LIGO

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

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LIGO PROJECT DEPUTY FOR INTEGRATION AND SYSTEMS ENGINEERING

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LIGO OVERVIEW

- NATIONAL SCIENCE FOUNDATION (NSF) PROJECT BEING DEVELOPED JOINTLY BY:
  - CALIFORNIA INSTITUTE OF TECHNOLOGY
  - MASSACHUSETTS INSTITUTE OF TECHNOLOGY
- PURPOSE:
  - EXPERIMENTAL VERIFICATION OF THE EXISTENCE OF GRAVITATIONAL WAVES (GW)
  - OPEN NEW WINDOW ON THE UNIVERSE
GRAVITATIONAL WAVE (GW) EFFECTS

- GWs CAUSE GEOMETRY/LENGTH FLUCTUATIONS
- QUADRUPOULAR
  - X and + POLARIZATIONS
- DIMENSIONLESS AMPLITUDE, STRAIN $h = \Delta L / L \sim 10^{-21}$

$$\sim \frac{\text{ATOMIC DIAMETER}}{\text{EARTH-SUN DISTANCE}} = \frac{1 \text{ Angstrom}}{150 \text{ Gm}}$$

$h(r, \hat{k}) = h e^{i(\hat{k}_{GW} \cdot \hat{r} - \omega_{GW} t)}$

where

$\hat{k}_{GW} = \text{GW wave vector}$
$\hat{r} = \text{coordinate vector}$
$\omega_{GW} = \text{GW temporal frequency}$

$$\frac{\omega_{GW}}{|\hat{k}_{GW}|} = c = \text{the speed of light}$$
GW SOURCES

- COMPACT BINARY COALESCENCES
  - NEUTRON STAR (NS)
  - BLACK HOLE (BH)
  - kHz SIGNALS
  - SHORT DURATION (~ 1 MINUTE)
- SUPERNOVAE
  - ASYMMETRIC COLLAPSE
  - VERY SHORT DURATION (~ ms)
- COSMIC BACKGROUND
  - GW ANALOGY TO THE COSMIC MICROWAVE BACKGROUND
  - EXTREMELY WEAK SIGNAL
GW SOURCES

- ROTATING QUADRUPOLES
  - LOW FREQUENCY (2 x ROTATION RATE)
  - EXAMPLES:

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>EMITTED POWER</th>
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<tbody>
<tr>
<td>EARTH-MOON</td>
<td>7 ( \mu )W</td>
</tr>
<tr>
<td>EARTH-SUN</td>
<td>190 W</td>
</tr>
<tr>
<td>TWO BHs WITH SOLAR MASS AND 3 km SEPARATION (extreme case)</td>
<td>2 ( \times 10^{50} ) W If in the Virgo Galaxy Cluster (3 ( \times 10^7 ) Light Years), then 10(^2) W/m(^2)</td>
</tr>
<tr>
<td>ROTATING STEEL CYLINDER</td>
<td>2 ( \times 10^{-30} )</td>
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</tbody>
</table>

\[\text{D=1m (breaking limit)}\]
\[\text{L=20m}\]
COMPARISON OF LIGO SENSITIVITY GOALS AND ESTIMATED GW SOURCES
IS THE MEASUREMENT MEANINGFUL?

RANDOM, THERMALLY INDUCED MOTIONS OF THE ATOMS IN THE MIRROR FACES >> ΔL

\[ \Delta L \approx 10^{-13} \text{m} \approx \frac{\text{Dia. of Nucleus of Atom}}{1000} \]

YES, IT IS MEANINGFUL!

- ATOMIC MOTIONS OCCUR AT VERY HIGH FREQUENCIES
  - ATOMIC MOTION AVERAGED AWAY DURING THE NIMS COLLECTION OF ≈ 10^{16} PHOTONS

- SPATIALLY AVERAGING OVER MANY ATOMS SO THAT ONLY THE LOW SPATIAL ORDER MODES ARE POTENTIALLY SIGNIFICANT (i.e. "Drum Head" modes)
  - MIRROR LOWEST FREQ., \( f_0 > 10 \text{ kHz} \)
  - \( \delta x = \frac{(kT/m)^{1/2}}{2\pi f_0} \approx 3 \times 10^{-16} \text{m} \) for \( T = 300 \text{K} \), \( m = 10 \text{kg} \)
    \[ \delta x \approx \frac{\text{Dia. of Nucleus of Atom}}{3} \approx 300 \times GW \text{ signal} \]

- OUT OF THE GW BAND

- HIGH Q ASSOCIATED WITH \( f_0 \) SO THAT THE "TAIL" OF THE RESONANCE HAS A SMALL EFFECT

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![PSD Diagram](image.png)
**IS THE MEASUREMENT POSSIBLE?**

**Strain,** \( h = \frac{\Delta L}{L} \sim 10^{-21} \) or \( \Delta L = 4 \text{km} \times 10^{-21} \)

\( \Delta L \sim 10^{-18} \text{m} \sim 10^{-12} \text{A} \) (Laser Wavelength) \( \lambda = 1.06 \mu\text{m} \)

**Outrageous? \( \Rightarrow \) Not at all:**

- **Phase Difference of Recombined Light:**
  \[ \Delta \varphi = \frac{2B(\Delta L_x - \Delta L_y)2\pi}{\lambda} = \frac{2hL B}{\lambda} \]

- **Photodetector Intensity Change Limited by Shot Noise:**
  \[ \Delta \varphi \approx \frac{\Delta I}{I_0} \sim \frac{1}{\sqrt{\Delta \text{photons}}} \]

- **Photodetector Can Integrate for 1/2 GW period**
  \[ \frac{1}{2} \sim 1 \text{ms} \]

Consequently:

\[ h_{\text{min}} \sim \frac{1}{2BL\sqrt{N}} = \frac{1}{2BL} \left( \frac{2h c \varphi}{I_0 \lambda} \right)^{\frac{1}{2}} \]

\[ h_{\text{min}} \sim 3 \times 10^{-21} \left( \frac{50}{B} \right) \left( \frac{4 \text{km}}{L} \right) \left( \frac{1}{1.06 \mu\text{m}} \right)^{\frac{1}{2}} \left( \frac{1000 \text{W}}{I_0} \right)^{\frac{1}{2}} \left( \frac{f}{1000 \text{Hz}} \right)^{\frac{1}{2}} \]

\[ \therefore \text{Measurement is possible} \]
GW OPTICAL DETECTION

- MICHELSON INTERFEROMETER
  - QUADRUPOLAR GW → TWO ORTHOGONAL ARMS
  - LASER FREQUENCY FLUCTUATIONS → EQUAL ARM LENGTHS
  - MINUTE STRAIN → LARGE L = 4 km
  → STORE LIGHT IN ARMS TO INCREASE EFFECTIVE LENGTH

Interferometer Response Function:
\[ \delta \varphi = h \frac{\omega L}{c} 2 \text{sinc} \left( \frac{\Omega L}{c} \right) \]

where
- \( \delta \varphi \) = optical light phase change
- \( \omega \) = laser frequency
- \( \Omega \) = GW frequency
- \( c \) = speed of light
- \( h \) = strain amplitude
- \( L \) = arm length
INITIAL INTERFEROMETER CONFIGURATION

- FABRY-PEROT ARM CAVITIES
- MODEST INPUT POWER (6 W)
- INITIAL LASER: Nd:YAG $\lambda = 1.06 \, \mu m$
- POWER RECYCLING
- MODEST RECYCLING FACTOR ($R \sim 30 \times$)
- MODEST CAVITY FINESSE ($F \sim 50$)

Interferometer Response Function:

$$\varphi = \frac{h \omega L}{c} \frac{2F}{\pi \sqrt{1 + (\Omega \tau)^2}}$$

where
- $\delta \varphi = $ optical light phase change
- $\omega = $ laser frequency
- $\Omega = $ GW frequency
- $c = $ speed of light
- $h = $ strain amplitude
- $L = $ arm length
- $F = $ Fabry-Perot finesse
- $\tau = $ Fabry-Perot time constant
# Noise Sources

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<thead>
<tr>
<th>THERMAL</th>
<th>QUANTUM</th>
<th>MECHANICAL</th>
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<tbody>
<tr>
<td>PENDULUM</td>
<td>SHOT NOISE</td>
<td>SEISMIC</td>
</tr>
<tr>
<td>MIRROR</td>
<td>RADIATION PRESSURE</td>
<td>SCATTERED LIGHT</td>
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<tr>
<th>LASER</th>
<th>ELECTROMAGNETIC</th>
<th>GRAVITATIONAL</th>
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<tbody>
<tr>
<td>FREQUENCY</td>
<td>AMPLIFIERS</td>
<td>MOVING PEOPLE</td>
</tr>
<tr>
<td>POWER</td>
<td>SERVO LOOPS</td>
<td>MOVING VEHICLES</td>
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<td>ALIGNMENT JITTER</td>
<td>EMI</td>
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**Diagram:**

- Thermal noise
- Quantum noise
- Mechanical noise
- Laser noise
- Electromagnetic noise
- Gravitational noise

- Suspended mirrors: 0% transmission
- End mirrors: 0% transmission
- Corner mirrors: 3% transmission
- Recycling mirror: 50% transmission

- Light scattering from residual gas
- Seismic noise

- From laser: Frequency variation, intensity fluctuations
- To detector: Shot noise electronics

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**Institute:**

- California Institute of Technology
- Massachusetts Institute of Technology

**Date:** 2/4-9/96
INITIAL LIMITS TO SENSITIVITY

• DISPLACEMENT NOISE (PHYSICAL MOTION)

• SEISMIC NOISE
  - SEISMICALLY QUIET SITES
  - CASCADED, MULTI-STAGE SEISMIC ISOLATION SYSTEM & PENDULUM SUSPENSIONS
  FOR THE TEST MASSES $T(f) \sim f^{-2n}$

• THERMAL NOISE
  - PENDULUM THERMAL $T(f) \sim f^{-5/2}$ above resonance
  - HIGH-Q WIRE SUSPENSION TO LIMIT THERMAL NOISE SPECTRAL CONTENT
  - HIGH-Q & HIGH-FREQUENCY (> 20 kHz) TEST MASSES $T(f) \sim f^{-1/2}$ below resonance

• SENSING NOISE

• SHOT NOISE
  - POWER RECYCLING
  - OPERATE ON DARK FRINGE
  - > 6 W INPUT, > 8 kW RESONANT IN ARM CAVITIES

Signal-to-Noise Ratio:

$$\text{SNR} = \frac{\phi}{\phi_N}$$
$$\phi_N = \sqrt{\frac{h \nu}{\eta P}}$$

where

$P$ = Laser Power
$\eta$ = Detector Quantum Efficiency
$h$ = Planck's constant
$\nu$ = Laser Frequency
INITIAL INTERFEROMETER DESIGN  
PERFORMANCE GOAL

INITIAL INTERFEROMETER SENSITIVITY

\[ \bar{h}(f) \text{ [Hz}^{-1/2}] \]

-19
-21
-23
-25
-27
-29

Frequency (Hz)

1
10
100
1000
10000

SUSPENSION THERMAL
SEISMIC
RADIATION PRESSURE
SHOT
TEST MASS THERMAL
RESIDUAL GASS, 10^{-6} TORR H_{2}
ADVANCED INTERFEROMETER DESIGN
PERFORMANCE GOAL

ADVANCED INTERFEROMETER, BROADBAND RECYCLING

\[
\tilde{h}(f) \text{ [Hz}^{1/2}] \\
\text{[kHz]} \\
\text{[MHz]} \\
\text{[GHz]} \\
\text{[THz]} \\
\text{[10$^{-9}$ TORR H$_2$]} \\
\text{[10$^{-5}$ TORR H$_2$]} \\
\text{[10$^{-3}$ TORR H$_2$]} \\
\text{[10$^{-1}$ TORR H$_2$]} \\
\text{[1 TORR H$_2$]} \\
\text{[10 TORR H$_2$]} \\
\text{[100 TORR H$_2$]} \\
\text{[1000 TORR H$_2$]} \\
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LIMITING PERFORMANCE DUE TO FACILITIES

\[ h(f) \text{ [Hz}^{-1/2}] \]

- **Gravity Gradient Noise**
- **Stray Light Noise**
  \(< \frac{1}{10} \text{ SQL, 1000 kg mass}\)
- **Residual Gas, }^{10^{-9}}\text{ Torr H}_2\)

Frequency (Hz)
VACUUM EQUIPMENT & BEAM TUBE

- WILL BE THE LARGEST ULTRA-HIGH VACUUM (<10^{-9} torr) SYSTEM IN THE WORLD (~ 20,000 m³)
  - VERY LOW ALLOWED AIR LEAKAGE:
    \[ \gamma < 10^{-9} \text{ ATM CC/S, He} \]
  - VERY LOW OUTGASSING:
    - \[ P_{\text{Advanced}} < 10^{-9} \text{ TORR (ALL RESIDUALS);} \]
    - \[ J[H_2]: < 10^{-13} \text{ torr-liter/cm}^2/\text{s} \]
    - \[ J[H_2O]: < 10^{-15} \text{ torr-liter/cm}^2/\text{s} \]
    - PARTIAL PRESSURES FOR CO + CO₂ + H₂N₂C₂ + ... MUST BE EVEN LOWER
  - QUALITY CONTROL AND CLEANLINESS MUST BE PURSUED DILIGENTLY THROUGHOUT FABRICATION AND INTEGRATION PROCESS
  - OVER 140 km OF WELDS

- MOSTLY STANDARD VACUUM PUMP & CONTROL HARDWARE

- VERY LARGE APERTURE GATE VALVES TO ISOLATE 1.24 m BEAM TUBES

- LARGE PUMPING SPEEDS AND VOLUMES -- BEAM TUBE PUMPING SOLELY FROM 4km ENDS
DETECTOR SYSTEM

- BASELINE CONFIGURATION EMPLOYS PROVEN TECHNIQUES
  - 40m AND 5m SCALE SYSTEMS (AT CIT & MIT)
  - OPTICAL CONFIGURATIONS, MODULATION & CONTROL CONCEPTS BEING VALI-
  - SUSPENSIONS & SEISMIC ISOLATION SYSTEMS
  - LASER FREQUENCY STABILIZATION

- COLLABORATIVE STUDIES WITH INDUSTRIAL PARTNERS
  - MIRROR SUBSTRATE POLISHING (HDOS, CSIRO)
  - MIRROR, HIGH REFLECTANCE COATINGS (REO)
  - ACTIVE SEISMIC ISOLATION (BARRY)
  - SEISMIC ISOLATION (HYTEC)

- STATE-OF-THE-ART PROCESS CONTROL TECHNIQUES FOR INSTRU-
  - EPICS
  - AVS
RESEARCH AND DEVELOPMENT

• FOCAL POINT OF R&D EFFORT IS TO CONTINUE TO RECONFIGURE EXISTING 40 m INTERFEROMETER AT CALTECH TO MORE CLOSELY REFLECT LIGO OPTICAL CONFIGURATION
  - PROOF-OF-CONCEPT FOR LIGO SUBSYSTEMS
  - DE-BUGGING TESTBED
  - FUNCTIONAL VERIFICATION FOR CERTAIN LIGO-SCALE SUBSYSTEMS
  - PROVIDES TRAINING TESTBED FOR NEW SCIENTIFIC STAFF

• OTHER MAJOR SUBSYSTEM EFFORTS CARRIED ON IN PARALLEL
  - PHASE NOISE INVESTIGATIONS AT MIT (5 m INTERFEROMETER)
  - ALIGNMENT CONCEPT INVESTIGATIONS
  - ACTIVE SEISMIC ISOLATION AND IMPROVED PASSIVE ISOLATION SYSTEMS
  - MODE CLEANER INTEGRATION AND DEBUGGING
  - PRE-STABILIZED LASER SUBSYSTEM
PHASE NOISE RESEARCH

- SHOT NOISE AT HIGH FREQUENCIES
  - BEST TO DATE: $5 \times 10^{-9} \text{rad}/\sqrt{\text{Hz}}$
  - REQUIRED: $1 \times 10^{-10} \text{rad}/\sqrt{\text{Hz}}$

- LOW FREQUENCY NOISE IS PROBABLY DUE TO BEAM JITTER
  - WILL BE REDUCED SIGNIFICANTLY BY RECYCLING

- NEXT PHASE: ADD RECYCLING MIRROR

Phase Noise Interferometer Spectrum on 09/27 (red) and 10/02 (blue)
PROGRESSIVE IMPROVEMENT IN THE 40-METER PROTOTYPE SENSITIVITY
40-METER DISPLACEMENT SPECTRA

Comparison of displacement spectra
Best recombined spectrum to date and best pre-recombined
CONCLUSION

• LIGO WILL OPEN A NEW WINDOW ON THE UNIVERSE
• LIGO FACILITIES ARE PROCEEDING FROM FINAL DESIGN INTO FABRICATION & CONSTRUCTION
  - BUILDINGS
    - FINAL DESIGN REVIEW 5/96
    - CONSTRUCTION 7/96 (START)
  - BEAM TUBES
    - SLABS/ENCLOSURE 2/96 (START)
    - BEAM TUBE INSTALLATION 10/96 (START)
  - VACUUM EQUIPMENT
    - CHAMBER FIRST ARTICLE 1/96 (START)
    - VACUUM EQUIPMENT INSTALLATION 7/97 (START)
• LIGO DETECTOR SYSTEM DESIGN PROCEEDING
  - BASELINE DESIGN EXPECTED TO MEET INITIAL GOALS
    - $10^{-8}$ m rms DISPLACEMENT SENSITIVITY FROM 100 TO 3000 Hz
    - $10^{-12}$ OF A WAVELENGTH OF VISIBLE LIGHT
    - $10^{-9}$ rad rms OPTICAL PHASE SENSITIVITY
  - DETECTOR INSTALLATION TO START AT WA SITE 7/98