Gravitational wave detectors and detection in the year 2012

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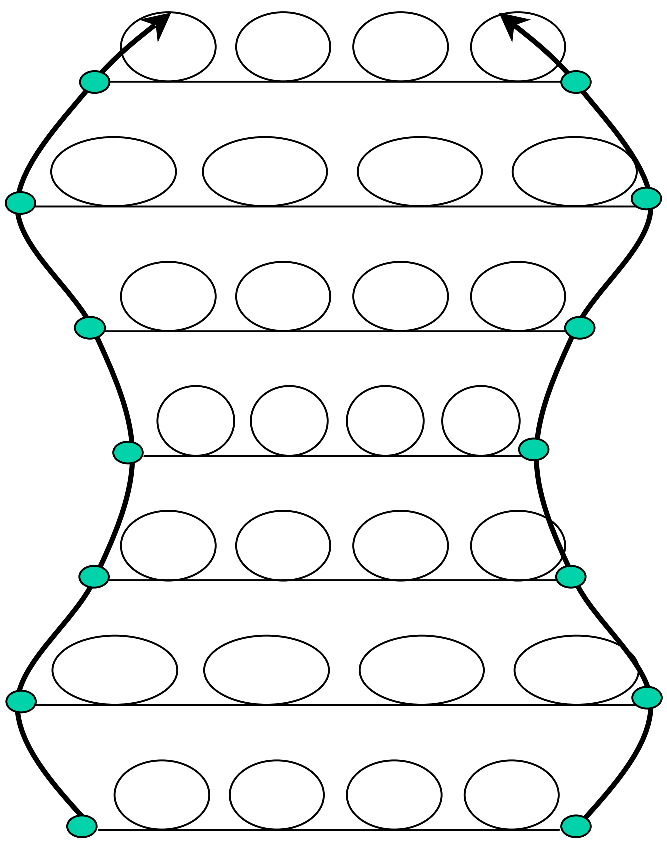
Goals and Outline

- Goal: anticipate spectrum of detector sensitivities when LISA becomes science operational
- Outline
  - Resonant Acoustic Detectors
  - Interferometers
  - ~~Pulsar Timing Arrays~~
  - Conclusions

Resonant Acoustic Detectors

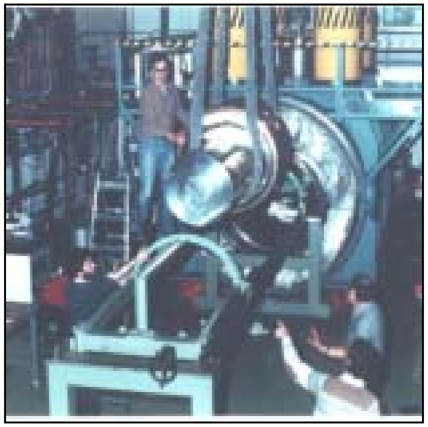
- How they work
- Where they're going

Detecting Gravitational Waves: "Bar" Detectors



Auriga "Bar" Detector, Italy

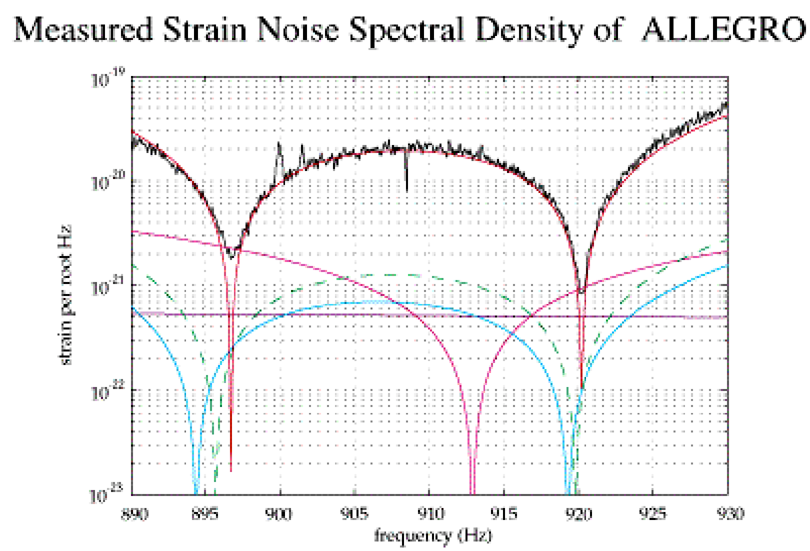
Bar Detectors Worldwide



- ALLEGRO (USA)
- Nautilus (Italy)
- Explorer (Italy)

Principal technical challenge: *in situ* low-noise amplifiers

- On-resonance mechanical response larger than off-resonance response
- Ratio signal to (amplifier) noise larger for on resonance gravitational wave power than for off resonance power
- Leads to effective narrowing of response
- Current best sensitivity
  - ~10^{-22} in 1 Hz bandwidth near 900 Hz



Measured strain noise spectral density of ALLEGRO and the various noise contributions which are predicted from the noise model of the detector.
— Measured total noise, — antenna brownian, — transducer brownian,
— transducer electrical loss, — SQUID white noise, — SQUID back action.

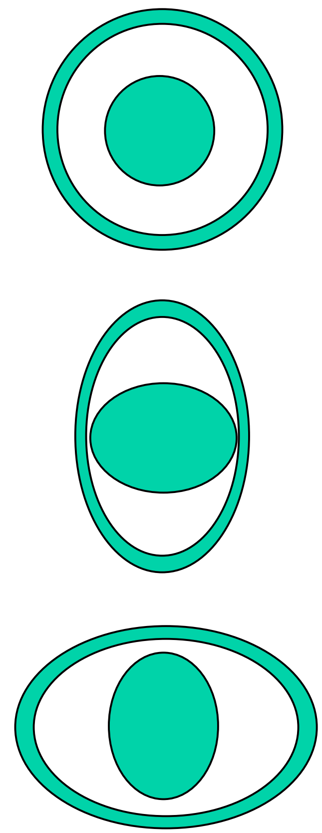
Spherical Detectors

- Why spherical? "Omni":
  - Equal sensitivity to waves from any incident direction
  - Equal sensitivity to either wave polarization
  - Ability to discern incident wave polarization, direction

Kamerlingh Onnes Laboratory, Leiden University

"Dual" spheres for increased bandwidth

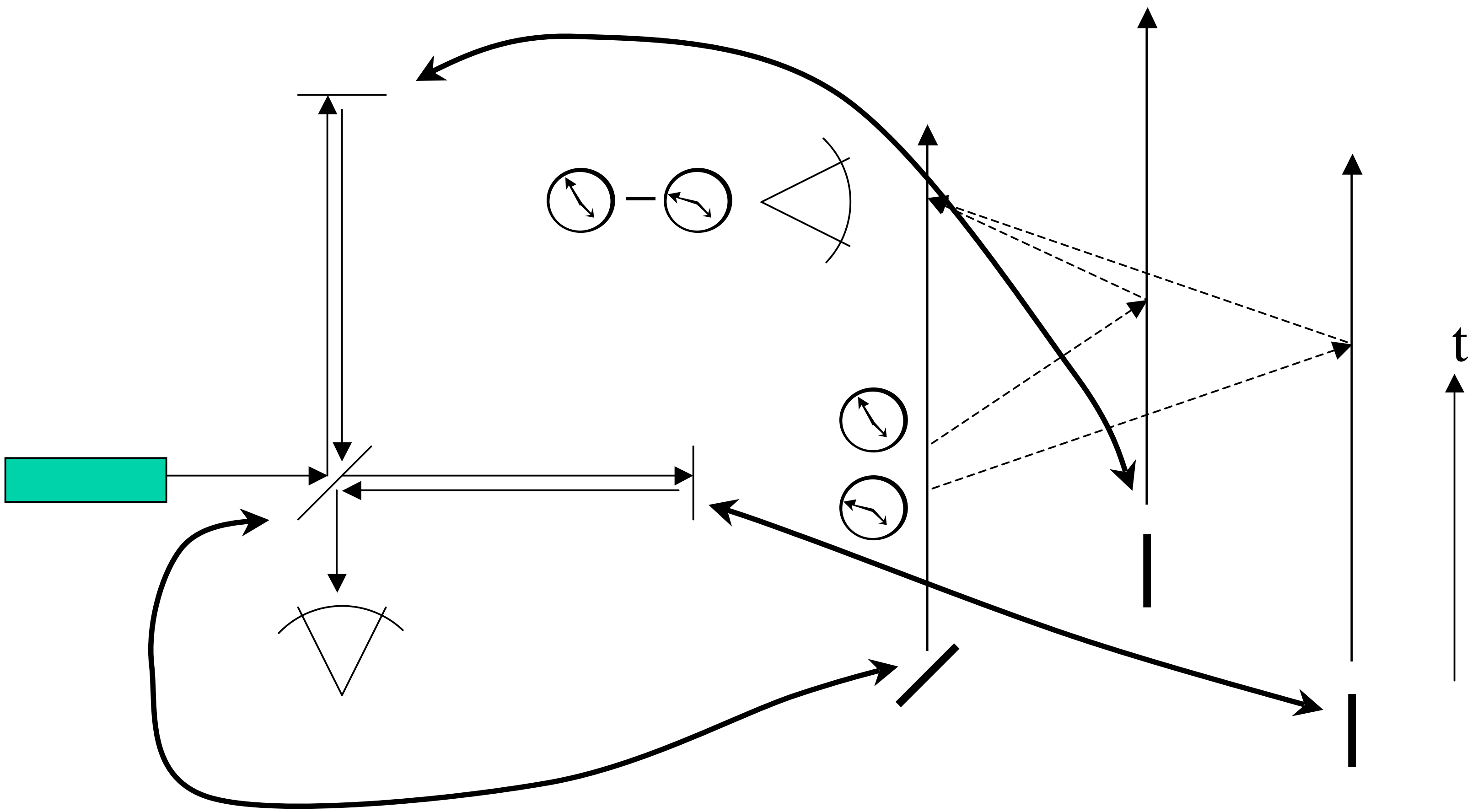
- Sphere inside a shell
  - Different resonant frequencies for inner sphere, outer shell
- Incident wave with characteristic frequency between resonant frequencies
  - Inner sphere, outer shell respond *out of phase*
  - Increased sensitivity in band between resonant frequencies
- Cf. Cerdonio et al., PRL 87 (2001) 082003



Interferometric Detectors

- How they work
- Where they’re going

Detecting Gravitational Waves: *Laser Interferometry*



LIGO: The **L**aser **I**nterferometer **G**ravitational-wave **O**bservatory

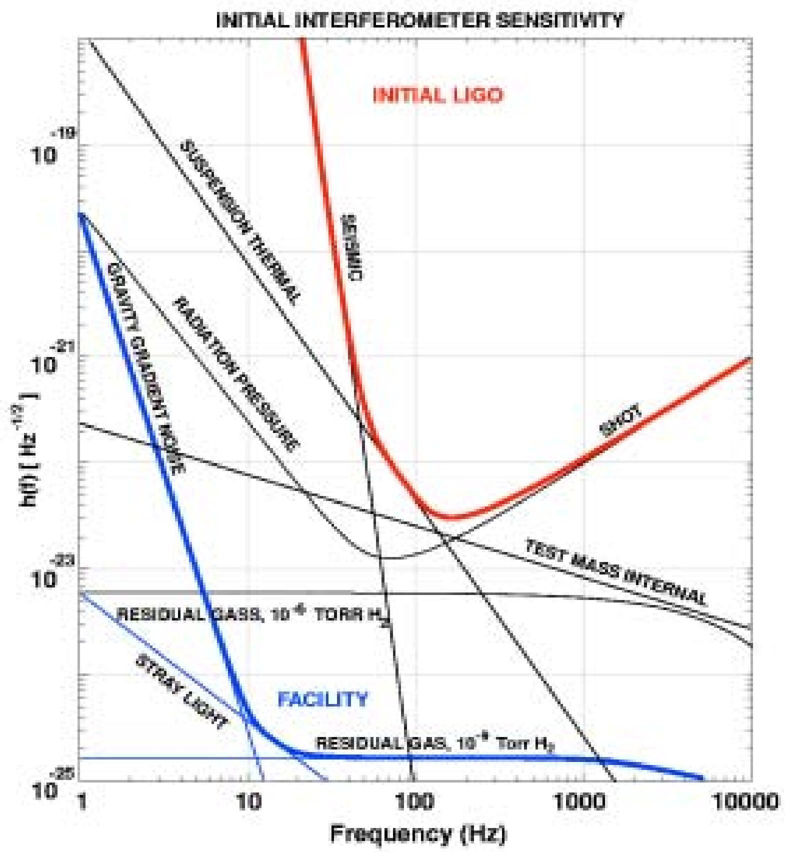
- United States effort funded by the National Science Foundation
- Two sites
  - Hanford, Washington & Livingston, Louisiana
- Construction from 1994-2000
- Commissioning from 2000 - 2002
- Operations: now!

Laser Interferometer Detectors Worldwide

- Virgo: Italy & France (3 Km arms)
- GEO: Germany & UK (600m arms)
- TAMA: Japan (300m arms)

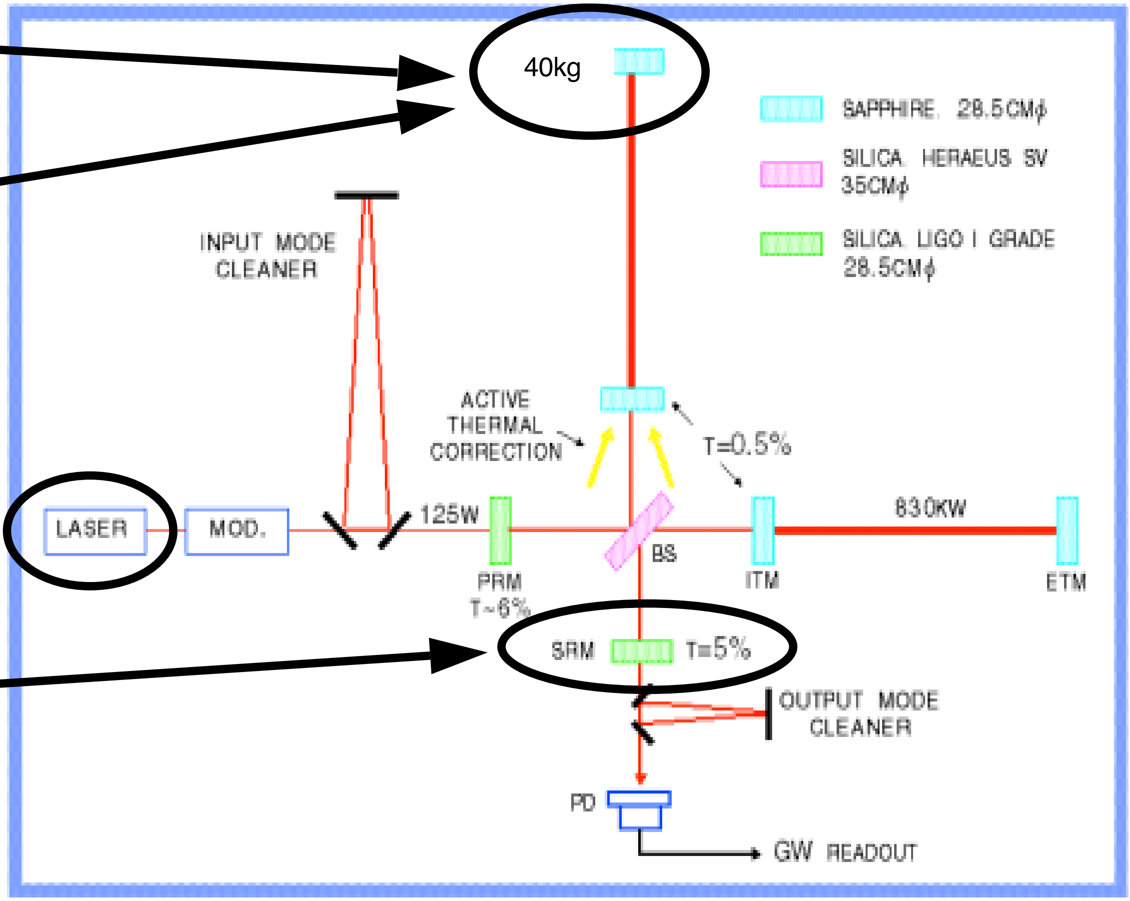
What limits LIGO's sensitivity?

- Initial LIGO detectors:
  - Different *f*, different limit
  - < ~50Hz : seismic noise
  - 50 - 200Hz : thermal noise
  - > 200Hz : "shot" noise
- Facility limits
  - Gravity gradients
  - Stray light
  - Residual gas



Building a better interferometer: Advanced LIGO

- Seismic isolation
- Thermal noise mitigation; high power optics
- High power lasers
- Tuning ifo response



High frequencies: improving photon counting statistics

- More photons, better statistics
  - Higher laser power
  - Greater light storage time in cavity
- Higher laser power
  - Initial LIGO: 6 W input to IFO
  - Advanced LIGO: 125 W input to IFO
- Greater light storage time
  - Initial LIGO: 0.84ms light storage time; 30 KW on test masses
  - Advanced LIGO: 5.0ms light storage time; 800 KW on test masses

Thermal noise contributions

- Suspensions:
  - kT energy in taut suspension wire violin modes
- Test masses:
  - Normal modes: kT energy in mirror modes
  - Thermoelastic: Temperature fluctuations and thermal expansion coefficient

Thermal noise mitigation: suspensions

- Noise proportional to mechanical losses: *reduce losses*
  - Initial LIGO: mirrors rest on cylindrical wires
  - Advanced LIGO: mirrors bonded to fused silica ribbons
- Coupling proportional to ratio wire/mirror mass
  - Initial LIGO: 11 Kg mass
  - Advanced LIGO: 40 Kg mass

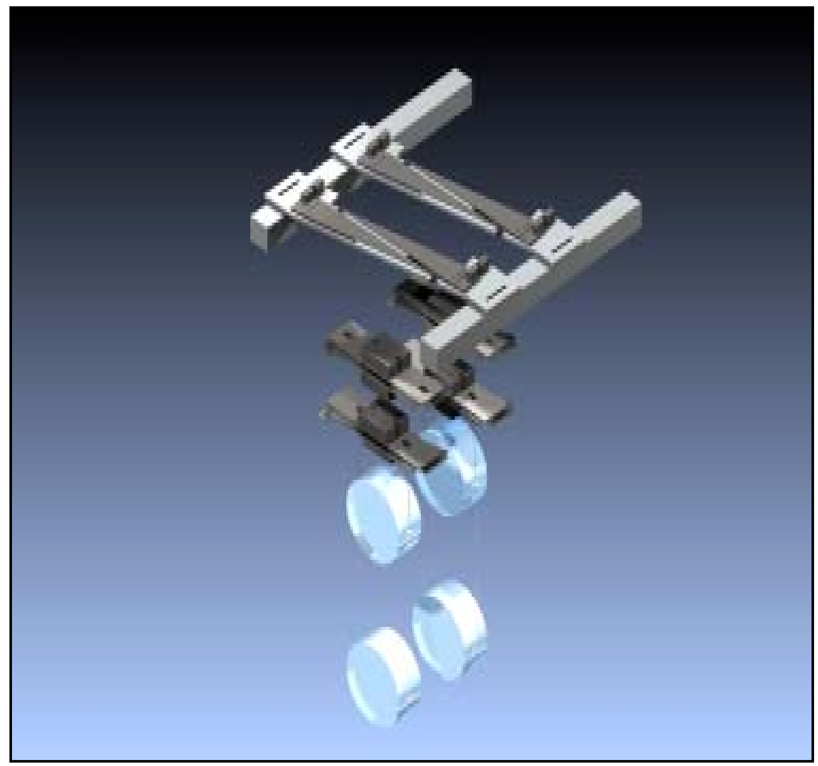
Thermal noise mitigation: test masses

- Material properties problem
  - Normal modes:
    - Increase Young's modulus: less motion for same thermal energy
  - Thermoelastic:
    - Decrease coefficient thermal expansion: less motion for same thermal fluctuations
  - Goal: single crystal sapphire
- Laser spot diameter, profile
  - Fluctuations averaged over effective spot area
  - Increase area, reduce effective fluctuation

- Initial LIGO: 25cm
- Advanced LIGO: 35cm

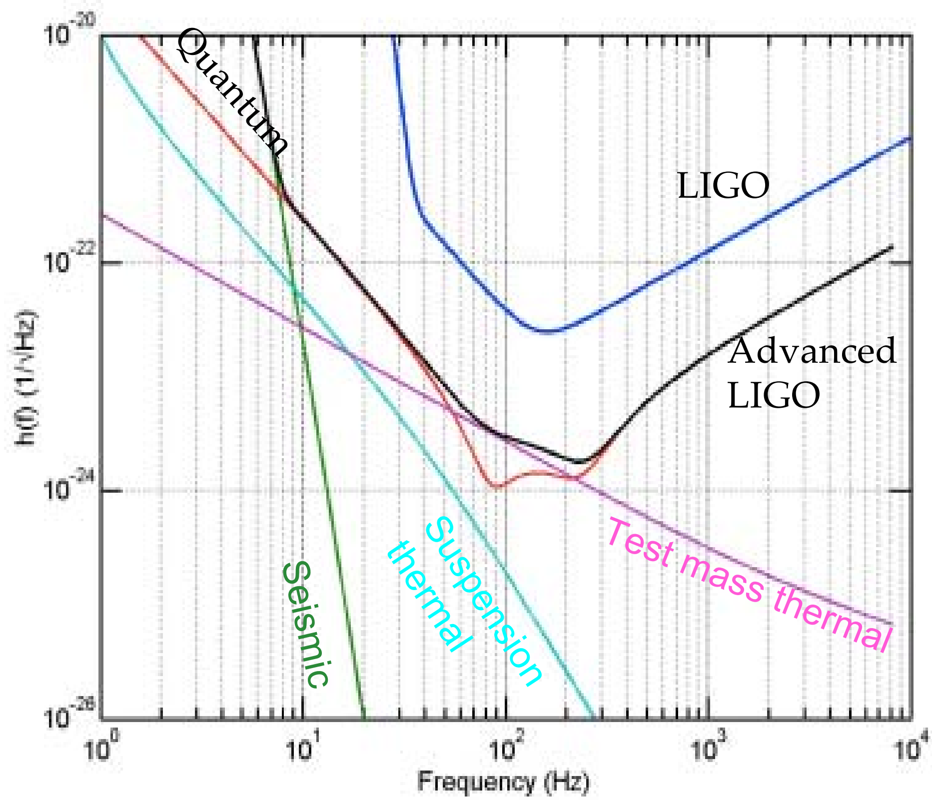
Seismic isolation

- Initial LIGO
  - Passive isolation: lossy springs
- Advanced LIGO
  - Active isolation
    - External hydraulic actuators
    - Suspension platform fine control
  - Multiple pendulum suspension
    - Mirrors at bottom of chain
    - Orientation forces applied at reaction masses



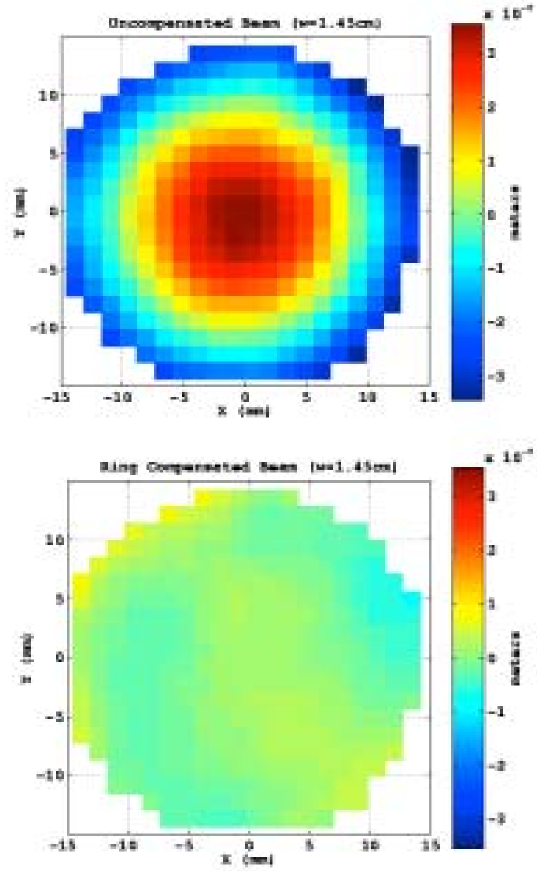
Sensitivity improvements: high power optics

- Radiation pressure: photons bouncing off mirrors
  – High power: high light pressure
- Mitigation: increased mirror mass
  – Smaller acceleration for same force
  – Initial LIGO: 11Kg
  – Advanced LIGO: 40Kg



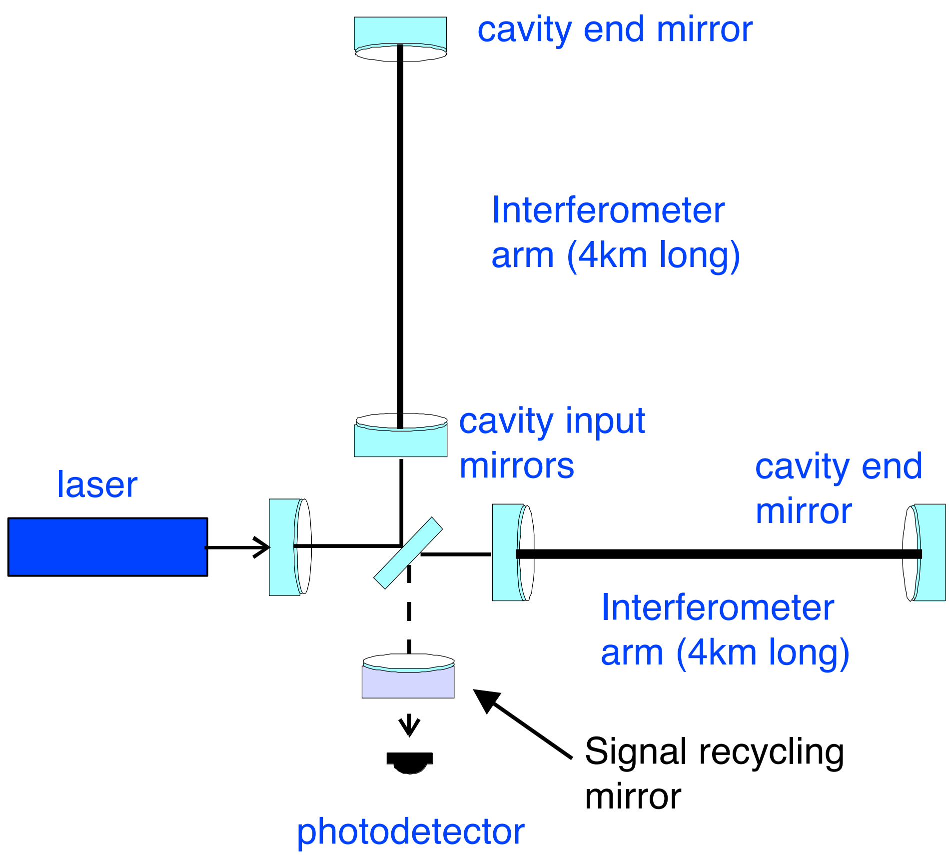
Sensitivity improvements: high power optics

- More laser power, greater mirror heating
  - Differential heating changes mirror shape: “thermal lensing”
- Mitigation: bring face to constant temp.
  - Heat optic radiatively with suspended heating element

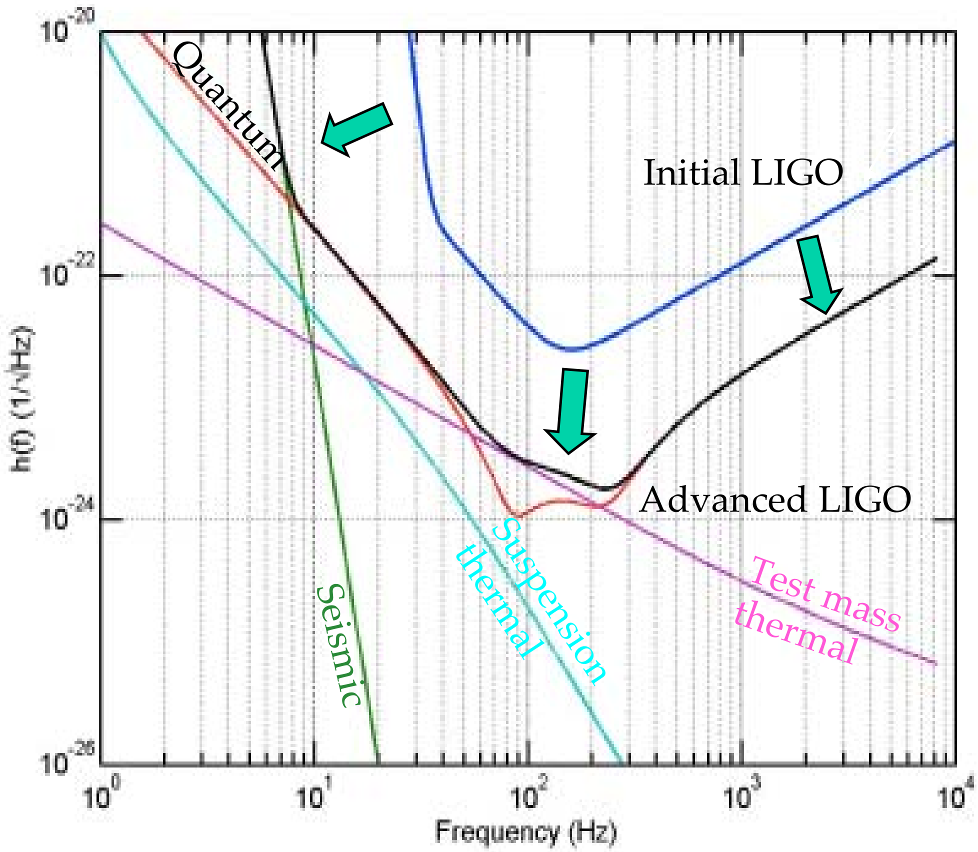


Tuning the detector response

- Undisturbed interferometer operates on dark fringe
  - Response to gravitational waves is light at output port
- Introduce partially reflecting mirror at output port
  - Make resonant cavity with rest of interferometer
  - Resonance enhances power at output port for excitation at resonant frequency
  - Higher power: lower shot noise
- Mitigate shot noise in narrow band



Advanced LIGO sensitivity goals



LISA: **L**aser **I**nterferometer **S**pace **A**ntenna

- Three spacecraft in equilateral triangle configuration
  - $5x10^6$ Km arm length
  - Solar orbit 20 deg behind Earth
- Constellation tracks changes in separation on

Courtesy Rutherford Appleton Laboratory, UK

LISA: critical technologies

- Space laser interferometry
  - Track fringes to establish separation changes with 10pm accuracy
- Inertial sensing
  - Sense deviations from inertial (geodesic) trajectories
- Micro-newton thrusters
  - Mitigate against deviations from inertial trajectories owing to, e.g., acceleration noise from solar wind

LISA technology tests

- ESA LISA Test Package (LTP), NASA Disturbance Reduction System (DRS)
  - Technology validation of space interferometry & inertial sensors, thrust technologies for drag-free flight
  - Flies on ESA SMART-2 August 2006

Conclusions, or What does this all mean?

- Ground-based "ifos" on-track for
  - Stochastic background sensitivity $\Omega h^2 < 10^{-9}$ @ 100Hz
  - NS/NS binary inspiral sensitivity to ~400 Mpc
  - $2 \times 10\ M_{sol}$ BH/BH binary inspiral sensitivity to z~0.5
  - Pulsars: $\varepsilon < 10^{-6}$ @ 100 Hz, 10^{-7} @ 300 Hz, 10^{-8} @ 1 KHz in 1 yr
- Resonant acoustic detectors
  - Could be competitive in ~100Hz bandwidth near 1 KHz
- LISA
  - Stochastic background sensitivity $\Omega h^2 < 10^{-10}$ @ 0.01Hz
  - Sensitive to galactic binaries with orbital $f > 10^{-3.5}$ Hz
  - Massive ($> 10^3\ M_{sol}$) black hole binary inspiral anyhwere
  - Massive ($10^{4.5}\ M_{sol} < M < 10^7\ M_{sol}$) black hole coalescence anywhere

Gravitational Wave Astronomy!