Gravitational Waves and LIGO

- Gravitational waves
- Detection of GW’s
- The LIGO project and its sister projects
- Astrophysical sources
- LIGO search for GWs
- Conclusions

Alan Weinstein, Caltech

"Colliding Black Holes"
National Center for Supercomputing Applications (NCSA)

AJW, CERN, July 14, 2004
The nature of Gravity

Newton’s Theory

“instantaneous action at a distance”

\[ F = m_1 a = G \frac{m_1 m_2}{r^2} \]

Einstein’s General Theory of Relativity

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]

Gravity is a local property of the space occupied by mass \( m_1 \).
Information carried by gravitational radiation at the speed of light
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

AJW, CERN, July 14, 2004
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

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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
- \textit{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 (\( \oplus \)) and cross (\( \otimes \)) (EM: two polarizations, \( x \) and \( y \))
  - \textit{Spin of graviton} = 2
- Conservation laws:
  - cons of energy \( \Rightarrow \) no monopole radiation
  - cons of momentum \( \Rightarrow \) no dipole radiation
  - lowest multipole is quadrupole wave (spin 2)

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

Contrast with EM dipole radiation:

- \( \hat{x} \) (left-right)
- \( \hat{y} \) (up-down)
Sources of GWs

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

\[ M \sim 10^{30} \text{ kg} \]
\[ R \sim 20 \text{ km} \]
\[ f \sim 400 \text{ Hz} \]
\[ r \sim 10^{23} \text{ m} \]

\[ h \sim 10^{-21} \]

Terrestrial sources TOO WEAK!
Contrast EM and GW information

<table>
<thead>
<tr>
<th>E&amp;M</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>space as medium for field</td>
<td>Space-time itself</td>
</tr>
<tr>
<td>incoherent superpositions of atoms, molecules</td>
<td>coherent motions of huge masses (or energy)</td>
</tr>
<tr>
<td>wavelength small compared to sources - images</td>
<td>wavelength ~large compared to sources - poor spatial resolution</td>
</tr>
<tr>
<td>absorbed, scattered, dispersed by matter</td>
<td>very small interaction; no shielding</td>
</tr>
<tr>
<td>$10^6$ Hz and up</td>
<td>$10^3$ Hz and down</td>
</tr>
<tr>
<td>measure amplitude (radio) or intensity (light)</td>
<td>measure amplitude</td>
</tr>
<tr>
<td>detectors have small solid angle acceptance</td>
<td>detectors have large solid angle acceptance</td>
</tr>
</tbody>
</table>

- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on E&M observations
- GW astronomy is a totally new and unique window on the universe

*AJW, CERN, July 14, 2004*
Observing the Galaxy with Different Electromagnetic Wavelengths

http://antwrp.gsfc.nasa.gov/apod/image/SagSunMW_up_big.gif
\[ \lambda = 5 \times 10^{-7} \text{ m} \]

http://antwrp.gsfc.nasa.gov/apod/image/xallsky_rosat_big.gif
\[ \lambda = 6 \times 10^{-13} \text{ m} \]

http://antwrp.gsfc.nasa.gov/apod/image/comptel_allsky_1to3_big.gif
\[ \lambda = 5 \times 10^{-10} \text{ m} \]

http://cosscc.gsfc.nasa.gov/cosscc/egret/
\[ \lambda = 1 \times 10^{-14} \text{ m} \]

http://www.gsfc.nasa.gov/astro/cobe
\[ \lambda = 2 \times 10^{-8} \text{ m} \]

\[ \lambda = 9 \times 10^{-1} \text{ m} \]

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What will we see?

A NEW WINDOW ON THE UNIVERSE WILL OPEN UP FOR EXPLORATION. BE THERE!

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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 [kg]</td>
<td>2296</td>
<td>2230</td>
<td>2270</td>
<td>2260</td>
<td>1500</td>
</tr>
<tr>
<td>Bar length [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

AJW, CERN, July 14, 2004
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!)

$P_{out} = P_{in} \sin^2 (2k\Delta L)$
LIGO – the first Km-class GW detector
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

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 (NASA/JPL, ESA) may fly in the next 10 years!

AJW, CERN, July 14, 2004
EM waves are studied over ~20 orders of magnitude
\(\text{»} \quad \text{(ULF radio} \rightarrow \text{HE } \gamma \text{ rays)}\)

Gravitational Waves over ~10 orders of magnitude
\(\text{»} \quad \text{(terrestrial + space)}\)
LIGO Observatories

Hanford (LHO): two interferometers in same vacuum envelope

Livingston (LLO): one interferometer

Both sites are relatively seismically quiet, low human noise

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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

Power recycling mirror sends reflected light back in, *coherently*, to be reused

Pattern to change at the photodiode

Suspended Masses
Seismic Isolation Stacks

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Interferometer Noise Limits

At present, noise in the LIGO detectors is dominated by “technical” sources, associated with as-yet-imperfect implementation of the design.
Commissioning and the First Science Runs

1999 2000 2001 2002 2003 2004

- 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q

- Inauguration
- First Lock
- Full Lock all IFO's
- Now

strain noise density @ 200 Hz [Hz^{-1/2}]

- 10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22}

Engineering
- E1 E2 E3 E4 E5 E6 E7 E8 E9 E10

Runs Science
- S1 S2 S3 S4

First Science Data

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Sensitivity in 3 Science Runs

Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1, S2, S3  LIGO-G030548-00-E

S1
1st Science Run
end Sept. 2002
17 days

S2
2nd Science Run
end Apr. 2003
59 days

S3
3rd Science Run
end Jan. 2004
64 days

LIGO Target Sensitivity
<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+</td>
<td>LIGO I data run (one year integrated data at $h \sim 10^{-21}$)</td>
</tr>
</tbody>
</table>

2007… Begin Advanced LIGO upgrade installation
2008… Begin Advanced LIGO observations…

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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

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Astrophysical Sources of Gravitational Waves

- **Compact binary systems**
  - Black holes and neutron stars
  - Inspiral → merger → ringdown
  - Probe internal structure, nuclear eqn of state of NS crust, populations, and spacetime geometry

- **Spinning neutron stars**
  - known & unknown pulsars
  - LMXBs
  - Probe internal structure and populations

- **Neutron star birth**
  - Supernova core collapse
  - Instabilities: tumbling, convection
  - Correlations with EM observations

- **Stochastic background**
  - Big bang & other early universe
  - Background of GW bursts

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GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

- Neutron star – neutron star (Centrella et al.)
Binary Orbit Evolution

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

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

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

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Hulse-Taylor binary pulsar

- A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / 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!

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

AJW, CERN, July 14, 2004
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 $\leftrightarrow$ 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

*emission of gravitational waves by compact binary system*
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

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The sound of a 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

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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 $\mathcal{R}_{\text{gal}}$ in our galaxy (with masses $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ for BH), the distances $D_I$ and $D_{\text{WB}}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_I$ and $\mathcal{R}_{\text{WB}}$; Secs. 1.1 and 1.2.

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

V. Kalogera (population synthesis)

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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

‘burst’ signal

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Zwerger-Müller SN waveforms

- astrophysically-motivated waveforms, computed from simulations of axi-symmetric SN core collapses.
- Almost all waveforms have duration < 0.2 sec
- A "menagerie", revealing only crude systematic regularities. Inappropriate for matched filtering or other model-dependent approaches.
  » Their main utility is to provide a set of signals that one could use to compare the efficacy of different filtering techniques.
- Absolute normalization/distance scale.
Pulsars and continuous wave sources

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

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Gravitational waves from Big Bang

Cosmic microwave background

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GWs probe the universe at earliest times after the Big Bang
LIGO limits and expectations on $\Omega_{GW}$

S1 result: $\Omega_{GW} < 23$

S2 prelim: $\Omega_{GW} < 0.02$

S3 expect: $\Omega_{GW} < \sim 10^{-3}$

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!

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Frequency-Time Characteristics of GW Sources

- Burst are short duration, broadband events
- Chirps explore the greatest time-frequency area
- BH Ringdowns expected to be associated with chirps
- CW sources have FM characteristics which depend on position on the sky (and source parameters)
- Stochastic background is stationary and broadband

For each source, the optimal signal to noise ratio is obtained by integrating signal along the trajectory:

- If SNR >> 1, kernel \( \propto |\text{signal}|^2 \)
- If SNR \( \leq 1 \), kernel \( \propto |\text{template}^* \text{signal}| \) or \( |\text{signal}^* \text{signal}_k| \)

Optimal filter:

\[
\mu \frac{1}{\text{noise power}} \text{time} \approx 2.6 \times 10^{-4}
\]

\[
\frac{\Delta f}{f} \approx 4 \times 10^{-6}
\]

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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
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

A new window on the universe!

AJW, CERN, July 14, 2004