Interferometric Gravitational-wave Detectors: New Levels of Sensitivity in Optical Measurements

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21st Congress

International Commission for Optics

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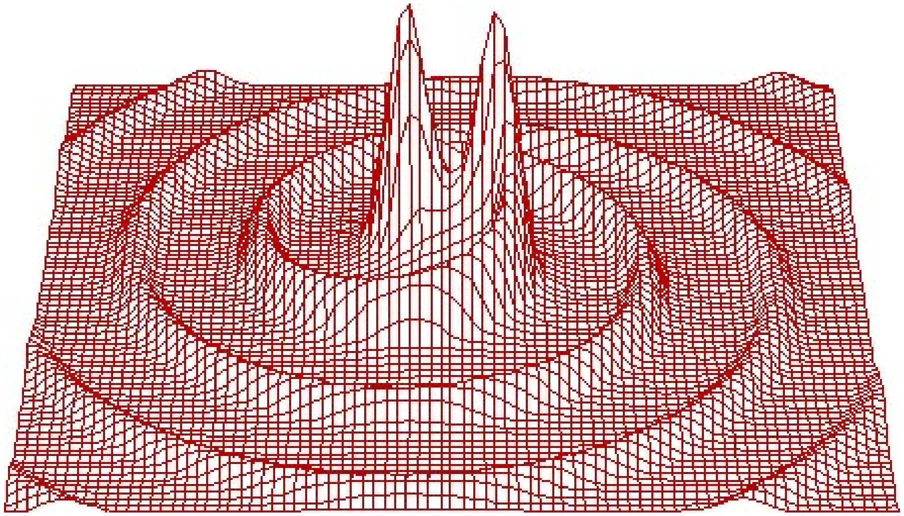
Outline of Talk

- Quick Review of GW Physics and Astrophysics
- Current GW interferometers
- The Future
  - » More sensitive detectors
  - » Global network

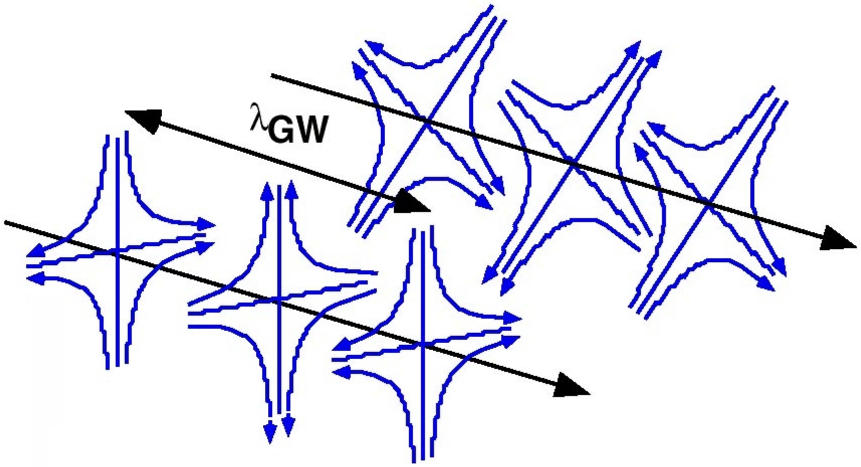


gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)

Gravitational Wave Physics

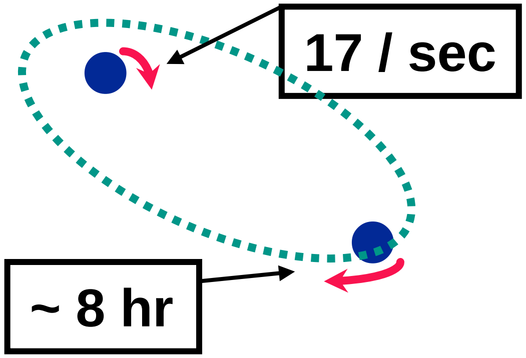
- Einstein (in 1916 and 1918) recognized gravitational waves in his theory of General Relativity
  - » Necessary consequence of Special Relativity with its finite speed for information transfer
  - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
  - » Propagate away from the sources at the speed of light
  - » Pure transverse waves
  - » Two orthogonal polarizations

$$h = \Delta L / L$$



Evidence for Gravitational Waves:

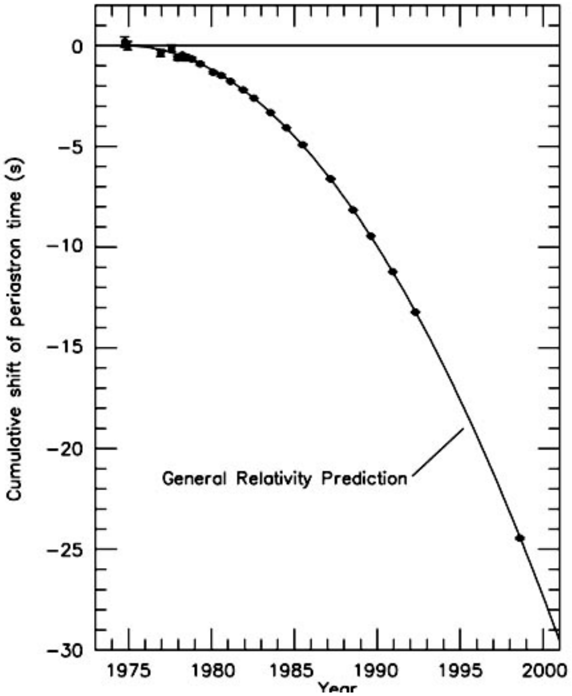
Binary Pulsar PSR1913+16



17 / sec

~ 8 hr

- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - » **Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (bending of "starlight", advance of "perihelion", etc.**

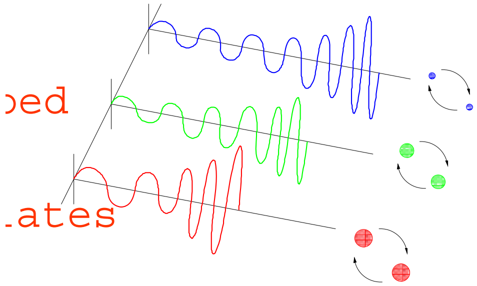


- **After correcting for all known relativistic effects, observe loss of orbital energy**

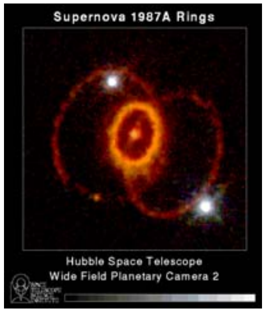
=> Emission of GWs

Astrophysical Sources for Terrestrial GW Detectors

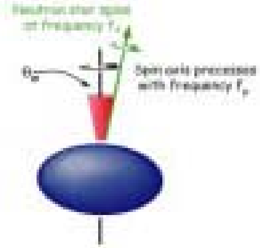
- Compact binary inspiral: “chirps”
  - » **NS-NS, NS-BH, BH-BH**



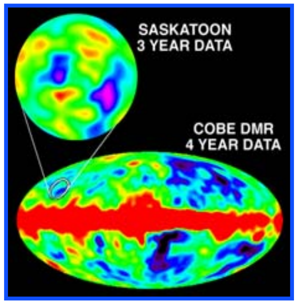
- Supernovas or GRBs: “bursts”
  - » **GW signals observed in coincidence with EM or neutrino detectors**



- Pulsars in our galaxy: “periodic waves”
  - » **Rapidly rotating neutron stars**
  - » **Modes of NS vibration**



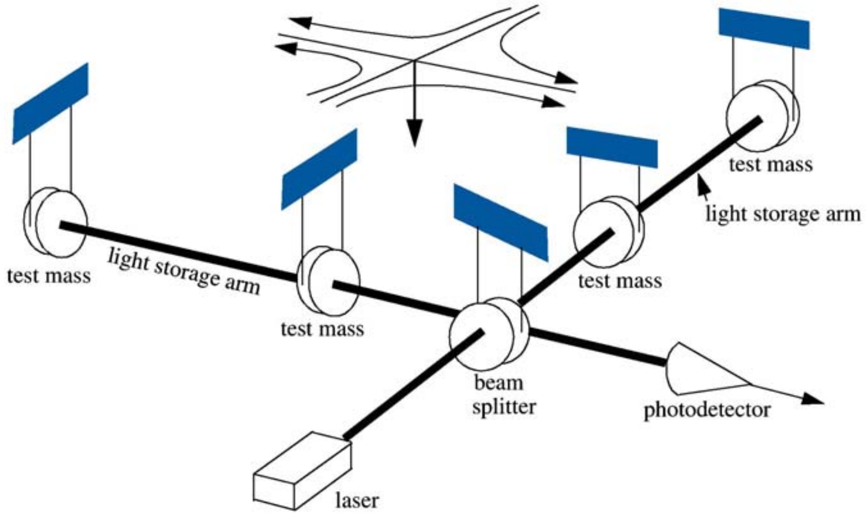
- Cosmological: “stochastic background”
  - » **Probe back to the Planck time (10^{-43} s)**



Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies f >> f_{pend}

$$h = \Delta L / L$$



Terrestrial detector

For $h \sim 10^{-22} - 10^{-21}$

L ~ 4 km (LIGO)

$\Delta L \sim 10^{-18}$ m

Ground-based Gravitational Wave Interferometers


TAMA Japan
300m


Virgo Italy
3000m


LIGO Louisiana, US
4000m

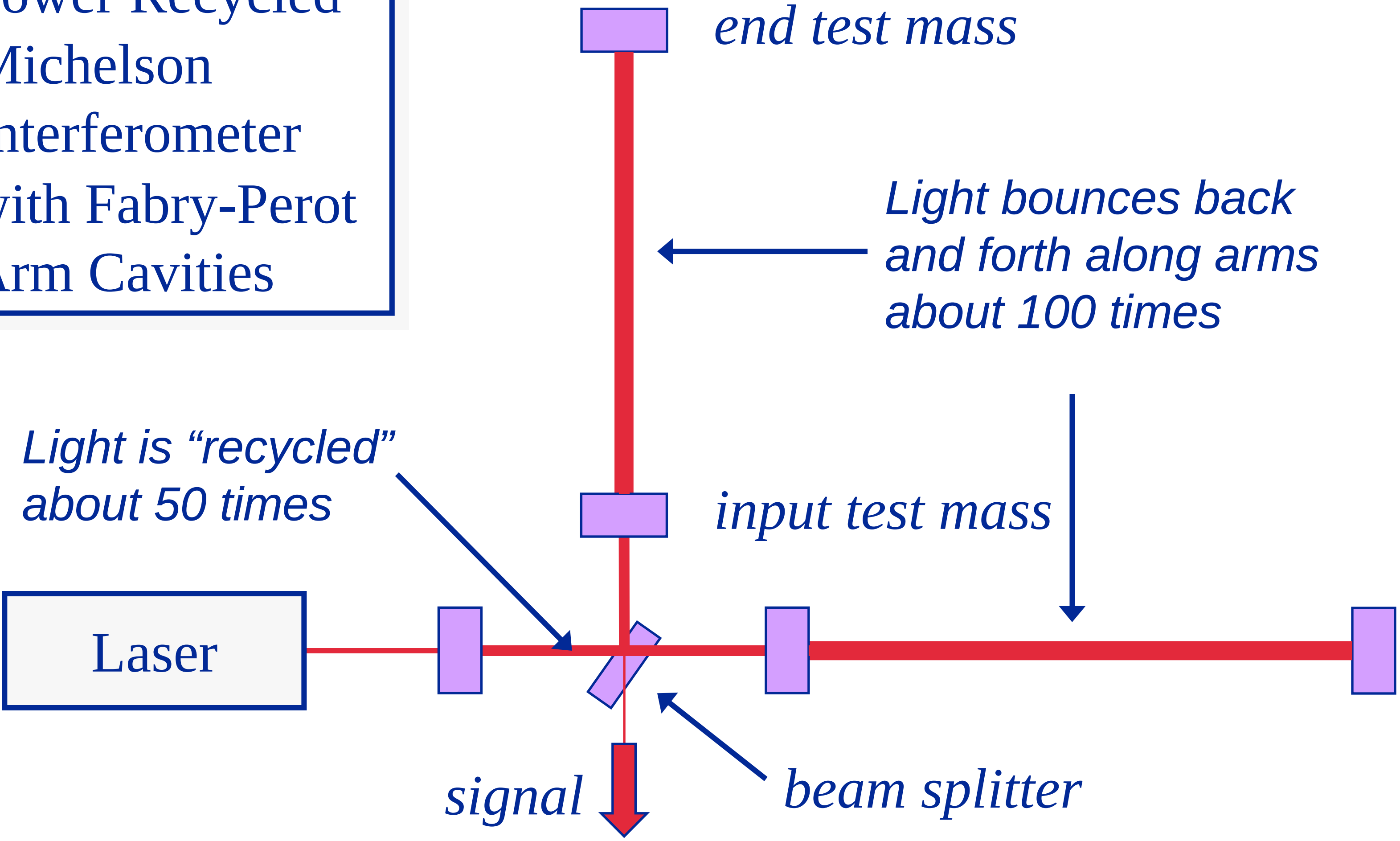

AIGO Australia
future


GEO Germany
600m


LIGO Washington, US
2000m & 4000m

Interferometer Configuration (Example: LIGO)

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



end test mass

Light bounces back and forth along arms about 100 times

Light is "recycled" about 50 times

input test mass

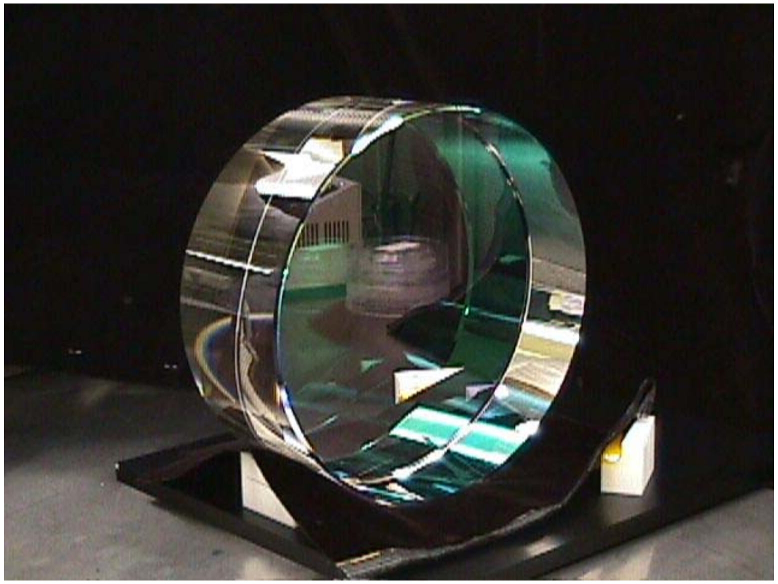
Laser

signal

beam splitter

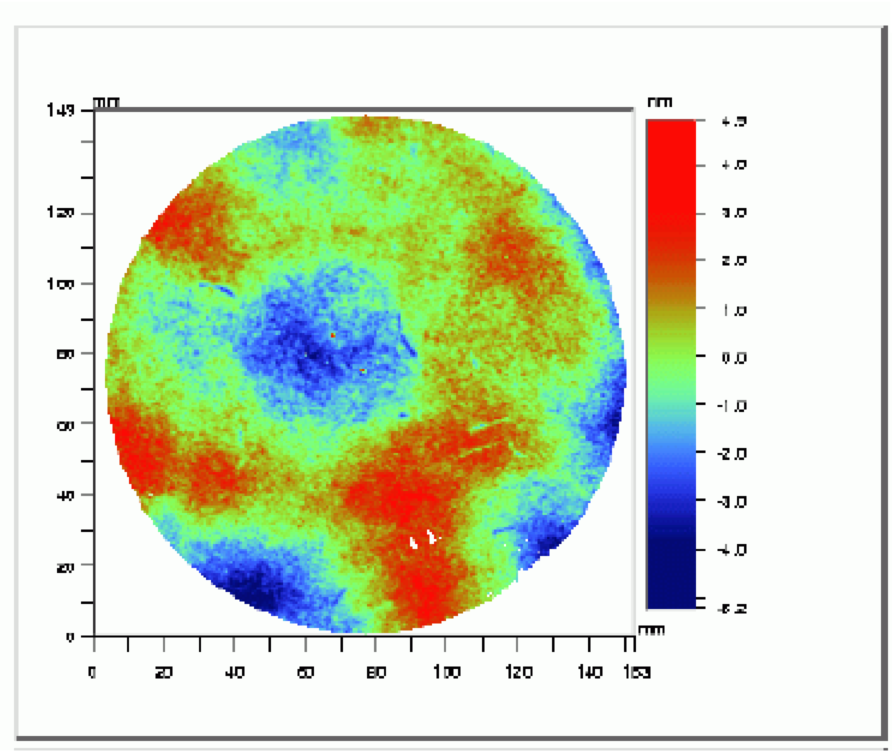
LIGO Test Mass/Mirrors

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5×10^{-7}
  - » Internal mode Q’s > 2×10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms (λ / 1000)
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 5 companies, CSIRO, NIST, and LIGO

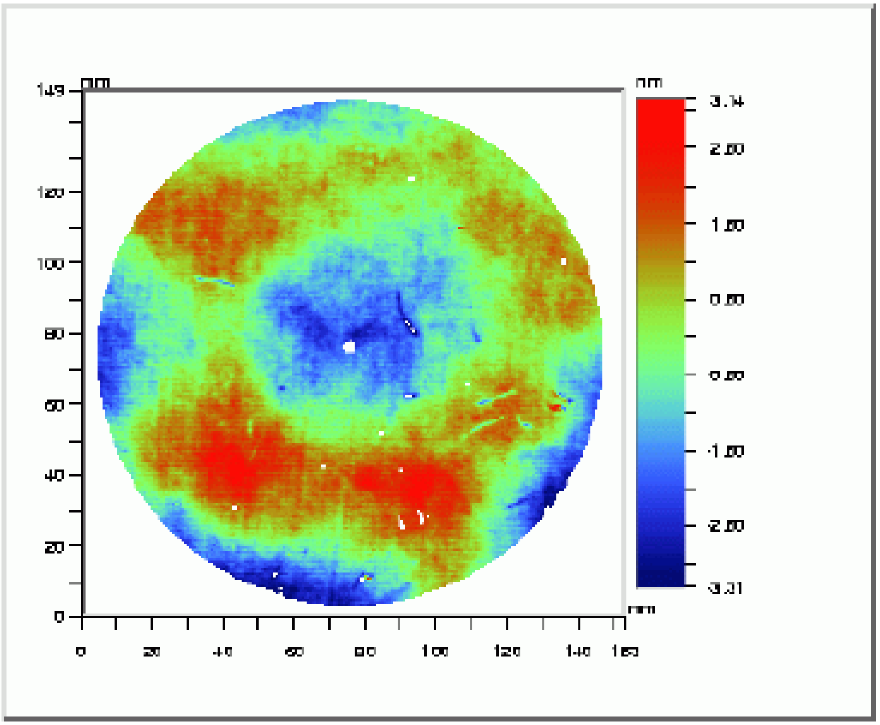


Core Optic Metrology

- Current state of the art: 0.2 nm repeatability



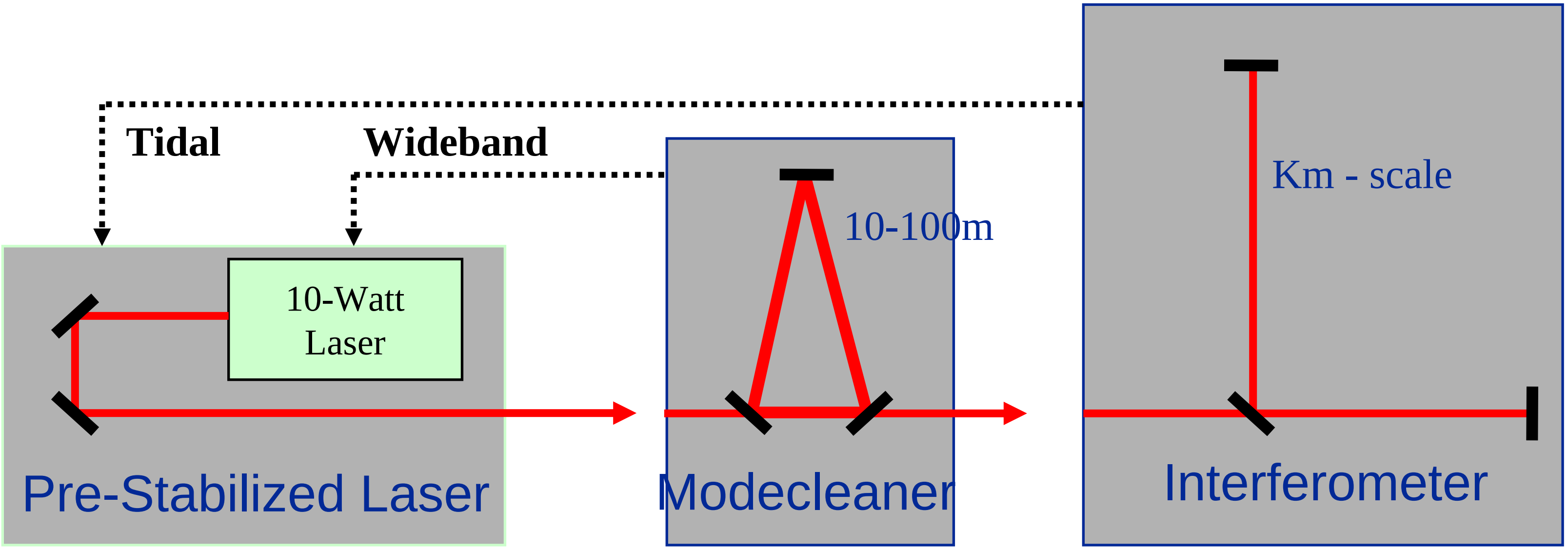
LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

Laser Stabilization

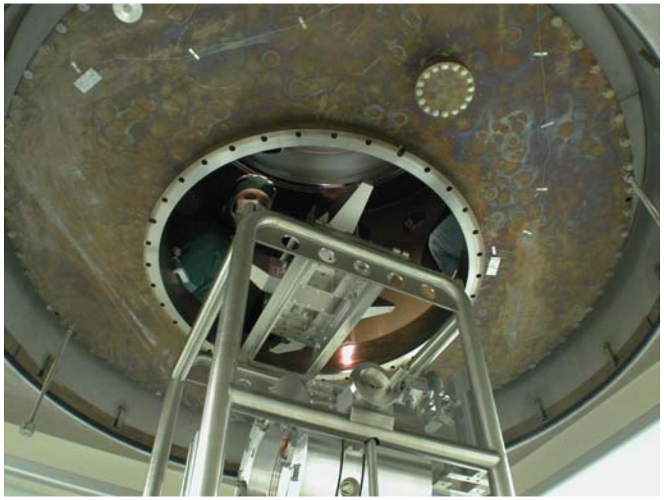
- Deliver pre-stabilized laser light to the mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**

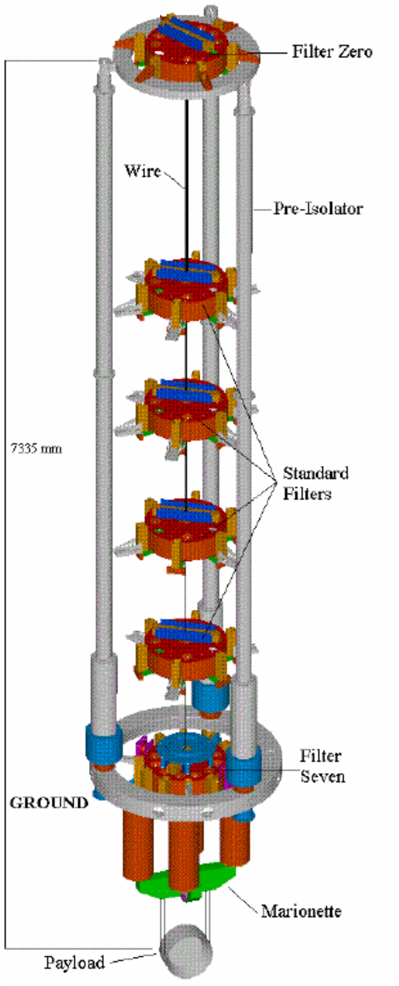


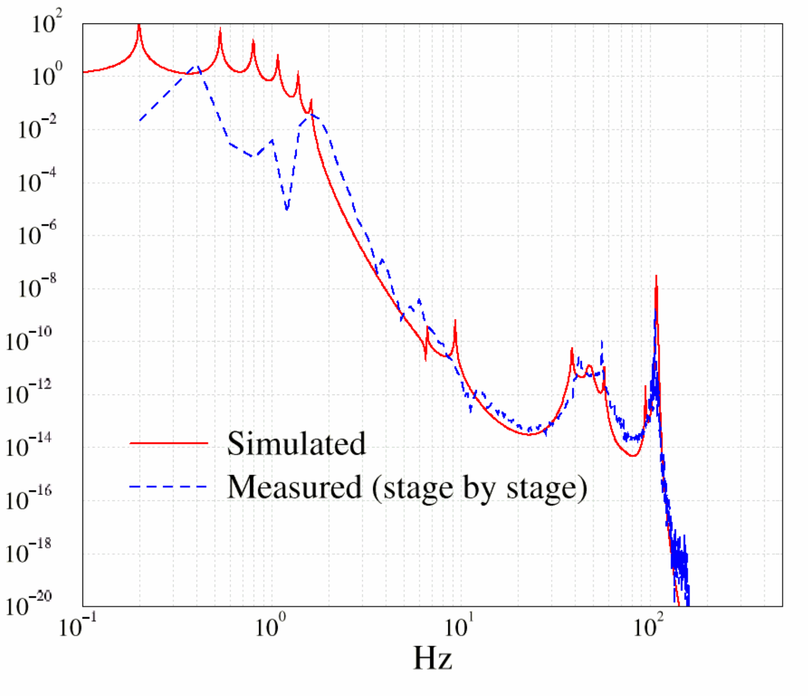
10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

VIRGO Super Attenuator

“Long Suspensions”
- **inverted pendulum**
- **five intermediate filters**

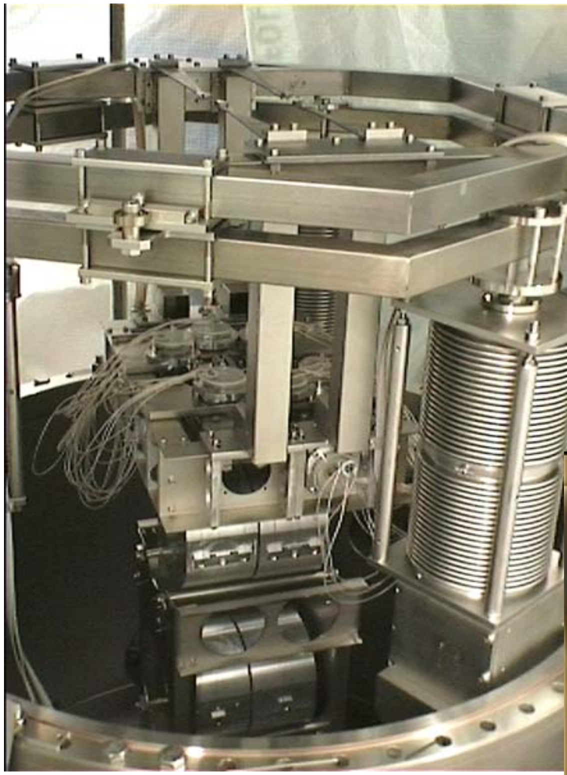


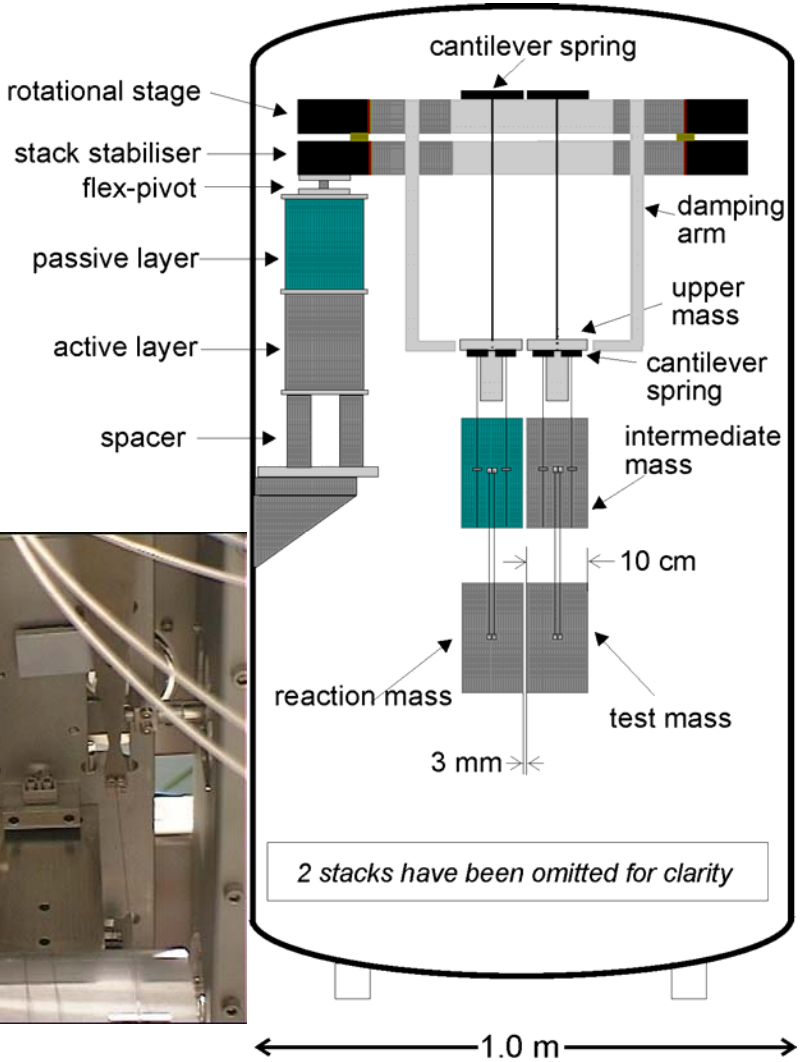




Suspension vertical transfer function measured and simulated (prototype)

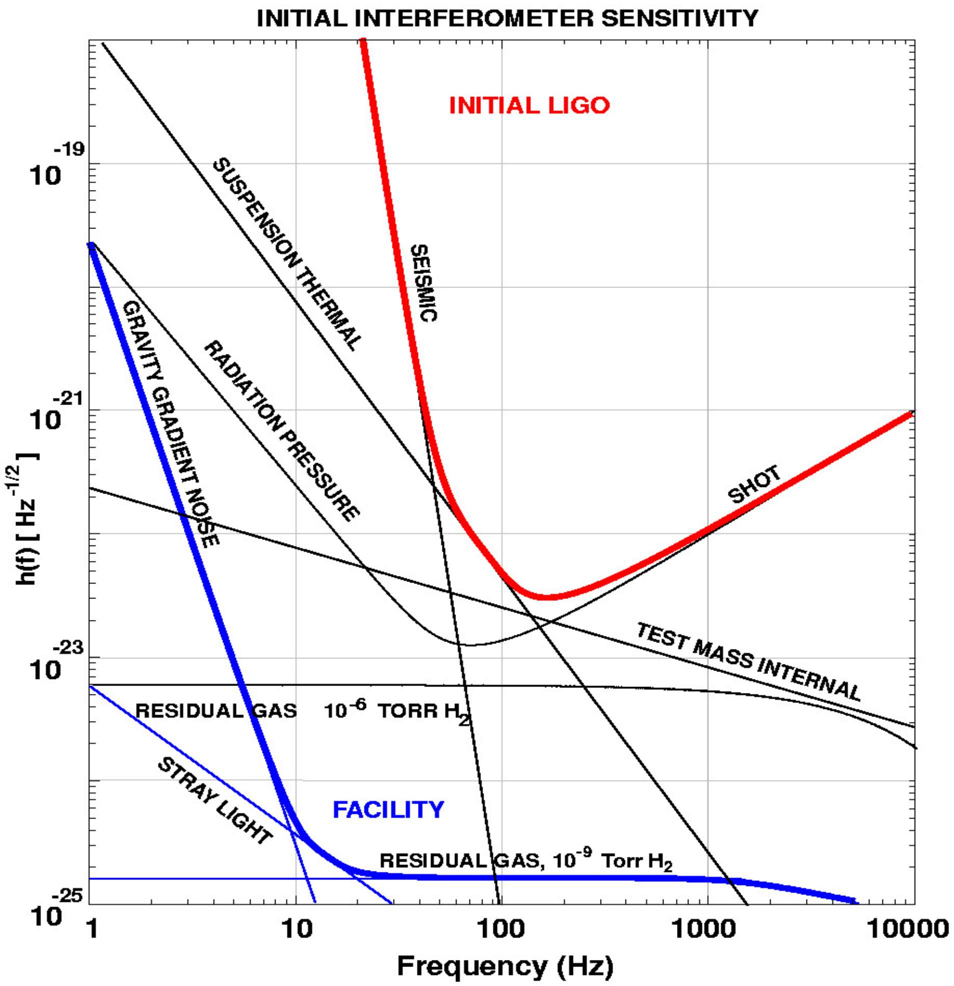
GEO600 Suspension





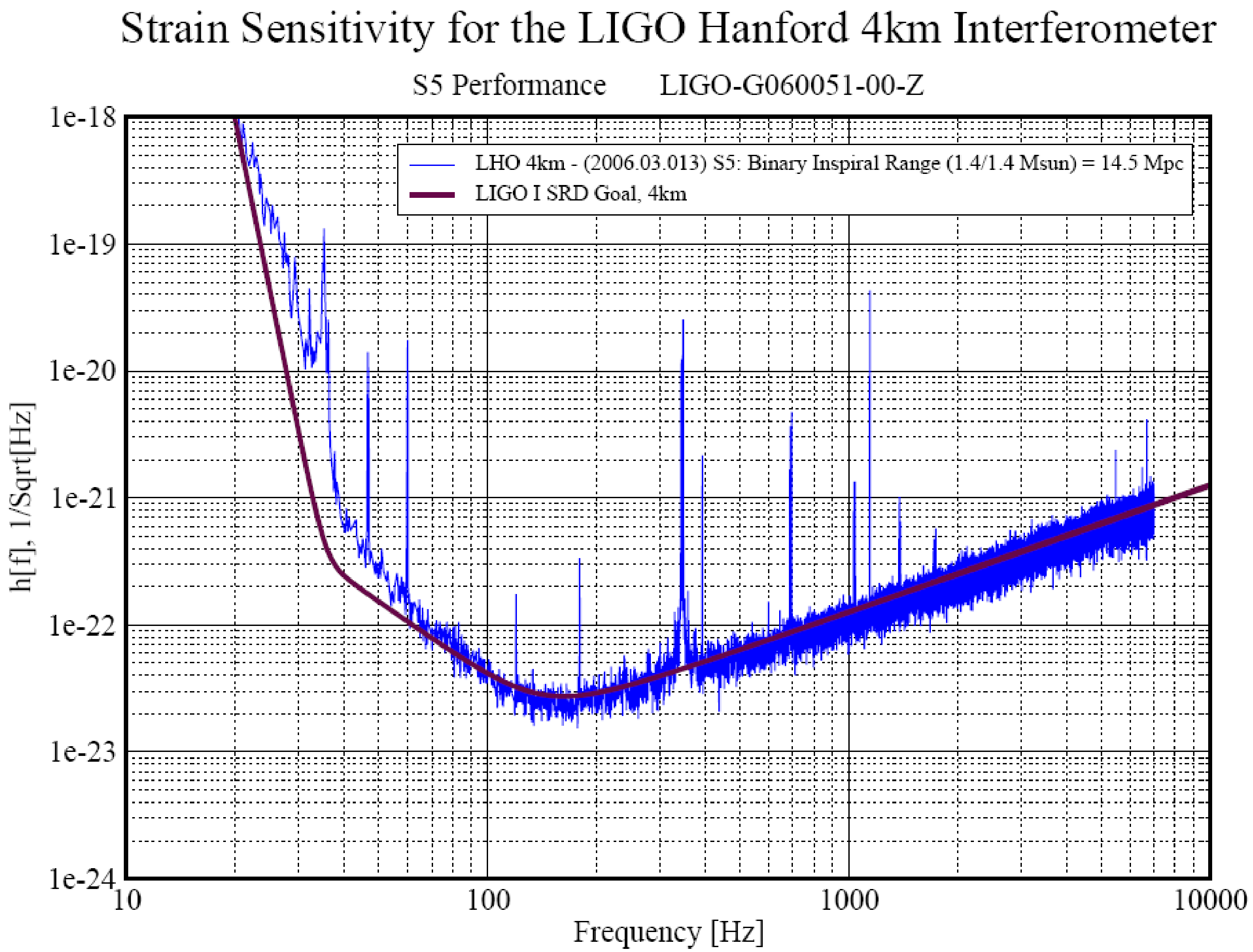
2 stacks have been omitted for clarity

Initial LIGO Sensitivity Goal



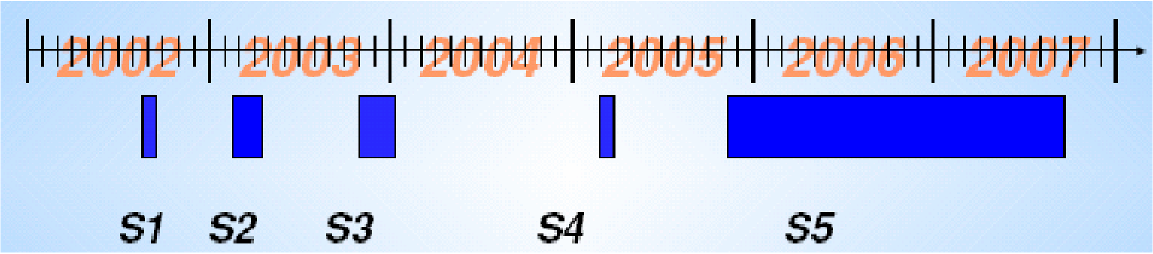
- Strain sensitivity $<3 \mathrm{x} 10^{-23}\ 1/\mathrm{Hz}^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

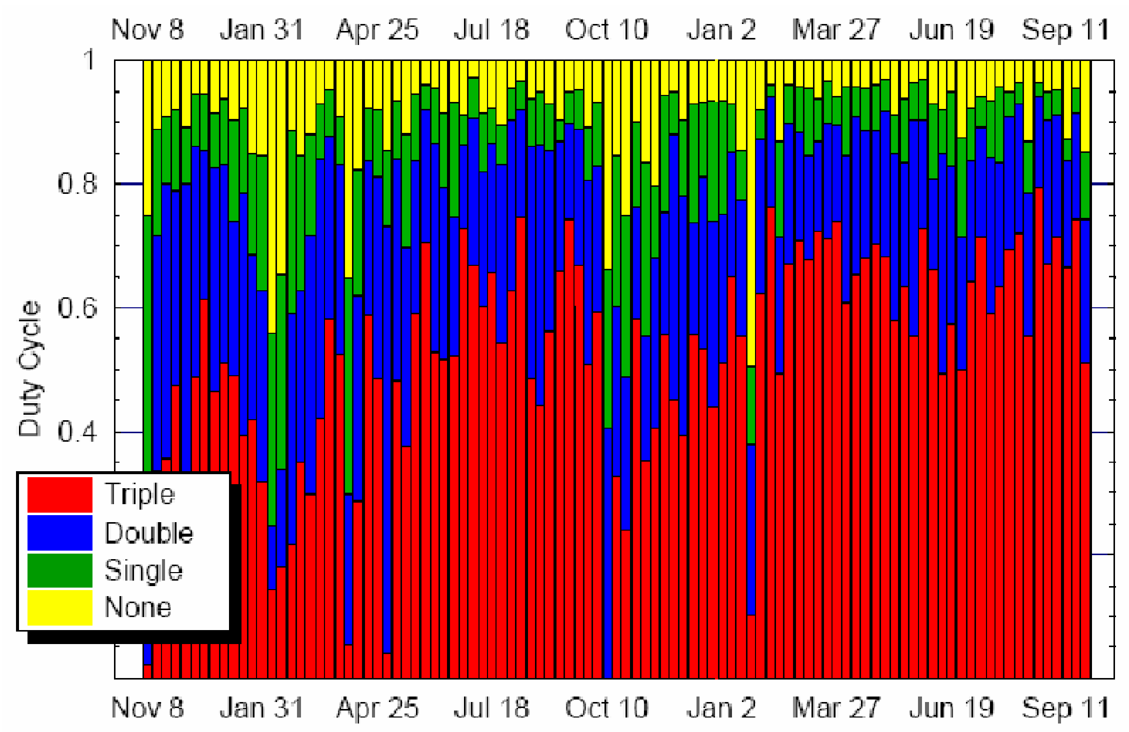
LIGO Sensitivity



LIGO Science Run ("S5")

- Nov 2005 – Oct 2007, 23 months
- One year of triple coincident data from H1, H2, L1
- Virgo joined in June 2007 for 7 months

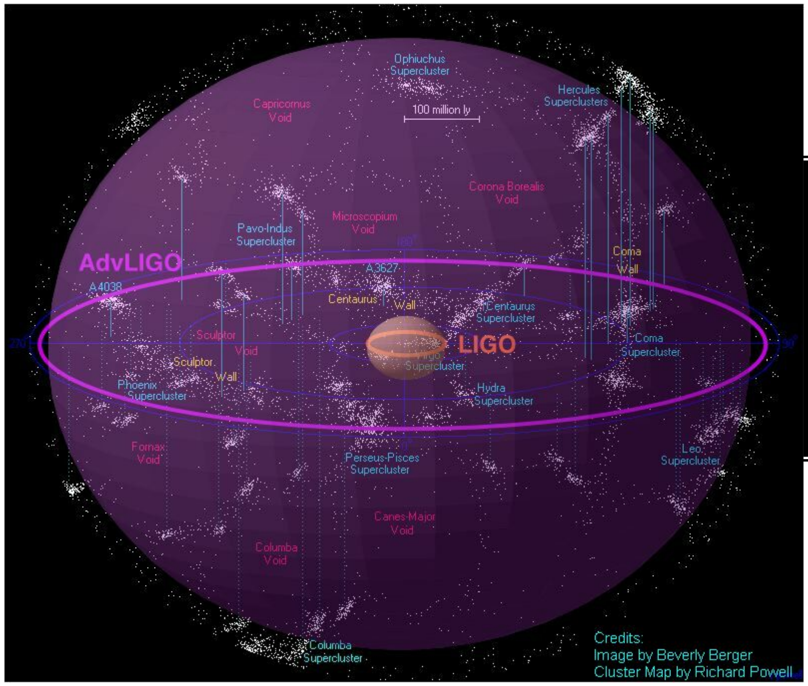




K. Riles, LIGO-G070793

What's next for LIGO?
Advanced LIGO

- Take advantage of new technologies and on-going R&D
  - » Active anti-seismic system operating to lower frequencies
  - » Lower thermal noise suspensions and optics
  - » Higher laser power
  - » More sensitive and more flexible optical configuration



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

x10 better amplitude sensitivity

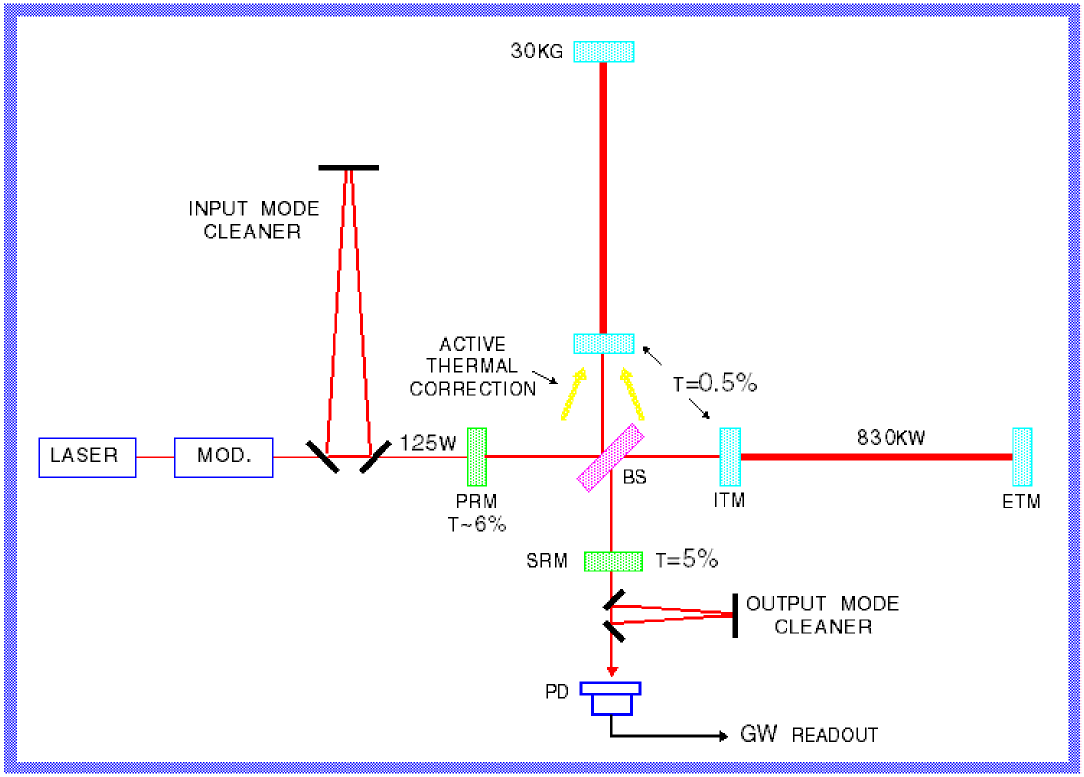
⇒ x1000 rate=(reach)^3

⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

2008 start,
installation beginning 2011

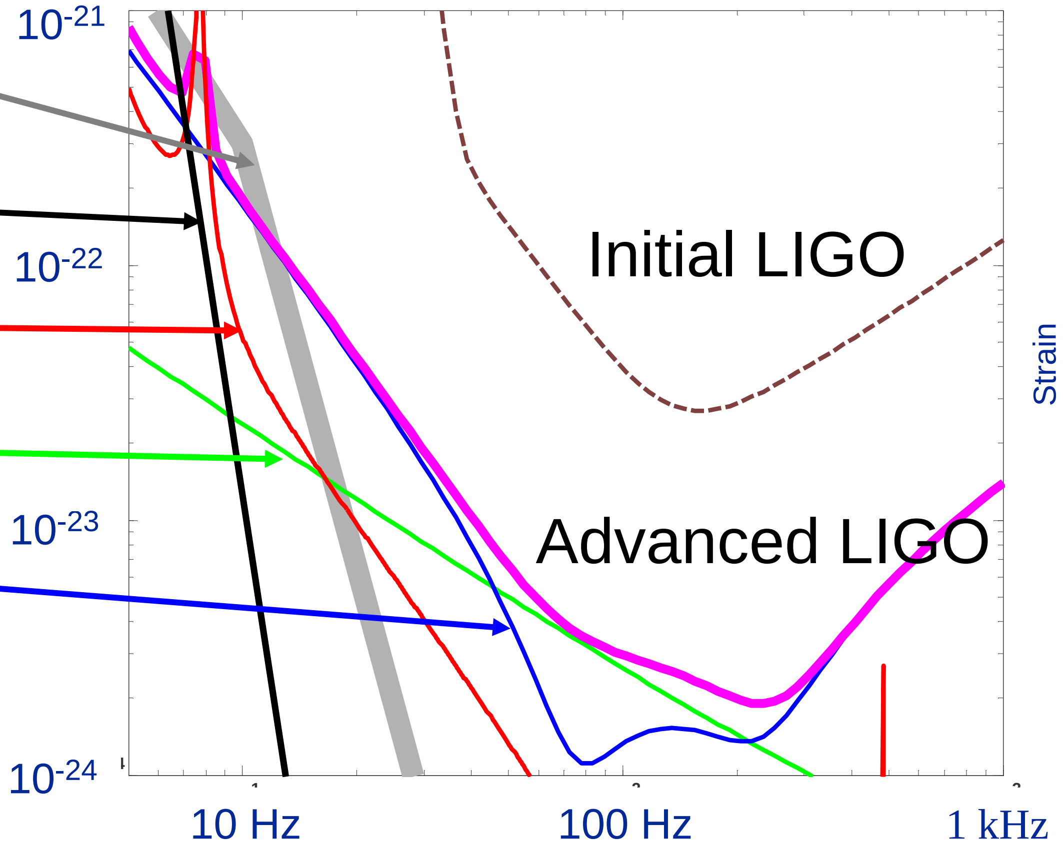
Advanced Interferometer Concept



- »Signal recycling
- »200-watt laser
- »Larger test masses
- »Multi-stage suspensions
- »Active thermal correction

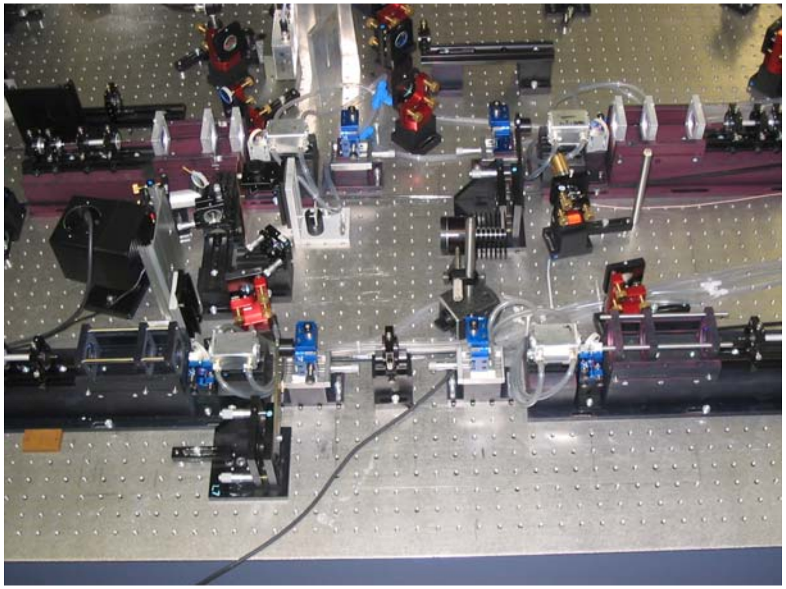
Advanced Detector Performance (Example: Advanced LIGO)

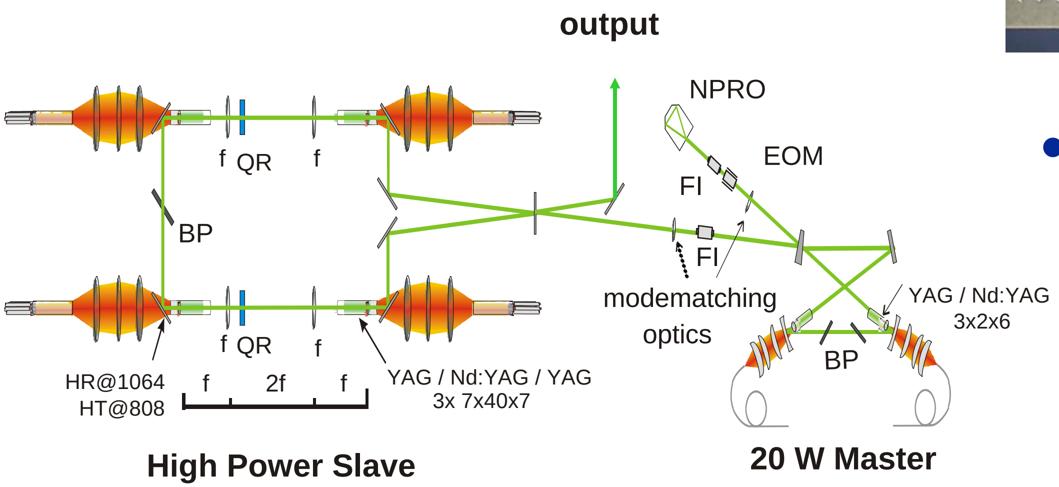
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Quantum noise dominates at most frequencies



Shot Noise Limits

- Increase laser power to lower shot noise
- Increased laser power (~0.8MW in FP cavities) leads to increased requirements on many components

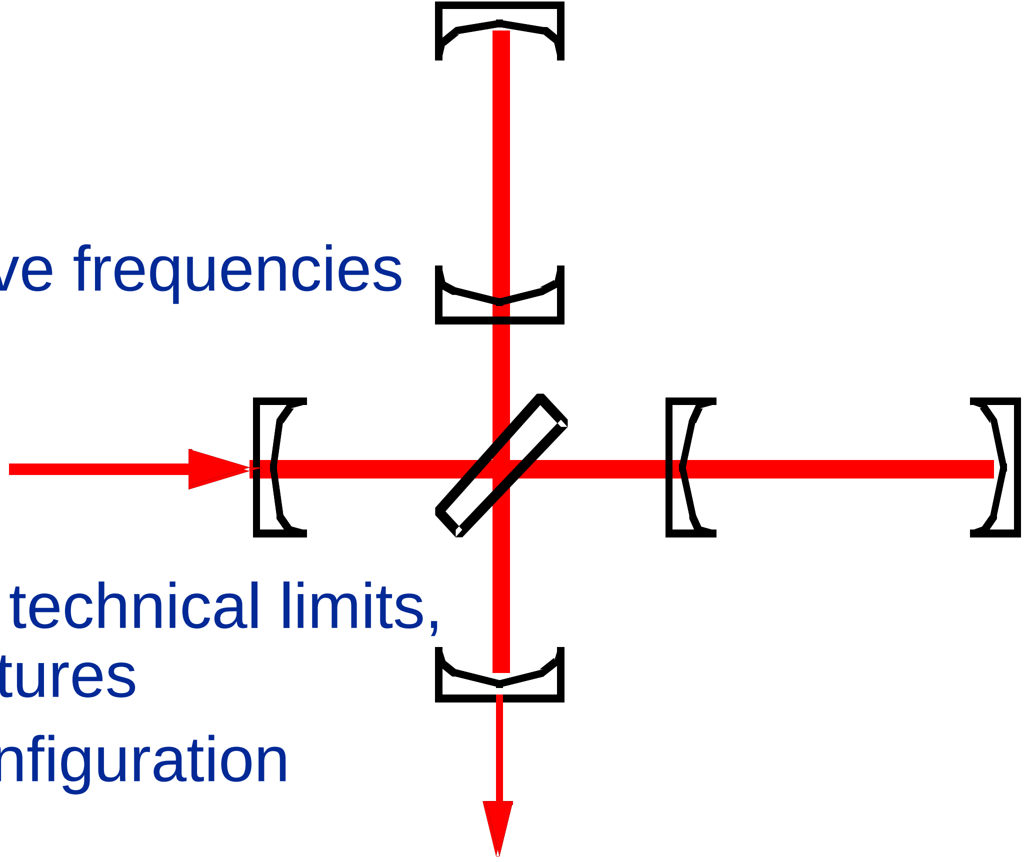




- Full injection locked master-slave system running, 200 W, linear polarization, single frequency, many hours of continuous operation

Tailoring the frequency response

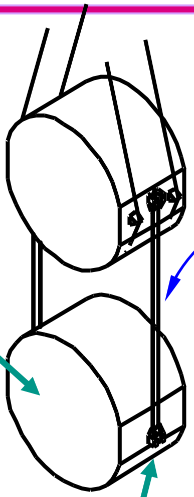
- Signal Recycling
- Additional cavity formed with mirror at output
- Can be resonant,
  or anti-resonant,
  for gravitational wave frequencies



- Allows optimum for technical limits, astrophysical signatures
- Advanced LIGO configuration

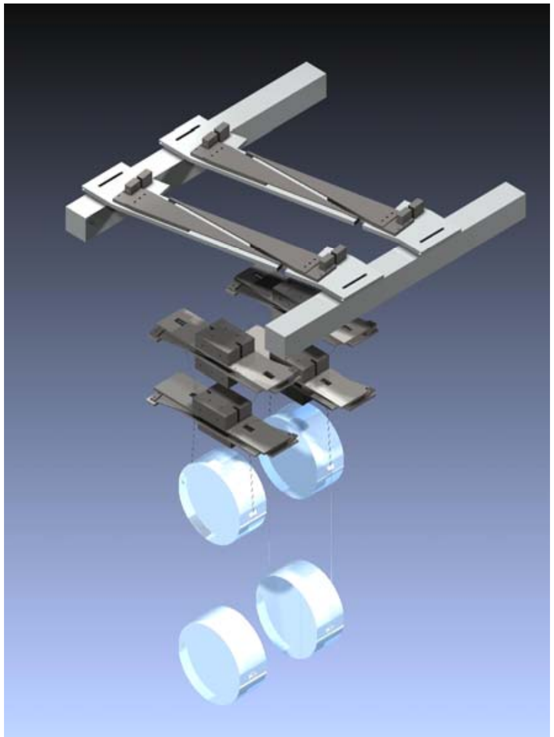
Thermal Noise Suppression

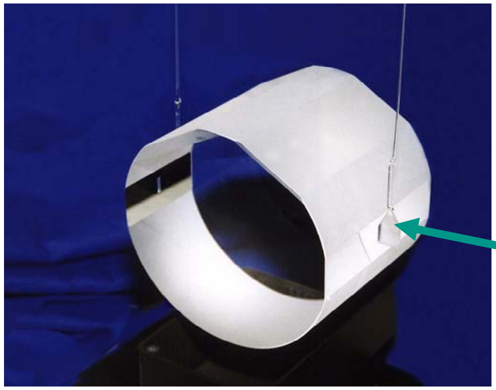
- Minimise thermal noise from pendulum modes and their electronic controls



Silica fibres

Test mass with mirror coating



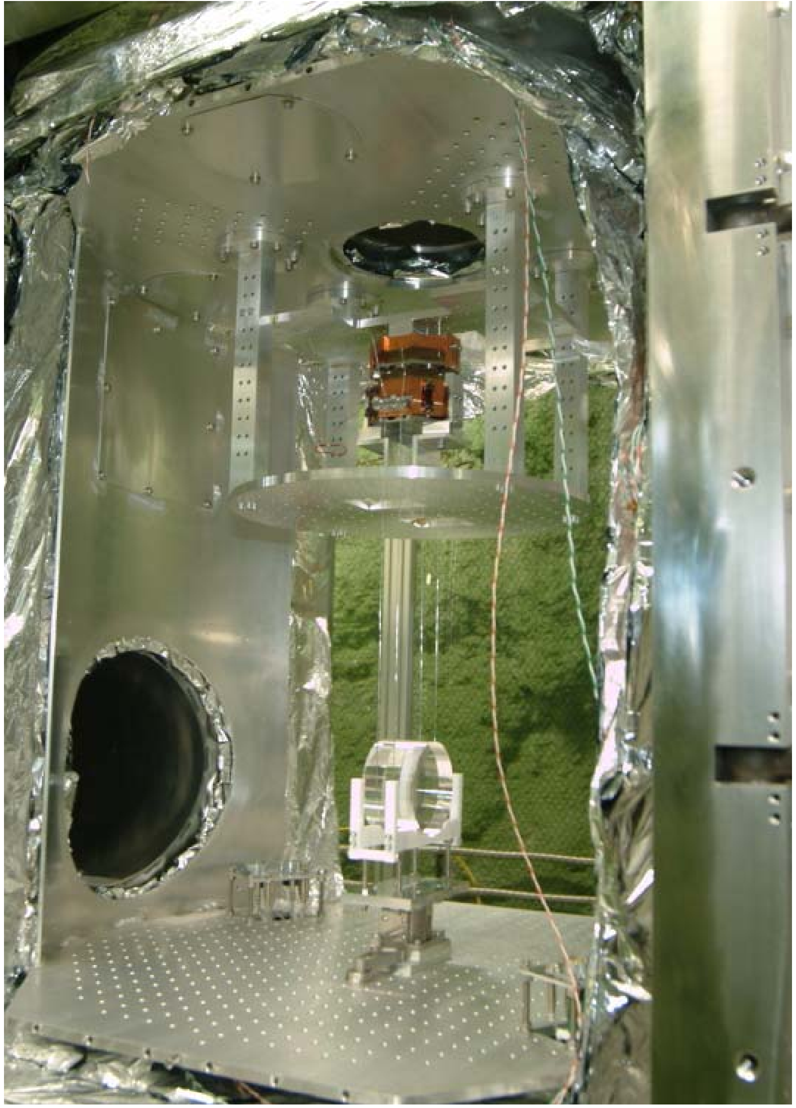


Silicate bonds

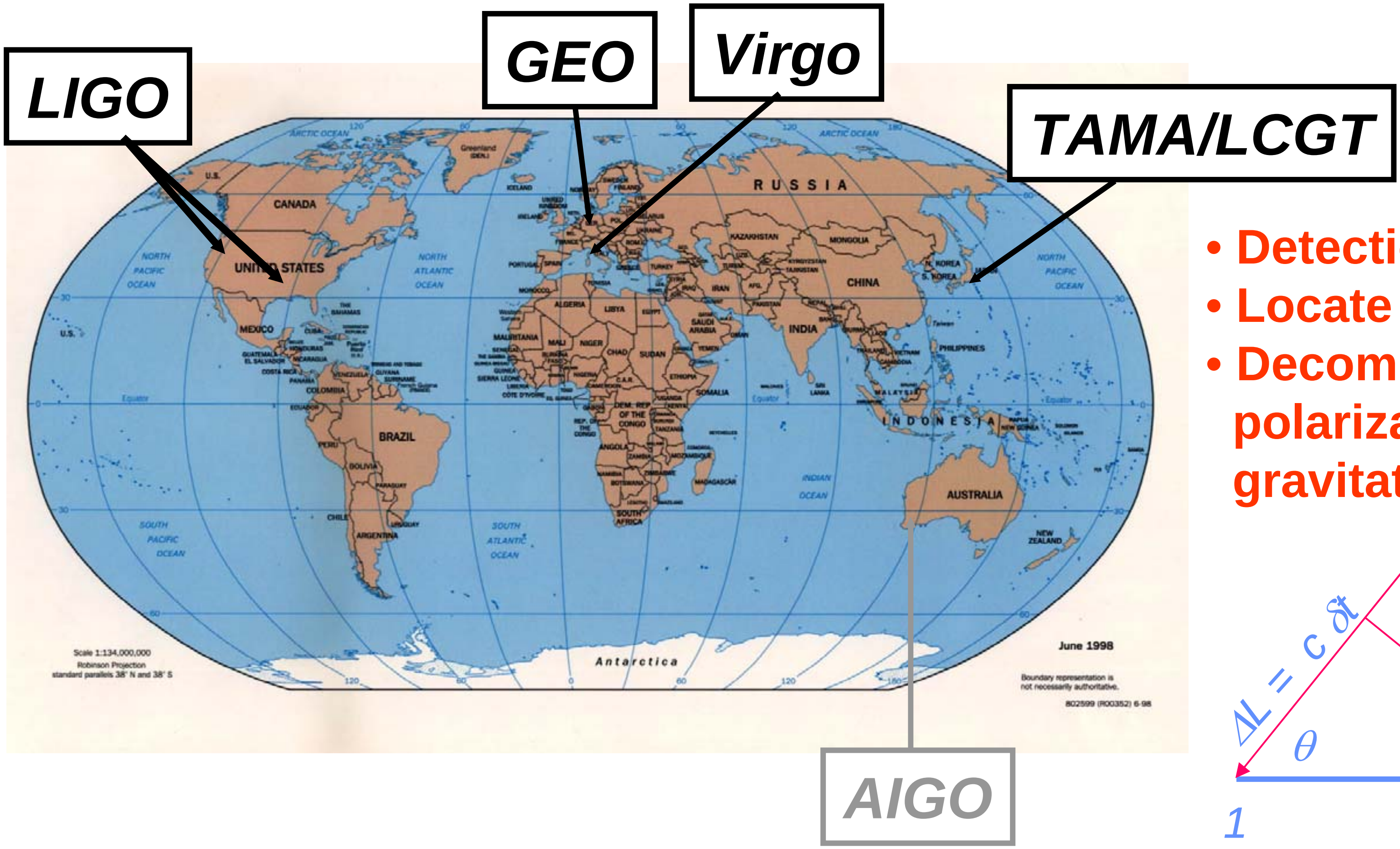
- Silicate bonds create quasi-monolithic pendulums using fused silica fibers to suspend interfrometer optics

Cryogenics to Reduce Thermal Noise

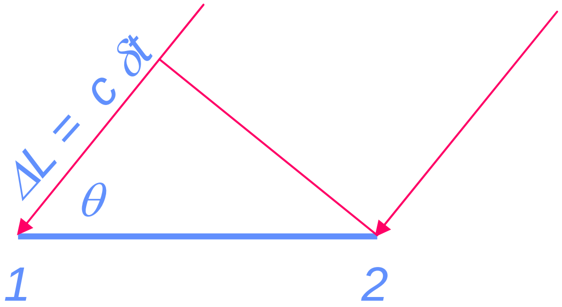
- Japanese Project LCGT (Large-scale Cryogenic Gravitational-wave Telescope) has pioneered use of cryogenics
- Challenge: 1 MW circulating optical power in arm cavities
- Successful demonstration on small scale interferometer



A Global Network of GW Detectors



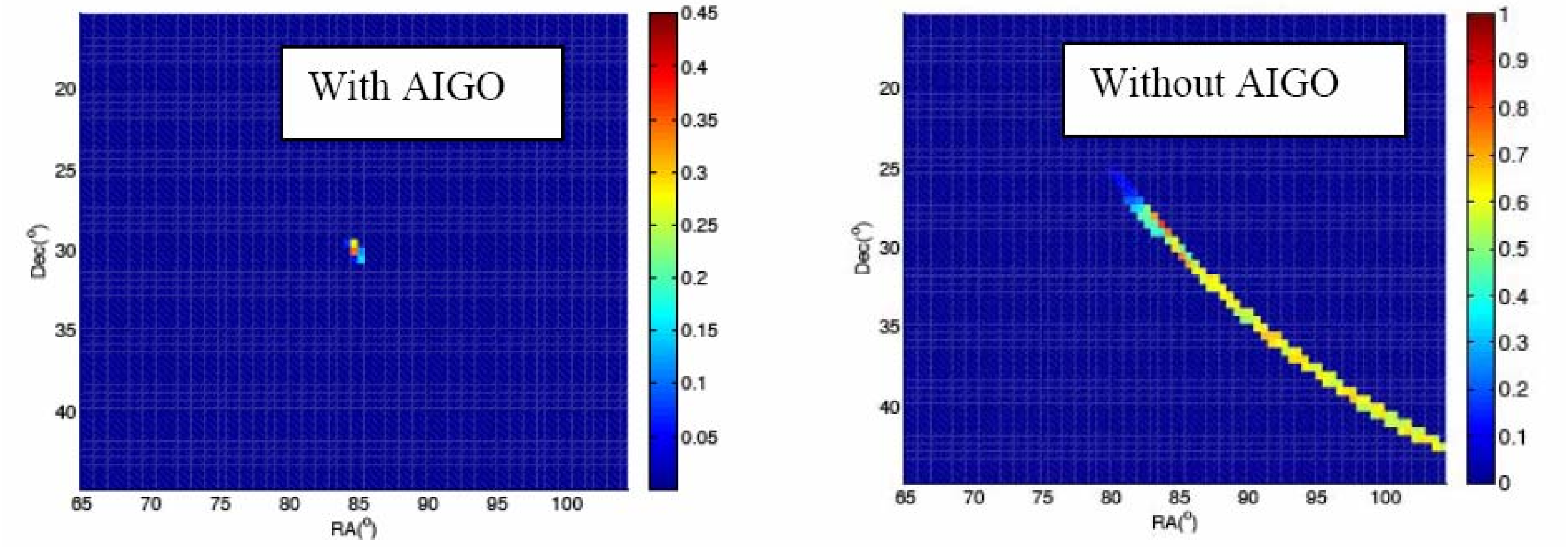
- **Detection confidence**
- **Locate sources**
- **Decompose the polarization of gravitational waves**



AIGO (Australian International Gravitational-wave Observatory)

- 8km x 8km AIGO site 70km north of Perth granted 1998.
- Site development begun 1999
- Currently operating 80m High Optical Power test facility in collaboration with LIGO

Importance of AIGO



- AIGO provides strong science benefits e.g. host galaxy localization
- Comparable sensitivity to Advanced LIGO
- Australian Consortium seeking partners and funding

Final Thoughts

- We are on the threshold of a new era in GW detection
  - » LIGO has reached design sensitivity and is taking data
- First generation detectors have broken new ground in optical sensitivity
- Second generation detectors are starting fabrication
  - » Will expand the “Science” (astrophysics) by factor of 1000
- A worldwide network is starting to come on line
  - » Groundwork has been laid for operation as a integrated system
  - » Australia could play a key role