LIGO: Status and Prospects

How does LIGO work and how well does LIGO work?

Barry Barish

University of Alberta
4-March-04
Einstein’s Theory of Gravitation

- a necessary consequence of Special Relativity with its finite speed for information transfer

- gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light

gravitational radiation
binary inspiral
of compact objects
Einstein’s equations have form similar to the equations of elasticity.

\[ P = Eh \quad (P = \text{stress, } h = \text{strain, } E = \text{Young’s mod.}) \]

\[ T = \left(\frac{c^4}{8\pi G}\right)h \quad T = \text{stress tensor, } G = \text{Curvature tensor and } c^4/8\pi G \sim 10^{42}\text{N is a space-time “stiffness” (energy density/unit curvature)} \]

- Space-time can carry waves.

- They have very small amplitude

- There is a large mismatch with ordinary matter, so very little energy is absorbed (very small cross-section)
Einstein’s Theory of Gravitation

gravitational waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, \( h_{mn} \). In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

\[
\left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu \nu} = 0
\]

• The strain \( h_{mn} \) takes the form of a plane wave propagating at the speed of light (c).

• Since gravity is spin 2, the waves have two components, but rotated by 45\(^0\) instead of 90\(^0\) from each other.

\[
h_{\mu \nu} = h_+ (t - z / c) + h_\times (t - z / c)
\]
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

...causing the interference pattern to change at the photodiode

Suspended Masses
change in different ways....
Simultaneous Detection

LIGO

Hanford Observatory

Caltech

Livingston Observatory

3082 km
(L/c = 10 ms)

MIT
LIGO Livingston Observatory
LIGO Facilities

**beam tube enclosure**

- minimal enclosure
- reinforced concrete
- no services

*Figure 2.1-1 -- Cross Section of Design Baseline at Hanford*
LIGO beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- Girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld
Vacuum Chambers

vibration isolation systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Compensate for microseism at 0.15 Hz by a factor of ten
» Compensate (partially) for Earth tides
Seismic Isolation

springs and masses

Constrained Layer
damped spring
LIGO vacuum equipment
Seismic Isolation
suspension system

- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz
LIGO Optics

fused silica

- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q’s > 2 x 10^6

Caltech data

CSIRO data
Core Optics
installation and alignment
Goals and Priorities

- **Interferometer performance**
  - Integrate commissioning and data taking consistent with obtaining one year of integrated data at $h = 10^{-21}$ by end of 2006

- **Physics results from LIGO I**
  - Initial upper limit results by early 2003
  - First search results in 2005
  - Reach LIGO I goals by 2007

- **Advanced LIGO**
  - Prepare advanced LIGO proposal this fall
  - International collaboration and broad LSC participation
  - Advanced LIGO installation beginning by 2007
LIGO Commissioning and Science Timeline

1999
Q1 Q2 Q3 Q4
Inauguration

2000
Q1 Q2 Q3 Q4
First Lock

2001
Q1 Q2 Q3 Q4
E1 E2 E3 E4 E5 E6 E7
Oscillometer

2002
Q1 Q2 Q3 Q4
S1 S2

2003
Q1 Q2 Q3 Q4
E9 S3

2004
Q1 Q2 Q3
E10

Now

Strain near 150 Hz
LHO4k
LHO2k
LLO4k

$10^{-17}$

$10^{-18}$

$10^{-19}$

$10^{-20}$

$3 \times 10^{-22}$

$10^{-21}$

$9 \times 10^{-23}$

One Arm

Power Recycled

Michelson

Recombined

Interferometer

Full

Interferometer

Washington Earthquake

Wire Accident

LHO 2km
Lock Acquisition
Tidal Compensation Data

Tidal evaluation 21-hour locked section of S1 data

Predicted tides
Feedforward
Feedback
Residual signal on voice coils
Residual signal on laser

4-March-04 University of Alberta
Controlling angular degrees of freedom

Trend Ch 2: H1:LSC-LA_SPOB_NORM

Trend Ch 1: H1:LSC-LA_PTRT_NORM

WFS1, WFS2A, WFS3, WFS4 not engaged

WFS1, WFS2A, WFS3, WFS4 engaged
Interferometer Noise Limits

Residual gas scattering

Seismic Noise

test mass (mirror)

Quantum Noise

Radiation pressure

"Shot" noise

LASER

Wavelength & amplitude fluctuations

Beam splitter

photodiode

Thermal (Brownian) Noise

4-March-04 University of Alberta
What Limits LIGO Sensitivity?

- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals
LIGO Sensitivity Evolution

Hanford 4km Interferometer

Dec 01

Nov 03
Science Runs

S2 ~ 0.9 Mpc
S1 ~ 100 kpc
E8 ~ 5 kpc
S3 ~ 3 Mpc
Design ~ 18 Mpc

Virgo Cluster

A Measure of Progress
NN Binary Inspiral Range

Milky Way Andromeda Virgo Cluster
Best Performance to Date ....

Range ~ 6 Mpc
Astrophysical Sources

- **Compact binary inspiral:** “chirps”
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates

- **Supernovae / GRBs:** “bursts”
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors

- **Pulsars in our galaxy:** “periodic”
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes

- **Cosmological Signal** “stochastic background”
Compact binary collisions

» Neutron Star – Neutron Star
  – waveforms are well described

» Black Hole – Black Hole
  – need better waveforms

» Search: *matched templates*

“chirps”
- Covers desired region of mass param space
- Calculated based on L1 noise curve
- Templates placed for max mismatch of $\delta = 0.03$
Optimal Filtering

*frequency domain*

- Transform data to frequency domain: \( \tilde{h}(f) \)
- Generate template in frequency domain: \( \tilde{s}(f) \)
- Correlate, weighting by power spectral density of noise:

\[
\frac{\tilde{s}(f) \tilde{h}^*(f)}{S_h(|f|)}
\]

Then inverse Fourier transform gives you the filter output

\[
z(t) = 4 \int_0^{\infty} \frac{\tilde{s}(f) \tilde{h}^*(f)}{S_h(|f|)} e^{2\pi i ft} df
\]

at all times:

Find maxima of \( |z(t)| \) over arrival time and phase
Characterize these by *signal-to-noise ratio* (SNR) and *effective distance*
Matched Filtering

- Top graph: Blue line represents data, red line represents time-shifted template.
- Bottom graph: Red line shows correlation vs. time shift.
Loudest Surviving Candidate

- Not NS/NS inspiral event
- 1 Sep 2002, 00:38:33 UTC
- S/N = 15.9, $\chi^2$/dof = 2.2
- $(m_1, m_2) = (1.3, 1.1)$ Msun

What caused this?
- Appears to be due to saturation of a photodiode
Sensitivity

neutron binary inspirals

Star Population in our Galaxy

- Population includes Milky Way, LMC and SMC
- Neutron star masses in range 1-3 Msun
- LMC and SMC contribute ~12% of Milky Way

Reach for S1 Data

Inspiral sensitivity
Livingston: $<D> = 176$ kpc
Hanford: $<D> = 36$ kpc
Sensitive to inspirals in Milky Way, LMC & SMC
Results of Inspiral Search

Upper limit binary neutron star coalescence rate

LIGO S1 Data
R < 160 / yr / MWEG

- Previous observational limits
  » Japanese TAMA → R < 30,000 / yr / MWEG
  » Caltech 40m → R < 4,000 / yr / MWEG

- Theoretical prediction R < 2 x 10^{-5} / yr / MWEG

Detectable Range of S2 data will reach Andromeda!
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Detection of Burst Sources

**Known sources -- Supernovae & GRBs**

» Coincidence with observed electromagnetic observations.
  » No close supernovae occurred during the first science run
  » Second science run – We are analyzing the recent very bright and close GRB030329

**Unknown phenomena**

» Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).
‘Unmodeled’ Bursts

**GOAL**

search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

**METHODS**

1. **‘Raw Data’**
2. **Time-domain high pass filter**
3. **Time-Frequency Plane Search**
   - ‘TFCLUSTERS’
   - frequency: 8Hz
   - time: 0.125s
4. **Pure Time-Domain Search**
   - ‘SLOPE’
   - frequency: 610us
Efficiency measured for ‘tfclusters’ algorithm

To measure our efficiency, we must pick a waveform.

1ms Gaussian burst
Burst Upper Limit from S1

1ms gaussian bursts

Result is derived using ‘TFCLUSTERS’ algorithm

Upper limit in \textit{strain} compared to earlier (cryogenic bar) results:

- IGEC 2001 combined bar upper limit: < 2 events per day having $h=1 \times 10^{-20}$ per Hz of burst bandwidth. For a 1kHz bandwidth, limit is < 2 events/day at $h=1 \times 10^{-17}$

- Astone \textit{et al.} (2002), report a 2.2 s excess of one event per day at strain level of $h \sim 2 \times 10^{-18}$
Astrophysical Sources


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Detection of Periodic Sources

- **Pulsars in our galaxy:** “periodic”
  - search for observed neutron stars
  - all sky search (computing challenge)
  - r-modes

- Frequency modulation of signal due to Earth’s motion relative to the Solar System Barycenter, intrinsic frequency changes.

- Amplitude modulation due to the detector’s antenna pattern.
Directed searches

NO DETECTION EXPECTED at present sensitivities

\[ \langle h_0 \rangle = 11.4 \sqrt{S_h(f_{GW})/T_{OBS}} \]

Limits of detectability for rotating NS with equatorial ellipticity \( \varepsilon = \delta/I_{zz} \): \( 10^{-3} \), \( 10^{-4} \), \( 10^{-5} \) @ 8.5 kpc.

PSR J1939+2134 1283.86 Hz

Crab Pulsar

PSR J1939+2134

NO DETECTION EXPECTED at present sensitivities
Two Search Methods

**Frequency domain**
- Best suited for large parameter space searches
- Maximum likelihood detection method + Frequentist approach

**Time domain**
- Best suited to target known objects, even if phase evolution is complicated
  - Bayesian approach

First science run --- use both pipelines for the same search for cross-checking and validation
The Data

\[ \sqrt{\langle S_h \rangle} \]

\[ \times 10^{-18} \]

- **GEO 600**
  - Days

\[ \sqrt{\langle S_h \rangle} \]

\[ \times 10^{-19} \]

- **Livingston 4km**
  - Days

\[ \sqrt{\langle S_h \rangle} \]

\[ \times 10^{-19} \]

- **Hanford 4km**
  - Days

\[ \sqrt{\langle S_h \rangle} \]

\[ \times 10^{-19} \]

- **Hanford 2km**
  - Days
The Data

**frequency behavior**

\[ \sqrt{S_h} \]
Frequency domain

- Fourier Transforms of time series
- Detection statistic: $F$, maximum likelihood ratio wrt unknown parameters
- use signal injections to measure $F$’s pdf
- use frequentist’s approach to derive upper limit

Injected signal in LLO: $h = 2.83 \times 10^{-22}$
**Time domain**

- time series is heterodyned
- noise is estimated
- Bayesian approach in parameter estimation: express result in terms of posterior pdf for parameters of interest

Injected signals in GEO:
\[ h = 1.5, 2.0, 2.5, 3.0 \times 10^{-21} \]
Results: Periodic Sources

- No evidence of continuous wave emission from PSR J1939+2134.

- Summary of 95% upper limits on h:

<table>
<thead>
<tr>
<th>IFO</th>
<th>Frequentist FDS</th>
<th>Bayesian TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>$(1.94 \pm 0.12) \times 10^{-21}$</td>
<td>$(2.1 \pm 0.1) \times 10^{-21}$</td>
</tr>
<tr>
<td>LLO</td>
<td>$(2.83 \pm 0.31) \times 10^{-22}$</td>
<td>$(1.4 \pm 0.1) \times 10^{-22}$</td>
</tr>
<tr>
<td>LHO-2K</td>
<td>$(4.71 \pm 0.50) \times 10^{-22}$</td>
<td>$(2.2 \pm 0.2) \times 10^{-22}$</td>
</tr>
<tr>
<td>LHO-4K</td>
<td>$(6.42 \pm 0.72) \times 10^{-22}$</td>
<td>$(2.7 \pm 0.3) \times 10^{-22}$</td>
</tr>
</tbody>
</table>

- Best previous results for PSR J1939+2134: $h_0 < 10^{-20}$
  (Glasgow, Hough et al., 1983)
Upper limit on pulsar ellipticity

\[ J1939+2134 \]

\[ h_0 = \frac{8\pi^2 G}{c^4} \frac{I_{zz}}{R} f_0^2 \epsilon \]

\[ h_0 < 3 \times 10^{-22} \Rightarrow \epsilon < 3 \times 10^{-4} \]

(M=1.4M_{\odot}, r=10km, R=3.6kpc)

Assumes emission is due to deviation from axisymmetry:
Multi-detector upper limits

**S2 Data Run**

- Performed joint coherent analysis for 28 pulsars using data from all IFOs.
- Most stringent UL is for pulsar J1629-6902 (~333 Hz) where 95% confident that $h_0 < 2.3 \times 10^{-24}$.
- 95% upper limit for Crab pulsar (~60 Hz) is $h_0 < 5.1 \times 10^{-23}$.
- 95% upper limit for J1939+2134 (~1284 Hz) is $h_0 < 1.3 \times 10^{-23}$. 

**95% upper limits**
Upper limits on ellipticity

Equatorial ellipticity:

\[ \varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} \]

Pulsars J0030+0451 (230 pc), J2124-3358 (250 pc), and J1024-0719 (350 pc) are the nearest three pulsars in the set and their equatorial ellipticities are all constrained to less than $10^{-5}$.
Approaching spin-down upper limits

- For Crab pulsar (B0531+21) we are still a factor of ~35 above the spin-down upper limit in S2.

- Hope to reach spin-down based upper limit in S3!

- Note that not all pulsars analysed are constrained due to spin-down rates; some actually appear to be spinning-up (associated with accelerations in globular cluster).
Astrophysical Sources

**signatures**

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- **Cosmological Signal** "stochastic background"
Signals from the Early Universe

**stochastic background**

**Cosmic Microwave background**

**LIGO**

**Planck Time**

10^{-43} SECONDS

Singularity creates Space & Time of our universe

1 SECOND

100,000 YEARS

10 billion YEARS

**EARTH NOW**

**WMAP 2003**

**SASKATOON 3 YEAR DATA**

**COBE DMR 4 YEAR DATA**
Signals from the Early Universe

- Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:

\[
\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(ln f)}
\]

- Detect by *cross-correlating* output of two GW detectors:

**First LIGO Science Data**

Hanford - Livingston
Limits: Stochastic Search

<table>
<thead>
<tr>
<th>Interferometer Pair</th>
<th>90% CL Upper Limit</th>
<th>( T_{\text{obs}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHO 4km-LLO 4km</td>
<td>( \Omega_{\text{GW}}(40\text{Hz} - 314\text{ Hz}) &lt; 72.4 )</td>
<td>62.3 hrs</td>
</tr>
<tr>
<td>LHO 2km-LLO 4km</td>
<td>( \Omega_{\text{GW}}(40\text{Hz} - 314\text{ Hz}) &lt; 23 )</td>
<td>61.0 hrs</td>
</tr>
</tbody>
</table>

- Non-negligible LHO 4km-2km (H1-H2) instrumental cross-correlation; currently being investigated.
- Previous best upper limits:
  - Garching-Glasgow interferometers:
    \( \Omega_{\text{GW}}(f) < 3 \times 10^5 \)
  - EXPLORER-NAUTILUS (cryogenic bars):
    \( \Omega_{\text{GW}}(907\text{Hz}) < 60 \)
Gravitational Waves from the Early Universe

- **results**
- **projected**

- Cosmic Strings
- Inflation
- Pulsar Timing
- Nucleosynthesis
- Phase Transitions
- LIGO
- Adv LIGO

- $\Omega_{GW}$
- $f$, Hz

- IFO + IFO
- Bar + Bar (Warm)
- Bar + Bar (Cryo.)
- IFO + Bar (1st Gen.)
- IFO + Bar (2nd Gen.)
- IFO (1st Gen.)
- N < 3.2 (95% CB)
Advanced LIGO
improved subsystems

Multiple Suspensions

Active Seismic

Sapphire Optics

Higher Power Laser

Date: 10/25/2001
Time: 13:59:18
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 81.6271 nm
RMS: 13.2016 nm
X Center: 172.00
Y Center: 145.00
Radius: 163.00 pix
Terms: None
Filters: None
Masks:
Anatomy of the projected Advanced LIGO detector performance

- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning
- Advanced LIGO's Fabry-Perot Michelson Interferometer is flexible – can tailor to what we learn before and after we bring it on line, to the limits of this topology
Design features

180 W LASER, MODULATION SYSTEM

40 KG SAPPHIRE TEST MASSES

ACTIVE THERMAL CORRECTION

T=0.5%

T=5%

125W

PRM T~6%

OUTPUT MODE CLEANER

GW READOUT

PD Photodiode

SRM Signal Recycling Mirror

ETM End Test Mass

ITM Input Test Mass

BS Beam Splitter

PRM Power Recycling Mirror

LASER

MOD.

INPUT MODE CLEANER

ACTIVE ISOLATION

QUAD SILICA SUSPENSION

SILIC 28.5°
Test Masses / Core Optics

Full-size Advanced LIGO sapphire substrate
Isolation: multi-stage solution
Suspensions

Prototype triple pendulum suspension
Event Rate

*Initial vs Advanced LIGO*

- **Factor 10** better amplitude sensitivity
  - Rate $\alpha (\text{Reach})^3$
- **Factor 4** lower frequency bound
- **NN Binaries**: for three interferometers,
  - Initial LIGO: $\sim 20$ Mpc
  - Adv LIGO: $\sim 350$ Mpc
- **BH Binaries**:
  - Initial LIGO: $10 \, M_\odot$, 100 Mpc
  - Adv LIGO: $50 \, M_\odot$, $z=2$
- **Stochastic background**:
  - Initial LIGO: $\sim 3 \times 10^{-6}$
  - Adv LIGO: $\sim 3 \times 10^{-9}$
Advanced LIGO
Cubic Law for “Window” on the Universe

Improve amplitude sensitivity by a factor of 10x...
...number of sources goes up 1000x!

Nearby mass distribution in the Universe

- Virgo cluster
- 3D visualization of cluster mass

Today  Initial LIGO  Advanced LIGO
Post S3 at LLO
*active external seismic*

External Pre-Isolators

HAM

BSC
Conclusions

- Construction is complete & commissioning is well underway

- New upper limits for neutron binary inspirals, a fast pulsar and stochastic backgrounds have been achieved from the first short science run

- Sensitivity improvements are rapid -- second data run was 10x more sensitive and 4x duration and results are beginning to be reported (e.g. improved pulsar searches)

- Enhanced detectors will be installed in ~ 5 years, further increasing sensitivity

- Direct detection should be achieved and gravitational-wave astronomy begun within the next decade!
End
Gravitational Wave Astronomy

LIGO will provide a new way to view the dynamics of the Universe
LIGO Organization & Support

LIGO Laboratory
- MIT + Caltech
- ~170 people

LIGO Scientific Collaboration
- 44 member institutions
- > 400 scientists

U.S. National Science Foundation

DESIGN
CONSTRUCTION
OPERATION

SCIENCE

Detector
R&D

Saulson

UK
Germany
Japan
Russia
India
Spain
Australia

$
Results from S1
Upper Limits on Periodic Sources

J1939+2134
(642 Hz x 2 = 1284 Hz)
upper limits on amp: $h < 2 \times 10^{-22}$
upper limit on ellip: $\varepsilon < 2.9 \times 10^{-4}$

Previous limits for same system:
• 40m: $\sim 10^{-17}$
• Glasgow detector: $\sim 10^{-20}$ (2nd harm.)

At other frequencies,
bars have set up limits $\sim 3 \times 10^{-24}$

Upper limit on ellipticity from spindown, $\varepsilon < 3.8 \times 10^{-9}$

gr-qc/0308050, Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors, The LIGO Scientific Collaboration, B. Abbott, et al, accepted for publication in PRD.
Results from S1
Upper Limits on NS Inspiral Sources

\[ \text{S1: L1 | H1=289 hrs,} \]
\[ \text{L1 &H1: 116 hrs;} \]
\[ \text{R< 170/hr BNS in Milky Way Equivalent Galaxy, with masses between 1 and 3 Ms.} \]
\( \text{(Expected:} \sim 10^{-5}/yr) \)

\textbf{Previous searches:}
- LIGO 40m ('94, 25 hrs) 0.5/hr, 25 kpc
- TAMA300 DT6: 82/yr (1,038 hr, D<33 kpc)
- Glasgow-Garching ’89 (100 hrs) no events, ~1kpc
- IGEC ’00-’01 (2yrs): no events, ~10 kpc

Results from S1
Upper Limits on Burst Sources

17 days yielded 55 hrs for 3x analysis:
<1.6 events/day for bursts
with duration 4-100 ms and frequencies
150-3000 Hz.
For Gaussians and SineGaussians,
$h_{rss} \sim 10^{-17} - 10^{-19}/\sqrt{\text{Hz}}$

Upper limit from bar results:
• IGEC 2000: <7/yr, $H_t < 3.5 \times 10^{-21}/\text{Hz}$
~1ms events, 3yrs yield 387d (2 or 3x),
PRD68 (2003) 022001
• Astone et al. 2001: $h \sim 2 \times 10^{-18}, 90d,
1/day, CQG 19 (2002) 5449-5463
Results from S1
Upper Limits on Stochastic Background Sources

S1 (50 hrs, H2-L1): $\Omega_0 h^2_{100} < 23$

Current best upper limits:

- **Inferred**: From Big Bang nucleosynthesis:

- **Measured**: Garching-Glasgow interferometers:

  $$\int \Omega_{GW}(f) \, d\ln f < 1 \times 10^{-5}$$

- **Measured**: EXPLORER-NAUTILUS:

  $$\Omega_{GW}(f) < 3 \times 10^5$$

  $$\Omega_{GW}(907\text{Hz}) < 60$$
Ongoing work

S2 analysis almost complete (see talks in this conference!), S3 run in progress. S3 will have LIGOx3, GEO, and TAMA!!

- **Inspiral Sources:**
  - Binary Black Holes!
  - Better background estimation for Binary Neutron Stars
  - MACHOs in the Galaxy

- **Pulsars:**
  - All known pulsars
  - Special searches for Crab, Sco-X1
  - Non targeted search

- **Bursts:**
  - Untriggered search: more time, better data, more method
  - Triggered search: GRBs
  - Modeled search: black hole ringdowns, supernova explosions
  - coincidence analysis with TAMA

- **Stochastic Background:**
  - Optimal filters, expect $\Omega \sim 0.01$ UL for H1-L1
  - ALLEGRO-L1 analysis
Conclusions

- Good progress toward design sensitivity
- Data analysis science results
- The future:
  - S2, S3 analysis ongoing
  - 6-months long S4 starting in 2004 (?).
  - One year of integrated data at design sensitivity before the end of 2006
  - Advanced interferometer with dramatically improved sensitivity – 2007+
GRB030329

Related Slides
Externally Triggered Search for Gravity Waves

Violent cosmic events can be seen as optical supernovae, neutrino bursts, GRBs, etc…

We expect such events to produce a significant flux of gravitational waves in the LIGO frequency band.

Various trigger and data distribution networks:
- International Supernovae Network (I.S.N.)
- Supernovae Early Warning System (SNEWS)
- The GRB Coordinates Network (GCN)
- The third InterPlanetary Network (IPN3)
- ...

Targeted coherent search for gravity wave counterpart
- Measured trigger properties
  - Time of arrival
  - Source direction
  - Duration, distance, type, etc…

- Timing and direction information is crucial for improved efficiency
- Measured parameters are essential for astrophysical interpretation of results
- Each trigger type has advantages and disadvantages
GRBs and their coverage during S2/DT8

<table>
<thead>
<tr>
<th>GRB</th>
<th>GPS time</th>
<th>Locked IFO</th>
<th>LIGO segment</th>
</tr>
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<tbody>
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Title: GCN GRB Observation Report
Number: 2120 Subject: GRB 030329: Supernova Confirmed
Date: 03/04/08 20:13:40 GMT From: T. Matheson et al.

Signal Region and GRB030329 Trigger

- Theory favors either
  - very short ~10ms burst
  - long (~1-10s) quasi-sinusoids (i.e. Araya-Góchez, M. Van Putten)

- Relative delay between the gravity wave and GRB is predicted to be small
  - Signal region: \([ T_0 - 120s, T_0 + 60s ]\) to cover most predictions
  - Model specific ranges can also be considered

- Known direction
  - Optical counterpart located
  - LIGO antenna factor identified
  - LIGO/TAMA arrival times are known

- Source distance is known
  - \(z = 0.1685\) (d~800Mpc)

- Unknown waveform/duration


4-March-04

University of Alberta
Schematic Analysis Flow Chart

External Trigger → Data → Astrophysically motivated simulations

Adaptive pre-conditioning

Non-parametric, coherent, multi-interferometer GW detection algorithm

Background region → False detection rate → Threshold

Simulations → Efficiency Measurements Upper limits

Signal region → Largest event → Candidates

Threshold
Correlation Analysis

\[ s_1(t) = h(t - t_1) + n_1(t) \]
\[ s_2(t) = h(t - t_2) + n_2(t) \]

\[
C(t, t_w, t_{off}) = \int_{t-t_w/2}^{t+t_w/2} s_1(t')s_2(t'+t_{off}) dt'
\approx \int_{t_w}^{t_0} h^2(t) dt + \int_{t_w}^{t_0} n_1(t)n_2(t) dt
\]

\[ h_{\text{rss}}^2 \quad \langle > = 0 \]
Cross-Correlated Signals

- Co-located detectors can have correlated signals
  - Various environmental effects
- The optimal integration length depends on:
  - the base noise
  - the signal duration
  - the signal strength

Example:
Sine-Gaussian (SG)

\[ h(t) = h_0 \sin(2\pi f_0 t) \exp\left(-\frac{t^2}{\tau^2}\right) \]

\[ t_0 = \frac{\sqrt{2\pi} f_0}{\sqrt{2\pi} f_0} h_0 \]

Optimal integration

Integration length [4-120 ms, uneven steps]
Strength of Correlated Events

Event strength [ES] calculation:

Average value of the “optimal” pixels

Notes:

The pipeline is based on relative measurements
Raw data and raw data with injections are processed through the very same pipeline
The described method targets only short bursts
False alarm rate measurement example:

Estimated rate:
\[ \sim \frac{1}{15} - \frac{1}{20} \text{ in } 180\text{s} \]

Based on \( \sim 15\) ks of H1 & H2 covering the coincident lock stretch around the GRB030329 trigger.

Note that this rate estimate is based on a small number of events in the tail, therefore it should be treated with some caution.

Note: We only relied on the co-located LHO 2K and 4K interferometers for this analysis!
Scan of the Parameter Space

Simulated waveforms to characterize the astrophysically motivated parameter space:

- Sine-Gaussians:
  - \( Q = 4.5, 8.9, 18 \)
  - \( F = 100 \text{ Hz}, 250 \text{ Hz}, 361 \text{ Hz}, 458 \text{ Hz}, 554 \text{ Hz}, 702 \text{ Hz}, 850 \text{ Hz}, 1000 \text{ Hz}, 1361 \text{ Hz}, 1458 \text{ Hz}, 1554 \text{ Hz}, 1702 \text{ Hz}, 1850 \text{ Hz} \)

- Gaussians and waveforms from numerical simulations (DFM)

For Sine-Gaussians:

\[
h_{\text{rss}} = \sqrt{\int_0^{\infty} |h(t)|^2 \, dt}
\]

For Sine-Gaussians:

\[
h_{\text{rss}} = \frac{Q}{4\sqrt{\pi f_0}} h_{\text{peak}}
\]

Example: Sine-Gaussian (SG), 361 Hz, \( Q = 8.9 \)
Calibrated detector noise curves and results of Sine-Gaussian simulations (Fixed false alarm rate)

- The calibration is known within ~10%

- Data reflects efficiencies obtained by choosing a threshold corresponding to ~4 x 10^{-4} Hz false alarm rate

- Averaged H1/H2 noise curves reflect calibrations at GRB030329 arrival time

Symbols: 50% detection efficiency points

Lines: 90% detection efficiency boundaries

Note: Preliminary information!
- The signal region seems to be “relatively quiet” when compared to the neighboring regions

- No event was detected with strength above the pre-determined threshold

- It is an upper limit result

Note: Preliminary information!
Observed Limit on $h_{\text{RSS}}$ Relates to GW Energy

$$P_{GW} \propto \left| \frac{dh(t)}{dt} \right|^2$$

for an observation (or limit) made at a luminosity distance $d$ from a source:

$$E_{GW} = \left( \frac{2\pi^2 c^3}{G} \right) d^2 \int_0^\infty f^2 \left| \tilde{h}(f) \right|^2 df \approx \left( \frac{2\pi^2 c^3}{G} \right) d^2 f_c^2 \int_0^\infty \left| \tilde{h}(f) \right|^2 df$$

- For Sine-Gaussians:

$$E_{GW} = \left( \frac{c^3 \pi^2}{2^{3/2} G} \right) \left( \frac{f_0 d}{Q} \right)^2 h_{\text{RSS}}^2 \left( 1 - e^{-2Q^2} \right)$$

$\textbf{Note the quadratic terms!}$

$h(t + t_0) = h_0 \sin (2\pi f_0 t) \exp (-t^2/\tau^2)$

$Q \equiv \sqrt{2\pi f_0} \approx 8.9$

$h_{\text{rss}} \equiv \sqrt{Q/(4\sqrt{\pi} f_0) h_0}$

$\tau$ - width of Gaussian (envelope), $f_0$ - characteristic frequency of Sine-Gaussian
Example: Estimating $E_{GW}$ for GRB030329

H1-H2 only

$\Rightarrow$ antenna attenuation factor $\sim$0.37 (assuming $\sim$optimal polarization)

$z=0.1685 \Rightarrow d 800\text{Mpc}$

For narrowband gravity waves, near minimum of LIGO noise curves (simulated with $Q \approx$9, 250 Hz sine-Gaussian), we obtain 90% efficiency:

$h_{RSS} \sim 5 \times 10^{-21} \text{[1/Hz]}$

$\Rightarrow E_{GW} \approx 125 \text{M}_\odot (1 / 0.37) \approx 340 \text{M}_\odot$
Very Encouraging Result

- Executed a very sensitive, cross-correlation based search to identify possible gravity wave signatures around the GRB trigger times.

- The (frequency dependent) sensitivity of the search was $h_{RSS} \sim \text{few } \times 10^{-21} \frac{\text{[1/Hz]}}{\text{[1/Hz]}}$
  - Limit of some hundreds of $M_{\text{SUN}}$ in gravity waves.

- The search was broadband – narrow band versions can increase sensitivity.

- We expect that the sensitivity of our instruments will improve.
  - All detectors; factor of 10 – 30 (in $h_{RSS}$) between S2 and final sensitivity (depending on frequency…)-> improvement of 100 – 300 in $E_{GW}$ (Please note that $E_{GW} \sim h^2$ !)

- GRB030329 was not even close to the best event we might expect.
  - One year of observation will give us hundreds of GRBs with LIGO data coverage.
    - Better source direction ?
    - Three or four observing interferometers ?
      - A GRB significantly closer ?

*Very realistic chance to set a sub-solar mass limit in the near future!*