Advanced LIGO as an element of a network of astrophysical detectors – gravitational and otherwise

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9 September 01

Points of departure

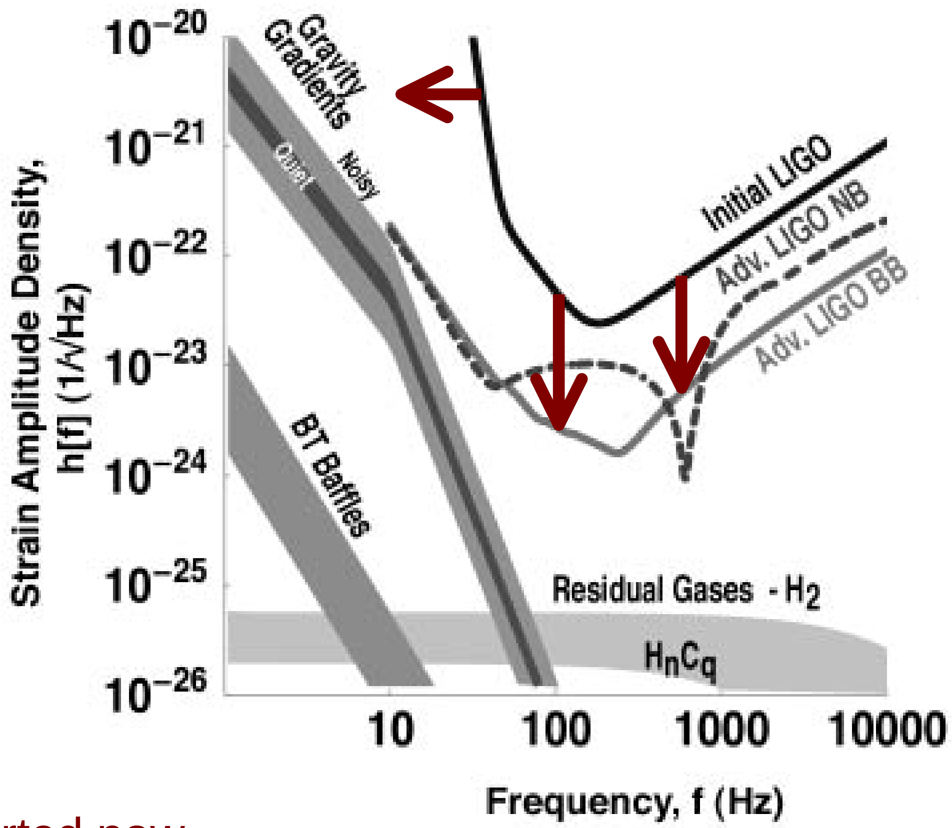
- Evolution is intrinsic to the mission of LIGO, and the LIGO Scientific Collaboration
- Next step in ifo. GW detector design (LIGO and elsewhere):
    - Should be of astrophysical significance if it observes GW signals or if it does not
    - Should be at the limits of reasonable extrapolations of detector physics and technologies
    - Should lead to a realizable, practical instrument
- A GW Interferometer Network is starting to be exercised, and is central to the planning, for all Laboratories
    - Instrument design
    - Observation and Operations
    - Data analysis

Choosing an upgrade path for LIGO

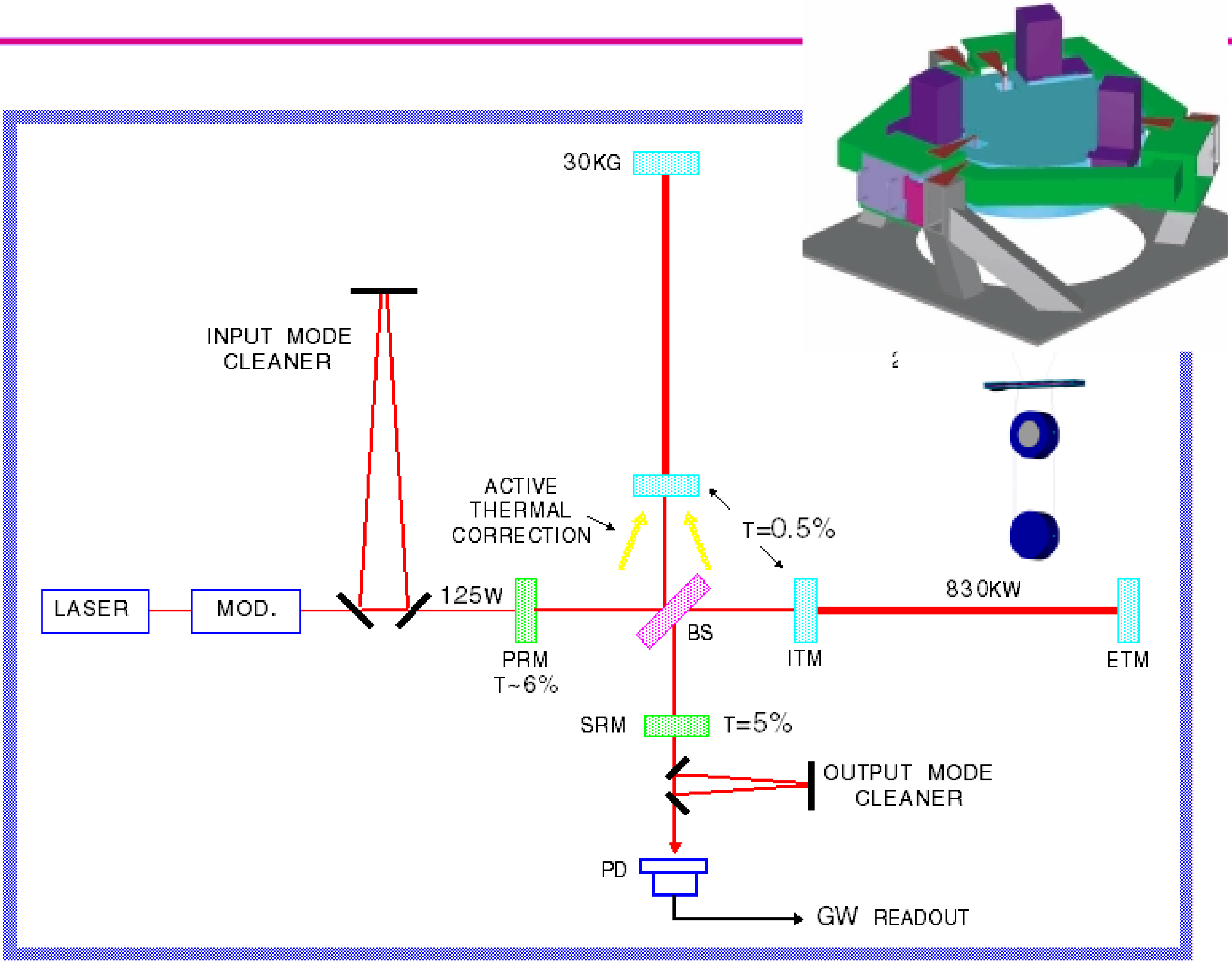
- Wish to maximize astrophysics to be gained
  - Must fully exploit initial LIGO
  - Any change in instrument leads to lost observing time at an Observatory
  - Studies based on LIGO I installation and commissioning indicate 1-1.5 years between decommissioning one instrument and starting observation with the next
  - → Want to make one significant change, not many small changes
- Technical opportunities and challenges
  - Can profit from evolution of detector technologies since initial LIGO design was ‘frozen’
  - ‘Fundamental’ limits: quantum noise, thermal noise provide point of diminishing returns (for now!)

Present and future limits to sensitivity

- Advanced LIGO
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
- Facility limits
  - » Gravity gradients
  - » Residual gas
- Beyond Adv LIGO
  - » Thermal noise: cooling of test masses
  - » Quantum noise: quantum non-demolition
  - » Not the central focus, but exploration must be started now

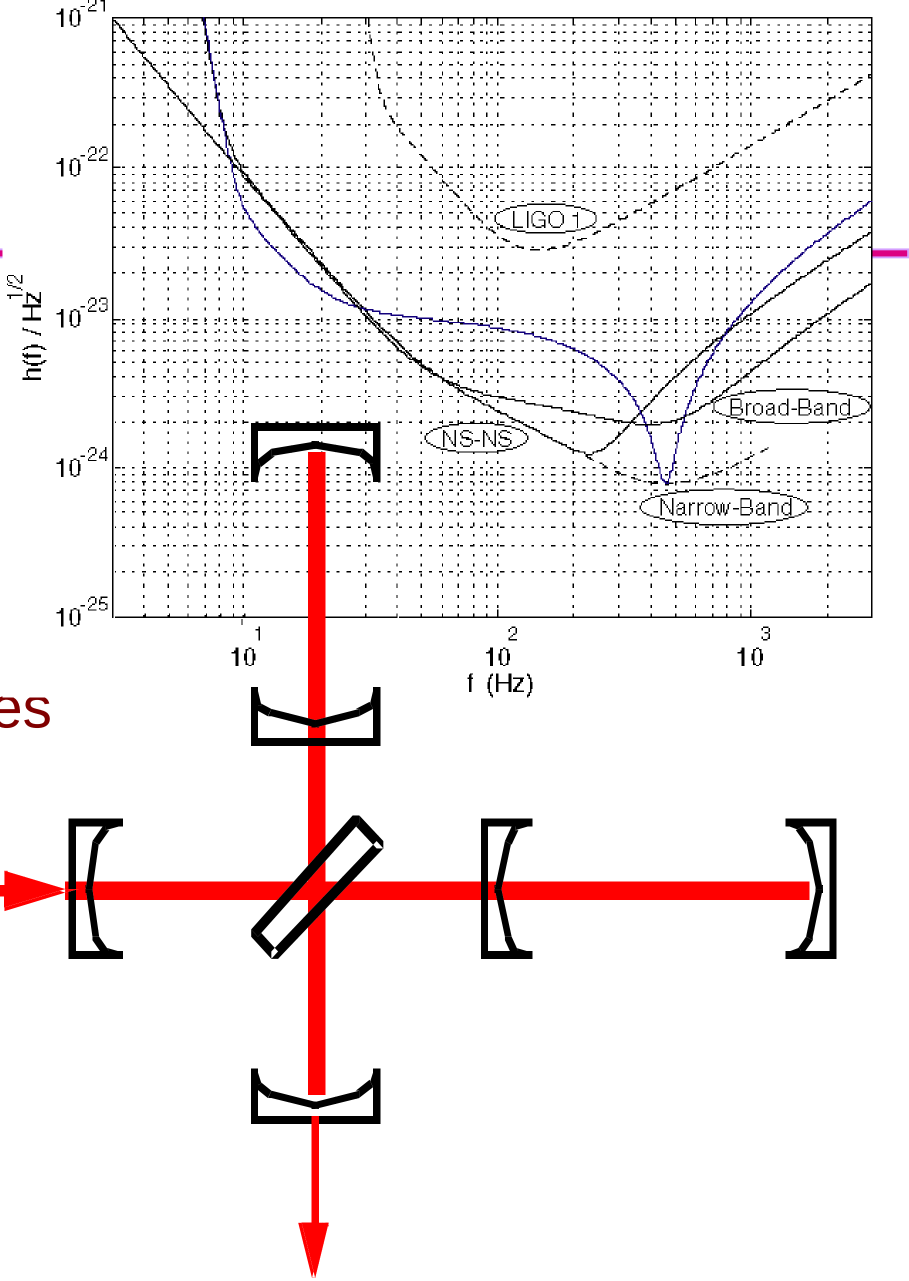


Advanced LIGO elements



Frequency response

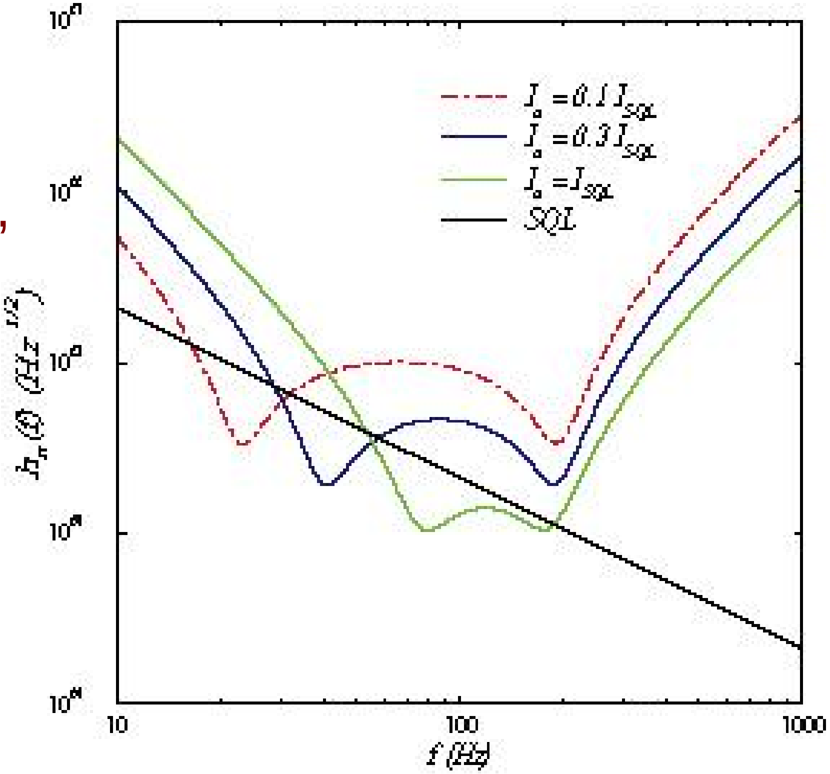
- Signal Recycling configuration
- Additional cavity formed with mirror at output
- Can be resonant, or anti-resonant, for gravitational wave frequencies



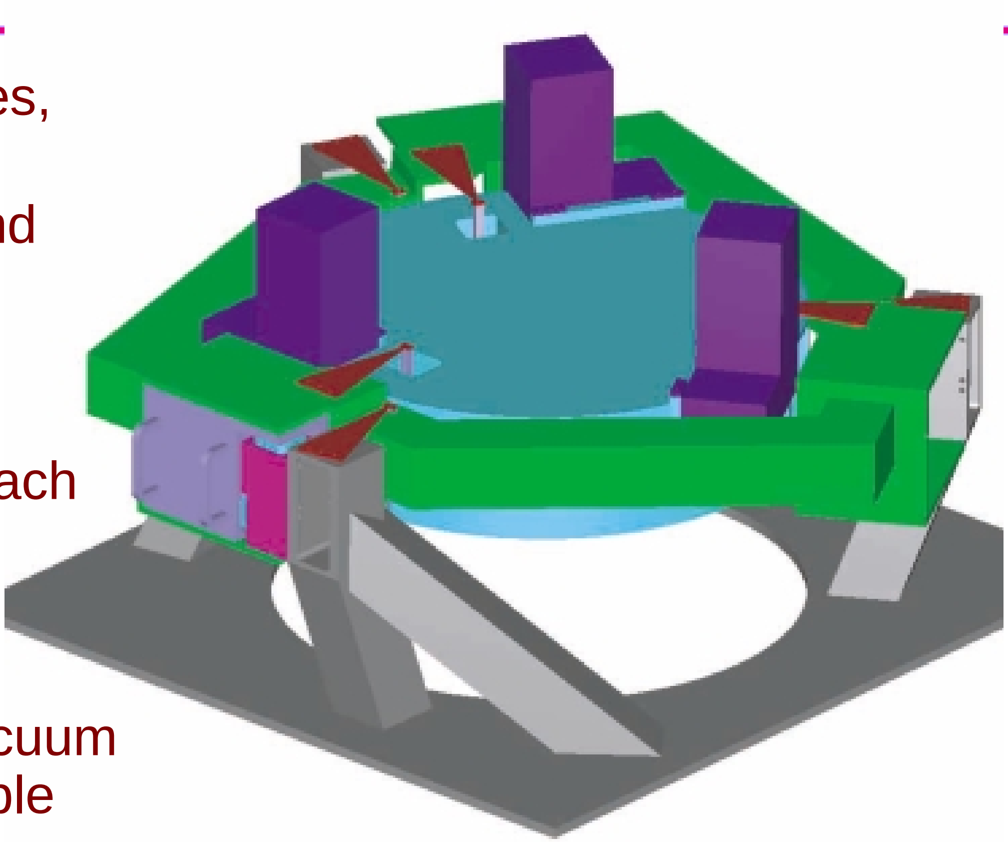
- Allows optimum to be chosen for technical limits, astrophysical signatures

Quantum Limits

- Increase in laser power increases resolution of readout of phase
  - » 10^{-11} rad/rHz required, some 10 kW of circulating optical power
  - » Achieve with ~200 W laser power, and resonant cavities
- Coupling of photon shot noise fluctuations (sqrt(n)), and the momentum transferred from photons to test masses, in Signal Recycled Interferometer –
- gives an optimum power for a given frequency of observation



Seismic Isolation

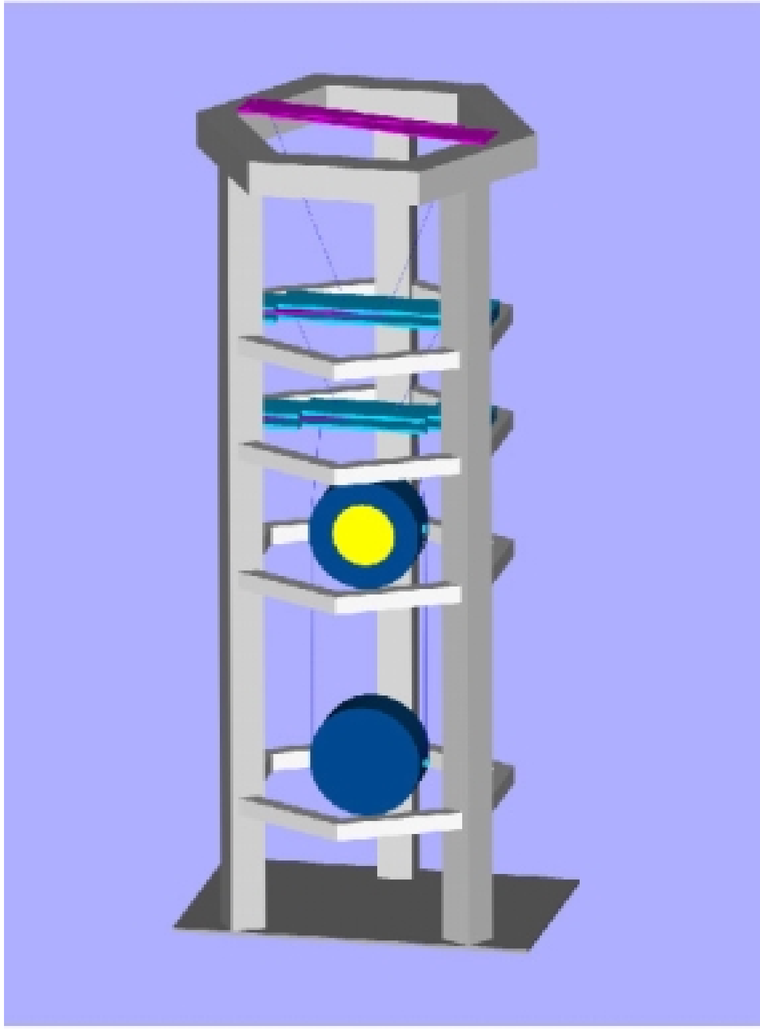


- Two in-vacuum stages in series, external slow correction
- Each stage carries sensors and actuators for 6 DOF
- Stage resonances ~5 Hz
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies

- Similar designs for various vacuum chambers; provides optical table for flexibility
- Result: 5 Hz crossover with suspension thermal noise: seismic noise becomes irrelevant.

Suspension system

- Thermal noise of suspension provides the real
  ‘low-frequency cutoff’
- Wish to use very low-loss materials to collect the motion due to kT in a small band around resonances,
  and then observe below or above these resonances
- Adopt fused silica ribbons
  for final stage of the system,
  Sapphire for bottom test mass/mirror
- Use a form of optical contacting
  and welding to final test mass
- Based closely on, and developed by, GEO collaborators



Test Masses/Main Optics

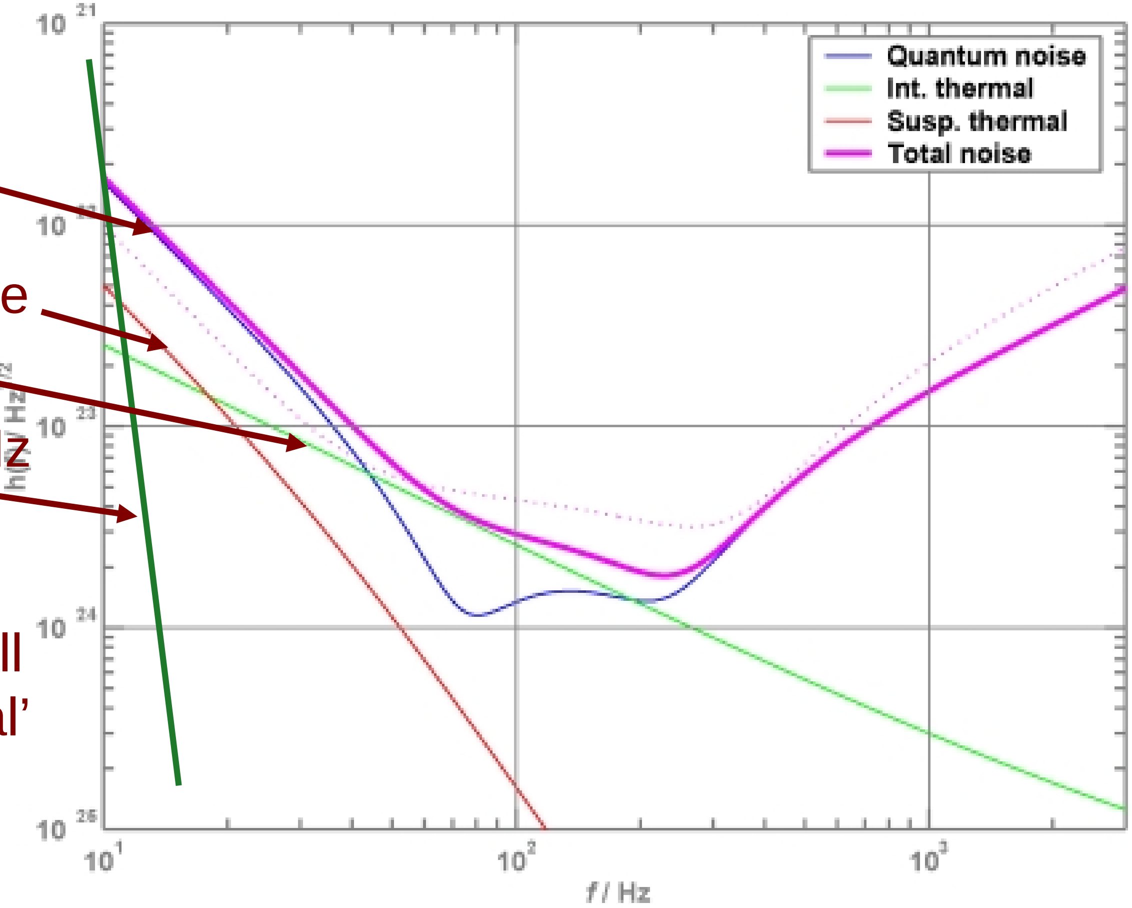
- Objects play key role in mechanical AND optical design
- Why Sapphire?
  - » Increased detection range due to smaller thermal noise
    - – 200 Mpc range for NS inspiral for sapphire vs 165 Mpc for fused silica
    - – Sapphire has higher Q (2 x 10^8 vs 3 x 10^7 for fused silica), but is thermoelastic noise limited
  - » Improved high power performance
    - – Thermal conductivity is ~ 30x higher than fused silica
    - – Rayleigh scattering is ~ 30x lower than fused silica
- Materials R&D effort needed
  - » R&D to produce large (40 kg, 32 cm diameter), high quality sapphire:
    - – Crystal Systems Inc.
    - – Shanghai Institute for Optics and Fine Mechanics (SIOM)
  - » Measure thermophysical, optical and mechanical properties
  - » Reduce bulk absorption
  - » Effect of coating, bonding, polishing on thermal noise

System trades

- Laser power
  - Trade between improved readout resolution, and momentum transfer from photons to test masses
  - Distribution of power in interferometer: optimize for material and coating absorption, ability to compensate
- Test mass material
  - Fused silica: familiar, but large, expensive, poorer performance
  - Sapphire: better performance, but development program, crystalline nature
- Lower frequency cutoff
  - ‘Firm’, likely, and possible astrophysics
  - Technology thresholds in isolation and suspension design
  - Newtonian background (changing local mass distribution)…

Anatomy of the projected detector performance

- Unified quantum noise dominates at most frequencies
- Suspension thermal noise
- Internal thermal noise
- Seismic ‘cutoff’ at 5-10 Hz
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises



Nominal top level parameters

	Sapphire	**Fused Silica**
Fabry-Perot arm length	4000 m	
Laser wavelength	1064 nm	
Optical power at interferometer input	125 W	80 W
Power recycling factor	17	17
FP Input mirror transmission	0.5%	0.50%
Arm cavity power	830 kW	530 kW
Power on beamsplitter	2.1 kW	1.35 kW
Signal recycling mirror transmission	6.0%	6.0%
Signal recycling mirror tuning phase	0.12 rad	0.09 rad
Test Mass mass	40 kg	30 kg
Test Mass diameter	32 cm	35 cm
Beam radius on test masses	6 cm	6 cm
Neutron star binary inspiral range (Bench)	300 Mpc	250 Mpc
Stochastic GW sensitivity (Bench units)	8 x 10-9	3 x 10-9

Astrophysics with Advanced LIGO

- Neutron Star & Black Hole Binaries
  - Inspiral of 1.4 Msun NS NS to ~300 Mpc, up to 2/day
  - Merger of 10 Msun BH BH to z ~ 0.4, up to 10/day
- Spinning NS's
  - LMXBs – SCO X-1 with high SNR
  - known pulsars - ε of $2\times10^{-8}\,(1000\mathrm{Hz}/f)^2 \times (\mathrm{distance}/10\mathrm{kpc})$
  - previously unknown
- NS Birth (SN, AIC)
  - Tumbling – if have waveform, up to 1/day
  - Convection, R modes
- Stochastic background
  - big bang, early universe – upper limit of Ω 5×10^{-9}

Source Predictions

- The Initial Interferometers may well detect cosmic gravitational waves.

- With Advanced Interferometers we can be confident of:
  - Detecting waves from a variety of sources
  - Extracting significant information about the astrophysical events which generate the waves

What, When, Who?

- LIGO, GEO, VIRGO
  - Observing starting in early 2002, full sensitivity and network in 2003
  - 5 interferometers
    - VIRGO: Cascina, Italy
    - GEO: Hannover, Germany
    - LIGO: Washington (2 interferometers), Louisiana (1 ifo), USA
- TAMA already observing at intermediate sensitivity
- Acoustic GW detectors already observing, will continue, data exchange
- Advanced LIGO observing starting in early 2008, 3 interferometers
- VIRGO planning incremental improvements based on present advanced infrastructure
- MOU for (present code name) EURO – a Pan-European effort to advance the art and build instruments in Europe this decade
- LCGT planning and R&D (TAMA!) in Japan: 2.5 or 3rd generation
- ACIGA: program and R&D in Australia

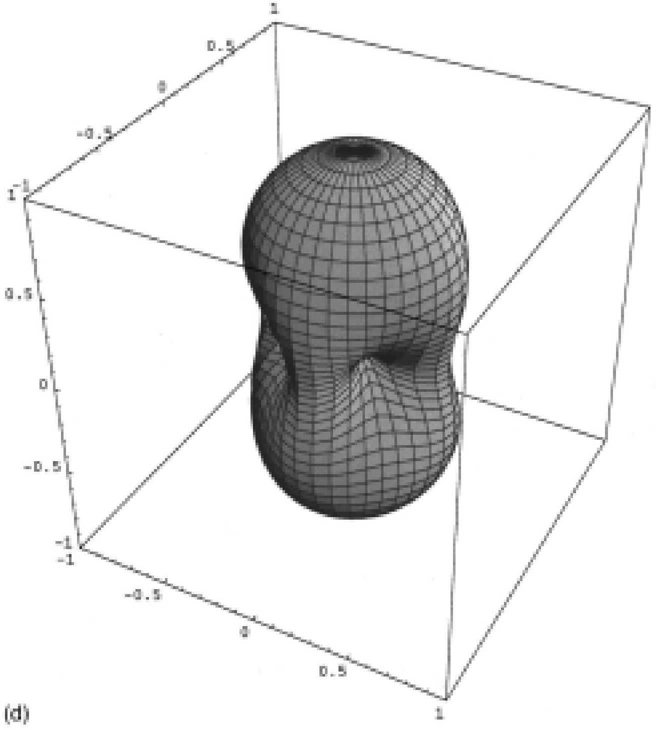
Multi-messenger Astrophysics

- ‘Known’ violent events producing GWs are, in general, expected to be associated with other radiation
  - » Neutrinos
  - » Gammas
  - » Photons/radio
- Independent of models, evident that more detectors of more kinds can provide valuable insights (even with no detected signals if at an astrophysically interesting level)
- Do interferometers have the right character to participate --
  - » Sufficiently Prompt?
  - » Precise enough Pointing?
  - » Good enough statistics to make a Positive detection?

Promptness

- Data arrive as a continuous real-time time series from each observatory, which can be calibrated in GW strain *h(f)*
- Time resolution of the instrument is typically 1-10 msec
  - » (absolute time to ~10 microsecs)
- Data can be filtered for each observatory in ‘real time’
  - » E.g., hundreds of templates in parallel for binary inspiral search
  - » Delays of typical lengths for the templates or filter ‘Q’
  - » 100s of msec for broad-band bursts, minutes for an inspiral
- Data can be combined from observatories in ‘internet time’
  - » Dedicated links planned within the US

Pointing



- An individual interferometer has a non-directional nature
- A pair over a baseline defines an annulus in sky
- A triplet defines a unique angular patch
- Size depends on SNR; ~5 degree box
- Presently 4 observatories coming on line; anticipate several more for the second generation (~2008), networked explicitly
- Will lead to tighter pointing, better statistics, ability to extract polarizations

Positivity

- First Instruments still in commissioning phase
- Nature of noise – Gaussianity – to be determined
- Previous experience, and the design criterion, is one false coincidence every 10 years for the LIGO observatory pair
- Additional detectors drive this *very* quickly to much longer intervals (greater certainty) for a given signal strength
- Our field will be very cautious!

Specific examples

- Neutrinos and GWs from SuperNovae
  - Reasonable models, reasonable expectation of simultaneous signals
- SNEWS – SN Early Warning System in operation
- LIGO has agreement to share signals with SNEWS

- Gamma Ray Bursts
  - Not clear if nature will conspire in our favor
  - Beaming, weak GW signals may be problematic
- GCN – GRB Coordinates Network
- Interferometers could easily exchange information with GCN

The Last Slide

- Direct detection of gravitational radiation is not far away – possibly in the very near future (bars, TAMA, initial searches)
- Sharing of data with other kinds of astrophysical observatories is possible immediately and may be key for first GW detection
- A real astronomy of gravitational radiation will be in place by the end of this decade
  …(or GR is quite wrong; take your choice!)
- Lastly,

An Interferometric GW Detector Network will be
a very solid partner in
Prompt, Pointed, Positively exciting
multi-messenger astrophysics.