Gravitational Waves and LIGO

- Gravitational waves and their astrophysical sources.
- GW detection: The LIGO project and its sister projects
- Fundamental noise sources
- LIGO detectors
- Advanced LIGO
- Opportunities for grad students

Alan Weinstein, Caltech
LIGO: Laser Interferometer Gravitational-Wave Observatory

- US project to build observatories for gravitational waves (GWs)
  - ...and laboratory to run them
- to enable an initial detection, then an astronomy of GWs
- collaboration by MIT, Caltech; other institutions participating
  - (LIGO Scientific Collaboration, LSC)
  - Funded by the US National Science Foundation (NSF)

Observatory characteristics

- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers (IFOs)

Evolution of interferometers in LIGO

- establishment of a network with other interferometers
- A facility for a variety of GW searches
- lifetime of >20 years
- goal: best technology, to achieve fundamental noise limits for terrestrial IFOs
Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.

Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

If the source is moving (at speeds close to c), eg, because it’s orbiting a companion, the “news” of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature.
Einstein’s Theory of Gravitation

**experimental tests**

---

**bending of light**
As it passes in the vicinity of massive objects

- First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

---

**Mercury’s orbit**
perihelion shifts forward twice Post-Newton theory

- Mercury’s elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or “perihelion”) shifts forward with each pass.

---

**“Einstein Cross”**
The bending of light rays gravitational lensing

- Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a ‘dark matter’ body as the central object
Strong-field

• Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)

• Space-time curvature is a tiny effect everywhere except:
  ➢ The universe in the early moments of the big bang
  ➢ Near/in the horizon of black holes

• This is where GR gets non-linear and interesting!

• We aren’t very close to any black holes (fortunately!), and can’t see them with light

But we can search for (weak-field) gravitational waves as a signal of their presence and dynamics
Nature of Gravitational Radiation

General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in the fabric of spacetime

- **transverse** space-time distortions, freely propagating at speed of light
  - *mass of graviton = 0*
- Stretches and squeezes space between “test masses” – strain \( h = \Delta L / L \)
- GW are tensor fields (EM: vector fields)
  - two polarizations: plus (⊕) and cross (⊗)
  - *(EM: two polarizations, \( x \) and \( y \))
  - *Spin of graviton = 2*

- Conservation laws:
  - cons of energy ⇒ no monopole radiation
  - cons of momentum ⇒ no dipole radiation
  - lowest multipole is quadrupole wave (spin 2)

Contrast with EM dipole radiation:

\[
\hat{x} (\text{left-right}) \quad \hat{y}
\]
Sources of GWs

- Accelerating charge ⇒ electromagnetic radiation (dipole)
- Accelerating mass  ⇒ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):
  \[ h_{\mu\nu} = \frac{2G}{c^4 r} \ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{\text{orb}}^2}{c^4 r} \]

- \( \ddot{I}_{\mu\nu} \) = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- \( G \) is a small number!
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:

\[ M \sim 10^{30} \text{ kg} \]
\[ R \sim 10 \text{ km} \]
\[ f \sim 400 \text{ Hz} \]
\[ r \sim 10^{23} \text{ m} \]

⇒ \[ h \sim 10^{-21} \]

Terrestrial sources TOO WEAK!

Energy-momentum conservation:
- cons of energy ⇒ no monopole radiation
- cons of momentum ⇒ no dipole radiation
- lowest multipole is quadrupole wave
A NEW WINDOW ON THE UNIVERSE

The history of Astronomy: new bands of the EM spectrum opened → major discoveries!

GWs aren’t just a new band, they’re a new spectrum, with very different and complementary properties to EM waves.

- Vibrations of space-time, not in space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can’t be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe
Astrophysical Sources of Gravitational Waves

- Inspiralling compact binaries (neutron stars, black holes) “chirps”
- Non-axi-symmetric supernova collapse, GRB’s, binary mergers “bursts”
- Non-axi-symmetric pulsars (rotating, beaming neutron star) “periodic”
- Cosmological background from the Big Bang “stochastic”
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

- Neutron star – neutron star (Centrella et al.)
Case 2 (mu = 2.2):
The initial distance between the holes is $L = 892M$, where $M$ is 1/2 the ADM Mass of the system.

In this case, the holes do not have a conjugate apparent or event horizon initially.
Binary Orbit Evolution

- A binary system in a close orbit has a time-varying quadrupole moment, emits gravitational waves.

\[ f_{GW} = 2f_{\text{orbit}} \]

Gravitational waves carry away energy and angular momentum.

\[ \frac{dE}{dt} \propto -f^{10/3} \]

- Frequency increases, orbit shrinks.

\[ \frac{df}{dt} \propto f^{11/3} \quad \frac{dr}{dt} \propto -f^2 \]

Objects spiral in until they finally coalesce.

Additional relativistic effects kick in as \((Gm/rc^2)\) grows away from zero.
Hulse-Taylor binary pulsar

Neutron Binary System
PSR 1913 + 16 -- Timing of pulsars

- A rapidly spinning pulsar (neutron star beaming EM radiation at us 17/1 sec)
- orbiting around an ordinary star with 8 hour period
- Only 7 kpc away
- discovered in 1975, orbital parameters measured
- continuously measured over 25 years!
GWs from Hulse-Taylor binary

- Only 7 kpc away
- Period speeds up 14 sec from 1975-94
- Measured to ~50 msec accuracy
- Deviation grows quadratically with time
- Merger in about 300M years
  - (<< age of universe!)
- Shortening of period $\Leftarrow$ orbital energy loss
- Compact system:
  - Negligible loss from friction, material flow
- Beautiful agreement with GR prediction
- Apparently, loss is due to GWs!
- Nobel Prize, 1993
Chirp signal from Binary Inspiral

- distance from the earth $r$
- masses of the two bodies
- orbital eccentricity $e$ and orbital inclination $I$

**Over-constrained parameters:** TEST GR
The sound of a chirp

BH-BH collision, no noise

The sound of a BH-BH collision, Fourier transformed over 5 one-second intervals (red, blue, magenta, green, purple) along with expected IFO noise (black)
Astrophysical sources: Thorne diagrams

Sensitivity of LIGO to coalescing binaries

- LIGO I (2002-2005)
- LIGO II (2007- )
- Advanced LIGO
Estimated detection rates for compact binary inspiral events

Brief Summary of Detection Capabilities of Mature LIGO Interferometers

- **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $R_{\text{gal}}$ in our galaxy (with masses $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ for BH), the distances $D_I$ and $D_{WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $R_I$ and $R_{WB}$; Secs. 1.1 and 1.2.

<table>
<thead>
<tr>
<th></th>
<th>NS/NS</th>
<th>NS/BH</th>
<th>BH/BH in field</th>
<th>BH/BH in globulars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{gal}}, \text{ yr}^{-1}$</td>
<td>$10^{-6} - 10^{-4}$</td>
<td>$\lesssim 10^{-7} - 10^{-4}$</td>
<td>$\lesssim 10^{-7} - 10^{-5}$</td>
<td>$10^{-6} - 10^{-5}$</td>
</tr>
<tr>
<td>$D_I$</td>
<td>20 Mpc</td>
<td>43 Mpc</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>LIGO I  $R_I, \text{ yr}^{-1}$</td>
<td>$1 \times 10^{-4} - 0.03$</td>
<td>$\lesssim 1 \times 10^{-4} - 0.3$</td>
<td>$\lesssim 3 \times 10^{-3} - 0.5$</td>
<td>$0.03 - 0.5$</td>
</tr>
<tr>
<td>$D_{WB}$</td>
<td>300 Mpc</td>
<td>650 Mpc</td>
<td>$z = 0.4$</td>
<td>$z = 0.4$</td>
</tr>
<tr>
<td>LIGO II $R_{WB}, \text{ yr}^{-1}$</td>
<td>0.5 - 100</td>
<td>$\lesssim 0.5 - 1000$</td>
<td>$\lesssim 10 - 2000$</td>
<td>100 - 2000</td>
</tr>
</tbody>
</table>

V. Kalogera (population synthesis)
Supernova collapse sequence

- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.
Gravitational Waves from Supernova collapse

Non axisymmetric collapse

Rate
1/50 yr - our galaxy
3/yr - Virgo cluster

Zwerger & Muller, 1997 & 2003
simulations of axi-symmetric SN core collapse
Pulsars and continuous wave sources

**Pulsars in our galaxy**

- non axisymmetric: $10^{-4} < \varepsilon < 10^{-6}$
- science: neutron star precession; interiors
- “R-mode” instabilities
- narrow band searches best

---

**Sensitivity of LIGO to continuous wave sources**

![Graph showing sensitivity of LIGO to continuous wave sources.](image)
Gravitational waves from Big Bang

Waves now in the LIGO band were produced $10^{-22}$ sec after the big bang.

- Cosmic microwave background -- WMAP 2003
LIGO limits and expectations on $\Omega_{GW}$

- **S1 result:** $\Omega_{GW} < 23$
- **S2 result:** $\Omega_{GW} < 0.02$
- **S3 result:** $\Omega_{GW} < 8 \times 10^{-4}$
- **LIGO design, 1 year:** $\Omega_{GW} \sim 10^{-5} - 10^{-6}$
- **Advanced LIGO, 1 year:** $\Omega_{GW} \sim 10^{-9}$

Challenge is to identify and eliminate noise correlations between H1 and H2!
Frequency-Time Characteristics of GW Sources

LIGO is a broad-band amplitude detector, measures waveforms.

The experimentalist thinks not in terms of astrophysical sources, but in terms of waveform morphologies.

Specific astrophysical sources suggest specific waveforms, but we don’t want to miss the unexpected!

Unmodeled broad-band bursts
Modeled bursts (chirps, ringdowns)
Continuous broadband
Continuous quasi-periodic

Each waveform morphology requires very different data analysis techniques.
Ultimate Goals for the Observation of GWs

- **Tests of Relativity**
  - Wave propagation speed (delays in arrival time of bursts)
  - Spin character of the radiation field (polarization of radiation from CW sources)
  - Detailed tests of GR in P-P-N approximation (chirp waveforms)
  - Black holes & strong-field gravity (merger, ringdown of excited BH)

- **Gravitational Wave Astronomy (observation, populations, properties):**
  - Compact binary inspirals
  - Gravitational waves and gamma ray burst associations
  - Black hole formation
  - Supernovae in our galaxy
  - Newly formed neutron stars - spin down in the first year
  - Pulsars and rapidly rotating neutron stars
  - LMXBs
  - Stochastic background
Gravitational wave detectors

- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60’s
  - Essentially, a large “bell”, set ringing (at ~ 900 Hz) by GW
  - Only discuss briefly, here – See EXPLORER at CERN!

- **Michelson interferometers**
  - At least 4 independent discovery of method:
    - Pirani ‘56, Gerstenshtein and Pustovoit, Weber, Weiss ‘72
    - Pioneering work by Weber and Robert Forward, in 60’s
  - Now: large, earth-based detectors. Soon: space-based (LISA).
Resonant bar detectors

- AURIGA bar near Padova, Italy (typical of some ~5 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- $Q = 4 \times 10^6$ at < 1K
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive transducer and electronics (SQUID)
Resonant Bar detectors around the world

International Gravitational Event Collaboration (IGEC)

<table>
<thead>
<tr>
<th>detector</th>
<th>ALLEGRO</th>
<th>AURIGA</th>
<th>EXPLORER</th>
<th>NAUTILUS</th>
<th>NIOBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode frequencies [Hz]</td>
<td>895, 920</td>
<td>912, 930</td>
<td>905, 921</td>
<td>908, 924</td>
<td>694, 713</td>
</tr>
<tr>
<td>Bar mass $M$ [kg]</td>
<td>2296</td>
<td>2230</td>
<td>2270</td>
<td>2260</td>
<td>1500</td>
</tr>
<tr>
<td>Bar length $L$ [m]</td>
<td>3.0</td>
<td>2.9</td>
<td>3.0</td>
<td>3.0</td>
<td>2.75</td>
</tr>
<tr>
<td>Bar temperature $[K]$</td>
<td>4.2</td>
<td>0.2</td>
<td>2.6</td>
<td>0.1</td>
<td>5.0</td>
</tr>
<tr>
<td>Longitude</td>
<td>91°10′44″W</td>
<td>11°56′54″E</td>
<td>6°12′E</td>
<td>12°40′21″E</td>
<td>115°49′E</td>
</tr>
<tr>
<td>Latitude</td>
<td>30°27′45″N</td>
<td>45°21′12″N</td>
<td>46°27′N</td>
<td>41°49′26″N</td>
<td>31°56′S</td>
</tr>
<tr>
<td>Azimuth</td>
<td>40°W</td>
<td>44°E</td>
<td>39°E</td>
<td>44°E</td>
<td>0°</td>
</tr>
</tbody>
</table>

Baton Rouge, LA USA  Legarno, Italy  CERN, Suisse  Frascati, Italy  Perth, Australia
Interferometric detection of GWs

GW acts on freely falling masses:

For fixed ability to measure $\Delta L$, make $L$ as big as possible!

Antenna pattern: (not very directional!)
Seismic motion --
ground motion due to
natural and
anthropogenic
sources

Thermal noise --
vibrations due to finite
temperature

\[ h = \frac{\Delta L}{L} \]

want to get \( h \leq 10^{-22} \);
can build \( L = 4 \text{ km} \);
must measure
\[ \Delta L = h L \leq 4 \times 10^{-19} \text{ m} \]

Shot noise --
quantum fluctuations
in the number of
photons detected
Global network of detectors

- Simultaneous detection (within msecs)
- Detection confidence
- Sky location
- Source polarization
- Verify light speed propagation
International network

Simultaneously detect signal (within msec)

- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!
LIGO, VIRGO, GEO, TAMA …
Event Localization With An Array of GW Interferometers

\[ \cos \theta = \frac{\delta t}{c D_{12}} \]
\[ \Delta \theta \sim 0.5 \text{ deg} \]
The Laser Interferometer Space Antenna (LISA) may fly in the next 10 years!

Three spacecraft in orbit about the sun, with 5 million km baseline.

The center of the triangle formation will be in the ecliptic plane 1 AU from the Sun and 20 degrees behind the Earth.
LISA Spacecraft
The orbit of the “triangle” of spacecraft *tumbles* as it orbits the sun, to be sensitive to all directions in the sky, and to even out the thermal load (from the sun) on the three spacecraft.
Electromagnetic waves
- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

Gravitational waves
- over ~8 orders of magnitude
- Terrestrial + space detectors
LIGO – the first Km-class GW detector

\[ \Delta L = h \quad L \lesssim 4 \times 10^{-16} \text{ cm} \]

\[ \lesssim 10^{-21} \quad 4 \text{ km} \]
Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure *difference in length* to one part in $10^{21}$ or $10^{-18}$ meters

![Diagram of interferometer concept with labeled parts: photodiode, beam splitter, suspended masses, power recycling mirror, seismic isolation stacks.]

- Power recycling mirror sends reflected light back in, *coherently*, to be reused
- Pattern to change at the photodiode

AJW, Caltech  Phys 242, 10/20/06
LIGO Observatories

Hanford (LHO) :
- two interferometers in same vacuum envelope

Livingston (LLO) :
- one interferometer

Both sites are relatively seismically quiet, low human noise
Interferometer Noise Limits

**Thermal (Brownian) Noise**
- Laser
- Test mass (mirror)
- Residual gas scattering
- Wavelength & amplitude fluctuations
- Photodiode

**Seismic Noise**

**Quantum Noise**
- "Shot" noise
- Radiation pressure

**Residual gas scattering**

**BIG CHALLENGE:**
reduce all other noise sources (non-fundamental, or technical, associated with imperfect implementation of the design) to insignificance

AJW, Caltech Phys 242, 10/20/06
Initial LIGO Sensitivity Goal

- Strain sensitivity $< 3 \times 10^{-23} \, 1/\text{Hz}^{1/2}$ at 200 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Facilities limits much lower
- BIG CHALLENGE: reduce all other (non-fundamental, or technical) noise sources to insignificance
Science Runs

4/03: S2 ~ 0.9Mpc
10/02: S1 ~ 100 kpc
4/02: E8 ~ 5 kpc

A Measure of Progress
Virgo Cluster
NN Binary Inspiral Range

11:03: S3 ~ 3 Mpc
Design ~ 18 Mpc

Andromeda
Milky Way
Virgo Cluster
Strain Sensitivity for the LIGO 4km Interferometers

S5 Performance - June 2006  LIGO-G060293-01-Z

Current: all three detectors are at design sensitivity from ~ 60 Hz up!
Time Line

Inauguration

First Lock

Full Lock all IFO

1999 2000 2001 2002 2003 2004 2005 2006

1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4

Inauguration
First Lock
Full Lock all IFO

4K strain noise

$10^{-17}$ $10^{-18}$ $10^{-20}$ $10^{-21}$ $10^{-22}$

at 150 Hz $[\text{Hz}^{-1/2}]$

Engineering

E2 E3 E5 E7 E8 E9 E10 E11

Science

S1 S2 S3 S4 S5

First Science Data

Begin November 2005
18 months at design sensitivity

AJW, Caltech Phys 242, 10/20/06
And on to the future
<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>NSF funding secured ($360M)</td>
</tr>
<tr>
<td>1996</td>
<td>Construction Underway (mostly civil)</td>
</tr>
<tr>
<td>1997</td>
<td>Facility Construction (vacuum system)</td>
</tr>
<tr>
<td>1998</td>
<td>Interferometer Construction (complete facilities)</td>
</tr>
<tr>
<td>1999</td>
<td>Construction Complete (interferometers in vacuum)</td>
</tr>
<tr>
<td>2000</td>
<td>Detector Installation (commissioning subsystems)</td>
</tr>
<tr>
<td>2001</td>
<td>Commission Interferometers (first coincidences)</td>
</tr>
<tr>
<td>2002</td>
<td>Sensitivity studies (initiate LIGO I Science Run)</td>
</tr>
<tr>
<td>2003-4</td>
<td>LIGO I data runs (S1, S2, S3, S4), first science results (upper limits)</td>
</tr>
<tr>
<td>2005+</td>
<td>LIGO I data run (one year integrated data at $h &lt; 10^{-21}$)</td>
</tr>
</tbody>
</table>

2004 | Advanced LIGO approved by the NSB |
2007… | Begin Advanced LIGO upgrade installation |
2010… | Begin Advanced LIGO observations… |
Advanced LIGO
incremental improvements

- Reduce shot noise:
  higher power CW-laser: 12 watts ⇒ 120 watts
- Reduce shot noise: Advanced optical configuration:
  signal recycling mirror (7th suspended optic) to tune
  shot-noise response in frequency
- To handle thermal distortions due to beam heating:
  advanced mirror materials, coatings, thermal de-lensing
  compensation (heating mirror at edges)
- Reduce seismic noise: Active seismic isolation.
  Seismic wall moved from 40 Hz ⇒ ~ 10 Hz.
- Reduce seismic and suspension noise: Multiple pendulum
  suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise:
  Last pendulum stage (test mass) is controlled via photonic and/or
  electrostatic forces (no magnets).
- Reduce test mass thermal noise:
  High-Q material (40 kg of single-crystal sapphire).
Improvement of reach with Advanced LIGO

Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!

Virgo cluster

LIGO I

LIGO II
Prototype IFOs

- **40 meter (Caltech)**: full engineering prototype for optical and control plant for AdvLIGO
- **Thermal Noise Interferometer (TNI, Caltech)**: measure thermal noise in AdvLIGO test masses
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)**: full-scale prototyping of AdvLIGO seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford)**: advanced IFO configs (Sagnac)
- **10 meter IFO at Glasgow**: prototype optics and control of RSE
- **TAMA 30 meter (Tokyo)**: Advanced technologies (SAS, RSE, control schemes, sapphire, cryogenic mirrors)
- **AIGO (Gingin, Western Australia)**: high powered lasers, thermal effects and compensation
Advanced LIGO prototyping

- **Caltech LIGO 40 Meter Gravitational Wave Interferometer (Weinstein)**
  - Full engineering prototype of the Advanced LIGO optical configuration and controls

- **Thermal Noise Interferometer (Libbrecht)**
  - Direct measurement of thermal noise in mirrors made of advanced materials
Advanced LIGO R&D

- Development of multiple pendulum suspensions with silica fibers
  » Willems et al
- Development of advanced seismic isolation and suspension systems
  » de Salvo et al
- Advanced interferometer techniques at the Drever laboratory
- Simulations of complex interferometer behavior
  » Yamamoto et al
- Advanced optical techniques to reduce quantum readout noise (squeezed light)
  » Whitcomb et al
Beyond Advanced LIGO

- Flat-top beams to reduce thermal noise.
- Quantum non-demolition techniques (squeezed light, etc) to get beyond the “Standard” quantum limit.
- Cryogenically-cooled test masses?
- Driving the seismic wall from \( \sim 12 \text{ Hz} \rightarrow 1 \text{ Hz or below} \)?
- Radically different optical design (Sagnac?)
- Non-transmissive optics (Sagnac?)

?
Opportunities for graduate students

- LIGO is taking data NOW; gravitational waves *might* be in the can!
- LIGO will DISCOVER gravitational waves (well, it might not happen till Advanced LIGO, 5 years from now...), and open up a new, unique, and deep field of astrophysics.
- The field has a rich future: world-wide network, LISA, correlations with CMB, neutrinos, optical, etc.
- Advanced LIGO will happen in the next few years.
- LIGO takes the field of precision measurement to new heights; in a sense, it is one of the *ultimate* realizations of the art of experimental physics.
- Much work, and many clever ideas, are required to realize the full potential of gravitational wave astrophysics.
- NOW is a good time to get involved!
What can grad students do?

- Contribute to understanding, commissioning, noise reduction efforts of the 3 LIGO interferometers. We’re only beginning to make LIGO work as a detector / observatory.

- Astrophysics of sources; simulations
  - black hole binaries, neutron star binaries, supernovas, pulsars, cosmic background

- Analyze LIGO data, searching for signals with ever-increasing sensitivity.
  - develop new algorithms, implement them, make them work on the large LIGO dataset, optimize, evaluate their performance…
  - Will we miss the most interesting waveforms?

- Contribute to development of new technologies and interferometry, to push the performance for Advanced LIGO, LISA, and beyond.

- Any combination of the above!

- Great challenges … fabulous scientific payoff!
Space-time of the universe is (presumably!) filled with vibrations: Einstein’s Symphony

LIGO will soon ‘listen’ for Einstein’s Symphony with gravitational waves, permitting
» Basic tests of General Relativity
» A new field of astronomy and astrophysics

LIGO is precision measurement at its finest!
Opening up new window on the universe…