Scientific Results from the first LIGO Science Runs

- Introduction to GW’s
- LIGO and its sister projects
- The LIGO Science runs and detector performance
- Physics, astrophysics, and Science run results from S2&S3:
  - Inspirals of compact binary systems
  - Stochastic Background
  - Pulsars and CW Sources
  - Bursts (Unmodeled transients)
- Prospects for S4, S5 runs

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

Alan Weinstein
Caltech
for the LIGO Scientific Collaboration

FNAL W&C Seminar,
October 28, 2005
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 \( h = \frac{\Delta L}{L} \)

- GW are tensor fields (EM: vector fields)
  - two polarizations: plus (\( \oplus \)) and cross (\( \otimes \))

  (EM: two polarizations, \( x \) and \( y \))

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)

Contrast with EM dipole radiation:

\[ \hat{x} \quad ((\quad)) \quad \hat{y} \]
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!

Can see full sky, but can’t localize sources with only a single detector.

$h = \frac{\Delta L}{L}$

$P_{out} = P_{in} \sin^2(2k\Delta L)$
International network

- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!
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>
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<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, FNAL W&C Seminar, October 28, 2005
LIGO Observatories

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

Livingston (LLO):
- One interferometer

Both sites are relatively seismically quiet, low human noise

AJW, FNAL W&C Seminar, October 28, 2005
The noise in the LIGO interferometers is dominated by three different processes depending on the frequency band:

- Shaking of ground transfers through the suspension into movement of the test mirrors.
- Thermal noise in mirrors and suspensions.
- Fluctuations in the number of photons arriving at the photodiode.

At present, noise in the LIGO detectors is dominated by “technical” sources, associated with as-yet-imperfect implementation of the design.
Time Line

1999  2000  2001  2002  2003  2004  2005  2006

Inauguration  First Lock  Full Lock all IFO  Now

4K strain noise

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

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Strain Sensitivities for the LIGO Interferometers
H1 Performance Comparison: S1 through post S4

LIGO Sensitivity progress
Lines: calibration, suspension violin modes, 60 Hz harmonics pickup

Graph showing strain sensitivities with frequency on the x-axis and strain sensitivity on the y-axis, comparing different configurations and performance metrics.
GEO Sensitivity

AJW, FNAL W&C Seminar, October 28, 2005

Stefan Hild
LIGO Data Analysis Groups

- **LIGO Scientific Collaboration (LSC) Analysis Groups**
  - Typically ~30 physicists / group
  - One experimentalist / One theorist co-lead each group

- **Compact binary inspiral:** "chirps"

- **Supernovae / GRBs / mergers:** "bursts"

- **Pulsars in our galaxy:** "periodic"

- **Cosmological Signal:** "stochastic background"
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.

$\delta f \approx 2.6 \times 10^{-4}$
$\delta f \approx 4 \times 10^{-6}$
Event search pipeline

Example from bursts -- prototypical for other searches
How is the Pipeline Tuned and Tested?

• **Playground data**
  » ~9% of the science data used for parameter tuning

• **Software injections**
  » Simulated inspiral signals added to playground data
  » Monte Carlo simulations with model population used to maximize detection efficiency with tolerable fake rate

• **Hardware injections**
  » Waveforms injected into mirror actuators
  » Provide validation of entire analysis chain
Detectability of coalescing binary sources during S1
(for optimal location & orientation relative to antenna pattern)

- Neutron star – neutron star (Centrella et al.)
Search results, and searches in progress

- Binary inspiral search method is similar for all mass ranges, but there are important differences
- Results from S2
  - Binary neutron star systems
  - Primordial black hole binaries
  - Binary black hole systems
- For S3, S4, and beyond:
  - all of the above
  - add spin-dependent searches
  - add Extreme Mass Ratio searches
Compact binary sources
What is expected?

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>$R_{I, \text{ yr}^{-1}}$</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>$R_{WB, \text{ yr}^{-1}}$</td>
<td>0.5 – 100</td>
<td>$\lesssim 0.5$ – 1000</td>
<td>$\lesssim 10$ – 2000</td>
<td>100 – 2000</td>
</tr>
</tbody>
</table>

**NOTE:** Rate estimates **DO NOT** include recent relativistic pulsar discoveries. Estimates will increase!

**NOTE:** Rate estimates **DO NOT** include recent association of s/h GRBs with black hole mergers.

Table from: V. Kalogera (population synthesis)

*AJW, FNAL W&C Seminar, October 28, 2005*
Inspiral Gravitational Waves

• Compact-object binary systems lose energy due to gravitational waves. Waveform traces history.

• In LIGO frequency band (40–2000 Hz) for a short time before merging: anywhere from a few minutes to <<1 second, depending on mass.

Waveform is known accurately for objects up to ~3 M\(_\odot\)

  “Post-Newtonian expansion” in powers of \(\frac{Gm}{rc^2}\) is adequate

\[ \Rightarrow \] Use matched filtering
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)
Illustration of Matched Filtering

- Bank of 2110 post-Newtonian stationary-phase templates for $1 < m_1 \leq m_2 < 3 \, M_\odot$ with 3% maximum mismatch.
S2 Binary Neutron Star Inspiral Search

- Average distance at which an optimally oriented 1.4 + 1.4 $M_{\text{sun}}$ neutron star binary gives SNR = 8:
  - LLO 4k: 1.8 Mpc reaches M31, M33, M32, M110
  - LHO 4k: 0.9 Mpc just reaches M31 in Andromeda
  - LHO 2k: 0.6 Mpc

- Recorded over 1200 hours of data
  - Did not use single IFO or H1/H2 only data
  - Applied “data quality” cuts
  - Applied auxiliary channel “vetoes”

- Used 355 hours of data in search

- Filter data with bank of ~2000 templates, record event triggers

- Required triggers to be coincident in time and in mass from at least two detectors
S2 Background Estimation Using Time Slides
For Gaussian noise, optimal coherent statistic would be

$$\rho = \sqrt{\rho_L^2 + \frac{\rho_H^2}{4}}$$
S2 Triggers in Coincidence

\[ \rho = \sqrt{\rho_L^2 + \frac{\rho_H^2}{4}} \]
Results for Neutron Star Binaries

Event Candidates
142 event candidates found in the data
Loudest candidates eliminated in follow up investigation...
Other candidates consistent with background of analysis pipeline
S2 BNS inspiral search efficiency

From detailed simulations:
- waveform injection into S2 data
- Galactic and extra-galactic source distribution
- $m_1/m_2$ distribution (pop synth)
- antenna pattern response
- full search pipeline

$\rho^2_{\text{max}}$
Upper Limit Result

\[ R_{90\%} = \frac{2.303 + \ln P_b}{T_{\text{obs}} \varepsilon N_{\text{MWEG}}} \]

- Observation time \((T_{\text{obs}})\): 345 hours
- Conservative lower bound on the product \((\varepsilon N_{\text{MWEG}})\): 1.2
- Omit background correction term \((\ln P_b)\)

\[ \Rightarrow \text{Conservative upper limit:} \]

\[ \Rightarrow \text{Rate} < 47 \text{ per year per MWEG} \ (90\% \text{ frequentist C.L.)} \]

\[ \Rightarrow \text{c.f. S1 result:} < 170 \text{ per year per MWEG} \]

\text{gr-qc/0505041, PRD 72 082001 (2005)}
Primordial Black Hole (MACHO) Binaries

Same analysis pipeline

Templates can be many seconds long in LIGO band

Population is unknown; assume uniform distribution in Galactic halo, uniform mass distribution from $0.1 - 1 \, M_{\odot}$

Event rate consistent with background of analysis pipeline

Upper limit set on the rate of PBHB coalescences:

$$R_{90} = 63 \, \text{year} \, \text{MWEG}$$

gr-qc/0505042, PRD 72 082002 (2005)
Binary black holes ($3 < M_{\text{tot}}/M_{\odot} < 40$) are louder (so can be seen from further away)

But they merge at lower frequencies, so they only enter into the LIGO band (50-100 Hz) in the last fraction of a second before they merge.

Very relativistic in the LIGO band; the waveforms are more uncertain. Some models predict much larger signals, at higher frequencies, than others!

We use “detection templates” to try to cover the range of models.

“Reach” is several Mpc with S2 data.

No candidates seen.

Population is uncertain (no BBHs have ever been observed!) For a toy population model:

$R_{90\%} = 35 / \text{year} / \text{MWEG}$
Upcoming results for BNS, MACHOs, BBHs, spinning BBHs

- S3/S4 analyses are under way.
- Reach for BNS > 15 Mpc (VIRGO cluster), 10x better than S2.
- All three detectors have comparable sensitivity.
- Duty cycle much higher (~75%), data more Gaussian and stationary.
- Results by end of this year: joint BPBH, BNS, BBH in S3&S4; and spinning BBH search.
Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!
Stochastic gravitational waves

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

Planck Time
$10^{-43}$ SECONDS
Singularity creates
Space & Time of our universe

1 SECOND

100,000 YEARS

10 billion YEARS

EART NOW

WMAP 2003
Stochastic signals

Stochastic backgrounds can arise either from

Cosmological processes, such as inflation, phase transitions, or cosmic strings, or from

Astrophysical processes, as the superposition of many signals from the other signal classes already described in this talk.

Characterize the strength by its energy density $\Omega_{gw}$, defined as

\[\int_0^\infty d(\ln f) \Omega_{GW}(f) = \frac{\rho_{GW}}{\rho_{critical}}\]

Strain power spectrum:

\[S_{gw}(f) = \frac{3H_0^2}{10\pi^2 f^3} \Omega_{gw}(f)\]

Strain amplitude:

\[h(f) = S_{gw}^{1/2}(f) = 5.6 \times 10^{-22} h_{100} \sqrt{\Omega_0} \left(\frac{100\text{Hz}}{f}\right)^{3/2} \text{Hz}^{1/2}\]
Log (\(\Omega_{0h_{100}}^2\)) -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 Log (f [Hz])

-18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10

-14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10

Laser Interferometer Space Antenna - LISA

CMB

Inflation

Pre-big bang model

Slow-roll

Cosmic strings

Pulsar

Nu

Cyclic model

EW or SUSY

Phase transition

f \sim H_0 - one oscillation in the lifetime of the universe

f \sim 1/Plank scale – red shifted from the Plank era to the present time

LIGO S1, 2 wk data
\(\Omega_{0h_{100}}^2 < 23\) PRD 69(2004)122004 (H2-L1)

LIGO S3, 2 month data
\(\Omega_{0h_{100}}^2 < 4.4 \times 10^{-4}\)

Initial LIGO, 1 yr data
Expected \(\Omega_{0h_{100}}^2 < 2 \times 10^{-6}\) (H1-L1)

Advanced LIGO, 1 yr data
Expected \(\Omega_{0h_{100}}^2 < 7 \times 10^{-10}\) (H1-L1)

Predictions and Experimental Limits

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Detecting a stochastic background

In a single detector, a stochastic signal is indistinguishable from noise. To detect it, we **cross-correlate** the outputs of multiple detectors.

**Signal model:**
- Isotropic, Gaussian, stationary (appropriate for cosmological background)
- Signal and noise uncorrelated, as is noise among detectors
- $\Omega_{GW}(f) \sim$ constant or power law in $f^\alpha$ in LIGO band (a weak assumption)

**Cross-correlation statistic**
- combine signal outputs from two detectors using *optimal filter* to optimize SNR

\[
Y = \int \tilde{s}_1(f)\tilde{Q}(f)s_2(f)df \quad \text{where} \quad \tilde{Q}(f) \propto \frac{\gamma(f)S_{gw}(f)}{P_1(f)P_2(f)}
\]

\[
\text{Mean}(Y) = \Omega_0 T, \quad \text{Var}(Y) \equiv \sigma^2 \propto T, \quad \text{SNR} \propto \sqrt{T}
\]

Result:

\[
\Omega_0 h_{100}^2 = \frac{(Y \pm \sigma_Y)}{T}
\]
S3 results H1-L1
Frequency and time dependence

\[ \Omega_{gw} \pm 2\sigma_{\Omega} \]

Cumulative Analysis Time (hr)

\[ \Omega_{gw} \pm 2\sigma_{\Omega} \]

Frequency (Hz)

(\(\alpha=0\))

AJW, FNAL W&C Seminar, October 28, 2005
S3 results
Upper limits based on H1-L1

\[ \Omega_{GW}(f) = \Omega_{100} \times (f / 100 \text{ Hz})^\alpha \]

<table>
<thead>
<tr>
<th>Power law</th>
<th>Freq. Range</th>
<th>Upper Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Omega^\wedge_{gw} \pm \sigma ) \times 10^{-4} at 100Hz</td>
<td>( \Omega_{gw} \times 10^{-4} ) (*)</td>
<td>( S_{gw}^{1/2} \times 10^{-23} \text{ Hz}^{-1/2} ) (*)</td>
</tr>
<tr>
<td>( \alpha=0 )</td>
<td>69-156Hz</td>
<td>(-6.0 \pm 7.0)</td>
<td>8.5</td>
</tr>
<tr>
<td>( \alpha=2 )</td>
<td>73-244Hz</td>
<td>(-4.7 \pm 7.2)</td>
<td>9.4</td>
</tr>
<tr>
<td>( \alpha=3 )</td>
<td>76-329Hz</td>
<td>(-4.0 \pm 6.2)</td>
<td>8.2</td>
</tr>
</tbody>
</table>

(*) 90% C.L. upper limit marginalized over calibration error (H1: 9%, L1: 15%)

\( h_{100} = 0.72 \)

Expect 10x improvement in sensitivity for S4!
Correlation between LLO and ALLEGRO

ALLEGRO Al bar detector
Located at Louisiana State University, Baton Rouge
40km from LIGO Livingston
  0.13msec light travel time

No penalty from overlap reduction function

Broad double-resonance in 850-950Hz band

Rotation of ALLEGRO modulates stochastic response (data taken in three orientations during S2)

Analyzing S2 data (won’t be competitive); S4 analysis to come

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The nearby universe is not isotropic:
- Our galactic center
- Nearest galaxy: M31 Andromeda
- Virgo galaxy cluster
- Voids
  ➔ Compare different sky patches

We can get source position information from
- Signal time delay between different sites (sidereal time dependent)
- Sidereal variation of the antenna pattern

Encoded into sidereal time & sky position dependent overlap reduction function $\gamma(f)$

Can exploit higher frequencies (>~100Hz) for stochastic search

Results from S4 coming soon!
Conclusions

• LIGO detectors are working better and better

• Sensitivity and duty cycle are close to design values

• The worldwide network is joining in

• Analysis techniques and pipelines are becoming more powerful and streamlined

• Look for MORE and MORE INTERESTING results, and sooner or later, DETECTION and study of GWs and their sources from LIGO in near future!
Periodic signals

- Rotating neutron stars make gravitational waves, if they aren’t symmetric about their rotation axis. Mechanisms include:
  - Spin precession at \( \sim f_{\text{rot}} \)
  - Excited oscillatory modes such as the \( r\)-mode at \( 4/3 * f_{\text{rot}} \)
  - Triaxial distortion of crystalline structure, at \( 2f_{\text{rot}} \)

- For known pulsars, we limit our search to gravitational waves from a triaxial neutron star emitted at twice its rotational frequency.

\[
h_0 = \frac{16 \pi^2 G}{c^4} \frac{I_{zz} f_0^2}{R} \varepsilon
\]

\[
\varepsilon = \frac{I_1 - I_2}{I_3} < 10^{-5}
\]
Sensitivity to periodic sources

There are ~28 known isolated pulsars in LIGO band which are spinning down; targeted in S2 search

\[ h_0: \text{Amplitude detectable with 99\% confidence during observation time } T \]

\[ \langle h_0 \rangle = 11.4 \sqrt{S_n(f_s)/T} \]

Known EM pulsars
- Values of \( h_0 \) derived from measured spin-down
  - IF spin-down were entirely attributable to GW emissions
  - Rigorous astrophysical upper limit from energy conservation arguments

PSR J1939+2134
- \( P = 0.00155781 \text{ s} \)
- \( f_{\text{GW}} = 1283.86 \text{ Hz} \)
- \( \dot{P} = 1.0519 \times 10^{-19} \text{ s/s} \)
- \( D = 3.6 \text{ kpc} \)
The expected waveform

- Expected waveform from an isolated spinning NS is sinusoidal with small spin-down:
  \[ h(t) = F_+ (t, \psi) h_+ (t) + F_\times (t, \psi) h_\times (t) \]
  \[ h_+ = A_+ \cos \Phi(t) \]
  \[ h_\times = A_\times \sin \Phi(t) \]
  \[ \Phi(t) = \phi_0 + 2\pi \sum_{n=0}^{\infty} \frac{f(n)}{(n+1)!} (t-t_0)^{n+1} \]

- Doppler frequency modulation due to motion of Earth and amplitude modulation due to detector antenna pattern.

- For setting upper limits only, we assume the emission mechanism is due to deviations of the pulsar's shape from perfect axial symmetry, \( f_{GW} = 2f_r \)

\[ A_+ = \frac{1}{2} h_0 (1 + \cos^2 t) \]
\[ A_\times = h_0 \cos t \]
\[ h_0 = \frac{16 \pi^2 G}{c^4} \frac{I_{zz} \varepsilon_f r^2}{d} \]
\[ f(t) - \hat{f}(t) = \hat{f}(t) \frac{v(t) \cdot n}{c} \]
\[ \hat{f}(t) = f_0 + \dot{f}(t-t_0) \]
Search for quasi-periodic signals

- Long lasting quasi-periodic signals from known (radio) pulsars
  - Account for Doppler induced frequency shifts and intrinsic spin evolution
  - Account for modulation of amplitude due to detector antenna pattern
  - Must know pulsar position in sky, and period P, dP/dt
  - Amplitude $h_0$, Orientation $\iota$, Phase, polarization $\varphi$, $\psi$: usually unknown
  - Can infer, from Doppler induced frequency shifts, deviation of $v_{GW}$ from $c_{\text{light}}$, and can test prediction that only two transverse polarizations are present

- For small numbers of pulsars observed in EM spectrum, can analyze in time domain, integrating demodulated signal over long observation times

- For large numbers of pulsars, or unknown source direction and period (most NSs!), frequency domain analysis is best, but is very much computationally bound!
  - Einstein@home!

\[ \frac{\delta f}{f} \approx 2.6 \times 10^{-4} \]

\[ \frac{\delta f}{f} \approx 4 \times 10^{-6} \]
Pulsar Analysis techniques

- Coherent searches (full use of frequency and amplitude mod)
  - Time-domain method
    (best if source ephemeris is known: sky location, $f_{GW}$, $df/dt$)
    - Target known pulsars with frequencies ($2f_{rot}$) in detector band
    - For S2, 28 isolated pulsars. S3 and beyond: binary pulsars, LMXBs
  - Frequency-domain method
    (optimal for detection of unknown signals)
    - All-sky, broadband search
    - Targeted searches (e.g. galactic core)
    - LMXB (e.g. ScoX-1) search

- Incoherent searches
  - Account for frequency modulation of source by appropriate averages of short-time power spectra.
  - Stack-slide, Hough transform, Power Flux methods

- In the future, we will implement hierarchical analyses that layer coherent and incoherent methods.
Time-domain method

- Start with known (from radio) source location \((\alpha, \delta)\) and source frequency \((f_{GW} \text{ and } df/dt)\)
- Heterodyne data with fixed frequency, down-sample to 4 samples/second
- Heterodyne data with doppler/spindown, to 1 sample/minute \(\Rightarrow B_k\)
- Compare \(B_k\) with source model (antenna pattern amplitude modulation)
- Calculate \(\chi^2(h_0, \iota, \varphi, \psi)\) for source model, easily related to probability (noise Gaussian)
- Marginalize over \(\iota, \varphi, \psi\) to get PDF for (and Bayesian upper limit on) \(h_0\)
- Verify that \(B_k\) data are Gaussian and uncorrelated
- Validate procedure with software and hardware injections (as in all LIGO searches)

\[
y(t_k; \alpha) = \frac{1}{4} F_+ (t_k; \psi) h_0 (1 + \cos^2 \iota) e^{i\phi_0} \\
- \frac{i}{2} F_\times (t_k; \psi) h_0 \cos \iota e^{i\phi_0}
\]
S2 results for 28 known pulsars
Time domain search

Crab pulsar: stay tuned!
Achieve expected sensitivity for S2!

SN observed in China and Arizona in 1054
Crab nebula observed in Britain and France in 1731

Probing ellipticities below $10^{-5}$

Gravitational wave amplitude $h_0$

PRL 94, 181103 (2005)
All sky searches

- Most spinning neutron stars are not pulsars; EM dim and hard to find.
- But they all emit GWs in all directions (at some level)
- Some might be very close and GW-loud!
- Must search over huge parameter space:
  - sky position: 150,000 points @ 300 Hz, more at higher frequency or longer integration times
  - frequency bins: 0.5 mHz over hundreds of Hertz band, more for longer integration times
  - $df/dt$: tens(s) of bins
- Computationally limited! Full coherent approach requires $\sim$100,000 computers (Einstein@Home)
- Many incoherent approaches being pursued: Hough transform, stack-slide, PowerFlux
Einstein@Home: the Screensaver

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants

- User name
- User’s total credits
- Machine’s total credits
- Team name
- Current work % complete
How big is Einstein@Home?

### Users and Hosts

<table>
<thead>
<tr>
<th>USERS</th>
<th>Approximate #</th>
</tr>
</thead>
<tbody>
<tr>
<td>in database</td>
<td>101,105</td>
</tr>
<tr>
<td>with credit</td>
<td>54,212</td>
</tr>
<tr>
<td>registered in past 24 hours</td>
<td>140</td>
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</table>

<table>
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<th>HOSTS</th>
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<tr>
<td>in database</td>
<td>166,155</td>
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<td>registered in past 24 hours</td>
<td>388</td>
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<tr>
<td>with credit</td>
<td>96,332</td>
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<tr>
<td>active in past 7 days</td>
<td>39,928</td>
</tr>
<tr>
<td>floating point speed</td>
<td>195.3 TFLOPS</td>
</tr>
<tr>
<td>floating point speed in past 7 days</td>
<td>48.3 TFLOPS</td>
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### Work and Results

<table>
<thead>
<tr>
<th>WORKUNITS</th>
<th>Approximate #</th>
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<tr>
<td>in database</td>
<td>100,267</td>
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<tr>
<td>with canonical result</td>
<td>74,045</td>
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<table>
<thead>
<tr>
<th>RESULTS</th>
<th>Approximate #</th>
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<tbody>
<tr>
<td>in database</td>
<td>437,150</td>
</tr>
<tr>
<td>unsent</td>
<td>15,922</td>
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<tr>
<td>in progress</td>
<td>78,212</td>
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<tr>
<td>deleted</td>
<td>268,233</td>
</tr>
<tr>
<td>valid</td>
<td>261,970</td>
</tr>
<tr>
<td>invalid</td>
<td>879</td>
</tr>
<tr>
<td>Oldest Unsent Result</td>
<td>3 d 11 h 49 m</td>
</tr>
</tbody>
</table>
E@H Participants

You can be here! Download now at www.physics2005.org!
Final S3 analysis results

• “Violin modes” of the mirror suspensions obscure large swath of sky around 340 Hz.
• 50-1500 Hz band shows no immediate evidence of strong pulsar signals in sensitive part of the sky, apart from the hardware and software injections.
• Overall, the outliers appear consistent with instrumental lines
The Hough transform

- All-sky semi-coherent approach: the Hough transform
- Invented to analyze bubble chamber pictures
- Take short, high-resolution Fourier transforms every hour. Pixelize.
- Associate pixels in t-f plane with pixels in parameter space \( \{\alpha, \delta, f_0, df/dt\} \).
- Number count exceeds threshold: detection candidate.

AJW, FNAL W&C Seminar, October 28, 2005
Results from S2 Hough search

- Covered a ~200 Hz band (200-400 Hz, excluding violin modes at ~340 Hz)
- All sky!
- Limits on GW strain < $10^{-22}$
- For NSs with ellipticity = $10^{-6}$, only sensitive out to ~1-2 pc.
- About 26x worse than targeted time-domain search.
- Optimal coherent approach requires ~$10^{19}$ points in parameter space; this search used $10^{12}$ points.
- Hierarchical search (coarse semi-coherent -> fine coherent) under development.

gr-qc/0508065, submitted to PRD
Burst sources

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

GW's from asymmetric supernova collapse
Bursts: what are we looking for?

- We look for short-duration GW bursts from
  - core-collapse of massive stars (Type-II SN)
  - mergers of NS/NS, NS/BH, BH/BH binaries
  - newly-formed NS bar modes, r-modes
  - ringdowns of newly-formed black holes
  - the engines that drive GRB’s
  - cosmic string cusps and kinks
  - the unknown!

- Unlike the other LIGO searches, a burst “signal” is ill-defined; waveforms unknown or untrustworthy – a menagerie!

- Matched filtering is inappropriate; must be open to a broad range waveforms with short-duration (<1sec) and enough power in LIGO’s sensitive band of ~50Hz to few kHz

Zwerger-Müller SN waveforms: astrophysically-motivated waveforms, computed from simulations of axi-symmetric SN core collapses.
We aim to be sensitive to bursts with generic t-f properties:
- longish-duration, small bandwidth (ringdowns, Sine-gaussians)
- longish-duration, large bandwidth (chirps, Gaussians)
- short duration, large bandwidth (BH mergers)
- In-between (Zwerger-Muller or Dimmelmeier supernova simulation waveforms)
- Characterize bursts by duration, frequency band, “amplitude”
Ad-hoc signals: (Sine)-Gaussians

These have no astrophysical significance.

But they are well-defined in terms of waveform, duration, bandwidth, amplitude.

They can constitute a crude “basis set” to “span” the detection band.

If our algorithms can detect these, they can detect any waveform with similar duration, bandwidth, amplitude (verified via extensive simulations).
Detection Confidence

- Multiple interferometers – coincidence!
  - Three interferometers within LIGO (H1, H2, L1)
  - Add GEO, TAMA, VIRGO as available.
  - Timing accuracy of ~ 100 usec (16 kHz digitization); 10 msec light travel time between LHO/LLO

- Veto environmental or other instrumental noise
  - Veto time coincidences with bursty glitches in environmental channels (seismic, acoustic, E-M, …) which are known to feed into GW channel
  - Bursty glitches in auxiliary interferometer channels which can feed into GW channel, but which would not respond measurably to a real GW signal

- Detection computation
  - Efficient filters for model-able signals
  - As tight a time-coincidence window as possible
  - Consistency amongst burst signals from multiple detectors, in amplitude, frequency band, waveform

- Data quality is really important in this analysis!

\[ r_k = \frac{\sum (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2} \sqrt{\sum (y_{i+k} - \bar{y})^2}} \]
Detection Efficiency Studies

- Measure test waveform efficiencies vs. signal strength $h_{rss} = \sqrt{\int |h(t)|^2 dt}$
- Different signal morphologies (ad hoc and astrophysically motivated)
  - Sine-Gaussians, Gaussians
  - Core collapse supernovae from three models (ZM, DFM, OBLW)
  - BBH merger (and ringdown) waveforms (Lazarus project)

- Source sky coordinates and polarizations were taken randomly; fixed inclination taken for SN, BBH
- Software injections: signals added to digitized interferometer output
- Hardware injections: signals added to length servo signal

![Graph showing Q=8.9 sine-Gaussian Efficiencies]
Interpreted results: rate-strength curves

- S2 search: no burst candidates seen
- Rate upper limit: less than 0.26 events/day at the 90% conf. level
- Divide by the efficiency curve for a particular waveform to get rate vs strength exclusion region
# Data taking and burst searches at a glance

<table>
<thead>
<tr>
<th></th>
<th>S1: 408 hours</th>
<th>S2: 1415 hours</th>
<th>S3: 1680 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lock</td>
<td>Sensitivity</td>
<td>Lock</td>
<td>Sensitivity</td>
</tr>
<tr>
<td>H1 (2km)</td>
<td>58% $1\times10^{-20}$ /sqrt(Hz)</td>
<td>74% $6\times10^{-22}$ /sqrt(Hz)</td>
<td>69% $6\times10^{-23}$ /sqrt(Hz)</td>
</tr>
<tr>
<td>H2 (4km)</td>
<td>73% $1\times10^{-20}$ /sqrt(Hz)</td>
<td>58% $6\times10^{-22}$ /sqrt(Hz)</td>
<td>63% $3\times10^{-22}$ /sqrt(Hz)</td>
</tr>
<tr>
<td>L1 (4km)</td>
<td>42% $3\times10^{-21}$ /sqrt(Hz)</td>
<td>37% $3\times10^{-22}$ /sqrt(Hz)</td>
<td>22% $2\times10^{-22}$ /sqrt(Hz)</td>
</tr>
<tr>
<td>H1&amp;H2&amp;L1</td>
<td>23% $h_{rss} \sim 1\times10^{-18}$</td>
<td>22% $h_{rss} \sim 1\times10^{-19}$</td>
<td>16% $h_{rss} \sim 2\times10^{-20}$</td>
</tr>
<tr>
<td></td>
<td>O(100hrs) x3coincidence GEO in coincidence</td>
<td>O(300hrs) x3coincidence TAMA in coincidence</td>
<td>O(300hrs) x3coincidence TAMA/GEO coincidence</td>
</tr>
</tbody>
</table>

**NO burst candidates seen!**

*AJW, FNAL W&C Seminar, October 28, 2005*
Conclusions

- LIGO detectors are working better and better
- Sensitivity and duty cycle are close to design values
- The worldwide network is joining in
- Analysis techniques and pipelines are becoming more powerful and streamlined
- Look for MORE and MORE INTERESTING results, and sooner or later, DETECTION and study of GWs and their sources from LIGO in near future!