Status of Gravitational Wave Detection

Adalberto Giazotto
INFN Pisa and EGO
The Indirect Evidences of GW Existence

1974: First Discovery
Taylor and Hulse

Coalescing Neutron Star System PSR 1913+16

Orbital period decreasing changes periaster passage time in total agreement with GR

Now there are about 6 similar systems, and the “double pulsar” PSR J0737-3039 is already overtaking 1913 in precision. All agree with GR
Some GW SOURCES

1) Coalescing Binary Systems: NS and Black Holes
   Rate ~ 0.01/year in a 100 Mly sphere.

2) Supernovae Explosions:
   Explosions Rate:
   Virgo Cluster (h~10^-23) ~30/year
   Milky Way (h~10^-20) 1/30 years

3) Periodic Sources: For rotating Neutron Stars h very "Small" h< 10^-25. Very long Integration time (1 year) increases S/N.

4) Big-Bang Cosmological BKG (CB): Since $\alpha_{\text{GRAV}} = 10^{-39}$ Big-Bang matter is mainly transparent to GW. In the Virgo bandwidth we may observe GW emitted after 10^{-24}s from time zero.
The Detection of Gravitational Waves

F.A.E. Pirani in 1956 first proposed to measure Riemann Tensor by measuring relative acceleration of two freely falling masses. If A and B are freely falling particles, their separation \( \xi^a = (x_A - x_B)^a \) satisfies the Geodesic Deviation equation:

\[
\frac{D^2 \xi^\alpha}{d\tau^2} = \frac{1}{2} h^{TT}_{\alpha\beta} \xi^\beta
\]

Riemann Force

\[
F^\alpha = \frac{1}{2} M \ddot{h}^{TT}_{\alpha\beta} \xi^\beta
\]

The receiver is a device measuring space-time curvature i.e. the relative acceleration of two freely falling masses or, equivalently, their relative displacement.
In 1959 Joseph Weber was the first to build a GW detector working on the principles of Geodesic Deviation Equation.

\[ M = 2.3 \, t \]
\[ L = 3m \]

Electronic noise
Resonance frequency
Thermal noise
Bandwidth

GW signal

Antenna Pattern summed on polarizations

Electromechanical Transducer tuned to the lowest longitudinal mode of the bar

Figure courtesy of Massimo Cerdonio
Cryogenic Bar Detectors

- ALLEGRO
- PROVIDER
- AURIGA
- NAUTILUS
- NIOBE
Cryogenic Bar Detectors

IGEC the Resonant Bar Detectors network

International Gravitational Event Collaboration established 1997 in Perth

The First GW Detector Network
Massimo Visco on behalf of the IGEC2 Collaboration
Rencontres de Moriond
Gravitational Waves and Experimental Gravity
March 11-18, 2007
La Thuile, Val d'Aosta, Italy

IGEC-1 (1997-2000)
- 29 days of four-fold coinc.
- 178 days of three-fold coinc.
- 713 days of two-fold coinc.
Followed by a series of upgrades resumed operations
EXPLORER in 2000
AURIGA in 2003
NAUTILUS in 2003
ALLEGRO in 2004
NIOBE ceased operation
IGEC-2 (2005-)
First data analyzed covered May-November 2005 when no other observatory was operating

Cryogenic Bar Detectors Sensitivity, Stability & Duty Cycle

EXPLORER
AURIGA
NAUTILUS
High Stability operation
Bar Detectors situation at Present

NIOBE (Perth) stopped operation and did not join IGEC-2

ALLEGRO (LSU) stopped operation in 2007

In 2006 INFN stopped R&D on Spherical Detectors and left running Auriga, Nautilus and Explorer on an annual evaluation. It is likely that at Virgo+ starting (6/2009) they will be shut down.

INFN left open R&D on DUAL
DUAL is a wide band high frequency detector with high bandwidth (5 kHz) and reduced Back Action.

The only existing Spherical Detector in commissioning phase is Minigrail (G. Frossati et al.) (Kamerlingh Onnes Laboratory, Leiden University, Nd)
INTERFEROMETRIC DETECTORS

Large L → High sensitivity
Very Large Bandwidth 10-10000 Hz

Displacement sensitivity can reach $\sim 10^{-19}-10^{-20}$ m, then, for measuring $\Delta L/L \sim 10^{-22}$, $L_A$ and $L_B$ should be km long.
Optical Noises can not be overcome with standard ITF but can with QND techniques.

Thermal Noise, the more subtle, can perhaps be overcome bringing Mirrors close to -273 K

\[ \hbar^{\text{SQL}} \approx \frac{1}{\mathcal{L} \sqrt{\mathcal{M}}} \]
Modern Interferometers with QND Signal Readout

Uncertainty Principle: \( \Delta \varphi \cdot \Delta N \sim 1 \)

We only measure \( \varphi \), the only one containing the signal, hence we can ignore \( \Delta N \).

In a Fix Mirror ITF, Rad. Press. Fluct. can’t move mirrors.

In a suspended Mirror ITF, Rad. Press. Fluct. move randomly mirrors, hence Phase noise is increased.

A Detuned Cavity can rotate in the \( \Delta \varphi, \Delta N \) plane. Phase noise \( \Delta \varphi \) has been decreased at expenses of \( \Delta N \).

Optical Noise can be less than SQL:

\[
\frac{4\pi}{\lambda} hL \geq \sqrt{K} + \frac{1}{\sqrt{K}}
\]

\[
\frac{4\pi}{\lambda} hL \geq \frac{1}{\sqrt{K}}
\]
Virgo Diagram

Freq. Stab.
0-2Hz 2-10000Hz
Δν=10^{-4}Hz^{1/2} Δν=10^{-6}Hz^{1/2}

Angular Alignment Matrix

F=30
GW Detectors have a very appealing Antenna pattern

Radiotelescope Antenna Pattern

Interferometric GW Detector Antenna Pattern

ALL sky seen at once.

Sources are localized

“Geometrically”
Global network of Detectors

Coherent Analysis: why?
- Sensitivity increase
- Source direction determination from time of flight differences
- Polarizations measurement
- Test of GW Theory and GW Physical properties

Astrophysical targets
- Far Universe expansion rate Measurement
- GW energy density in the Universe
- Knowledge of Universe at times close to Planck’s time
In 1999, TAMA is the first large ITF to start observations, in 2001 attained the world best sensitivity and made continuous observation more than 1000 hr with the highest sensitivity. Joint observations with LIGO/GEO during DT7-DT9

Best sensitivity: \( h = 1.710^{-21} \frac{1}{\sqrt{Hz}} @ 1KHz \)  
Recycling gain of 4.5
GEO 600 is a Dual Recycling Interferometer

- Power Recycling 1%
- Signal Recycling 1%

1W

GEO 600 m- Hannover

Typical Sensitivity: Science Runs

- S1 Aug 26 '02
- S3H Nov 5 '03
- S3H Dec 31 '03
- S4 Feb 22 '05
- S5 NW Mar 23 '06
- S5 Jun 3 '06

Typical Sensitivity

Strain [1e-16/Hz]

Frequency [Hz]
Virgo Sensitivity, Duty Cycle and Stability
First 5 weeks (started 18/5/2007) of Coincidence with LIGO/GEO
One Vacuum Tube with 2 ITF: 4 km and 2 km

Present LIGO Sensitivity

Strain Sensitivity for the LIGO Hanford 4km Interferometer

4 km Arms
GW DETECTION STATUS

IGEC: Network of Bar Detectors Started in 1997 (Auriga, Explorer, Nautilus, Allegro) for impulsive GW detection.
No evidence of a significant GW signal

LIGO-GEO600: GW from Pulsar (28 known) - $\varepsilon < 10^{-5} - 10^{-6}$ (no mountains > 10 cm) - $\tilde{h}$ upper limits: $2 \times 10^{-24} @ 200 \text{Hz}$, $5 \times 10^{-24} @ 400 \text{Hz}$, $10^{-23} @ 1 \text{KHz}$
No evidence of a significant GW signal

LIGO, GEO600, TAMA: Up. lim.: Coalescing NS-NS $< 1$ event/(gal.year) $2 < M_0 < 6$
Coalescing BH-BH $< 1$ event/(gal.year) $10 < M_0 < 80$
No evidence of a significant GW signal

LIGO: Stockastic BKG

Virgo, LIGO, GEO 600: May 18th 2007 started common data taking and coherent analysis; main target impulsive events ???
CLIO: The First Cryogenic Interferometer for GW Detection

Construction of CLIO

Achieved Pressure
- 100m Arm -
  $6 \times 10^{-5}$ Pa
- Cryostat -
  $2 \times 10^{-6}$ Pa
by Cryostat itself

“Status of TAMA 300” N.Kanda & the TAMA collab.
|                | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|----------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| **RUNNING**    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| TAMA300        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|                 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| **UNDER**      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| GEO600         |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|                 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Virgo          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|                 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LIGO Hanford   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LIGO Livingston|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|                 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| **FAR AWAY**   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LISA ??        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Einstein ??    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| **CONSTRUCTION**|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LCGT ?         |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AIGO ?         |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| **LAUNCH**     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LISA ??        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Einstein ??    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| **COMMISSIONING**|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LISA ??        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Einstein ??    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| **DATA**       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| LISA ??        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Einstein ??    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

The Future

- **TAMA300**: New Suspensions
- **GEO600**: GEO HF
- **Virgo**: Virgo+, Advanced Virgo
- **LIGO Hanford Livingston**: LIGO H, Advanced LIGO
- **LCGT**?: Construction
- **AIGO**?: Construction
- **LISA ??**: Launch Transfer data
- **Einstein ??**: PCP, Construction Commissioning data
**Virgo+**

1) Cure low freq. Noise
2) Fused silica suspens
3) Increase arm finesse
4) Higher power laser

Final Decision to be made late 2007

(Data taking starts 6/2009)

**Henanced Ligo**

1) DC readout
2) Higher laser power
3) Output modecleaner

A factor of 2 improv. in sensitivity (8 in event rate)

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**Advanced Virgo**

1) Larger mirror
2) Improved coatings
3) Higher laser power
4) DC readout

R&D underway

Design decisions late 2007

(Data taking starts 2014)

**Advanced Ligo**

1) Active anti-seismic system operating to down to 10 Hz
2) Lower thermal noise suspensions and optics
3) Higher laser power
4) More sensitive and more flexible optical configuration
<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>LIGO</strong></th>
<th><strong>Advanced LIGO</strong></th>
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<tr>
<td>Input Laser Power</td>
<td>10 W</td>
<td>180 W</td>
</tr>
<tr>
<td>Mirror Mass</td>
<td>10 kg</td>
<td>40 kg</td>
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<tr>
<td>Interferometer Topology</td>
<td>Power-recycled</td>
<td>Dual-recycled</td>
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<td></td>
<td>Fabry-Perot arm cavity</td>
<td>Fabry-Perot arm cavity</td>
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<tr>
<td></td>
<td>Michelson</td>
<td>Michelson</td>
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<tr>
<td>GW Readout Method</td>
<td>RF heterodyne</td>
<td>DC homodyne</td>
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<tr>
<td>Optimal Strain Sensitivity</td>
<td>$3 \times 10^{-23} / \text{rHz}$</td>
<td>Tunable, better than $5 \times 10^{-24} / \text{rHz}$</td>
</tr>
<tr>
<td>Seismic Isolation</td>
<td>$f_{\text{low}} \sim 50 \text{ Hz}$</td>
<td>$f_{\text{low}} \sim 10 \text{ Hz}$</td>
</tr>
<tr>
<td>Mirror Suspensions</td>
<td>Single Pendulum</td>
<td>Quadruple pendulum</td>
</tr>
</tbody>
</table>
GEO 600

- Emphasize high frequencies—length less important
- Pioneer advanced techniques for other large interferometers
- Tuned signal recycling and squeezing?
**LCGT: A CRYOGENIC INTERFEROMETER**

### Suspension Conceptual Design

- **Vacuum is common**
- **Radiation outer shield**
- **Heat links start from this stage to inner radiation shield**
- **SAS: 3 stage anti-vibration system with inverted pendulum**
- **SPI auxiliary mirror Sapphire fiber suspending main mirror**
- **Mirrors Cooled at 20 K**

**COST** US$ 135M

Does not include salaries & maintenances of facilities.
AIGO

- Project prospectus completed 2006
- AIGO concept plan submitted to Minister for Science Oct 2006
- AIGO International Advisory Committee appointed

- AIGO provides strong science benefits e.g. host galaxy localization
- 5km baseline sensitive to inspirals in the range ~250Mpc
- Australian Consortium welcomes new partners in this project
Interferometers Under Far Away Approval
LISA

- ESA & NASA have exchanged letters of agreement.
- Mission duration up to 10 yrs.
- LISA Pathfinder technology demonstrator (ESA: 2008)

Courtesy B. Shutz
LISA Sensitivity

- Vibration control limit
- Resolvable binaries
- Binary confusion noise
- Detection threshold (S/N = 5) for a 1-year observation
- Massive black holes

Graph shows sensitivity levels for different mass ranges.
ET Baseline Concept

• Underground location
  – Reduce seismic noise
  – Reduce gravity gradient noise
  – Low frequency suspensions

• Cryogenic & Squeezed

• Overall beam tube length ~ 20km

• Possibly different geometry
Einstein Telescope Configuration

1) ET will be the only surviving project. Virgo and LIGO will not have enough sensitivity for making a Network with ET

2) ET will be formed by at least 4 interferometers, well spaced. For solving the “Inverse Problem” 4 variables have to be measured: 2 angles and 2 polarizations.

3) Possibly the ET network should have highly spaced interferometers. A wise decision could be in the same spirit as ESO whose telescopes are not in Europe. ET network should be scattered in best sites for better solving the “Inverse Problem”
Einstein Gravitational-Wave Telescope (ET)

Harald Lück
for the European Gravitational-Wave Community
Some Final Considerations

• Bar detectors have grown up, by means of a fantastic technological effort, to enormous and unexpected sensitivity and operation stability. Their operation was so good as to create the first GW network.

• The big steps forward in the last decade has been in the Interferometers technology. They reached design sensitivity above 100 Hz and stability is so good (unexpectedly) that we have created an efficient network. Advanced LIGO and Virgo will open the very low frequency region.

• Class Einstein, after what we have lorned by the big machine, seems feasible with a very high probability of success. 1 Day of data of ET is equivalent to $10^6$ days of data taking with Virgo or LIGO. This seems to be the right way to go for starting GW astronomy.
So Gravity waves do exist and Astrophysical phenomena involve:

- enormous masses and big accelerations
- According to GR: Copious emission of GW
- amazing matter density
  - $\alpha_{\text{GRAV}} = 10^{-39}$:
    - Matter easily traversed by GW

Gravitational Waves are then odd objects by means of which we may start a new Astronomy: **GW Astronomy.**
The Indirect Evidences of GW Existence

1974: First Discovery by Taylor and Hulse (Nobel Prize 1993)
Coalescing Neutron Star System PSR 1913+16

Further evidences
PSR J0737-3039:
The binary Neutron Star system PSR J0737-3039 was discovered in 2003.
The system is doing exactly what GR theory predicts.

T. Strohmayer:
White Dwarf very tight Binary System (80000 km). The system's orbital period is 321.5 seconds and is decreasing by 1.2 milliseconds every year in complete agreement with GR theory.
Virgo Superattenuator

Inertial Damping

Inverted Pendulum
\( \nu_{\text{RES}} = 40 \text{ mHz} \)

Mechanical Filters

Marionette

Seismic noise

Attenuation: \(10^{-10}\)

Filtered seismic noise

Frequency (Hz)

\(6 \times 10^{-21}\)
Cryogenic Bar Detectors

In 1959 J.W. was the first to propose a GW detector working on the principles of Geodetic Deviation Equation.

Antenna Pattern summed on polarizations

\[ \rho = \sin^2 \theta \]

Bar Detector
Why is Gravity so Appealing

Why is Gravitational Coupling Constant amazingly small?

Three ingredients for a New Astronomy

1) Smallness of $\alpha_{\text{GRAV}} = 10^{-39}$ means that interaction of Gravitational Waves (GW) with matter is extremely small.

2) General Relativity Theory (GR) predicts the existence of GW and shows that an accelerated mass emits GW.

3) Taylor and Hulse showed observationally that GW exist and their rate of emission follows “EXACTLY” GR predictions.
**The Generation of GW**

**Einstein eq.s**
\[ \Psi_{\mu\nu} = (8\pi G/c^4) \tau_{\mu\nu} \]
\[ \Psi_{\mu\nu} = h_{\mu\nu} - \frac{1}{2} \delta_{\mu\nu} h^\lambda_\lambda \]

**The GW Generator**
\[
h_{\alpha\beta}^{TT} = - \frac{2G}{c^4 R_o} \left( \frac{\partial^2}{\partial t^2} \int \rho(x_\alpha x_\beta) F^T dV \right)_{t = R_o / c}
\]

**GW are produced by the second time derivative of the source**

**Quadrupole Momentum of the mass distribution**

**The GW Generator**

\[
h_{\mu\nu}^{TT} = h_{11}^{TT} + h_{12}^{TT}
\]

\[
\begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

\[
\begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

= \( h^{+e^+}_{\text{ik}} + h^x_{\text{ik}} \)

**GW along X_3**

**The polarizations** \( e^{+}_{\text{ik}} \) and \( e^{x}_{\text{ik}} \) **are exchanged with a \( \pi/4 \) rotation around \( x_3 \) axis i.e. GW are spin 2 massless field**

**Symmetrical** \( h=0 \) **Low Asymmetry** **Max. Asymmetry**
1) Coalescing Binary Systems: NS and Black Holes

Maximal Asymmetry → “Large” $h$

“known” waveform

Rate: 1~2/year in a 50Mpc sphere.

2) Supernovae Explosions

Low Asymmetry: “Small” $h$

Explosions Rate:
- Virgo Cluster ($h \sim 10^{-23}$) 1~2/year
- Galaxy ($h \sim 10^{-20}$) 1/30 years
3) Periodic Sources: $10^9$ Galactic rotating Neutron Stars emitting in the Hz region
Very Low Asymmetry: Very “Small” $h$ but very long Integration Time

Affected by Earth Doppler shift

$e^{i\omega t} \Rightarrow e^{i\omega(t-\vec{n}\cdot\vec{R}/c)}$

$h < 10^{-25}$

4) Big-Bang Cosmological BKG (CB): In the Virgo bandwidth we may observe GW emitted after $10^{-24}$s from time zero. GW are the only way to investigate Bing-Bang close to time zero. Detection of CB requires Coincidence of two close detectors extremely sensitive.
**Periodic sources: upper limits**

This is the Hanford all sky upper limit for periodic sources strain (95% confidence level), obtained for the Hanford observatory. The plot compares several search method, documented in the S4 paper LIGO-P060010-05-Z
Periodic sources: upper limit

The same of the previous figure, for the Livingston observatory.
Upper limits: bursts

Exclusion diagrams (rate limit at 90% confidence level, as a function of signal amplitude) for sine-Gaussian simulated waveforms for the S4 analysis compared to the S1 and S2 analyses (the S3 analysis did not state a rate limit). These curves incorporate conservative systematic uncertainties from the fits to the efficiency curves and from the interferometer response calibration. The 849 Hz curve labeled “LIGO-TAMA” is from the joint burst search using LIGO S2 with TAMA DT8 data [8], which included data subsets with different combinations of operating detectors with a total observation time of 19.7 days and thereby achieved a lower rate limit. The h_{rss} sensitivity of the LIGO-TAMA search was nearly constant for sine-Gaussians over the frequency range 700–1600 Hz.
Upper limit: inspirals

Upper limits on the binary inspiral coalescence rate per year and per L10 as a function of total mass of the binary, for Primordial Black Hole binaries. The darker area shows the excluded region after accounting for marginalization over estimated systematic errors. The lighter area shows the additional excluded region if systematic errors are ignored.
Upper limits: inspirals

Same as the previous figure for Binary Neutron Stars
Upper limits: inspirals

Same as the previous figure for Binary Black Holes
Upper bounds: stochastic background

90% Upper Limit on GW spectrum at 100 Hz (see the model on the right) as a function of $\alpha$ for S3 H1L1 and S4 H1L1+H2L1 combined, and expected final sensitivities of LIGO H1L1 and H1H2 pairs, assuming LIGO design sensitivity and one year of exposure.

$$\Omega_{GW}(f) = \frac{f}{\rho_c} \frac{d\rho_{GW}}{df}$$

Model:

$$\Omega_{GW}(f) = \Omega_\alpha \left( \frac{f}{100 \text{ Hz}} \right)^\alpha$$
Three ingredients for a new Astronomy

2) Einstein in his General Relativity showed that:
- Accelerated masses emit GW.
- In presence of masses, the Space-Time (ST) is curved.
- Gravitational Waves are ripples in the ST traveling at speed of light.

1) Smallness of $a_{\text{GRAV}}=10^{-39}$ means that interaction of Gravity with matter is extremely small.

3) Taylor and Hulse demonstrated, indirectly, that GW exist and their rate of emission follows “EXACTLY” General Relativity predictions.
The Detection of Gravitational Waves

F.A.E. Pirani in 1956 first proposed to measure Riemann Tensor by measuring relative acceleration of two freely falling masses. If A and B are freely falling particles, their separation $\xi^\alpha = (x_A - x_B)^\alpha$ satisfies the Geodesic Deviation equation:

\[
\frac{D^2 \xi_\alpha}{d\tau^2} = \frac{1}{2} \ddot{h}^{TT}_{\alpha\beta} \xi^\beta
\]

The receiver is a device measuring space-time curvature i.e. the relative acceleration of two freely falling masses or their relative displacement.

Effect of Riemann Force

\[\Delta L / L \sim h < 10^{-22}\]

Effect of 2 Polarizations

\[h_+ \quad h_x\]
Cryogenic Bar Detectors
Modern Interferometers with QND Signal Readout

Uncertainty Principle: \( \Delta \varphi \cdot \Delta N \sim 1 \)

We only measure \( \varphi \), the only one containing the signal, hence we can ignore \( \Delta N \).

Optical Noise can be less than SQL:

\[
\frac{4\pi}{\lambda} hL \geq \sqrt{K} + \frac{1}{\sqrt{K}}
\]

In a Fix Mirror ITF, Rad. Press. Fluct. can’t move mirrors.

In a suspended Mirror ITF, Rad. Press. Fluct. move randomly mirrors, hence Phase noise is increased.

A Detuned Cavity can rotate in the \( \Delta \varphi, \Delta N \) plane. Phase noise \( \Delta \varphi \) has been decreased at expenses of \( \Delta N \).
Current sensitivity of CLIO

After reaching thermal limit, start cooling

Mirror thermal noise (300K)
1970
The first Interferometer for GW detection was built by Robert Forward (Hughes Lab)

1980
The Max Planck 30 m Delay Lines Interferometer. Problem: Too much Diffused Light

Break Through: 1981
The 10 m Glasgow and 40 m CALTEC Fabry Perot Interferometers
**LCGT: A CRYOGENIC INTERFEROMETER**

**Suspension Conceptual Design**
- Vacuum is common
- Radiation outer shield
- Heat links start from this stage to inner radiation shield
- SPI auxiliary mirror
- Sapphire fiber suspending main mirror
- SAS: 3 stage anti-vibration system with inverted pendulum
- Main mirror

**Mirrors Cooled at 20 K**

**COST** US$ 135M

Does not include salaries & maintenances of facilities.