The Present Gravitational Wave Detection Effort

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What are Gravitational Waves?

- Gravitational Waves = “Ripples in space-time”
- Perturbation propagation similar to light (obeys same wave equation!)
  - Propagation speed = c
  - Two transverse polarizations - quadrupolar: + and x

Example:
- Ring of test masses responding to wave propagating along z

Amplitude parameterized by (tiny)
  dimensionless strain $h$: $\Delta L \sim h(t) \times L$
Why look for Gravitational Radiation?

• Because it’s there! (presumably)

• Test General Relativity:
  – Quadrupolar radiation? Travels at speed of light?
  – Unique probe of strong-field gravity

• Gain different view of Universe:
  – Sources cannot be obscured by dust / stellar envelopes
  – Detectable sources some of the most interesting, least understood in the Universe
  – Opens up entirely new non-electromagnetic spectrum
What might the sky look like?
What makes Gravitational Waves?

- Radiation generated by quadrupolar mass movements:

\[ h_{\mu\nu} = \frac{2G}{rc^4} \frac{d^2}{dt^2} (I_{\mu\nu}) \]

(with \( I_{\mu\nu} = \) quadrupole tensor, \( r = \) source distance)

- Example: Pair of 1.4 \( M_{\text{sol}} \) neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

\[ h \approx \frac{10^{-21}}{(r/15\text{Mpc})} \]
Strong Indirect Evidence: Binary Orbit Decay

Neutron Binary System – Hulse & Taylor
PSR 1913 + 16 -- Timing of pulsars

Neutron Binary System
• separated by $10^6$ miles
• $m_1 = 1.44m_\odot$; $m_2 = 1.39m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity
• spiral in by 3 mm/orbit
• rate of change orbital period

Emission of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves.

What makes Gravitational Waves?

- Compact binary inspiral: "chirps"
  - NS-NS waveforms are well described
  - Recent progress on BH-BH waveforms

- Supernovae / GRBs: "bursts"
  - burst signals in coincidence with signals in electromagnetic radiation / neutrinos
  - all-sky untriggered searches too

- Pulsars in our galaxy: "periodic"
  - search for observed neutron stars
  - all-sky search (computing challenge)

- Cosmological Signals "stochastic background"
Gravitational Wave Detection

• Suspended Interferometers
  – Suspended mirrors in “free-fall”
  – Michelson IFO is “natural” GW detector
  – Broad-band response (~10 Hz to few kHz)
  – Waveform information (e.g., chirp reconstruction)
The Global Interferometer Network

The three (two) LIGO, Virgo and GEO interferometers are part of a Global Network. Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations.
Major Interferometers world-wide

<table>
<thead>
<tr>
<th>Interferometer</th>
<th>Location</th>
<th>Distance</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGO</td>
<td>Livingston, Louisiana &amp; Hanford, Washington</td>
<td>2 x 4000-m (1 x 2000-m)</td>
<td>Completed 2-year data run at design sensitivity – “enhancement” finishing</td>
</tr>
<tr>
<td>VIRGO</td>
<td>Near Pisa, Italy</td>
<td>1 x 3000-m</td>
<td>Took ~4 months coincident data with LIGO – approaching design sensitivity</td>
</tr>
<tr>
<td>GEO</td>
<td>Near Hannover, Germany</td>
<td>1 x 600-m</td>
<td>Took data during L-V downtime, about to undergo upgrade</td>
</tr>
<tr>
<td>TAMA</td>
<td>Tokyo, Japan</td>
<td>1 x 300-m</td>
<td>Used for R&amp;D aimed at future underground detector</td>
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Data Runs

Have carried out a series of Engineering Runs (LIGO E1–E14, Virgo WSR 1-13) and Science Runs (LIGO S1--S5, Virgo VSR1) interspersed with commissioning

S1 run:

17 days (Aug / Sept 2002) – Rough but good practice

S2 run:

59 days (Feb—April 2003) – Many good results

S3 run:

70 days (Oct 2003 – Jan 2004) -- Ragged

S4 run:

30 days (Feb—March 2005) – Another good run

S5 run: (VSR1 for Virgo)

23 months (Nov 2005 – Sept 2007) – At design sensitivity – focus of today
LIGO S1 → S5 Sensitivities

Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs

LIGO-G060009-01-Z

Strain spectral noise density

Strain spectral noise density
Virgo Sensitivities

- Black measurements – VSR1 – 2007
- Red measurements – May 2009

- Much better sensitivity than LIGO below ~40 Hz
- Binary black holes
- “Young” pulsars, e.g., Vela
Use calculated templates for inspiral phase ("chirp") with optimal filtering.

Search for systems with different masses:

- Binary neutron stars (\(\sim 1-3\) solar masses):
  - \(~15\) sec templates, \(1400\) Hz end freq
- Binary black holes (< \(\sim 30\) solar masses):
  - shorter templates, lower end freq
- Primordial black holes (<1 solar mass):
  - longer templates, higher end freq
Searching for binaries

- Use two or more detectors: search for double or triple coincident “triggers”
- Can infer masses and “effective” distance.
- Estimate inverse false alarm probability of resulting candidates: detection?

S5 Year 1 Search for “Low-Mass” Inspirals
Searching for binaries

- No evidence of excess
- Use detection efficiency and surveyed galaxies
  → Set upper limit vs stellar mass


$L_{10} = 10^{10} \times$ blue solar luminosity
Milky Way = 1.7 $L_{10}$
Searching for bursts

**GRB 070201**

- Short, hard gamma-ray burst
  - A leading model for short GRBs: binary merger involving a neutron star
- Position (from IPN) consistent with being in M31 (Andromeda)
- LIGO H1 and H2 were operating
- Result from (several) LIGO searches: No plausible GW signal found; therefore very unlikely to be from a binary merger in M31


⇒ Likely was SGR giant flare in M31

IPN 3-sigma error region from Mazets et al., ApJ 680, 545
Searching for bursts (untriggered)

- Search for double or triple coincident triggers (three algorithms)
- Check waveform consistency among interferometers – apply vetoes
- Set a threshold for detection for low false alarm probability
- Evaluate efficiency for variety of simple waveforms

Parameterize strength in terms of “root sum square of h” : $h_{\text{RSS}}$

$$\left( h_{\text{RSS}} \right)^2 = \int_{-\infty}^{+\infty} \left( |h_+(t)|^2 + |h_\times(t)|^2 \right) dt$$

Sampling of efficiency curves:

S5 Year 1 Search for Untriggered Bursts
Searching for bursts (untriggered)

Detected triggers and expected background for one algorithm (Coherent WaveBurst – wavelet-based) for triple-coincident triggers with $f_{\text{central}} > 200$ Hz

No candidates found above threshold in any of the searches

$\Rightarrow$ Set upper limits on rate vs $h_{\text{RSS}}$

![Graph showing rate vs $h_{\text{RSS}}$ with thresholds labeled as S1, S2, S4, S5.](image)

Coherent network amplitude

[arXiv:0905.0020 (May 2009)]
Searching for continuous waves

Crab Pulsar

Use coherent, 9-month, time-domain matched filter

Upper limits on GW strain amplitude $h_0$

- Single-template, uniform prior: $3.4 \times 10^{-25}$
- Single-template, restricted prior: $2.7 \times 10^{-25}$
- Multi-template, uniform prior: $1.7 \times 10^{-24}$
- Multi-template, restricted prior: $1.3 \times 10^{-24}$

Implies that GW emission accounts for $\leq 4\%$ of total spin-down power

Searching for continuous waves

Same matched-filter algorithm applied to 116 known pulsars over 23 months of S5
**Searching for continuous waves**

All-sky search for unknown isolated neutron stars

Semi-coherent, stacks of 30-minute, demodulated power spectra

(“PowerFlux”)

Searching for continuous waves

All-sky search for unknown isolated neutron stars

Coincidence among multiple 30-hour coherent searches

(Einstein@Home)

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

Improved (hierarchical) algorithm now running

Your computer can help too!

http://www.einsteinathome.org/
Searching for a stochastic background

- A primordial isotropic GW stochastic background is predicted by most cosmological theories.
- Given an energy density spectrum $\Omega_{gw}(f)$, there is a strain power spectrum:

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

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

\[
h(f) = S_{gw}^{1/2}(f) = 5.6 \times 10^{-22} \ h_{100} \sqrt{\Omega_0} \left( \frac{100 \text{Hz}}{f} \right)^{3/2} \ \text{Hz}^{1/2}
\]

- The signal can be searched from cross-correlations in different pairs of detectors: L1-H1 and H1-H2.
- The farther the detectors, the lower the frequencies that can be searched.
**Searching for a stochastic background**

Early-S5 H1-L1 Bayesian 90% UL:

\[ \Omega_{90\%} = 9.0 \times 10^{-6} \text{ (42-177 Hz)} \]
Other S5 Searches (released)

Search for Gravitational Wave Bursts from Soft Gamma Repeaters

Search for High Frequency Gravitational Wave Bursts in the First Calendar Year of LIGO's Fifth Science Run
arXiv:0904.4910

Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm
arXiv:0905.0005

Search for Gravitational Waves from Low Mass Compact Binary Coalescence in 186 Days of LIGO's fifth Science Run
arXiv:0905.3710
Other S5 (S6) Searches Underway (planned)

**Inspirals:**
- High-mass, spinning black holes
- Year 2, joint LIGO-Virgo Ringdowns
- GRBs

**Bursts:**
- Year 2, Joint LIGO-Virgo
- GRBs

**Continuous wave:**
- Full-S5 all-sky searches (semi-coherent, Einstein@Home)
- Directed searches (Cassiopeia A, globular clusters, galactic center, SN1987A)
- “Transient CW” sources
- All-sky binary

**Stochastic:**
- Full-S5 isotropic – imminent
- Directed (anisotropic)
- H1-H2
- High-frequency (37 kHz – LIGO arm free spectral range)
Looking Ahead

Both LIGO and Virgo underwent significant upgrades since last science run:

Initial LIGO → “Enhanced LIGO”
Initial Virgo → “Virgo +”

Data taking resumes next week, but with significant commissioning breaks scheduled to fix noise sources that sustained running reveals

→ Running/commissioning strategy worked very well for LIGO in S5
→ Aiming at up to factor of two improvement in strain sensitivity
  (most feasible for higher frequencies)

Shutdown for installation of Advanced LIGO and Virgo – early 2011
(see presentation by G. Losurdo)
Searching for very-low-frequency stochastic gravity waves – Pulsar Timing Arrays

By precisely monitoring the timings of an array of many millisecond pulsars in different directions, radio astronomers hope to detect direct evidence of stochastic gravitational waves

→ Look for quadrupolar pattern in solar system timing residuals

Several groups:

- Parkes Pulsar Timing Array (Australia)
- European Pulsar Timing Array (U.K., France, Netherlands, Italy)
- Nano-Grav (USA)

→ Aiming to improve upon existing limit: $\Omega(\text{nHz}) < 10^{-8}$

Eventual followup with proposed Square Kilometer Array (SKA)
→ Aiming to reach $\Omega(\text{nHz}) < 10^{-13}$
Summary

Bottom line:

No GW signal detected yet 😞

But

• Not all S5 / VSR1 searches completed
• Upcoming S6 / VSR2 searches should be more sensitive
• Advanced LIGO / Virgo promise major sensitivity improvements with orders of magnitude increase in expected event rates

And

• Radio pulsars may provide alternative first glimpse of the elusive graviton
Extra Slides
LIGO Observatories

Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts
Virgo

Have begun collaborating with Virgo colleagues (Italy/France)

Took data in coincidence for last ~4 months of latest science run

Data exchange and joint analysis underway

Will coordinate closely on detector upgrades and future data taking

3-km Michelson Interferometer just outside Pisa, Italy
GEO600

Work closely with the GEO600 Experiment (Germany / UK / Spain)

- Arrange coincidence data runs when commissioning schedules permit
- GEO members are full members of the LIGO Scientific Collaboration
- Data exchange and strong collaboration in analysis now routine
- Major partners in proposed Advanced LIGO upgrade

600-meter Michelson Interferometer just outside Hannover, Germany
LIGO Detector Facilities

- Stainless-steel tubes
  (1.24 m diameter, ~10^{-8} torr)
- Gate valves for optics isolation
- Protected by concrete enclosure

Vacuum System
LIGO Detector Facilities

LASER
- Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- Elaborate intensity & frequency stabilization system, including feedback from main interferometer

Optics
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils
LIGO Detector Facilities

Seismic Isolation

• Multi-stage (mass & springs) optical table support gives $10^6$ suppression
• Pendulum suspension gives additional $1/f^2$ suppression above $\sim 1$ Hz
LIGO Interferometer Optical Scheme

Michelson interferometer
With Fabry-Perot arm cavities

• Recycling mirror matches losses, enhances effective power by ~ 50x

4 km Fabry-Perot cavity

end test mass

LASER/MC

recycling mirror

6W

150 W

(~0.5W)

20000 W
What Limits the Sensitivity
of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

Best design sensitivity:
\[ \sim 3 \times 10^{-23} \text{ Hz}^{-1/2} \text{ @ 150 Hz} \]
“Locking” the Interferometer

Sensing gravitational waves requires sustained resonance in the Fabry-Perot arms and in the recycling cavity

→ Need to maintain half-integer # of laser wavelengths between mirrors
→ Feedback control servo uses error signals from imposed RF sidebands
→ Four primary coupled degrees of freedom to control
→ Highly non-linear system with 5-6 orders of magnitude in light intensity

Also need to control mirror rotation ("pitch" & "yaw")
→ Ten more DOF’s (but less coupled)

And need to stabilize laser (intensity & frequency), keep the beam pointed, damp out seismic noise, correct for tides, etc.,…