What can gravitational waves do to probe early cosmology?

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"Kavli-CERCA Conference on the Future of Cosmology"
Case Western Reserve University
October 10-12, 2003
Signals from the Early Universe

The smaller the cross-section, the earlier the particle decouples

- **Photons:** \( T = 0.2 \text{ eV} \) \( t = 300,000 \text{ yrs} \)
- **Neutrinos:** \( T = 1 \text{ MeV} \) \( t \sim 1 \text{ sec} \)
- **Gravitons:** \( T = 10^{19} \text{ GeV} \) \( t \sim 10^{-43} \text{ sec} \)

Cosmic Microwave background

WMAP 2003
Primordial stochastic backgrounds: *relic GWs produced in the early Universe*

- Cosmology
- Unique laboratory for fundamental physics at very high energy
Astrophysically generated stochastic backgrounds (foregrounds): *incoherent superposition of GWs from large populations of astrophysical sources*

- Populations of compact object in our galaxy and at high redshift
- 3D distribution of sources
- Star formation history
The Gravitational Wave Signal

- The spectrum:

\[ \Omega_{gw}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{gw}(f)}{d \ln f} \]

- The characteristic amplitude

\[ h_c(f, \Delta f) \approx 7.1 \times 10^{-22} \left[ \frac{h_{100}^2 \Omega_{gw}(f)}{10^{-8}} \right]^{1/2} \left( \frac{f}{1 \text{ mHz}} \right)^{-3/2} \left( \frac{\Delta_b f}{3.17 \times 10^{-8} \text{ Hz}} \right)^{1/2} \]
What we know

**limits on primordial backgrounds**

White dwarf and neutron star binary system has second clock, the orbital period! Change in orbital period can be computed in GR, simplifying fitting. Gives limit from $10^{-11}$ to $4.4 \times 10^{-9}$ Hz

ms pulsars are fantastic clocks! Stability places limit on gravitational waves passing between the pulsar and us. Integrating for one year gives limit at $f \sim 4.4 \times 10^{-9}$ Hz
Theoretical Predictions

Maggiore 2000
Expected Signal Strength

-5
-10
-15

log Omega(f)

Nucleosynthesis

Slow-roll inflation
Detection of Gravitational Waves

Gravitational Wave Astrophysical Source

Terrestrial detectors
Virgo, LIGO, TAMA, GEO AIGO

Detectors in space
LISA
Astrophysics Sources

**frequency range**

- Gravitational Waves can be studied over ~10 orders of magnitude in frequency
  - terrestrial + space
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
International Network

- Network Required for:
  - Detection Confidence
  - Waveform Extraction
  - Direction by Triangulation

+ “Bar Detectors” : Italy, Switzerland, Louisiana, Australia
Stochastic Background Signal

auto-correlation
Overlap Reduction Function

(LIGO–LA and other detectors)

- LIGO–WA
- ALLEGRO (co-aligned)
- ALLEGRO (mis-aligned)
- GEO–600

Frequency (Hz)
Simultaneous Detection

*LIGO*

- **Hanford Observatory**
- **Caltech**
- **Livingston Observatory**
- **MIT**

Distance: 3002 km
(V/c = 10 ms)
LIGO Livingston Observatory
LIGO Hanford Observatory
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

Livingston 4km Interferometer

First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03
Signals from the Early Universe

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

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

- **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

Log[Ω_GW]
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
Log [f, Hz]
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6

SCOBE

Inflation

Cosmic Strings

Pulsar Timing

Phase Transitions

Nucleosynthesis

Adv LIGO

1IFO + IFO
8Bar + Bar (Warm)
9Bar + Bar (Cryo.)
1IFO + Bar (1st Gen.)
1IFO + Bar (2nd Gen.)
IFO (1st Gen.)
IFO (2nd Gen.)

LIGO

S1

S2

E7
Interferometers in Space

The Laser Interferometer Space Antenna (LISA)

- The center of the triangle formation will be in the ecliptic plane
- 1 AU from the Sun and 20 degrees behind the Earth.
LISA: Sources and Sensitivity
LISA: Astrophysical Backgrounds

LISA and GW Background Radiation
r.m.s. amplitudes after 1 year of observation

Compact WD binary background -- estimate
LISA's instrumental noise budget
Possible cosmological gw background, $\Omega_{gw} = 10^{-10}$
Possible cosmological gw background, $\Omega_{gw} = 10^{-8}$
Detecting the Anisotropy

(1) Break-up the yrs long data set in short (say a few hrs long) chunks

\[ \tilde{o}(f; t) = \int_{t-\tau/2}^{t+\tau/2} dt' e^{-2\pi i f t'} o(t') \]

(2) Construct the new signal

\[ S(t) = \int_{-\infty}^{+\infty} df \tilde{o}_j(f, t) \tilde{Q}(f) \tilde{o}_k^*(f, t) \]

The LISA motion is periodic

\[ \langle S(t) \rangle = \sum_{-\infty}^{+\infty} e^{i2\pi mt/T} \langle S_m \rangle \]

(3) Search for peaks in \( S(t) \):

\[ S_m = \frac{1}{T_{\text{obs}}} \int_0^{T_{\text{obs}}} e^{-i2\pi mt/T} S(t) \, dt \]

\( S_m \) is the observable
Instrument’s sensitivity

\[ h_{100}^2 \Omega_{\text{min}} = \frac{K}{T^{1/2}} \sqrt{\frac{50\pi^2}{3H_0^2}} \left[ \int_0^{\infty} df \frac{\gamma^2(f)}{f^6 S_n^2(f)} \right]^{-1/2} \]
Sensitivity

Primordial Stochastic Background
Stochastic Background

Astrophysical Foregrounds

- White-dwarf binary systems (galactic and extra-galactic) \( (Hils \ et \ al, \ 1990; \ Schneider \ et \ al, \ 2001) \)

- Neutron star binary systems (galactic and extra-galactic) \( (Schneider \ et \ al, \ 2001) \)

- Rotating neutron stars (galactic and extra-galactic) \( (Giazzotto \ et \ al, \ 1997; \ Regimbau \ and \ de \ Freitas \ Pacheco, \ 2002) \)

- Solar mass compact objects orbiting a massive black hole (extra-galactic) \( (Phinney \ 2002) \)

- Super-massive black hole binaries (extra-galactic) \( (Rajagopal \ and \ Romani, \ 1995) \)
Astrophysical Signals

Limit Sensitivity for Primordial Sources

![Graph showing sensitivity limits for different types of sources (extra-galactic NS-NS, WD-WD, and WDS-WD) compared to LISA - 1yr sensitivity.]
Ultimate GW Stochastic Probes

$31$

$-11$

$-12$

$-13$

$-14$

$-15$

$-16$

$log \Omega(f)$

$log f$

$LISA$ sensitivity limit (1yr)

$3^{rd}$ generation sensitivity limit (1yr)

$WD-WD$

$NS-NS$

$BH-MBH$

$NS$

$\text{CORRUPTED}$

$\text{CLEAN}$

$\hbar^{2} \epsilon_{p}^{(\text{min})} \approx 8 \times 10^{-17} \left( \frac{f}{0.1 \text{ Hz}} \right)^{3/2} \left( \frac{T}{10^8 \text{ sec}} \right)^{-1/2} \left[ \frac{h_{\text{rms}}}{10^{-24}} \right]^2$
Future experiments in the “gap” (?)

A. Vecchio
Conclusions

- Primordial Gravitational Wave Stochastic Background is potentially a powerful probe of early cosmology
- Present/planned earth/space-based interferometers will begin to probe the sensitivity regime of interest.
- They will either set limits constraining early cosmology or detect the stochastic background
- They are ultimately limited to $\sim 10^{-11}$ and $10^{-13}$ in energy density
- A future short arm space probe could probe the gap (0.1 – 1 Hz region looks cleanest)