Gravitational waves and LIGO: Status Report

- Brief introduction to LIGO
  - What is a gravitational wave?
  - Astrophysical sources
  - Gravitational wave interferometers
  - LIGO and its sister projects

- Progress report on Engineering runs

- Data analysis – finding signals in the noise

Alan Weinstein, Caltech
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*

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**BENDING LIGHT**

- **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**

- **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.

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*AJW, Caltech/LIGO, at UC Riverside*
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:

- **transverse space-time distortions,** freely propagating at speed of light
  
  \( \text{mass of graviton} = 0 \)

- Stretches and squashes space between “test masses” – strain
  
  \( h = \Delta L/L \)

- Conservation laws:
  
  - cons of energy \( \Rightarrow \) no monopole radiation
  
  - cons of momentum \( \Rightarrow \) no dipole radiation
  
  - quadrupole wave (spin 2) \( \Rightarrow \) two polarizations

  plus (\( \oplus \)) and cross (\( \otimes \))

  \[ Spin \text{ of graviton} = 2 \]

Contrast with EM dipole radiation:

\( \hat{x} ((\rightarrow)) \quad \hat{y} \)
## 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

LIGO-G020007-00-R

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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!)
LIGO – the first Km-class GW detector

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

\[ \lesssim 10^{-21} \quad 4 \text{ km} \]
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
Observing the Galaxy with Different Electromagnetic Wavelengths

\[ \lambda = 1 \times 10^{-14} \text{ m} \]

http://cossc.gsfc.nasa.gov/cossc/egret/

\[ \lambda = 5 \times 10^{-10} \text{ m} \]

http://antwrp.gsfc.nasa.gov/apod/image/SagSumMW_dp_big.gif

\[ \lambda = 6 \times 10^{-13} \text{ m} \]

http://antwrp.gsfc.nasa.gov/apod/image/xallsky_rosat_big.gif

\[ \lambda = 5 \times 10^{-7} \text{ m} \]

http://antwrp.gsfc.nasa.gov/apod/image/comptel_allsky_1to3_big.gif

\[ \lambda = 2 \times 10^{-8} \text{ m} \]

http://www.gsfc.nasa.gov/astro/cobe

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


AJW, Caltech/LIGO, at UC Riverside
What will we see?

A NEW WINDOW ON THE UNIVERSE WILL OPEN UP FOR EXPLORATION. BE THERE!
Astrophysical Sources of Gravitational Waves

- Coalescing compact binaries (neutron stars, black holes)
- Non-axi-symmetric supernova collapse
- Non-axi-symmetric pulsar (rotating, beaming neutron star)
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

- Neutron star – neutron star (Centrella et al.)

LIGO-G020007-00-R

AJW, Caltech/LIGO, at UC Riverside
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
How many sources can we see?

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

⇒ Number of sources goes up 1000x!
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><strong>LIGO I</strong></td>
<td>$R_I, \text{ yr}^{-1}$</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>
</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><strong>LIGO II</strong></td>
<td>$R_{WB}, \text{ yr}^{-1}$</td>
<td>0.5 – 100</td>
<td>$\lesssim 0.5 - 1000$</td>
<td>$\lesssim 10 - 2000$</td>
</tr>
</tbody>
</table>

V. Kalogera (population synthesis)
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

‘burst’ signal

Rate
1/50 yr - our galaxy
3/yr - Virgo cluster
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
Gravitational waves from Big Bang
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!
Event Localization With An Array of GW Interferometers

\[ \cos \theta = \frac{\delta t}{c D_{12}} \]

\[ \Delta \theta \sim 0.5 \text{ deg} \]
Hanford, WA (LHO)
- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- Two IFOs: H2K and H4K

Livingston, LA (LLO)
- located in forested, rural area
- commercial logging, wet climate
- 50 km from Baton Rouge, LA
- One L4K IFO

Both sites are relatively seismically quiet, low human noise
LIGO Livingston (LLO)

- 30 miles from Baton Rouge, LA (LSU)
- forested, rural area
- Commercial logging, wet climate
- need moats (with alligators)
- Seismically quiet, low human noise level
LIGO Hanford (LHO)

• DOE nuclear reservation
• treeless, semi-arid high desert
• 15 miles from Richmond, WA
• Seismically quiet, low human noise level
**Interferometer for GWs**

- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in $10^{10}$, in order to obtain the required sensitivity.
The effects of gravitational waves appear as a deviation in the phase differences between two orthogonal light paths of an interferometer.

For expected signal strengths, the effect is tiny:

Phase shift of $\sim 10^{-10}$ radians

The longer the light path, the larger the phase shift...

Make the light path as long as possible!
Light storage: folding the arms

How to get long light paths without making huge detectors:

Fold the light path!

Delay line interferometer

Simple, but requires large mirrors; limited $\tau_{stor}$

Fabry Perot interferometer

(LIGO design) $\tau_{stor} \sim 3 \text{ msec}$

More compact, but harder to control
LIGO I configuration

Power-recycled Michelson with Fabry-Perot arms:

- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in (coherently!) to be reused
Suspended test masses

- To respond to the GW, test masses must be “free falling”
- On Earth, test masses must be supported against DC gravity field
- The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical):
  - can’t simply bolt the masses to the table (as in typical ifo’s in physics labs)
- So, IFO is insensitive to low frequency GW’s
- Test masses are suspended on a pendulum resting on a seismic isolation stack
  - “fixed” against gravity at low frequencies, but
  - “free” to move at frequencies above ~ 100 Hz

“Free” mass: pendulum at $f \gg f_0$
Interferometer

Requires test masses to be held in position to $10^{-10}$-$10^{-13}$ meter:
“Locking the interferometer”

Light is “recycled” about 50 times

Light bounces back and forth along arms about 150 times
Interferometry is limited by three fundamental noise sources:
- **Seismic noise** at the lowest frequencies
- **Thermal noise** at intermediate frequencies
- **Shot noise** at high frequencies

Many other noise sources lurk underneath and must be controlled as the instrument is improved.
LIGO I schedule

1995  NSF funding secured ($360M)
1996  Construction Underway (mostly civil)
1997  Facility Construction (vacuum system)
1998  Interferometer Construction (complete facilities)
1999  Construction Complete (interferometers in vacuum)
2000  Detector Installation (commissioning subsystems)
2001  Commission Interferometers (first coincidences)
2002  Sensitivity studies (initiate LIGO I Science Run)
2003+ LIGO I data run (one year integrated data at $h \sim 10^{-21}$)

2007  Begin Advanced LIGO upgrade
LIGO Engineering runs

- Commissioning GW IFO’s is a very tricky business!
  - They are complex, non-linear, non-reductionistic systems
  - There’s precious little experience…
- First task is to get the IFO’s to operate in the correct configuration, with all optical cavities resonating – “In Lock”
- Next task is to reduce the noise (reduce all non-fundamental noise sources to insignificance), improve sensitivity
- LIGO has had 6 engineering runs in 2000-2001, focusing on keeping IFO’s In Lock for long periods of time (duty cycle)
- “First Lock” achieved at H2K on October 2000
- Rarely had more than one IFO (of 3) operating at a time – till E7!
- Engineering Run 7 (Dec 28, 2001 – Jan 14, 2002) is by far the most successful we’ve had!
- Plan E8 next month, and first Science run by late summer 2002.
LIGO Engineering run 7 (E7)

- Focus on duty-cycle, not noise or noise reduction
- ALL 3 IFO's were running and achieving lock for significant fraction of the time
- GEO IFO is also up, and is participating; also ALLEGRO and GRBs
- Some ongoing investigations:
  - Compile statistics on lock acquisition and lock loss, study sources of lock loss
  - Quantify correlations between GW and other (IFO and environmental) channels
  - Correlations between noise, transients in GW channel between IFOs
  - Test simulated astrophysical signal injection
  - Identify environmental disturbances
  - Gaussianity, stationarity of noise in GW channel
- "physics searches" ran online in LIGO Data Analysis System (LDAS)
A variety of learning experiences

- Computer crashes
- Earthquakes
- No fire or floods yet…
- Logging at Livingston
- Cars driving over cattle guards
- Wind at Hanford
- Snow in Louisiana

6 hrs
Logging at Livingston

Less than 3 km away…
Dragging big logs …
Remedial measures at LIGO are in progress; this will not be a problem in the future.
Earthquakes...

This one, on February 28, 2000 knocked out the H2K
For months...

Earthquakes have not been a problem for E7, but we can “hear” them with the IFO

Vanuatu, 1/2/02, 6.3M

From GEO
LIGO IFO duty cycle, E7

Livingston 4k:
Total locked time: 265 hrs
Duty cycle: 69.8 %
Total time locked with locks longer than 15min: 232 hrs
Duty cycle for long locks: 61.3 %

Hanford 4k:
Total locked time: 274 hrs
Duty cycle: 71.3 %
Total time locked with locks longer than 15min: 216 hrs
Duty cycle for long locks: 56.3 %

Hanford 2k:
Total locked time: 210 hrs
Duty cycle: 54.9 %
Total time locked with locks longer than 15min: 156 hrs
Duty cycle for long locks: 40.6 %

Hanford and Livingston 4k:
Total locked time: 209 hrs
Duty cycle: 54.5 %
Total time locked with locks longer than 15min: 143 hrs
Duty cycle for long locks: 54 %

Three LIGO Interferometers:
Total locked time: 138 hrs
Duty cycle: 35.9 %
Total time locked with locks longer than 15min: 70.8 hrs
Duty cycle for long locks: 18.5 %

We are thrilled!!

AJW, Caltech/LIGO, at UC Riverside
Gamma Ray Bursts during E7 and LIGO coverage

<table>
<thead>
<tr>
<th>Detector</th>
<th>Tr#</th>
<th>Date</th>
<th>Time (UTC)</th>
<th>GPS</th>
<th>Locked Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEPPOSAX GRBM</td>
<td>1</td>
<td>01/12/28</td>
<td>23:19:15</td>
<td>693616768</td>
<td>LHO 4K</td>
</tr>
<tr>
<td>KONUS WIND</td>
<td>2</td>
<td>01/12/29</td>
<td>10:23:20</td>
<td>693656613</td>
<td>LHO 2K, 4K, LLO 4K</td>
</tr>
<tr>
<td>BEPPOSAX GRBM</td>
<td>3</td>
<td>01/12/30</td>
<td>08:48:23</td>
<td>693737316</td>
<td>LHO 2K, 4K, LLO 4K</td>
</tr>
<tr>
<td>BEPPOSAX GRBM</td>
<td>4</td>
<td>01/12/31</td>
<td>03:34:40</td>
<td>693804893</td>
<td>LHO 2K, LLO 4K</td>
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<tr>
<td>BEPPOSAX GRBM</td>
<td>5</td>
<td>01/12/30</td>
<td>15:03:29</td>
<td>693759822</td>
<td>LHO 2K, LLO 4K</td>
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<tr>
<td>GCN/HETE</td>
<td>1885</td>
<td>02/01/05</td>
<td>12:46:00.91</td>
<td>694269973.91</td>
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<td>GCN/HETE</td>
<td>1887</td>
<td>02/01/08</td>
<td>08:20:37.48</td>
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<td>LHO 2K, 4K, LLO 4K</td>
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<td>GCN/HETE</td>
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<td>08:27:26.42</td>
<td>694513659.42</td>
<td>LHO 2K, LLO 4K</td>
</tr>
</tbody>
</table>

We are also running simultaneously with ALLEGRO bar at LSU.
Strain Sensitivity of LIGO IFO’s during E7 (preliminary…)

Contributions:
- PSL frequency noise (need common mode servo on all IFOs)
- Misalignments (reduce noise in oplevs; tuning of alignments servos needed)
- Laser glitches & bursts (reduce acoustic coupling into PSL)
- Periscope vibrations on PSL table (~200 Hz)
- Photodetector preamp Johnson noise (high-f)
- Excess noise in Pentek ADCs
- Excess coil driver/DAC noise
- Unidentified electronics noise
- Low laser power (operating at 1 watt, not 6 watts)

ALL technical noise; No fundamental noise exposed yet.
Time-frequency spectrogram of GW signal – stationary?

Time frequency plot, L1:LSC-ASQ, 693754800–693754928, T = 128 s

AJW, Caltech/LIGO, at UC Riverside
Initial LIGO Sensitivity Goal

- Strain sensitivity goal: $<3\times10^{-23} \text{ 1/Hz}^{1/2}$ at 200 Hz
- So far, getting $\sim(5-10)\times10^{-20} \text{ 1/Hz}^{1/2}$ at $\sim1000$ Hz

- Better than we expected!
- During E7, sensitivity is a bit better than for H2K during previous runs; but…
- We’re getting similar sensitivity out of all 3 IFO’s, simultaneously!
LIGO E7 summary

- Coincident operation of 3 LIGO detectors, GEO, ALLEGRO is unprecedented.
- Duty cycle has greatly exceeded our expectations.
- We are operating in a new regime of sensitivity and bandwidth; will be able to set new experimental limits.
- Coincidence with ALLEGRO will permit a limit for a stochastic background limited by the sensitivity of the bar.

- MANY lessons learned and needs being addressed.
- Work on improving sensitivity has now recommenced.
- Already major improvements have been made!
  - new and/or tuned servos; better laser isolation; higher laser power; better alignment and mis-alignment sensing; seismic pre-isolation upgrade; …
- First science run (S1) planned for this summer.
Post-E7 sensitivity (LHO2K)

New and important servos commissioned. Still operating at low power. Improvements being made continuously…
LIGO Data analysis

- 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!
- Waveform morphologies being considered:
  » Bursts (of limited duration), for which we have models (chirps, ringdowns)
  » Bursts, for which we have no reliable models (supernovas, …)
  » Continuous waves, narrow bandwidth - periodic (pulsars)
  » Continuous waves, broad bandwidth - stochastic (BB background)
- Each requires radically different data analysis techniques.
- Algorithms, implementation development is in its infancy.
Waveforms of Gravitational Waves

- **“Chirps”** (reasonably known waveforms)
  - Neutron star (NS/NS) binary pairs
  - Black hole (BH/BH) binaries; NS/BH binaries

- **Periodic** (well defined waveforms)
  - Pulsars with ellipticity, in our galaxy
  - R-modes (neutron stars spinning up, with instabilities)

- **Impulsive** (unknown waveforms)
  - Supernova bursts, BH mergers

- **Stochastic** (random, indistinguishable from noise)
  - Background from primordial cosmological event (Big Bang)

- **Unknown???
  - Rates, signal sizes, waveforms for all the above are very uncertain
  - Surprises are *certain*!
If we don’t have a well-modeled waveform: Detection Confidence

With all the noise faking GW signals,

How can we be sure we’ve seen the real thing (for first time!)?

VETO Environmental noise
- Try to eliminate locally all possible false signals
- Detectors for many possible sources
  - seismic, acoustic, electromagnetic, muon
- Also trend (slowly-varying) information
  - tilts, temperature, weather

Detection computation
- Coincidences (lack of inconsistency) among detectors
  - also non-GW: e.g., optical, X-ray, GRB, neutrino
- Matched filter techniques for ‘known’ signals
- Correlations for broad-band suspects
- Deviations from explicable instrumental behavior

Multiple interferometers – coincidence!
- Three interferometers within LIGO
  - 4 km at Hanford, 4 km at Livingston
  - Also 2 km at Hanford
- Absolute timing accuracy of 10 microsec
  - 10 msec light travel time between sites
- AND: other detectors (interferometers, bars)

With all the noise faking GW signals,

How can we be sure we’ve seen the real thing (for first time!)?
Frequency-Time Maps ("Images")
- your PC may already be doing them!

SETI@home uses frequency-time analysis methods to detect unexpected or novel features in otherwise featureless “hiss”
Frequency-Time Characteristics of GW Sources

- **Bursts** 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 < 1, kernel \( \propto |\text{template} \ast \text{signal}| \) or \( |\text{signal}_j \ast \text{signal}_k| \)
- **Optimal filter:** kernel \( \propto 1/(\text{noise power}) \)

Earth's orbit: \( \frac{\Delta f}{f} \approx 2.6 \times 10^{-4} \)
Earth's rotation: \( \frac{\Delta f}{f} \approx 4 \times 10^{-6} \)
Interferometer Data Channels

- All interferometric detector projects have agreed on a standard data format
- Anticipates joint data analysis
- LIGO Frames for 1 interferometer are ~3MB/s
  - 32 kB/s strain
  - ~2 MB/s other interferometer signals
  - ~1MB/s environmental sensors
- Strain is ~1% of all data

Gravitational waves
Seisms
Laser Fluctuations
Thermal Noise
Electromagnetics

Interferometer

Strain
Common mode signals
Alignment signals
Acoustic signals
Seismometer signals

GW Signal
Channel 1
Channel 2
Channel 3
Channel n
GPS Time

Frame 1
Frame 2
Frame 3
Frame 4
...

LIGO-G020007-00-R

AJW, Caltech/LIGO, at UC Riverside
DAQS data channels and rates

• Each IFO has dozens of fast (16 kHz) and hundreds of slow (< 1 kHz) channels; equivalent of ~ 150 fast channels/IFO.
• (16 kHz) \times (2 \text{ bytes}) \times (3 \text{ IFOs}) \times (150 \text{ ch/IFO}) \times (3 \times 10^7 \text{ sec/year}) \times (2 \text{ years}) \times (50\% \text{ duty cycle}) = 500 \text{ Tbytes}!
• Store full data stream on disk for ~ 1 day.
• Archive 10\% of data to tape: 50 \text{ Tbytes}!
• GW stream alone, decimated to 1 kHz: 200 \text{ GB}
• Data stored in Frames and in Meta-Database

<table>
<thead>
<tr>
<th>System</th>
<th>DAQS Network</th>
<th>Data Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channels</td>
<td>Rate (MByte/sec)</td>
</tr>
<tr>
<td>LHO-4K</td>
<td>510</td>
<td>4.22</td>
</tr>
<tr>
<td>LHO-2K</td>
<td>548</td>
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<tr>
<td>LHO-PME</td>
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<td>LHO-VAC</td>
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<td>LHO-GDS</td>
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<tr>
<td>LLO-4K</td>
<td>515</td>
<td>4.22</td>
</tr>
<tr>
<td>LLO-PME</td>
<td>95</td>
<td>0.46</td>
</tr>
<tr>
<td>LLO-VAC</td>
<td>300</td>
<td>0.01</td>
</tr>
<tr>
<td>LLO-GDS</td>
<td>76</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Data Flow: Pre-processing

Pre-processing & Conditioning:
- Dropouts
- Calibration
- Regression
- Feature removal
- Decimation
- ...

Data Acquisition:
- Whitening filter
- Amplification
- Anti-aliasing
- A/D

Reduced data tape

Data analysis

Pipelines
(Template Loop)

Strain reconstruction

6 MB/s

Master data tape

AJW, Caltech/LIGO, at UC Riverside
Interferometer Transients --
Examples from 40m Data

Real interferometer data is UGLY!!!
(Glitches - known and unknown)

LOCKING

RINGING

NORMAL

ROCKING
Interferometer Strain Signal (Simulated)

Dominated by narrowband features in spectrum ("violin resonances" of suspension wires")

Chirped waveform

Broadband noise spectrum

Design LIGO I limiting strain sensitivity

Initial LIGO Noise Curves

AJW, Caltech/LIGO, at UC Riverside
"Clean up" data stream

Effect of removing sinusoidal artifacts using multi-taper methods

Non stationary noise
Non gaussian tails
Chirp signal from Binary Inspiral

determine

• distance from the earth $r$
• masses of the two bodies
• orbital eccentricity $e$ and orbital inclination $i$
Optimal Wiener Filtering

- Matched filtering (optimal) looks for best overlap between a signal and a set of expected (template) signals in the presence of the instrument noise -- correlation filter
- Replace the data time series with an SNR time series
- Look for excess SNR to flag possible detection

$$\xi_p(t_c) = \int \frac{\hat{T}_p^*(f) \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$
Got to get the templates RIGHT

- Compute the dynamics of sources and their emitted waveforms

  » Why we need waveforms:
    - As templates to use in searches for waves via matched filtering
Lots to learn from the waveforms!

- **Compute the dynamics of sources and their**

  Last 5 days of inspiral of a $10^5$ Msun / $10^6$ Msun BH/BH binary
Compact Binary Inspirals
Data Analysis Flow

Launch

Get overlapping data segment

Pre-processing

Time window taper

FFT data segment

Data Loop

Reduced data stream

Get overlapping data segment

Pre-processing

Time window taper

FFT data segment

NO

Remaining templates?

YES

Display/record events

Broadcast candidate event(s)

NO

Change in noise floor?

YES

Update template parameters & noise floor

Template Loop

NO

Remaining templates?

YES

Display/record events

Broadcast candidate event(s)

NO

Change in noise floor?

YES

Update template parameters & noise floor

Data Loop

\[ \xi_p [t_c] = 2 \left[ \frac{\hat{T}_p * (f) \hat{S}(f)}{\hat{S}_n(f)} \right] e^{-2\pi f_{c} t_c} df \]

Based on formalism of:

Non-hierarchical Search

- Process data at real time rate
- Improvements:
  - Hierarchical searches developed
  - Phase coherent analysis of multiple detectors (in progress)
Simulations

- Test search codes with simulated inspirals and bursts added to the noisy data stream.
- Can also inject arbitrary waveform signals directly into the IFO, by moving the end mirrors.
- This also tests the interferometer response function, as measured through calibration procedure.
- It also tests the detailed E2E simulations of IFO performance.
Unmodeled bursts

- Look for excess power in time-frequency plane.
- Unfortunately, there are MANY noise bursts.
- Set excess power thresholds carefully; noise is NOT (yet) Gaussian and stationary!
- Veto on ones that correlate with environmental or non-GW-related IFO signals.
- Try not to veto away all the live time!
- Trade-off between efficiency and live-time.
- Must rely on in-time coincidences between sites
- Study correlations between sites very carefully!
- Can also look for coincidences with other IFOs, bars, GRBs, etc.
Perform CPU-intensive searches near real-time on parallel compute farms

LIGO labs and LSC institutions maintain 6 (and growing) LDAS installations with Beowulf PC/linux/MPI-based search engines.

Also involved in GRID computing initiatives (CACR, Harvey’s group).
When will physics results be available?

- We have hundreds of hours of E7 data in the can
  » LLO4K, LHO2K, LHO4K, GEO600, ALLEGRO, GRB alerts
- Work on improving detectors is ongoing.
- Plan on first science run (S1) in summer 2002.
- Currently working towards a pile of papers (Various inspiral, burst, periodic, stochastic searches) based on E7 data.
- It is not yet clear whether this will bear fruit before the first science run!
- If so, first papers might appear this summer.
- Else, papers based on S1 should be available by the end of 2002.

In parallel with science running,
Intense R&D on AdvLIGO – aim to install in 2007-9
Einstein’s Symphony

- 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!

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