Status of Interferometers and Data Analysis

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LIGO - MIT
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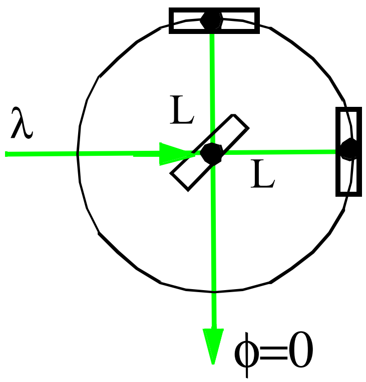
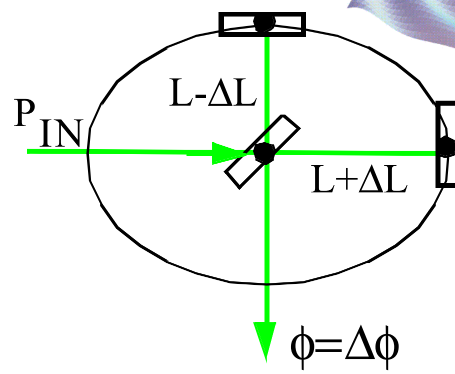
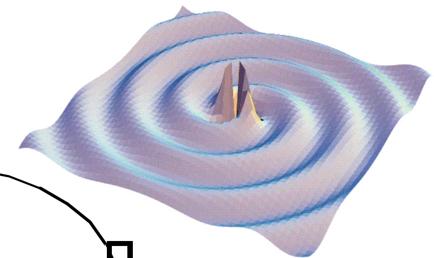
Overview

- Fundamental and practical design drivers
- Principal elements of realistic systems
- For each of several signal classes:
  - » Character of signals for ground-based systems
  - » Data analysis challenges
  - » Status, Plans of endeavors around the world

Basic sensing principle

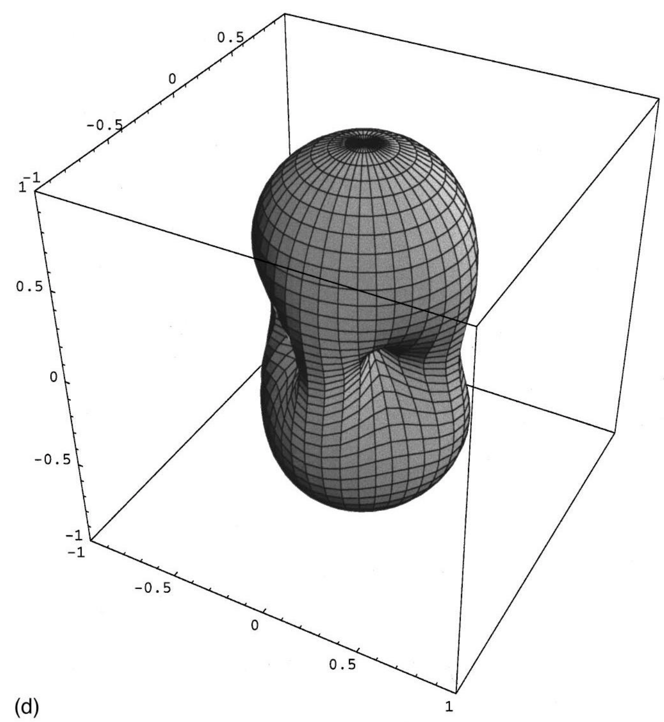






- Quadrupolar strain, differential response
- Transduction into light intensity changes

- Antenna pattern: the ‘peanut’



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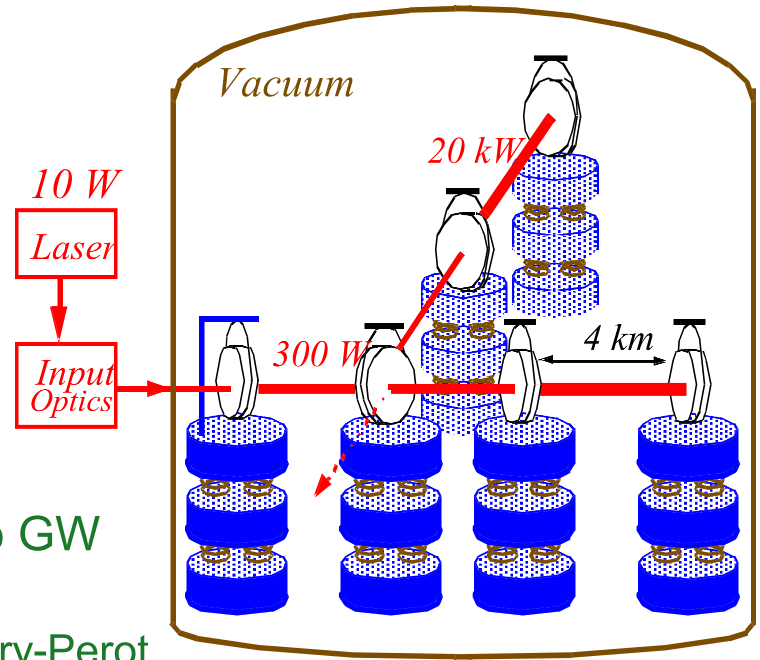
…how to make this a useful instrument?

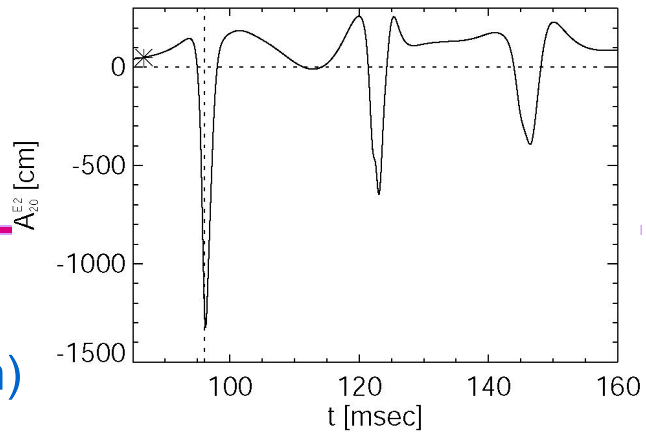
Basic design rules, consequences

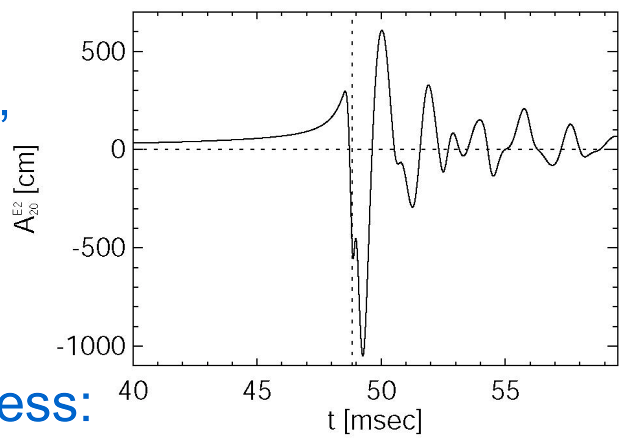


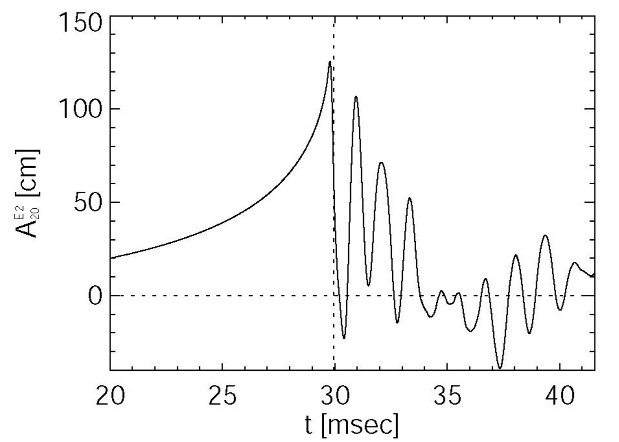
- Goal: minimize other forces on masses
  - » Seismic noise: Active and Passive isolation
  - » Thermal noise: Choice of materials, assembly
  - » Internally generated noise: keep strains low
- Goal: maximize light phase modulation due to GW
  - » 0.3-4 km Interferometer arm length
  - » Optical ‘folding’ of light path: Delay Line or Fabry-Perot
  - » Tailoring of frequency response:
    RSE (Resonant Sideband Extraction)
- Goal: minimize other sources of phase modulation
  - » Ultra High Vacuum path for light
  - » Laser pointing, intensity and frequency stabilization via transmissive Mode Cleaners
  - » Quantum limited sensing: High-power Nd:YAG lasers
    - – (photon pressure; thermal focussing)
- Goal: maximize observation time and value
  - » Reliable operation of individual detectors
  - » Many detectors, closely coordinated, shared data

Impulsive sources

- Sources and signatures
  - » Some predictions for simple objects (BH ringdown)
  - » Supernovae – great zoo of possible signatures
  - » Unpredicted signals, but allowed by physics
- Challenge: many instrumental sources of ‘bursts’
  - » Requires excellent characterization of instrument
  - » Similar ‘data analysis’ to be performed on many diagnostic channels
- Data analysis (or detector characterization) process:
  - » resolve the channel into sub-bands
  - » identify statistics on the sub-bands
  - » identify epochs when the detector output is uncharacteristic of its behavior in the mean

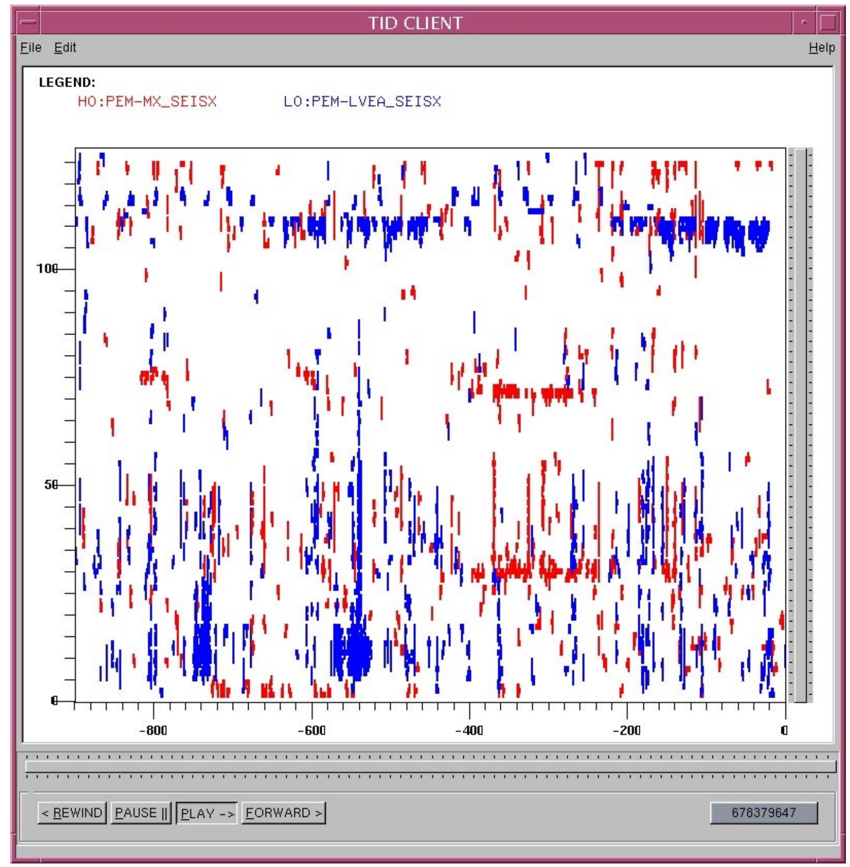






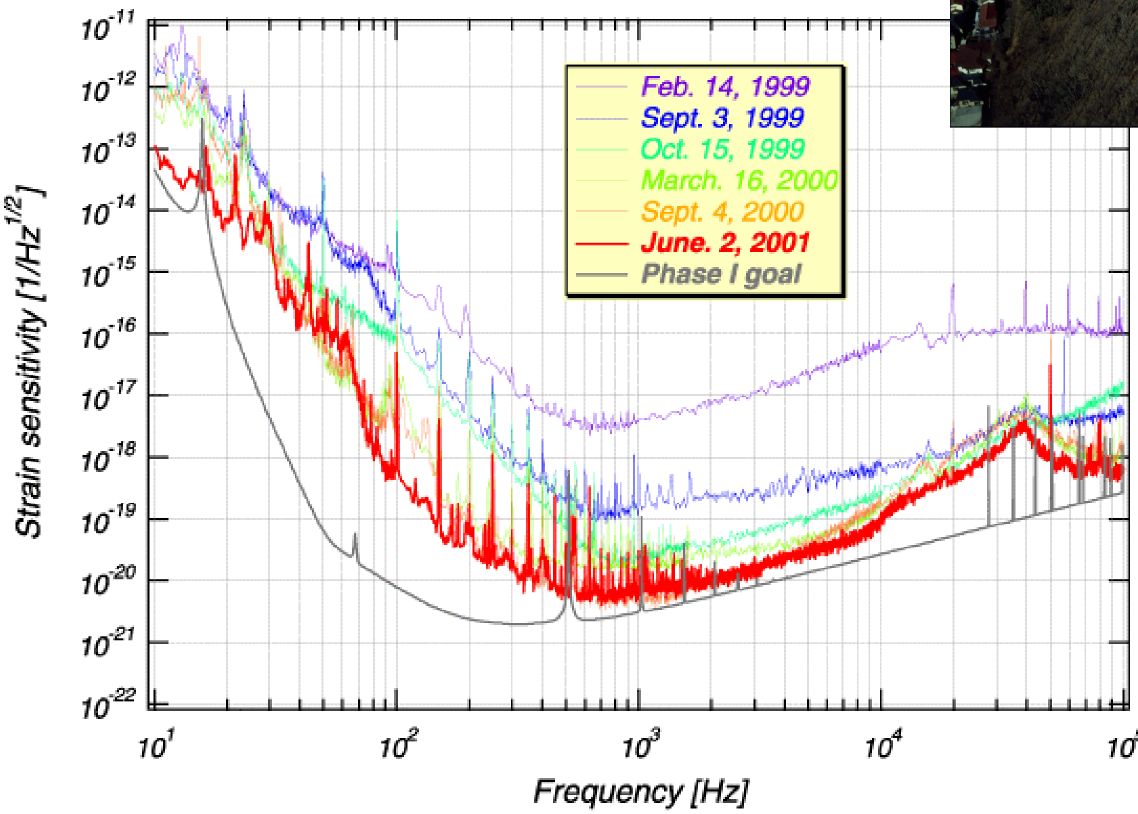
Impulsive sources

- Search with variety of filters
  - » Power fluctuations larger than measured statistics
  - » Time-frequency techniques
  - » Wavelet or other general approaches
- Must have second astrophysical sensor for coincidence -
  - » Other interferometers, or acoustic detectors
  - » Neutrino detectors
  - » GRB and optical telescopes
- Computation:
  - » GW and auxiliary channels may present comparable demands
- Example of detector well suited: **TAMA**



TAMA300

- FP Michelson, 300m arm length
- Best interferometer sensitivity to date: ~5x10^{-21} h/rHz, ~700 Hz
- Continuous lock >24hours



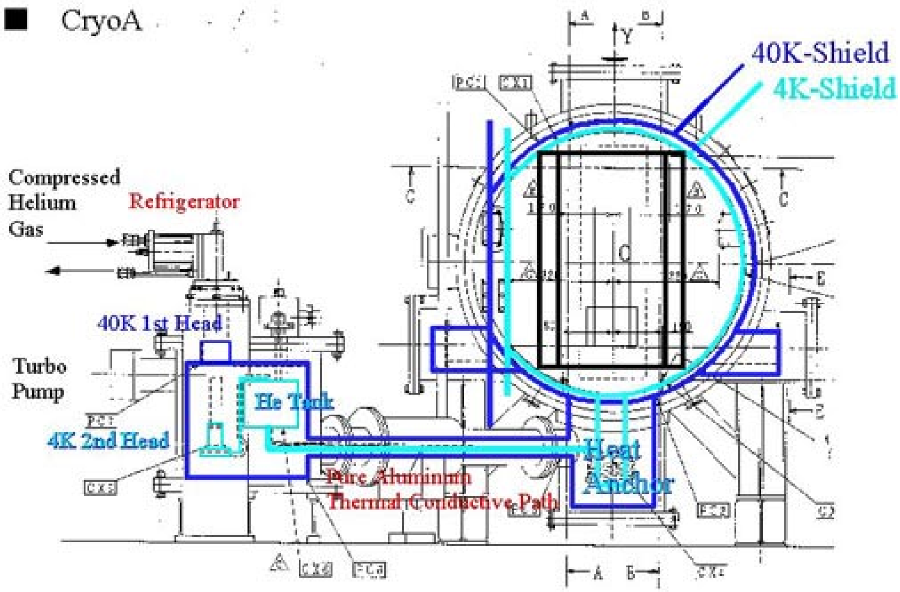
•Sensitivity for supernova: 0.01M_{solar}, SNR 10, galactic center

•In conjunction with e.g., Kamiokande neutrino detection

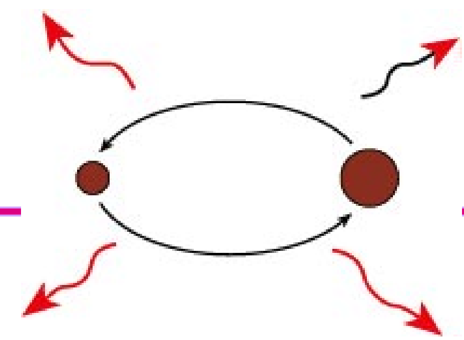
TAMA →LCGT

Large-scale Cryogenic
Gravitational wave Telescope

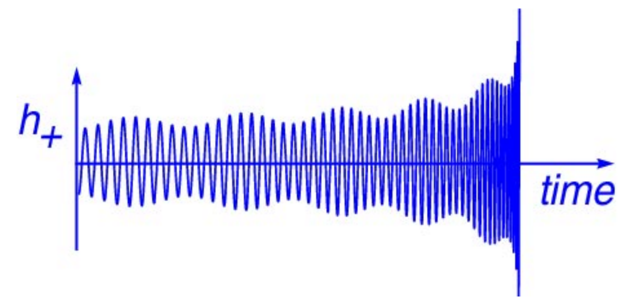
- Planned cryogenic detector
- Next to Kamiokanda
- 3km arm length
- 20 K sapphire mirrors
- Goal: $3x10^{-24}$ h/rHz at 70 Hz
- Strong R&D program underway

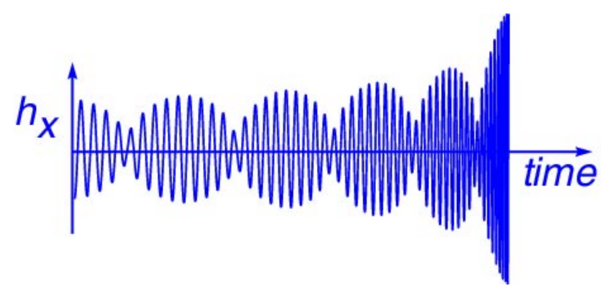


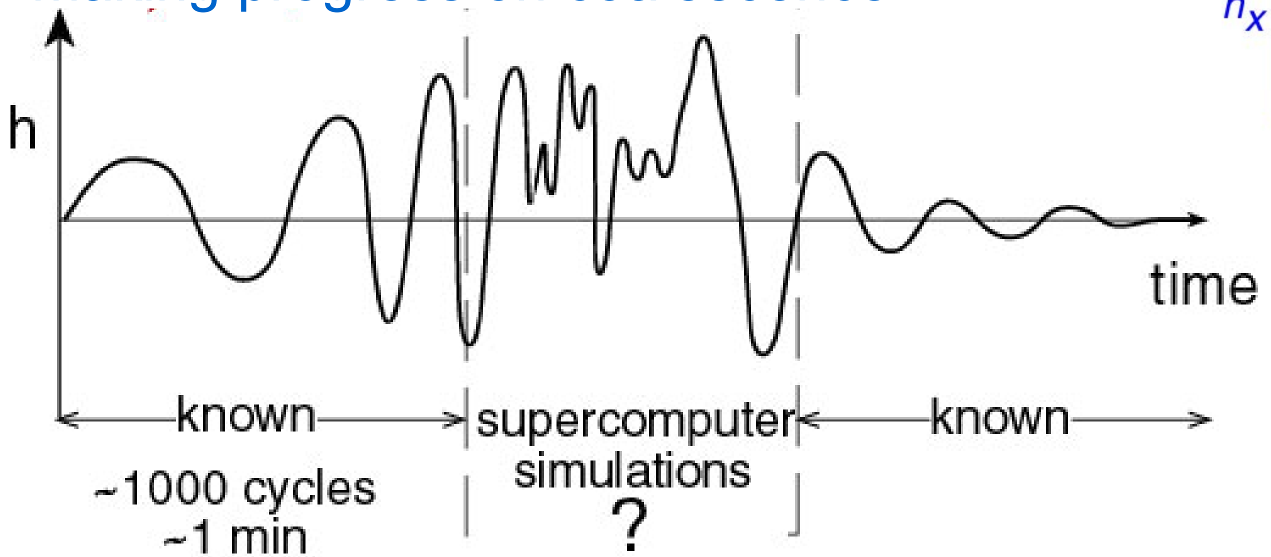
Inspiraling Binaries



- Our best understood source
- Chirp signature:
  - » Sweep upward in frequency
  - » Low frequency instrument response → longer observation time, better SNR and more information extracted
- Can calculate up to, and after – making progress on coalescence

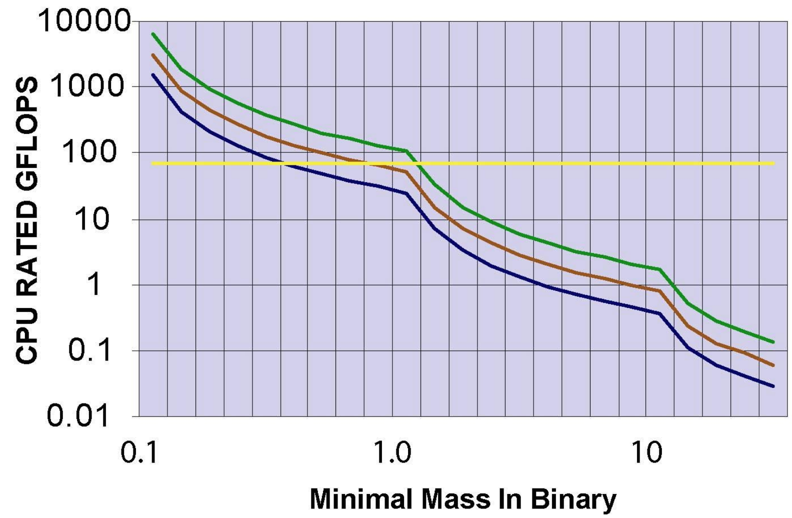






Inspiraling Binaries

- Computational challenge – many templates required
- Number of templates: $(1/M)^{5/3} * (1/f_{best})^{8/3}$
- Hierarchical search methods, 'mother templates' to help
- 'Slow' Parallelization works well – Beowulf CPU configuration



- Practice in studies of Caltech 40m, TAMA interferometer data
- Example of detector well suited: **Virgo**

Virgo

- Italian and French collaboration
- 3km arm detector near Pisa
- Power-recycled Fabry-Perot Michelson

- Both tunnels complete
- North beam tube installed and aligned over more than 2.5 km
- The first 300m section pressure is below $6x10^{-10}$ mbar
- Construction to be complete mid-2002

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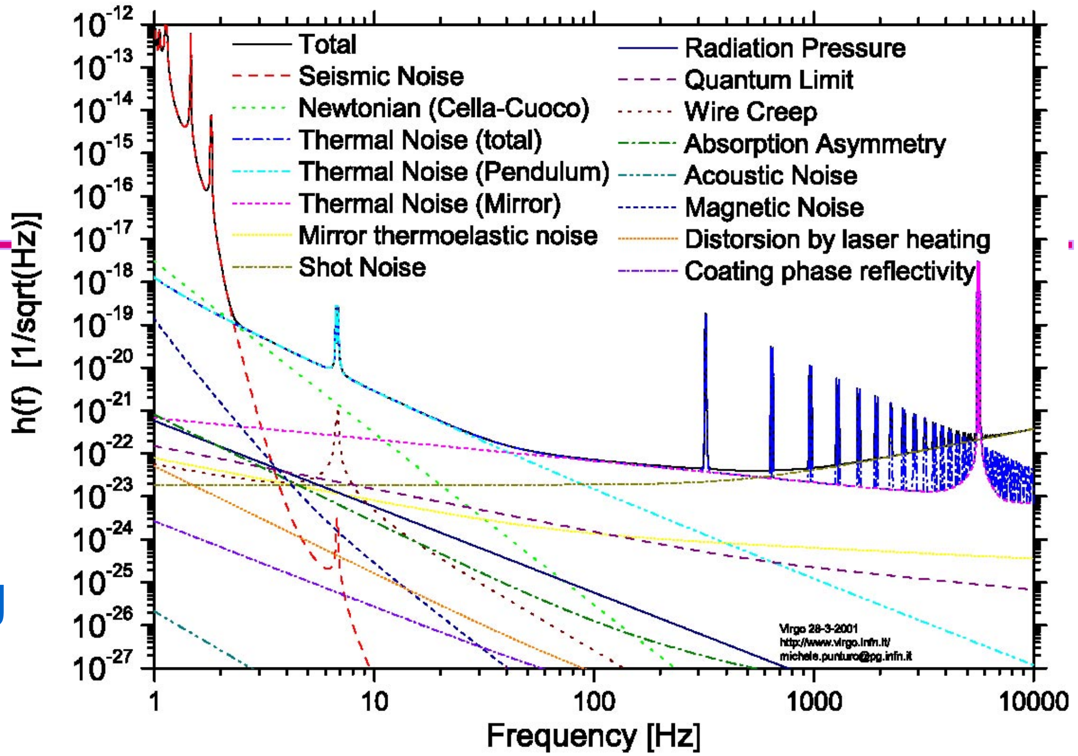
Virgo

- Excellent seismic isolation
- Allows long observation of binaries – better SNR, more precision in parameters
- Mirror suspensions may be steel or (again to improve low frequency response) fused quartz

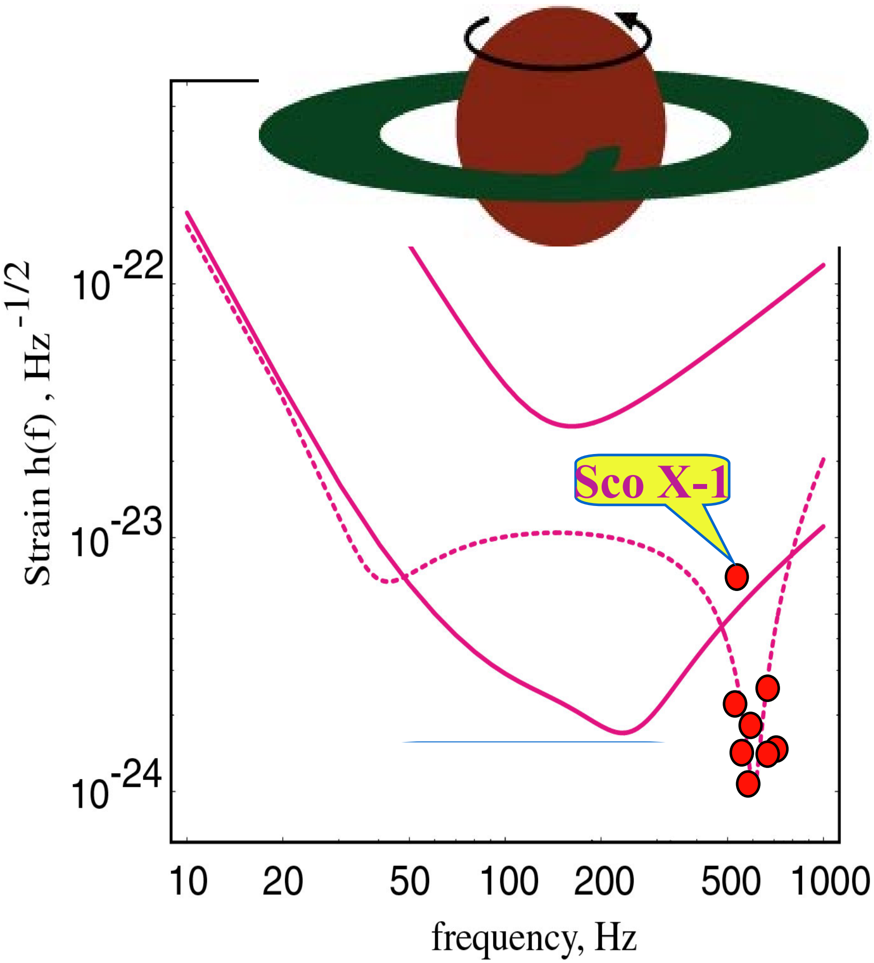
Virgo - Status



- Central interferometer operating, under study
- Laser, mode cleaner, beamsplitter, near mirrors
- Superattenuators, including inertial damping, operating continuously;
  Transfer functions have been measured
- Final optics near delivery; Lyon coating facility operational
- Filters for the pulse detection and coalescing binaries are being tested. New filters include complete black hole coalescence (Damour-Buonanno model). A 50-100 Gflop analysis system will be implemented in 2001
- Full interferometer commissioning in 2002

Coherent sources

- Pulsars
- Low-mass X-ray binaries
- Possibly supernova remnants, r-mode oscillations
- Possibility of synchronous detection with other kinds of instruments

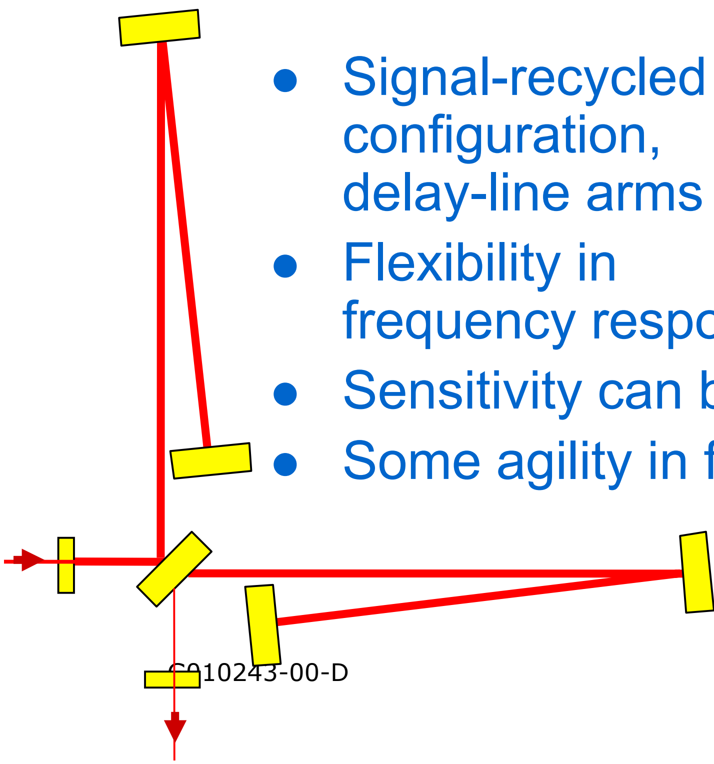


Coherent Sources

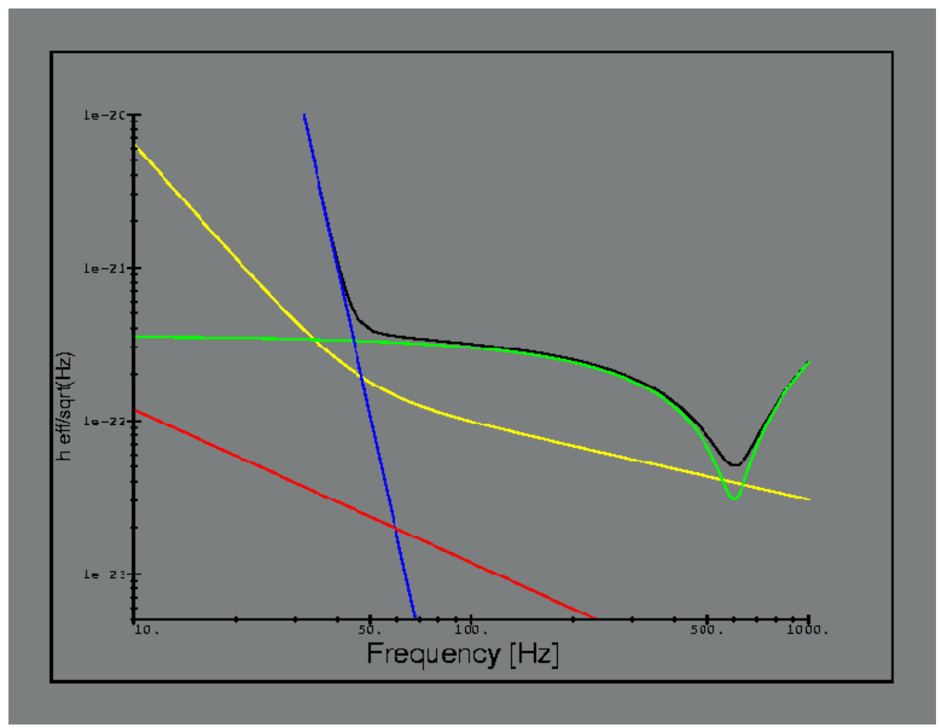
- All-sky challenge:
  - » Must correct for Doppler shifts for each pixel in sky
  - » Computationally limited
- Start with short (1-day) transforms, then either knit together into longer coherent transforms, or add incoherently
- Instrumental line sources must be well characterized…
- Known pulsar search easier – position, Doppler shift calculable
- Interesting to focus instrument sensitivity at fixed frequency; simplifies analysis problem, increases absolute sensitivity
- Example of detector well suited: **GEO**

GEO-600

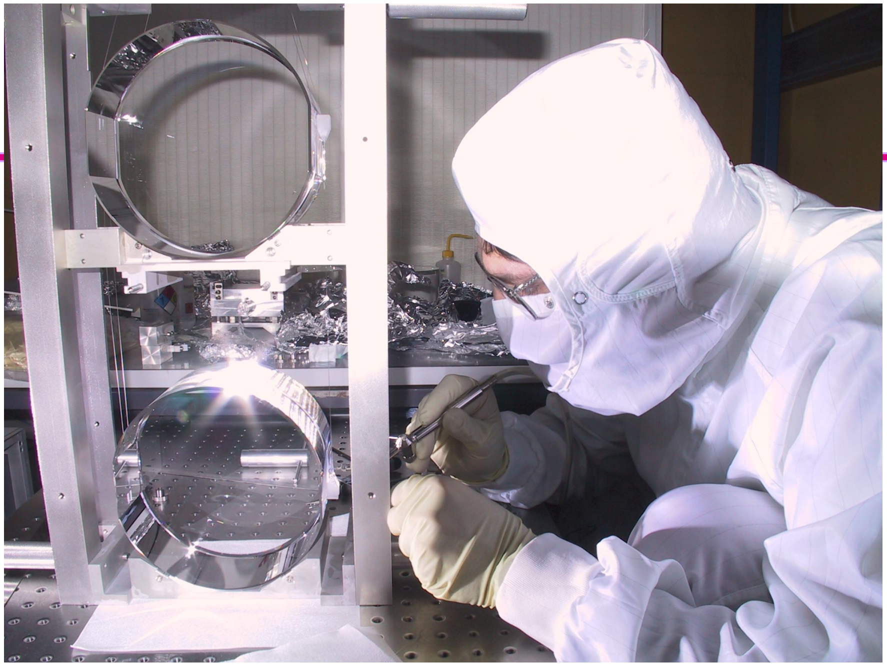
- UK-German collaboration
- 600 m arm detector near Hannover
- Infrastructure, vacuum complete



- Signal-recycled configuration, delay-line arms
- Flexibility in frequency response
- Sensitivity can be targeted
- Some agility in frequency



GEO-600

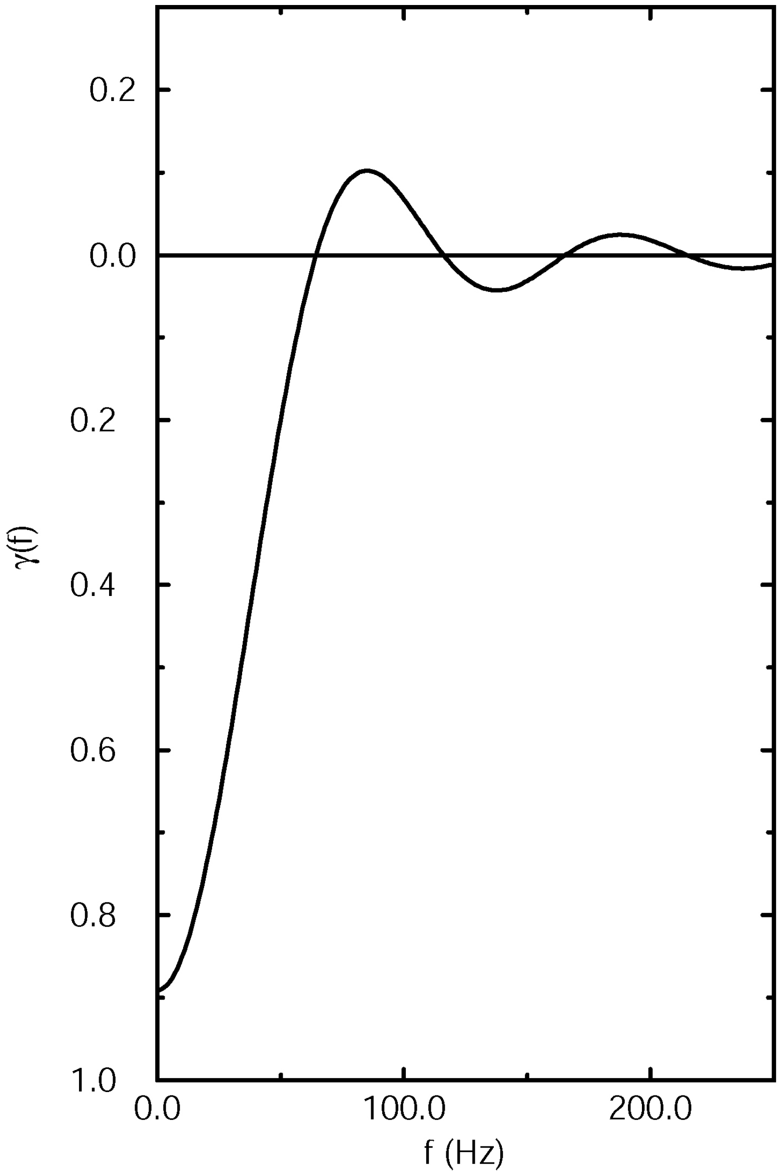


- Fused-silica suspension fibers
- Multiple pendulums for isolation, control; monolithic construction
- Suspensions installed and operating at GEO-600
- This, and RSE, as model for most next-generation detectors

- Prototype tests of interferometer configuration, control complete
- Characterization of laser, mode cleaners underway
- Final optic installation in coming months
- Commissioning of complete interferometer this year

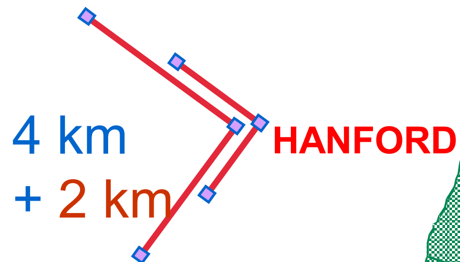
Stochastic sources

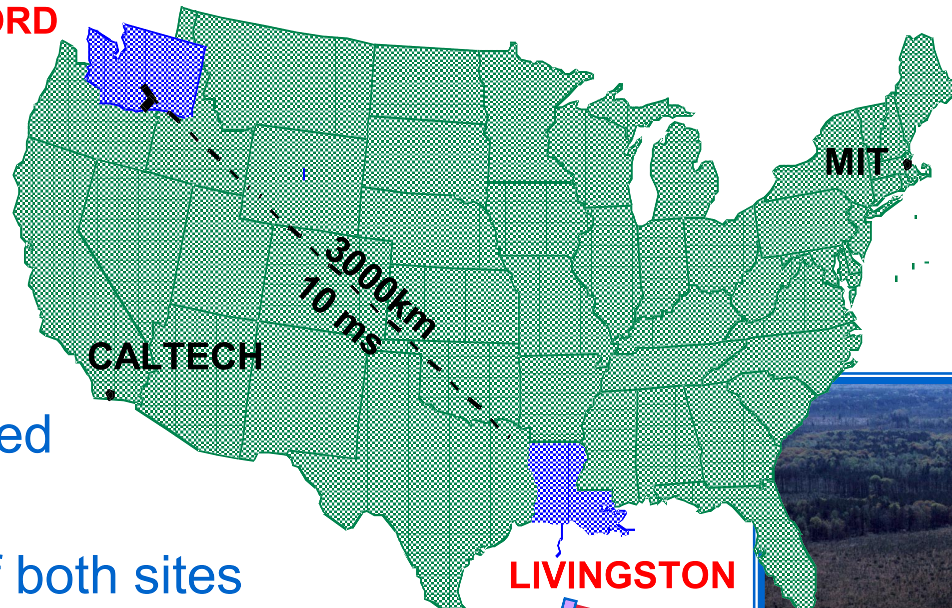
- Standard Big Bang (analogy to infrared background) probably not detectable
- Possible sources in superstring models of BigBang, other string predictions
- Confusion limit of many sources
- Definitely uncertain!
  But definitely to be searched for.
- Requires minimum of two detectors –
  - » Two interferometers, or
  - » Interferometer and acoustic detector
- Cross-correlated detector noise must be understood
- Overlap function: both instruments must see same wave ‘in phase’
- Example: the two **LIGO** instruments



LIGO

- US/LIGO Scientific Collaboration
- Two 4km arm observatories
- 2km and 4km interferometers at Hanford,
- 4km interferometer at Livingston





- Power-recycled Fabry-Perot
- Installation of both sites complete
- Commissioning underway

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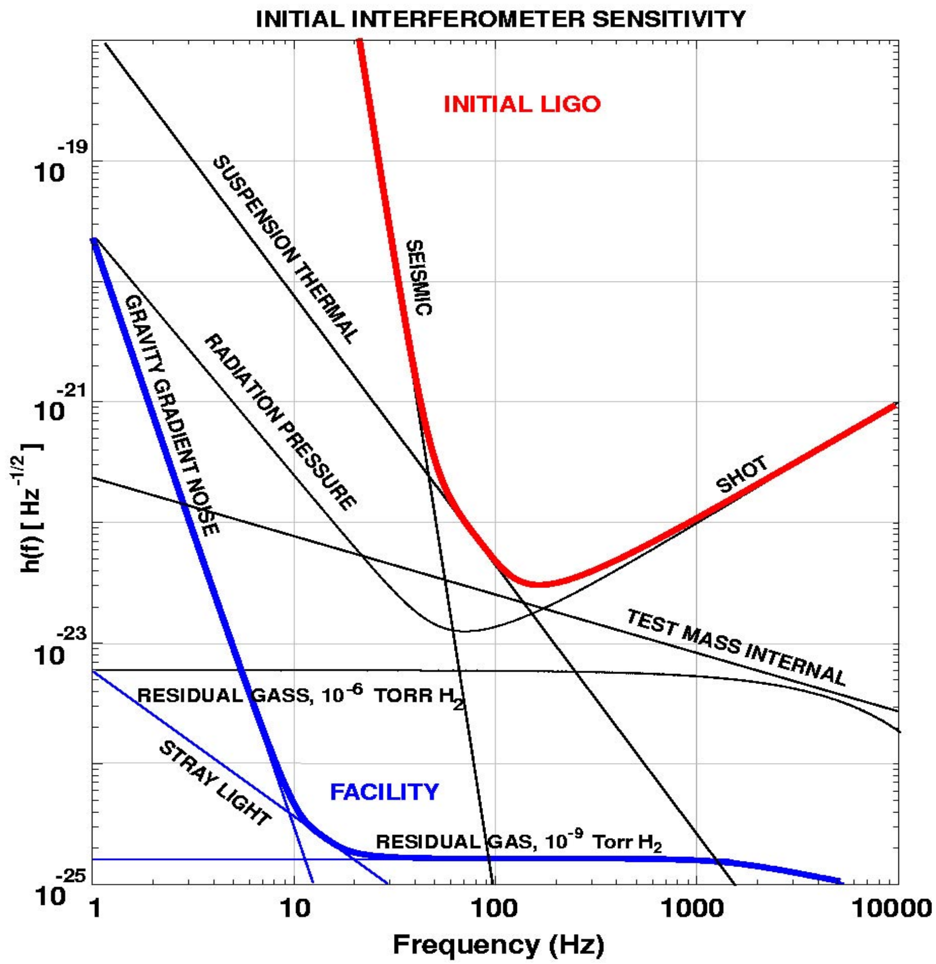
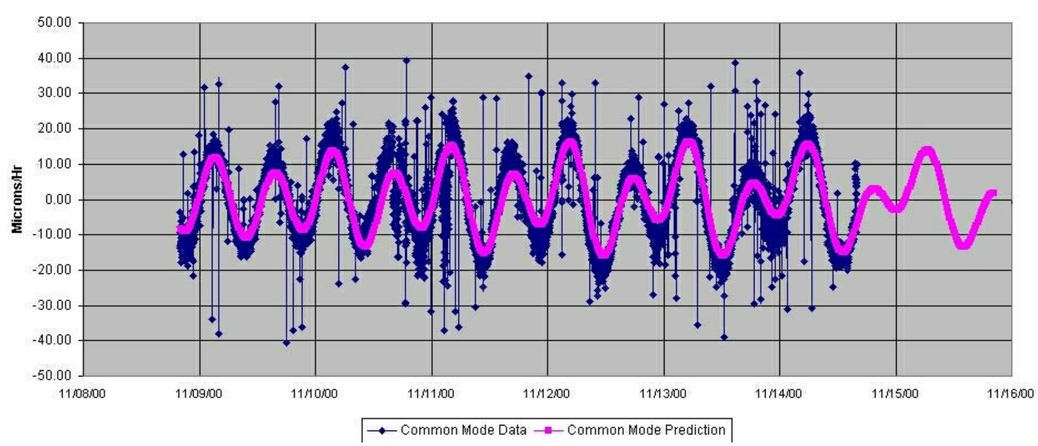
LIGO

- Laser, mode cleaner working near design sensitivity
- Complete recycled 2km system locks (when no earthquakes…)
- Strain sensitivity to be ~3×10^{-23} $1/\mathrm{Hz}^{1/2}$
- Data analysis algorithms in test
- Detector characterization, diagnostics underway

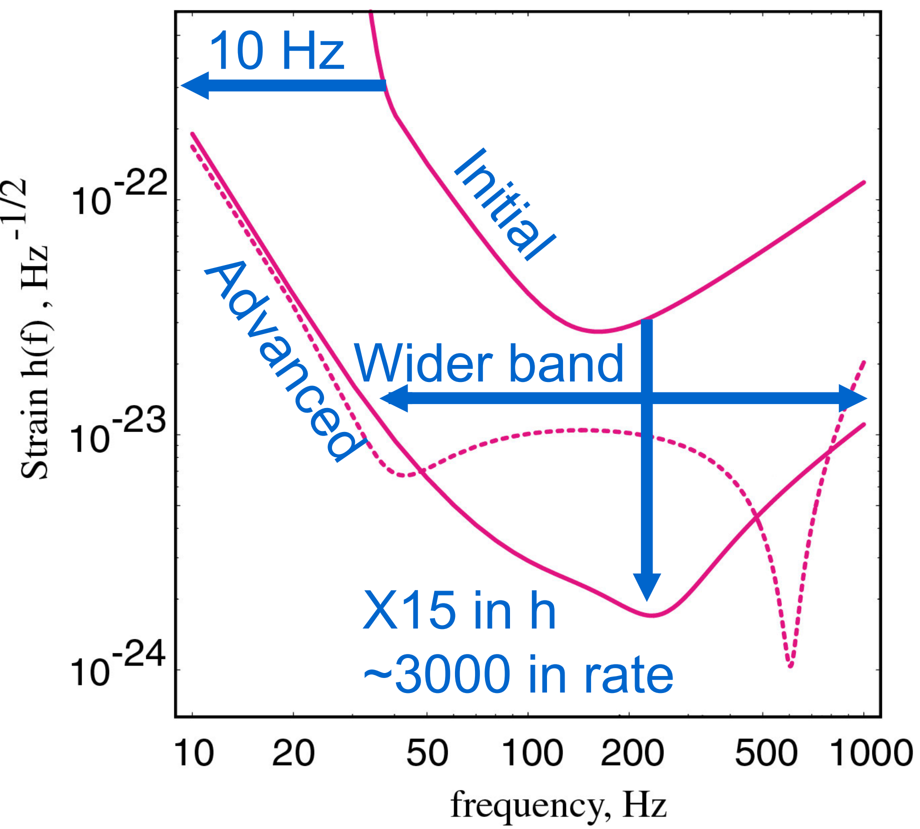




- Coincidence runs planned for Fall 2001
- Science running starting early 2002

LIGO→ Advanced LIGO

- R&D for the next generation of instruments housed at the LIGO Observatories well underway
- LIGO Scientific Collaboration playing major role
- Quantum-limited at >100W input power
- RSE tunable response
- Sapphire test masses, fused silica suspensions
- Active seismic isolation systems
- Baseline: start updating interferometers in 2006



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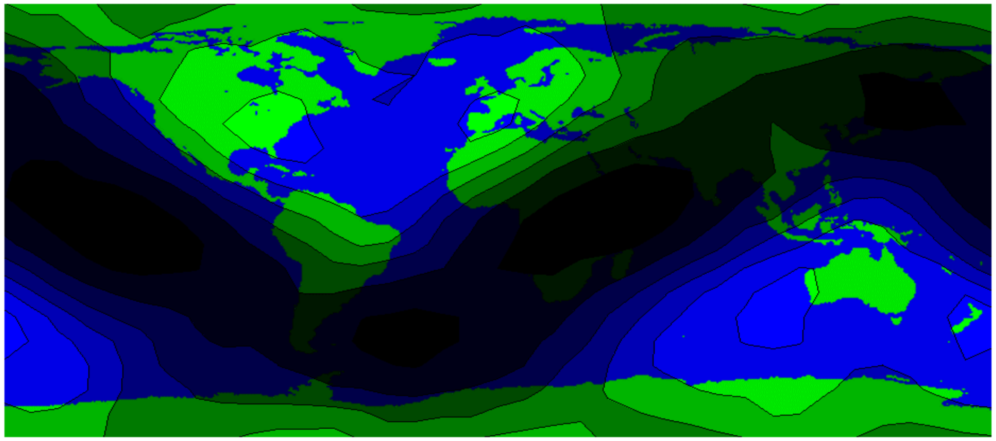
Networks of GW detectors

- A single interferometer requires some independent confirmation to claim a detection – e.g., GRBs, neutrinos, etc.
- A pair of interferometers can make a believable detection, and measure one polarization; position can be fixed to an annulus
- Three interferometers can add information about the polarization, and place the source in the sky
- Further interferometers improve further the quality and quantity of information, confidence in observations, probability of a complete network given uptime, flexibility for operating conditions – all *required for an astronomy of gravitational radiation*.
- Detector-to-be well suited to contribute to this endeavor: **AIGO**.

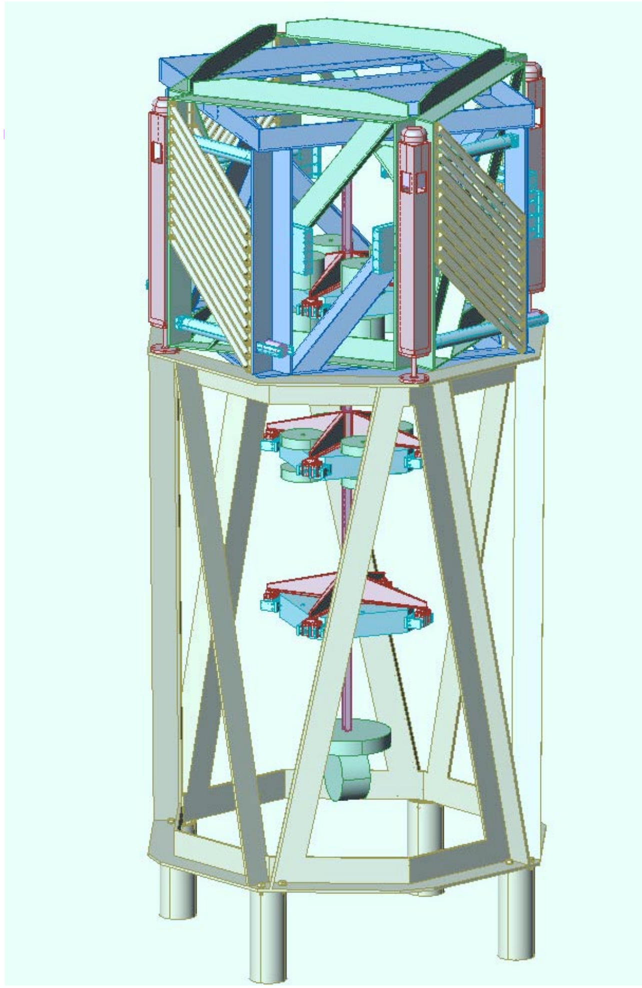
AIGO

- AIGO – concept from ACIGA for an Australian interferometer
- A detector in Australia is 'aligned' with US, European detectors – good overlap (and still good for those elsewhere)



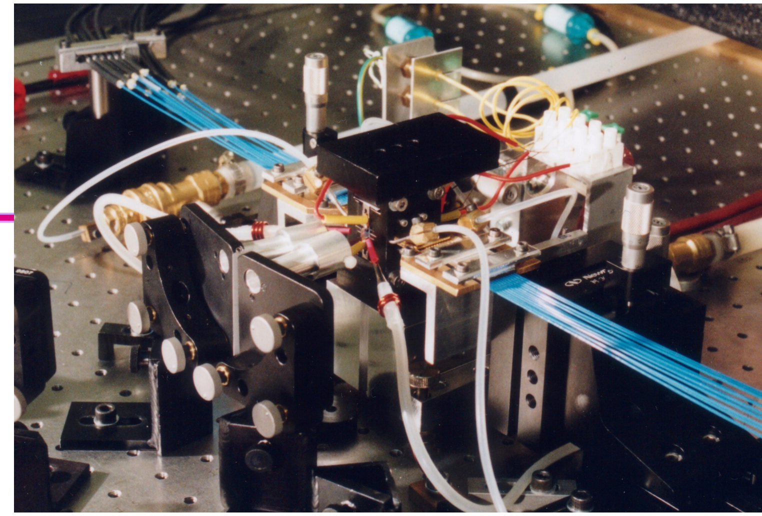
- The Gingin High Power Research Facility:
  - » high power optical test facility to diagnose cavity performance at MW circulating powers
  - » A starting point for scaling up
- Considerable range and depth of expertise in Australia for GW detection

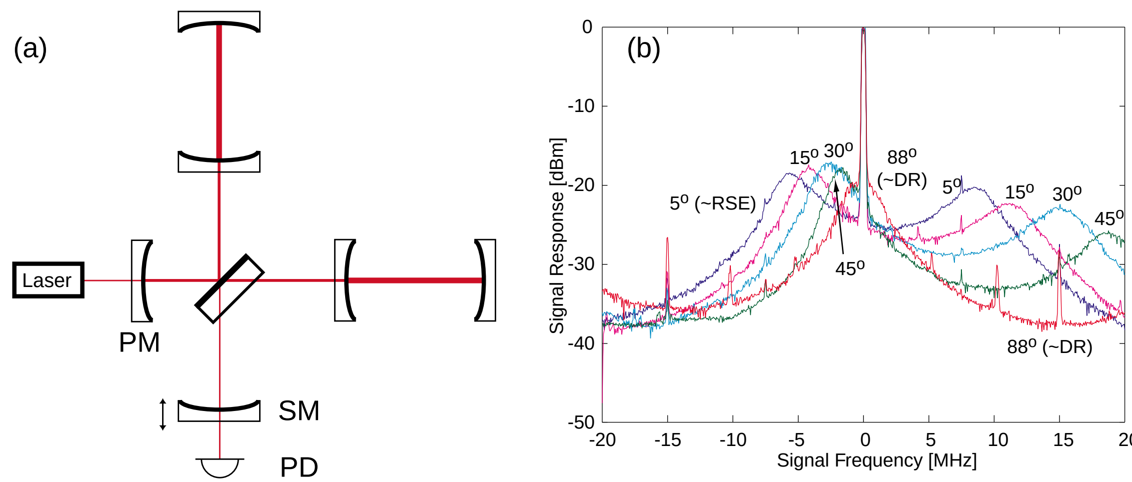
ACIGA R&D



Isolation, thermal noise research

High power laser development





Configurations and readout systems

The future with a little optimism

Two years from now:

- LIGO, Virgo, GEO, TAMA in networked operation
- AIGO planning underway
- …first detections?

Ten years from now:

- Next generation instruments in full operation,
  - » Advanced LIGO
  - » Second generation Virgo
  - » LCGT
  - » AIGO
  - » EURO
- How many discoveries per day? What new astrophysics revealed?
- …LISA on the launch pad!