The LIGO Interferometers

Initial and Advanced

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Outline

- Limiting Noise Sources for Initial LIGO
  - Seismic, thermal, photon shot noise
- Circumventing them for Advanced LIGO
  - Advanced isolation, improved materials, quantum optical noise
- Beyond 2010?
  - Terrestrial detectors ➔ cryogenic, QND
  - Space detector ➔ LISA
- Implications for Astrophysical Sources
Initial LIGO Sensitivity Goal

- Strain sensitivity < $3 \times 10^{-23} \ 1/\text{Hz}^{1/2}$ at 200 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Facilities limits much lower
Limiting Noise Sources: Seismic Noise

- Motion of the earth few μm rms at low frequencies
- Passive seismic isolation ‘stacks’
  - amplify at mechanical resonances
  - but get $f^{-2}$ isolation per stage above 10 Hz
Limiting Noise Sources: Thermal Noise

- Suspended mirror in equilibrium with 293 K heat bath \( \Rightarrow k_B T \) of energy per mode

- Fluctuation-dissipation theorem:
  - Dissipative system will experience thermally driven fluctuations of its mechanical modes
  \[
  \tilde{h}(f) = \frac{\sqrt{k_B T}}{\pi f L} \sqrt{\text{Re}(Z(f))}
  \]
  - \( Z(f) \) is impedance (loss)

- Low mechanical loss (high Quality factor)
  - Suspension \( \Rightarrow \) minimize stresses due to bends or ‘kinks’ in pendulum wire
  - Test mass \( \Rightarrow \) minimize internal material defects in optic
Limiting Noise Sources: Quantum Noise

- **Shot Noise**
  - Uncertainty in number of photons detected $\Rightarrow$
    \[
    h(f) = \frac{1}{L} \sqrt{\frac{hc\lambda}{8F^2P_{bs}}} \frac{1}{T_{ifo}(\tau_s, f)}
    \]
  - Higher input power $P_{bs} \Rightarrow$ need low optical losses
  - (Tunable) interferometer response $\Rightarrow$ $T_{ifo}$ depends on light storage time of GW signal in the interferometer

- **Radiation Pressure Noise**
  - Photons impart momentum to cavity mirrors
    - Fluctuations in the number of photons $\Rightarrow$
      \[
      h(f) = \frac{2F}{ML} \sqrt{\frac{2hP_{bs}}{\pi^3c\lambda}} \frac{T_{ifo}(\tau_s, f)}{f^2}
      \]
  - Lower input power, $P_{bs}$
    $\Rightarrow$ Optimal input power for a chosen (fixed) $T_{ifo}$
Power-recycled Interferometer

Optical resonance: requires test masses to be held in position to $10^{-10} - 10^{-13}$ meter

Light is "recycled" ~50 times $\rightarrow$ 300 W

Light bounces back and forth along arms ~100 times $\rightarrow$ 30 kW

Laser + optical field conditioning

6W single mode

end test mass

input test mass

signal
Core Optics

- 25 cm diameter, 10 kg fused silica optics
- Polished substrates
  - Micro-roughness \( \leq 10 \) ppm scatter
- Optical coatings
  - \( \leq 2 \) ppm scatter
  - \( \leq 1 \) ppm absorption
- Metrology
  - Surface uniformity
    \( \sim 1 \) nm rms
Initial LIGO: Present Status

- Engineering runs 1 through 7 (2000 -- 2002)
- First astrophysical data run in 2002

- Some subsystems still to be installed (e.g. ASC)
- Some retrofitting to do
  - Seismic pre-isolation
  - Low-noise electronics
- Some more troubling problems (e.g. scattered light, “what-in-the-world-is-this?”)
Advanced LIGO (> 2006): A Quantum Limited Interferometer

Scientific motivation
- 10x increase in sensitivity
- 1000x increase in range (event rate)
- One day > 2 yr integ. run

Advanced LIGO
- Seismic noise 40 \rightarrow 10 \text{ Hz}
- Thermal noise 1/15
- Optical noise 1/10

Beyond Adv LIGO
- Thermal noise: cooling of test masses
- Quantum noise: quantum non-demolition
How will we get there?

- **Seismic noise**
  - Active isolation system (lower seismic cutoff from 40 to 10 Hz)
  - Mirror suspended as last stage of quadruple pendulum

- **Thermal noise**
  - Suspension: fused quartz; ribbons or variable diameter circular
  - Test mass: higher mechanical Q material, fused silica $\rightarrow$ crystalline sapphire
    - Optical and thermal properties not always commensurate

- **Optical noise**
  - Input laser power: increase to ~200 W
    - Power handling and thermal deformation issues
  - Optimize interferometer response, $T_{ifo} \rightarrow$ signal recycling
    - Compounds optical complexity (another coupled dof to control)
    - Exposes quantum correlations since signal photons re-enter ifo
Optimizing the optical response: Signal Tuning

Cavity forms compound output coupler with complex reflectivity. Peak response tuned by changing position of SRM

Reflects GW photons back into interferometer to accrue more phase

\[ r(l)e^{i\Phi(l)} \]
Optical configuration

125W

PRM T~6%

BS

T=0.5%

SAPPHIRE, 28.5CMφ

SILICA HERAEUS SV 35CMφ

SILICA LIGO I GRADE 28.5CMφ

OUTPUT MODE CLEANER

GW READOUT
Optical/Mechanical Intersection: Issues in Sapphire Optics

- Both optical and mechanical properties crucial
  - Mechanical losses → thermal noise
  - Optical absorption → thermal deformations

Material development: Substrates
- Large size (25 to 30 cm diameter) influences growth axis
- Internal mechanical losses low: $Q \sim 10^8$ (cf. fused SiO$_2$ $Q \sim 10^6$)
- Thermal conductivity higher → smaller thermal deformation
- Thermal expansion coefficient larger → thermoelastic damping
- Bulk absorption → need < 10ppm/cm, to date 20 to 45 ppm/cm after annealing treatment

- Optical coating properties also being studied
Advance LIGO Sensitivity: Improved and Tunable
Astrophysical sources of GWs

- **Coalescing compact binaries**
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown

- **Other periodic sources**
  - Spinning neutron stars ➔ numerically hard problem

- **Burst events**
  - Supernovae ➔ asymmetric collapse

- **Stochastic background**
  - Primordial Big Bang
  - Continuum of sources

- **The Unexpected**

- GWs ➔ neutrinos ➔ photons ➔ now
Implications for source detection

- **NS-NS Inpiral**
  - Optimized detector response

- **NS-BH Merger**
  - NS can be tidally disrupted by BH
  - Frequency of onset of tidal disruption depends on its radius and equation of state ⇒ broadband detector

- **BH-BH binaries**
  - Merger phase ⇒ non-linear dynamics of highly curved space time
    ⇒ broadband detector

- **Supernovae**
  - Stellar core collapse ⇒ neutron star birth
  - If NS born with slow spin period (< 10 msec) hydrodynamic instabilities ⇒ GWs
Source detection

- Spinning neutron stars
  - Galactic pulsars: non-axisymmetry uncertain
  - Low mass X-ray binaries: If accretion spin-up balanced by GW spin-down, then X-ray luminosity → GW strength
  Does accretion induce non-axisymmetry?

- Stochastic background
  - Can cross-correlate detectors (but antenna separation between WA, LA, Europe ⇒ dead band)
  - $\Omega(f \sim 100 \text{ Hz}) = 3 \times 10^{-9}$ (standard inflation ⇒ $10^{-15}$)
  
  **GW energy / closure energy**
  - (primordial nucleosynthesis ≲ $10^{-5}$)
  - (exotic string theories ⇒ $10^{-5}$)
Other science from gravitational wave detectors

- **Astrophysics**
- **Tests of general relativity**
  - Waves ➔ direct evidence for time-dependent metric
  - Black hole signatures ➔ test of strong field gravity
  - Polarization of the waves ➔ spin of graviton
  - Propagation velocity ➔ mass of graviton
- **Precision measurements at and below the quantum limit set by Heisenberg on photons**
  - Story of NEMs