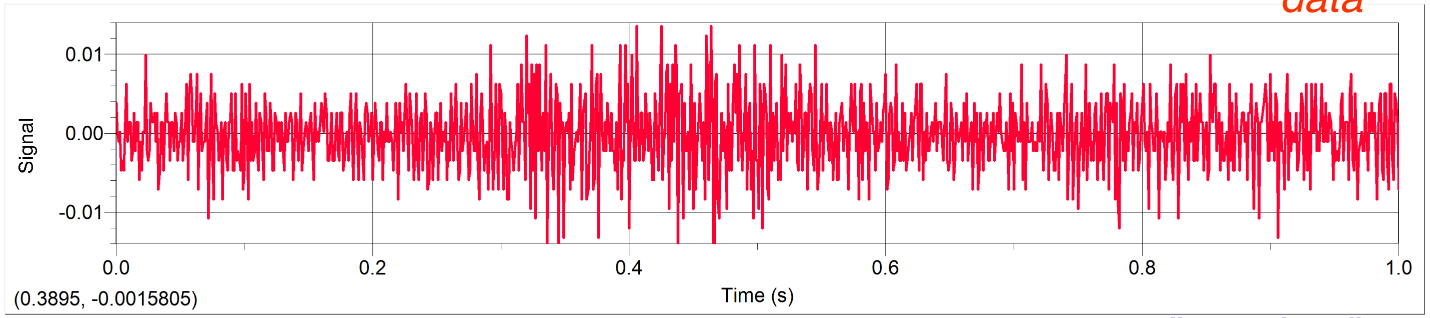
3. Doppler shift due to Earth's rotation about its axis (one part in 10^6, with period 1 sidereal day)

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

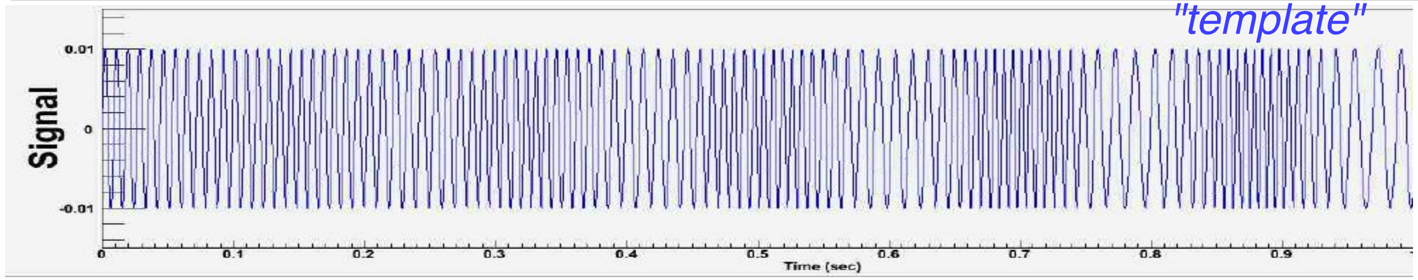


Matched Filtering

data



"template"



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

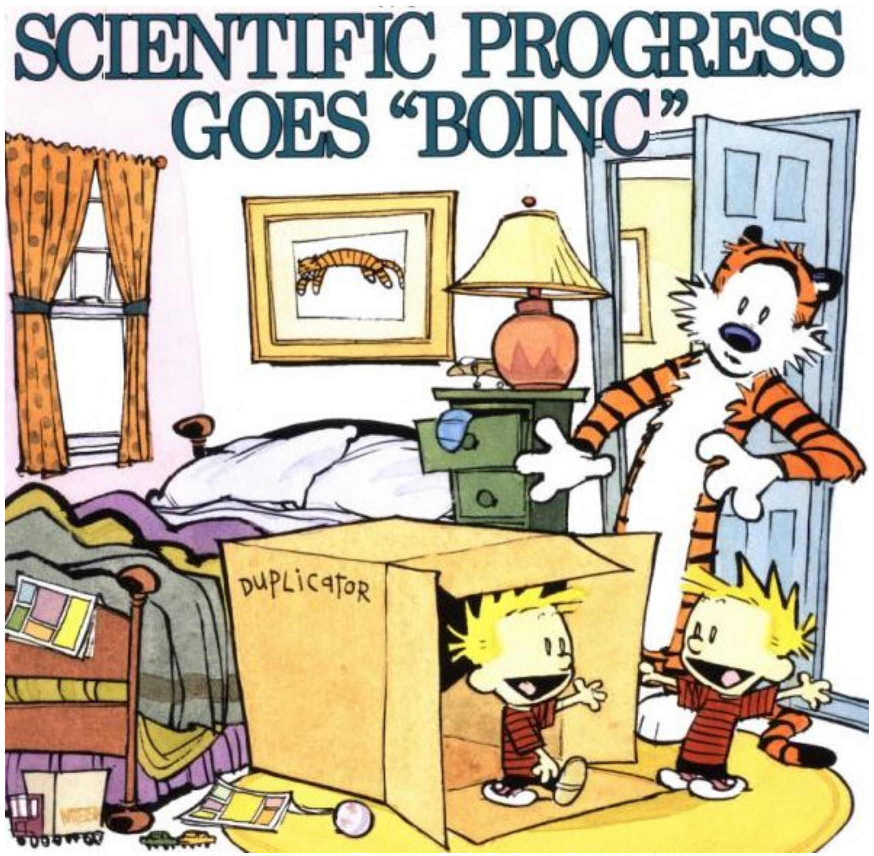
"the F statistic"

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

And the 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

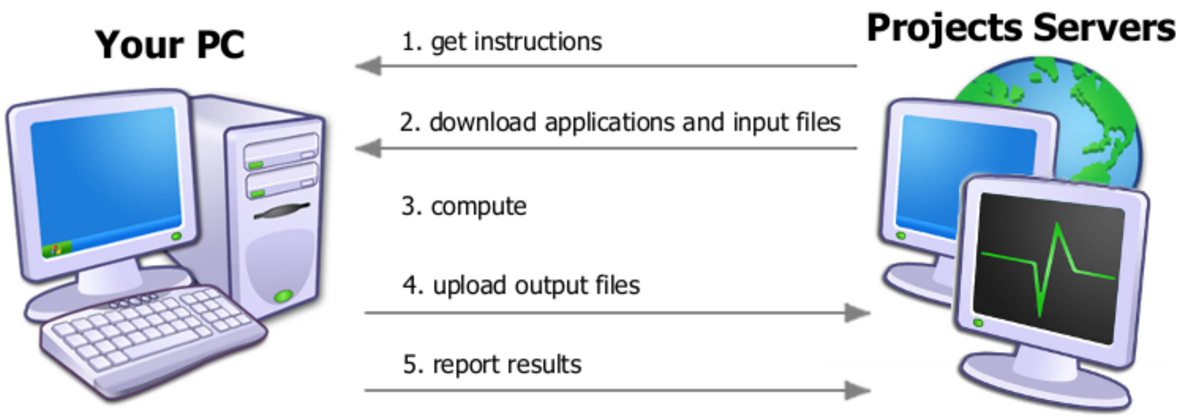
BOINC is modular, so that one can replace the "computation thread" and the "graphics thread".

So we did. $\Longrightarrow$ Einstein@Home

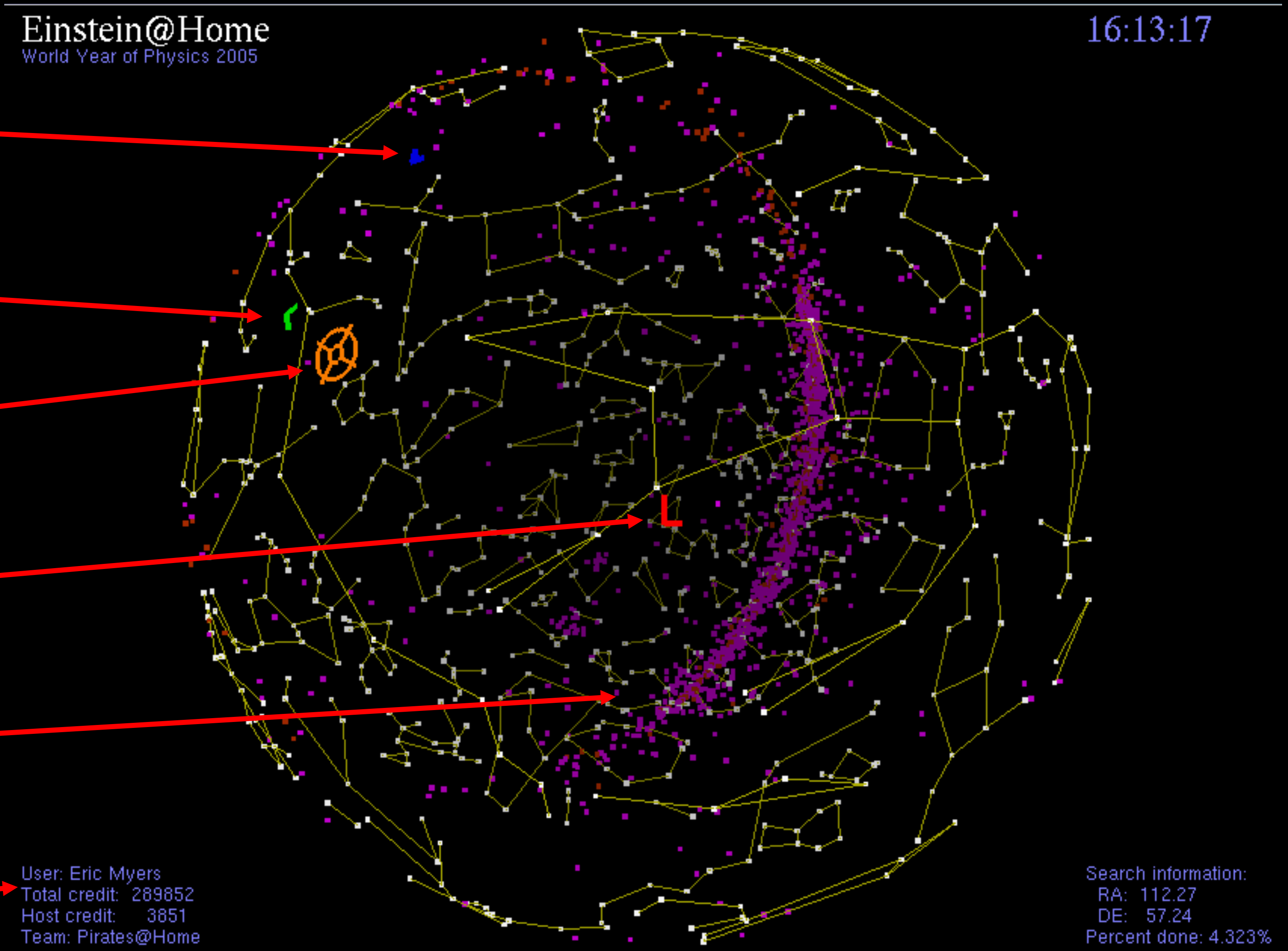
Einstein@Home

How to use BOINC to search for a CW GW 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

Einstein@Home - Server Status (as of 17 January 2009)

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	157
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

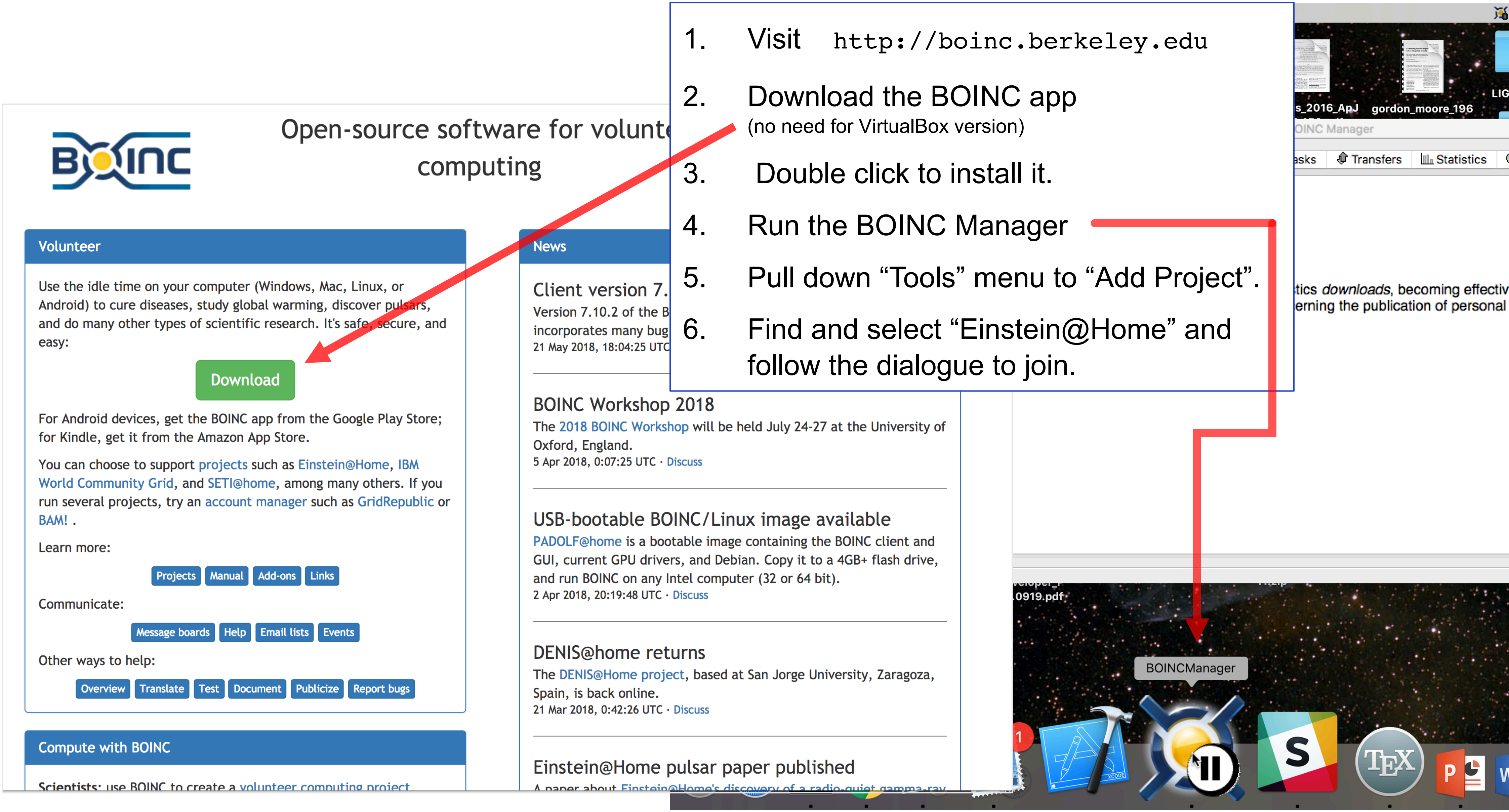
Work and Results

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

As of 16 March 2019: Participants: 1,015,315 (with credit : 469,715) Computers: 1,770,350 (over × 2 improvement) Floating Point Speed: 5790 TFLOPS (over × 36 improvement)

How you can join

1. Visit `http://boinc.berkeley.edu`
2. Download the BOINC app (no need for VirtualBox version)
3. Double click to install it.
4. Run the BOINC Manager
5. Pull down “Tools” menu to “Add Project”.
6. Find and select “Einstein@Home” and follow the dialogue to join.



Questions?

✓What are Gravitational Waves?

✓How have they been detected?

✓What is LIGO?

✓Why has this been so difficult?

✓What has LIGO found so far?

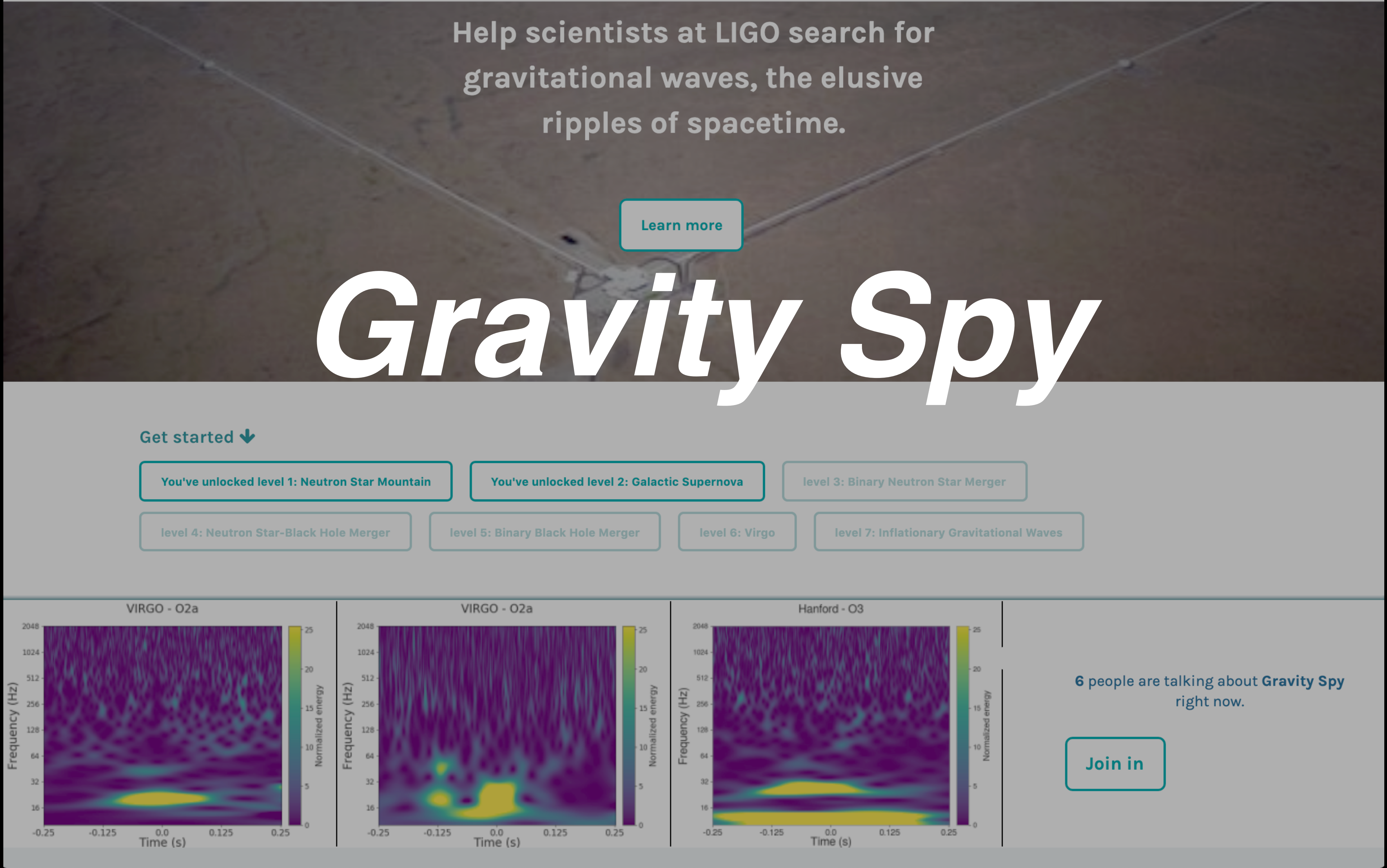
✓What's next?

- Can I play too?

  GWOSC & Pioneer Academics

  Einstein@Home

  Gravity Spy


Help scientists at LIGO search for gravitational waves, the elusive ripples of spacetime.
Learn more
Gravity Spy
Get started
You've unlocked level 1: Neutron Star Mountain
You've unlocked level 2: Galactic Supernova
level 3: Binary Neutron Star Merger
level 4: Neutron Star-Black Hole Merger
level 5: Binary Black Hole Merger
level 6: Virgo
level 7: Inflationary Gravitational Waves
VIRGO - O2a
VIRGO - O2a
Hanford - O3
Frequency (Hz)
Time (s)
Normalized energy
6 people are talking about Gravity Spy right now.
Join in

Select Language

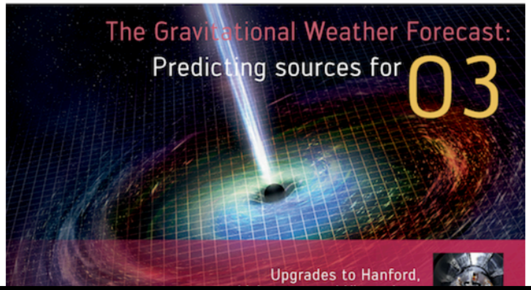
LSC LIGO Scientific Collaboration

Visit www.ligo.org

NEWS

Feb 15, 2019	LIGO Receives New Funding to Upgrade Detectors
Dec 3, 2018	LIGO and Virgo release catalog of gravitational-wave events from first and second observing runs
Nov 21, 2018	Winners of 2018 Excellence in Detector Characterization and Calibration Award Are Announced
Nov 1, 2018	LIGO and Virgo Collaborations Working to Make Data and Analysis Techniques Available to All
Oct 18, 2018	LIGO Scientists Awarded New Horizons in Physics Prize
Oct 16, 2018	"Ripples of Gravity, Flashes of Light" One Year On
Oct 3, 2018	LIGO Lab Announces Award for Excellence in Detector Characterization and Calibration
Jul 12, 2018	LSC Congratulates our IceCube colleagues on multi-messenger breakthrough
Apr 24, 2018	Update on the start of LIGO's 3rd observing run

Read the latest issue of LIGO MAGAZINE



PRESS RELEASES

May 2, 2019
LIGO and Virgo Detect Neutron Star Smash-Ups

Mar 26, 2019
LIGO and Virgo Resume Search for Ripples in Space and Time

Dec 3, 2018
LIGO and Virgo Announce Four New Gravitational-Wave Detections

Oct 16, 2017
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

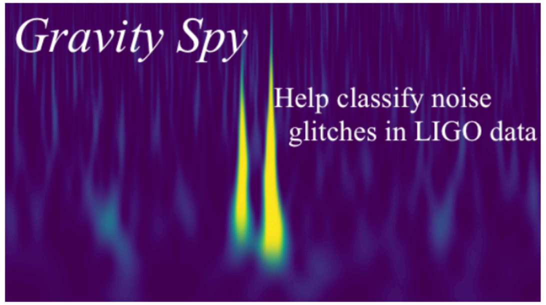
Sep 27, 2017
Gravitational waves from a binary black hole merger observed by LIGO and Virgo

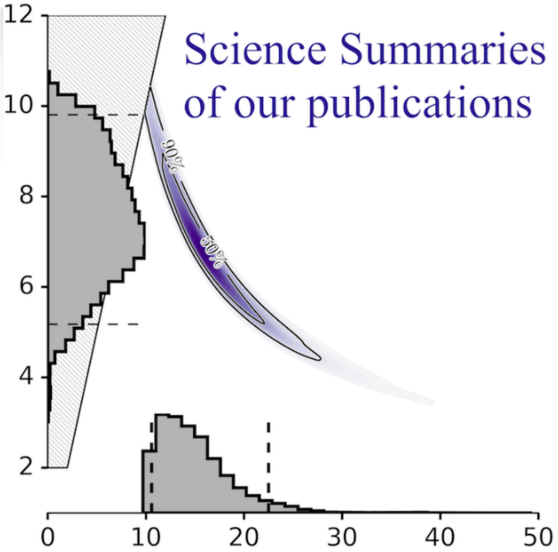
Jun 1, 2017
LIGO Detects Gravitational Waves for Third Time

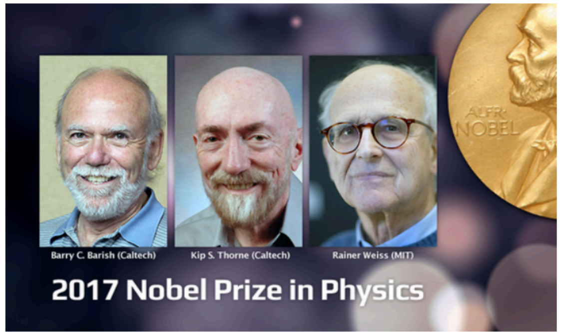
Jun 15, 2016
Gravitational Waves Detected from Second Pair of Colliding Black Holes

Feb 11, 2016
Gravitational Waves Detected 100 Years After Einstein's Prediction

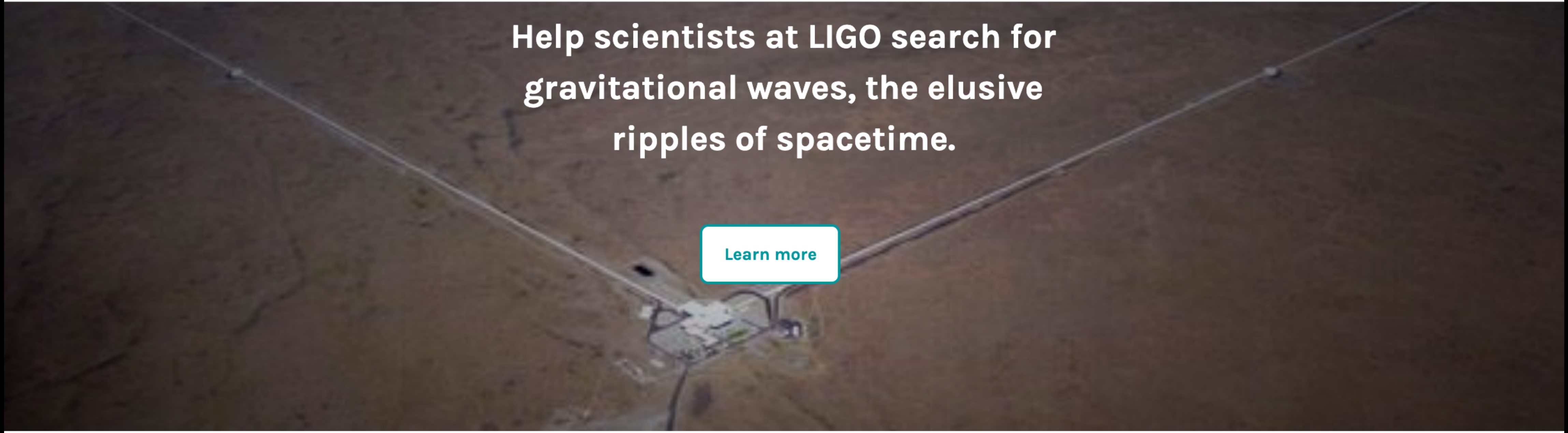
GET INVOLVED







← Click Here



Help scientists at LIGO search for gravitational waves, the elusive ripples of spacetime.

Learn more

Get started

You've unlocked level 1: Neutron Star Mountain

You've unlocked level 2: Galactic Supernova

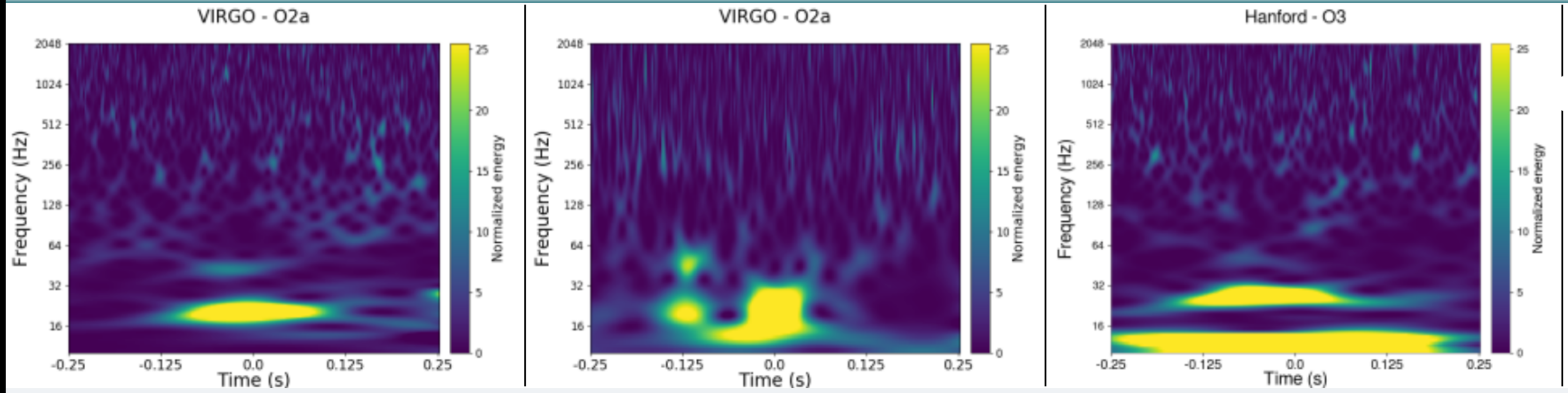
level 3: Binary Neutron Star Merger

level 4: Neutron Star-Black Hole Merger

level 5: Binary Black Hole Merger

level 6: Virgo

level 7: Inflationary Gravitational Waves



6 people are talking about **Gravity Spy** right now.

Join in

Try it…

Questions?

- ✓What are Gravitational Waves?
- ✓How have they been detected?
- ✓What is LIGO?
- ✓Why has this been so difficult?
- ✓What has LIGO found so far?
- ✓What's next?

- Can I play too?
  - GWOSC & Pioneer Academics
  - Einstein@Home
  - Gravity Spy