Ground-based GW interferometers in the LISA epoch

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Points of departure

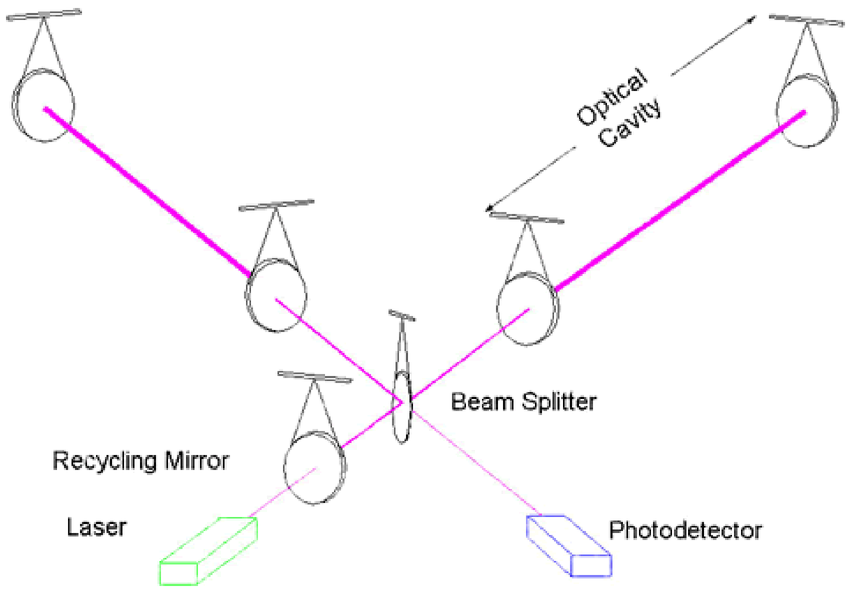
- LISA will join the network of ground-based detectors ~2011, with a 10-year lifetime
- What will the interferometric detector ground network look like at this time?

- Labels (not designed to commit or limit named institutions!):
  - » 1st generation: e.g., TAMA, initial LIGO, initial VIRGO….: in operation ~now.
  - » 2nd generation: e.g., [GEO (now)], updated VIRGO, Advanced LIGO…; in operation ~2008
  - » 3rd generation: e.g., LCGT, EURO….; in operation ~2010-15

Limits to sensitivity

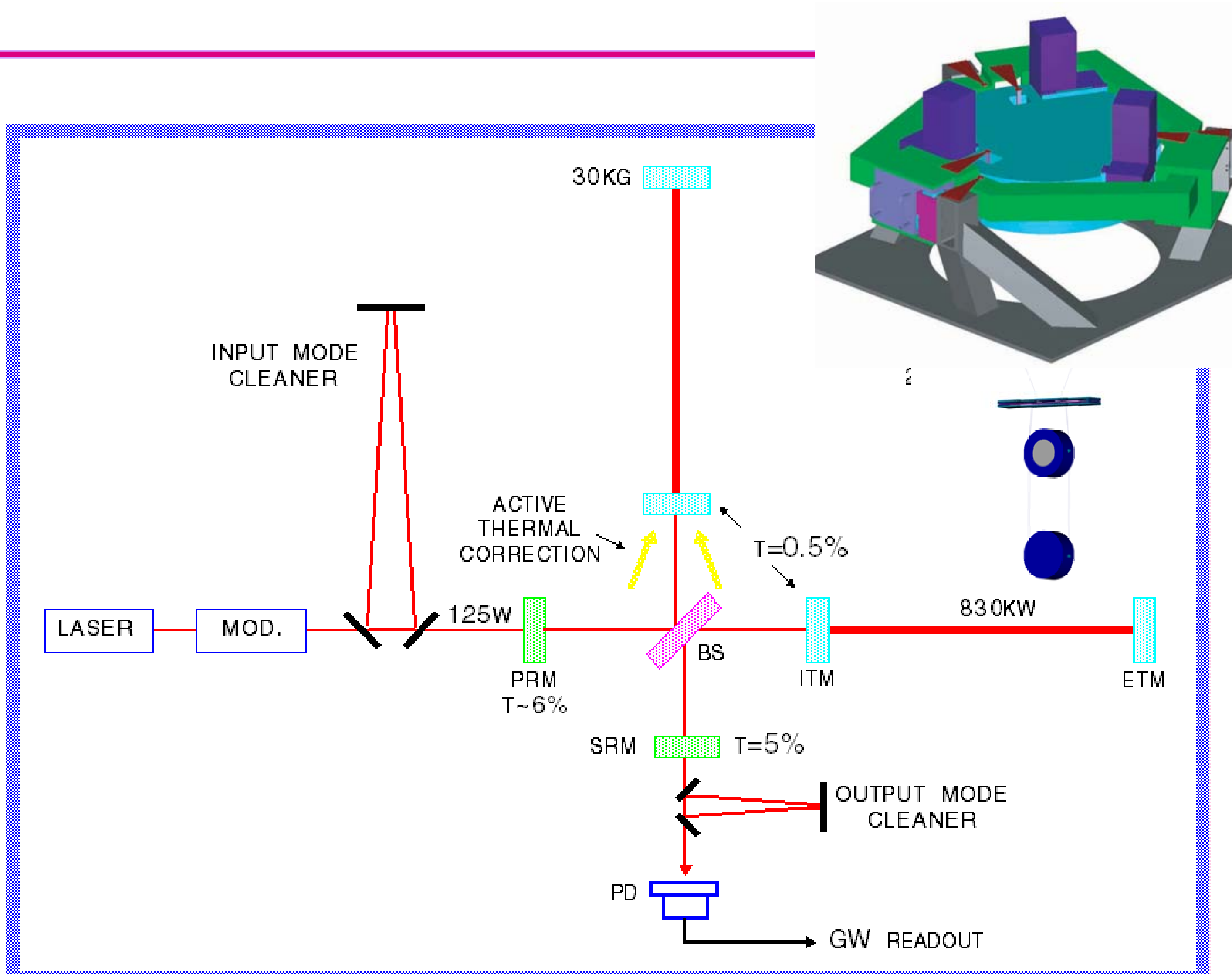
Basic measurement:

- GW strains produce differential changes in optical path between free masses' along orthogonal arms
- Phase difference in returning light read out as deviations from a dark Michelson interferometer fringe



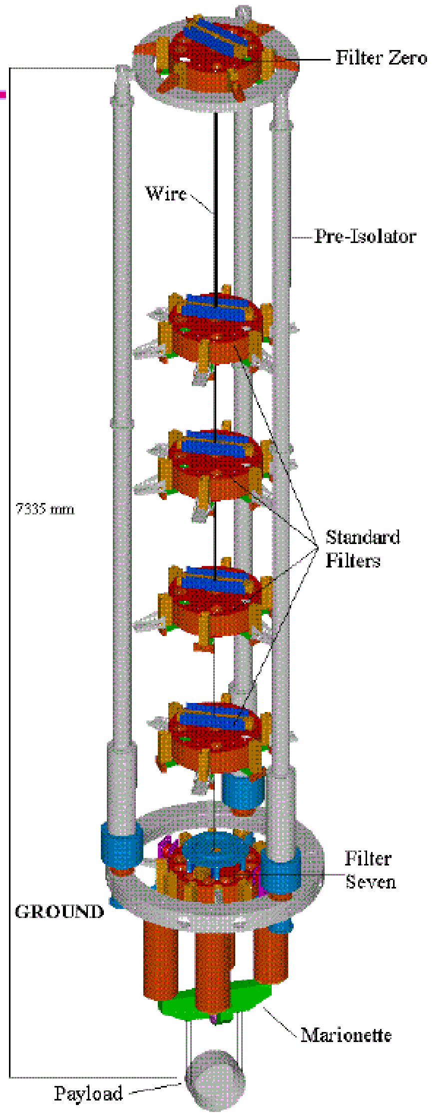
- How sensitive an instrument can we build?
  - » Undesired physical motions of the test masses
  - » Limits to precision of the distance measurement system

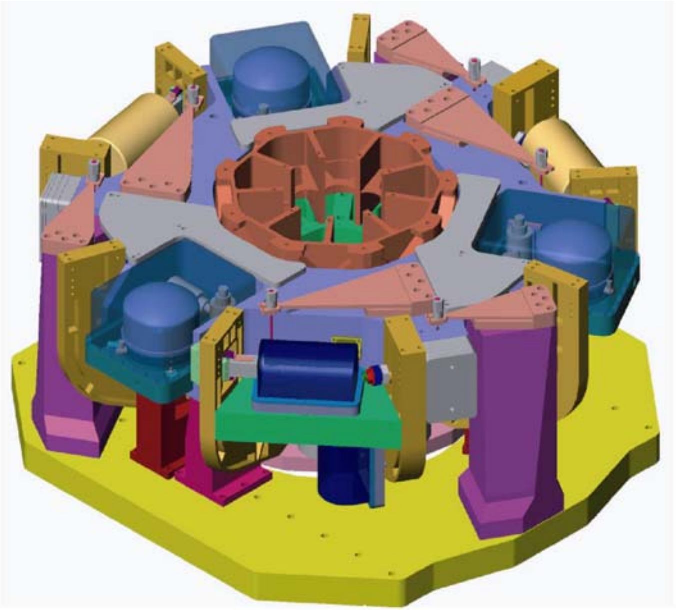
LIGO Typical interferometer elements



Seismic noise

- Physical environmental motion transmitted to test mass
- Require that this make a negligible impact on astrophysical sensitivity
- Also: keep control authority away from the test masses (0.1-10 Hz)
- 2nd Generation: Filter with some combination of active means (sensors, actuators, and servos) and passive means (pendulums or similar used above their resonant frequency)

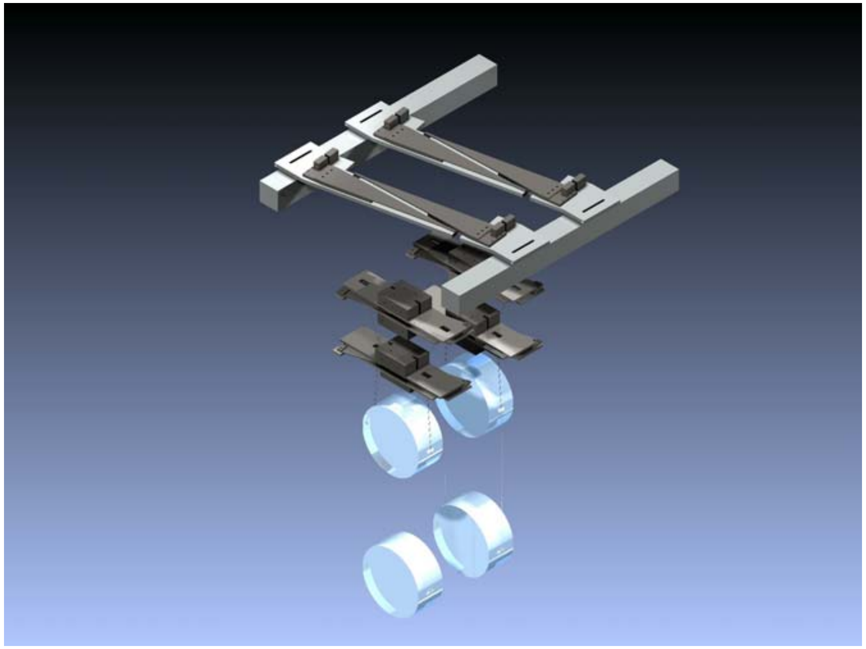




- 3rd Generation: similar approaches
- Other limits to sensitivity will dominate future instruments.

Thermal Noise

- Internal modes of test mass, and its suspension, have kT of energy per mode
- Use very low-loss materials to collect the motion due to kT in a small band at, and around, resonances, and then observe below or above these resonances
- Provides a broad-band limit to performance
  - » Low Freq.: Pendulum modes
  - » Mid Freq: testmass internal modes
- 2nd Generation:
  - » Sapphire for test mass/mirror
  - » Fused silica ribbons or tapered fibers for final stage of the suspension system

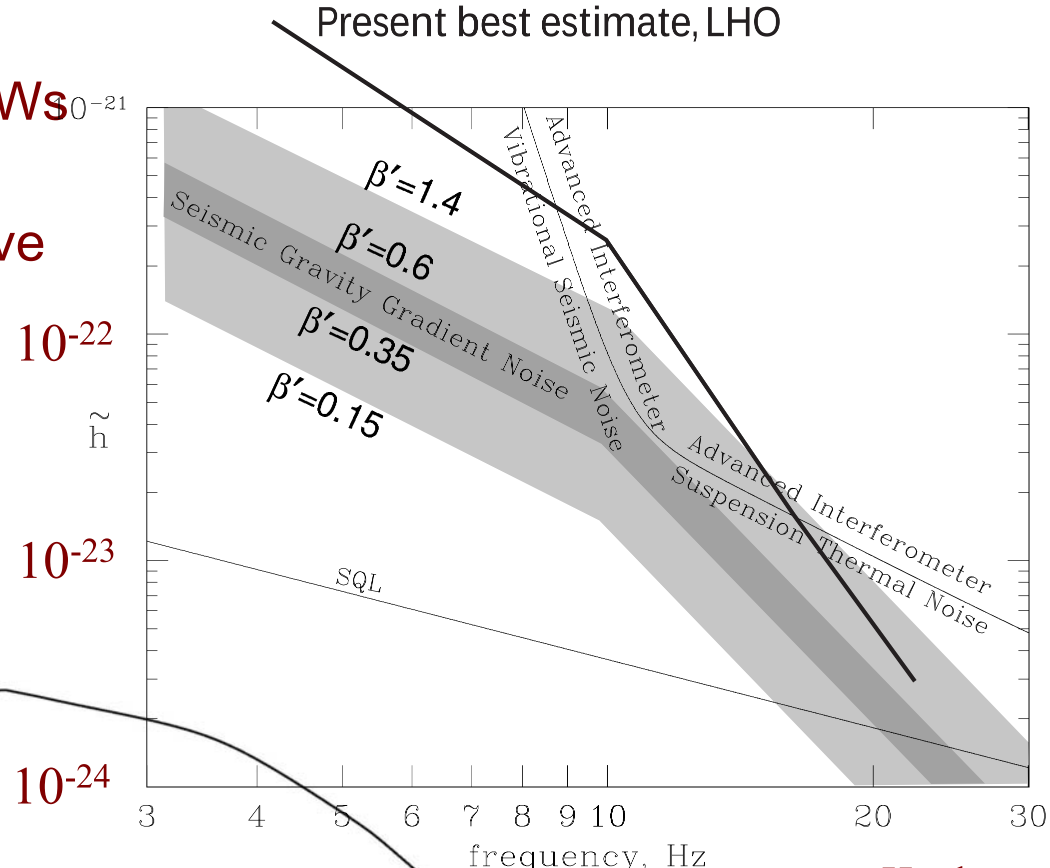


- 3rd Generation:
  - » cooling of masses and suspensions (win as √T, maybe better);
  - » non-transmissive lower loss materials; possibly remote sensing of motion, feedback or compensation

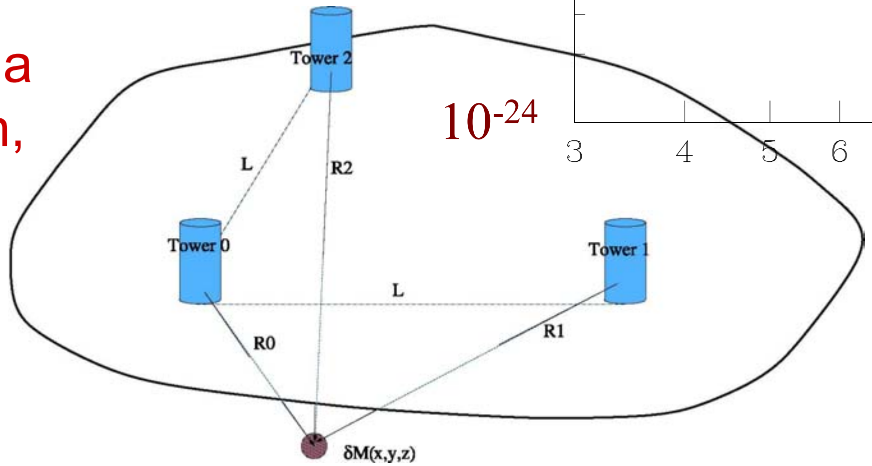
Newtonian background

- Fluctuations in the local gravitational field, mimicking GWs
- Due to fluctuations in ground density, passing clouds, massive objects
- Can't be shielded; THE low-frequency limit on the ground
- 2nd: Some reduction possible through monitoring and subtraction
- 3rd: Needed: a breakthrough, aided by tunneling

Present best estimate, LHO

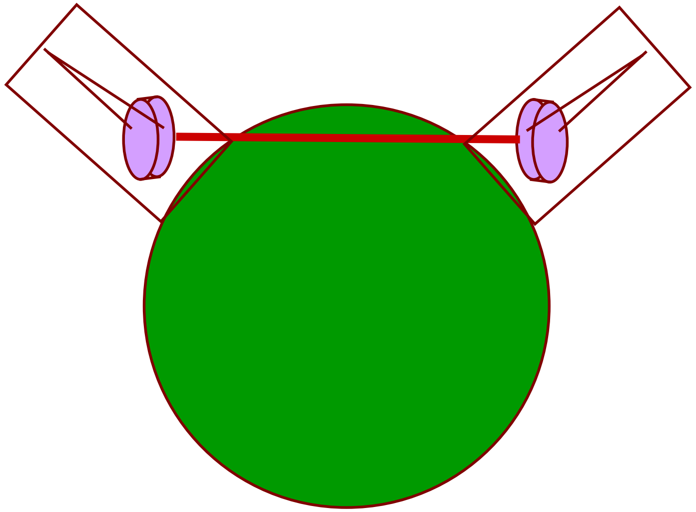


Hughes, Thorne, Schofield



Length of ground-based interferometers

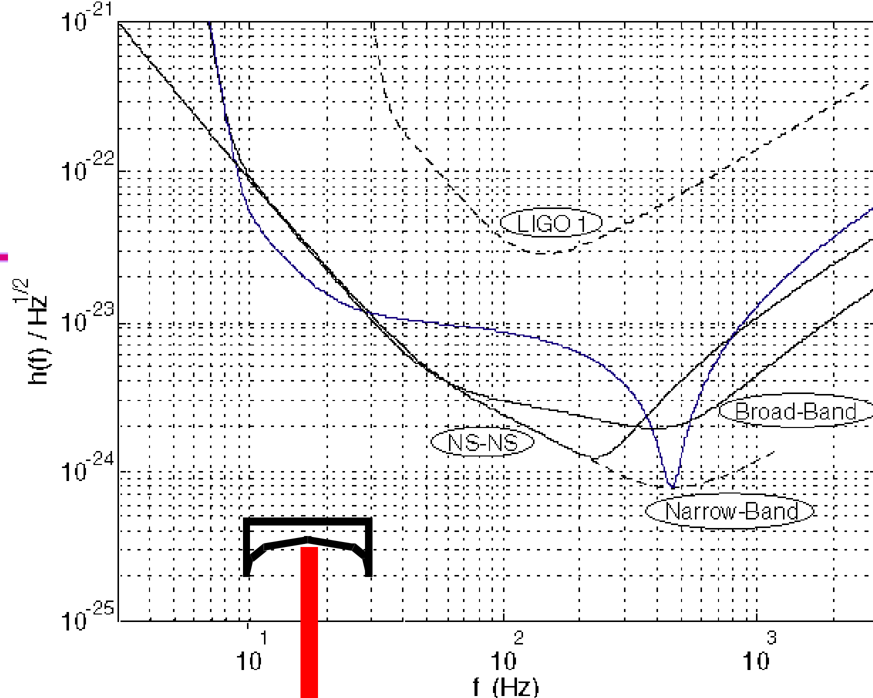
- Mechanical sources of noise, important at low frequencies, are independent of length, but strain signal grows; is there an optimum?

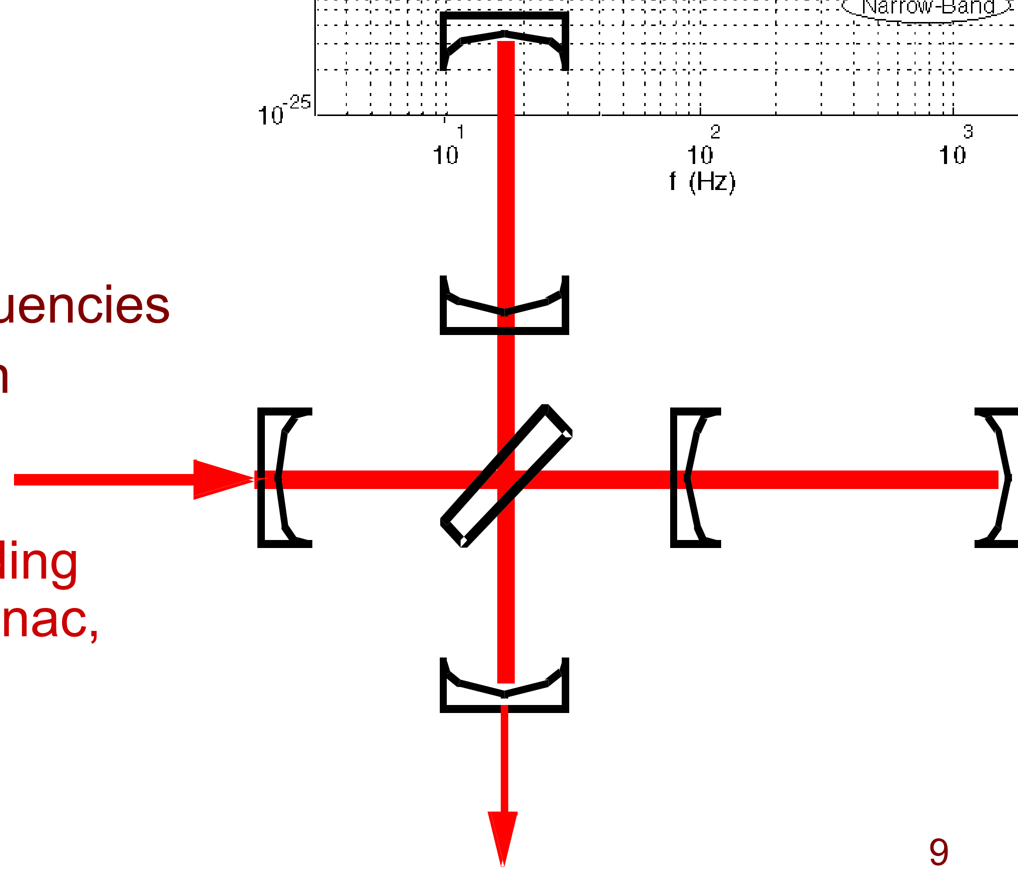


- Coupling of vertical (towards earth center) motion to optical axis motion – grows with length
  - » Practical difficulties of seismic isolation; can be mastered
  - » Suspension vertical thermal noise more of a challenge
  - » Energy stored directly in fiber (contrast to horizontal pendulum case)
  - » Diminishing returns when vertical thermal noise dominates
- Cost of tunneling, tubing – taxpayer noise increases with length!
- Present interferometers are 300m, 600m, 3 km, 4 km
- Further interferometers could exploit the scaling by ? x2 ?

Interferometric Sensing

- Fabry-perot cavities –
  increased interaction time
  with GWs
- Power recycling –
  impedance match
- 2nd: Signal Recycling –
  can be resonant,
  or anti-resonant,
  for gravitational wave frequencies
- Allows optimum to be chosen
  for technical limits,
  astrophysical signatures
- 3rd: lots of possibilities, including
  non-transmissive optics, Sagnac,
  delay-lines in arms

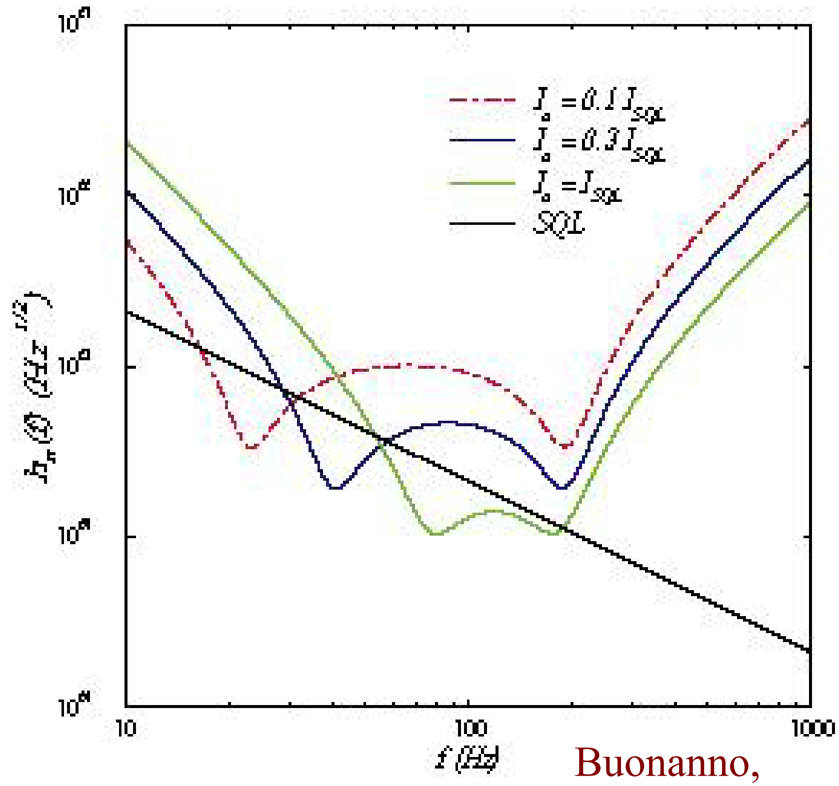




LIGO

Quantum Limits

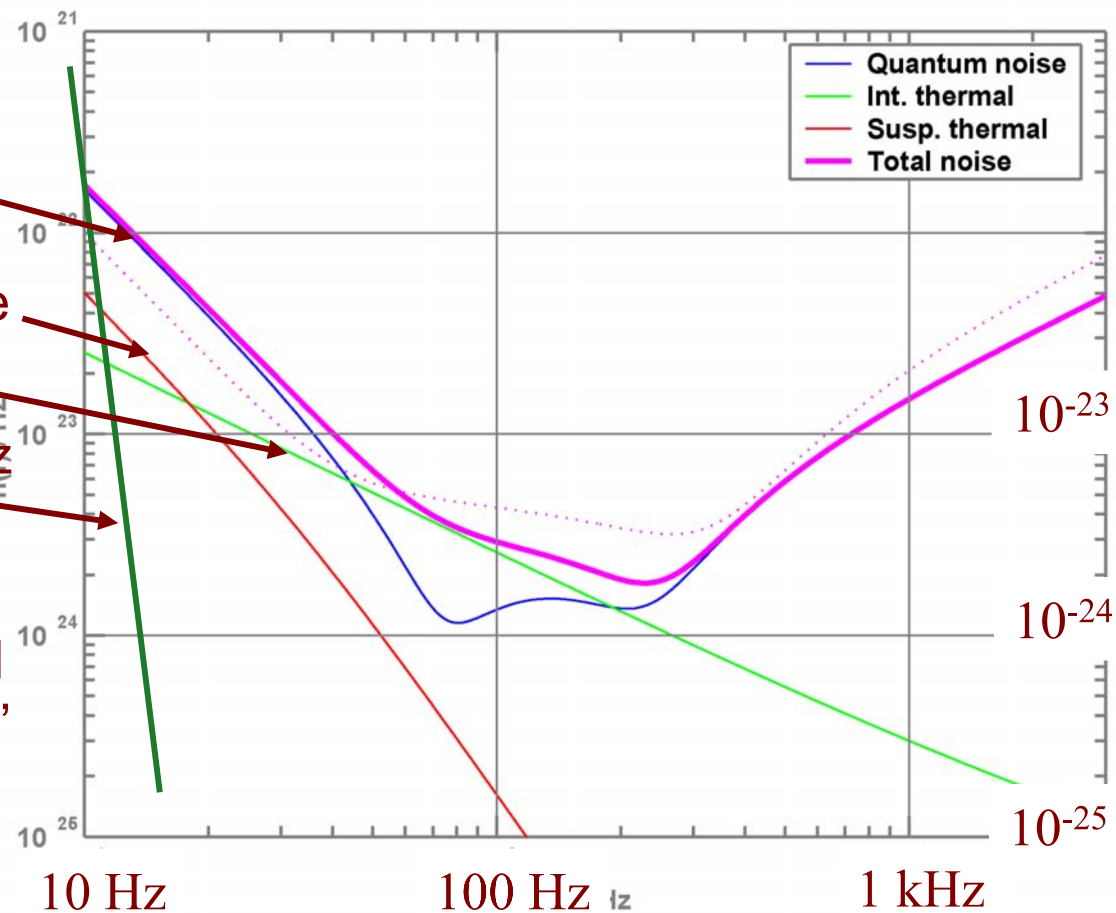
- Increase in laser power increases resolution of readout of phase as sqrt(power)
  - » e.g., 10^{-11} rad/rHz requires some 10 kW of circulating optical power
  - » Achieve with ~200 W laser power, and resonant cavities
- But momentum transferred to test masses also increases
- Coupling of photon shot noise fluctuations, and the momentum transferred from photons to test masses, in Signal Recycled Interferometer
  - » Brute force: larger test masses, longer interferometer arms
- 3rd: Quantum Non-Demolition, speed-meter configurations for greater sensitivity for given circulating power



Buonanno, Chen

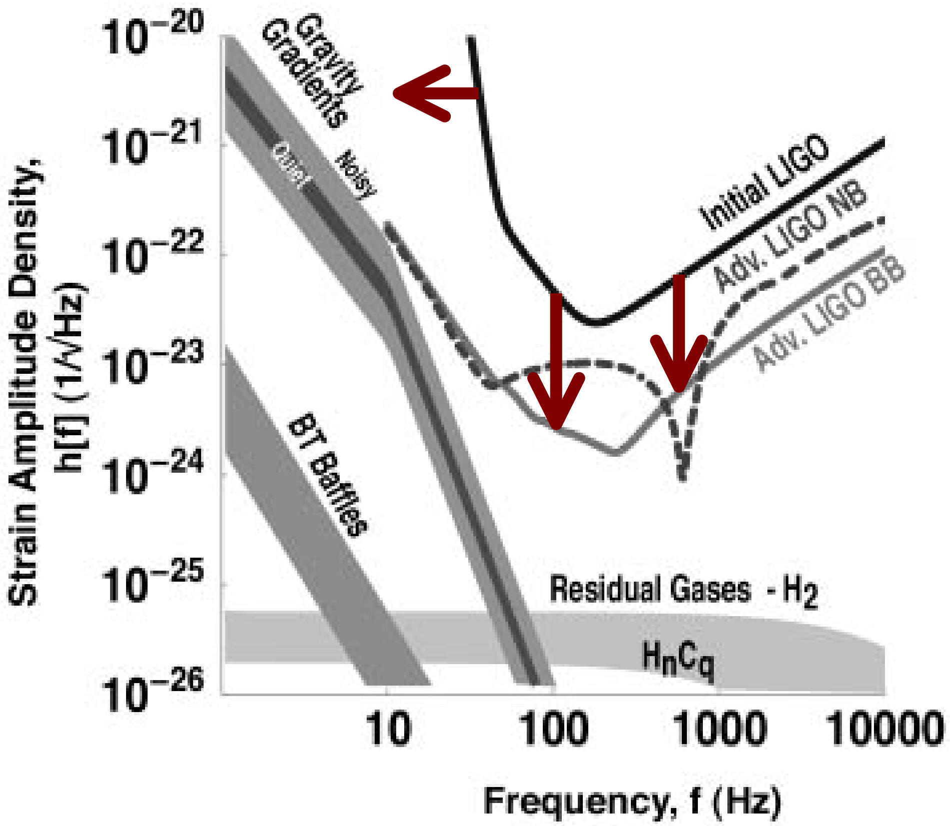
Performance of 2nd generation detectors

- Adv LIGO as example
- 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



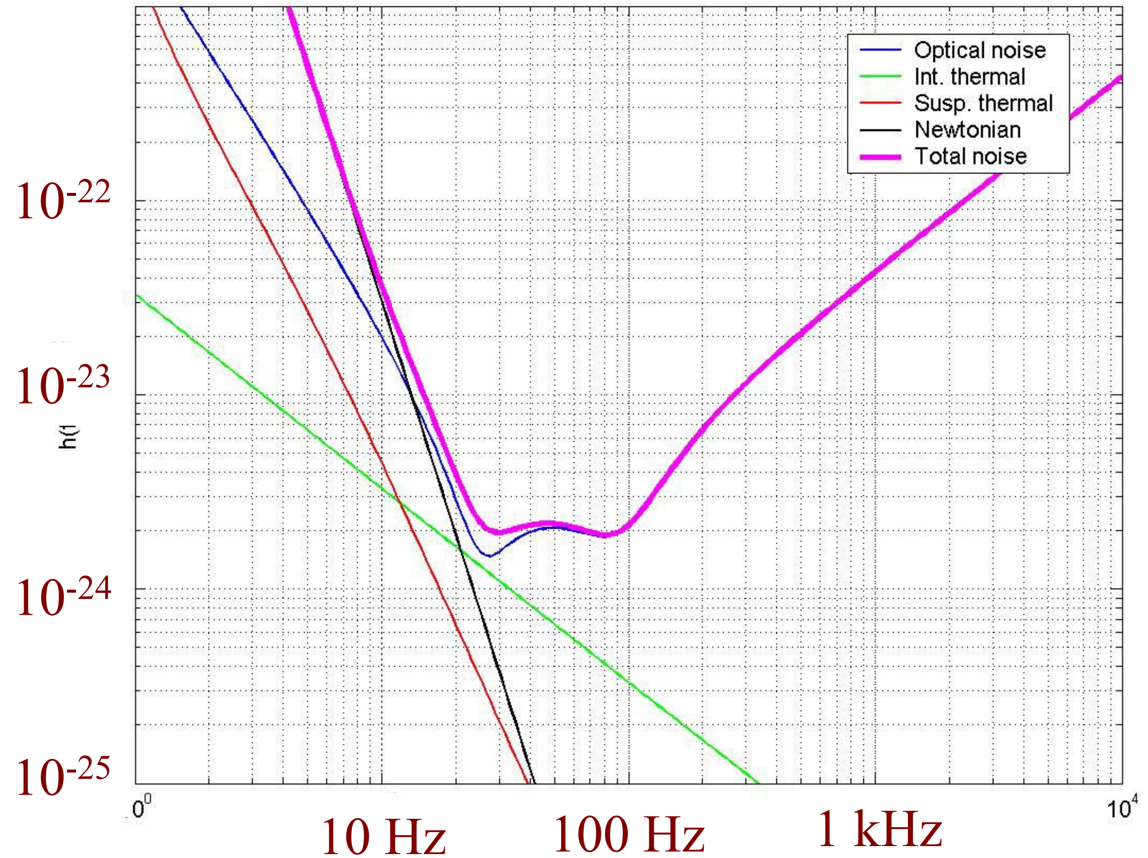
Limits to sensitivity

- Instrument limits
  - » Thermal noise
  - » Quantum noise
- Facility constraints
  - » Length
  - » Seismic environment
  - » Gravity gradients
  - » Residual gas in beam tube
  - » Configuration



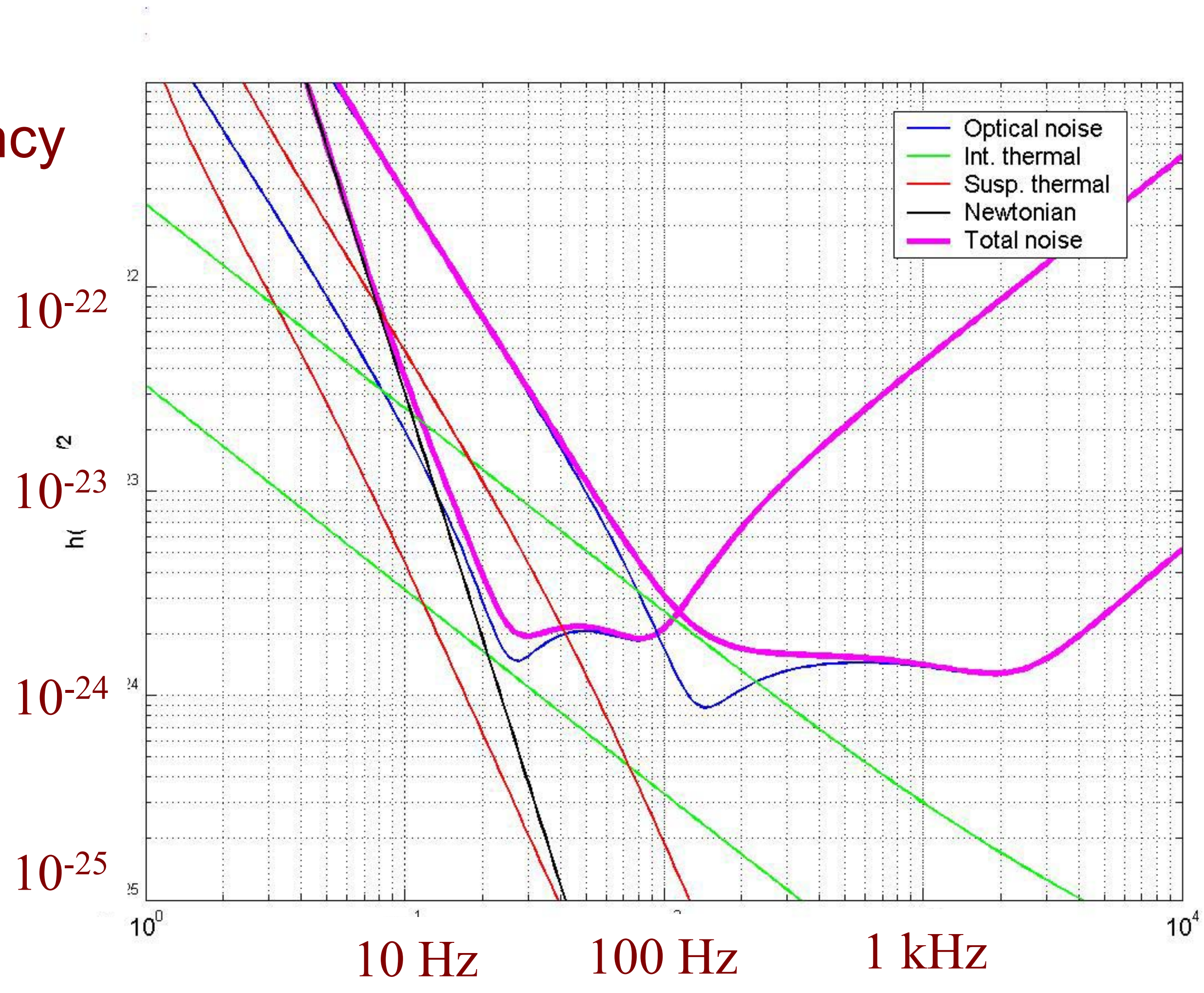
Performance of 3rd generation detectors: Toy Models

- 2nd generation, with…
- 30W, 230 kg
- Crygogenically cooled masses, suspensions
- Large beams
- Signal recycling
- 505 Mpc, 1 ifo



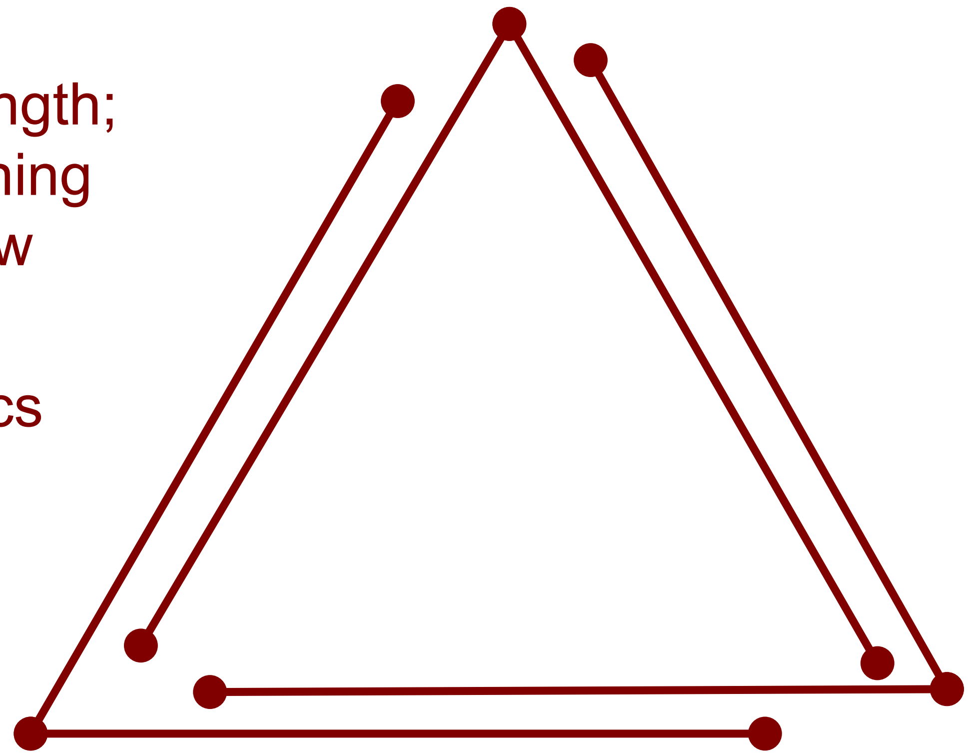
Multiple interferometers at a site: complementary specifications

- Low- and high-frequency instruments, or broad- and narrow-band
- Very powerful decoupling of technical challenges
- Complementary frequency response
- Potential for tracking sources



Multiple interferometers at a site: geometric differentiation

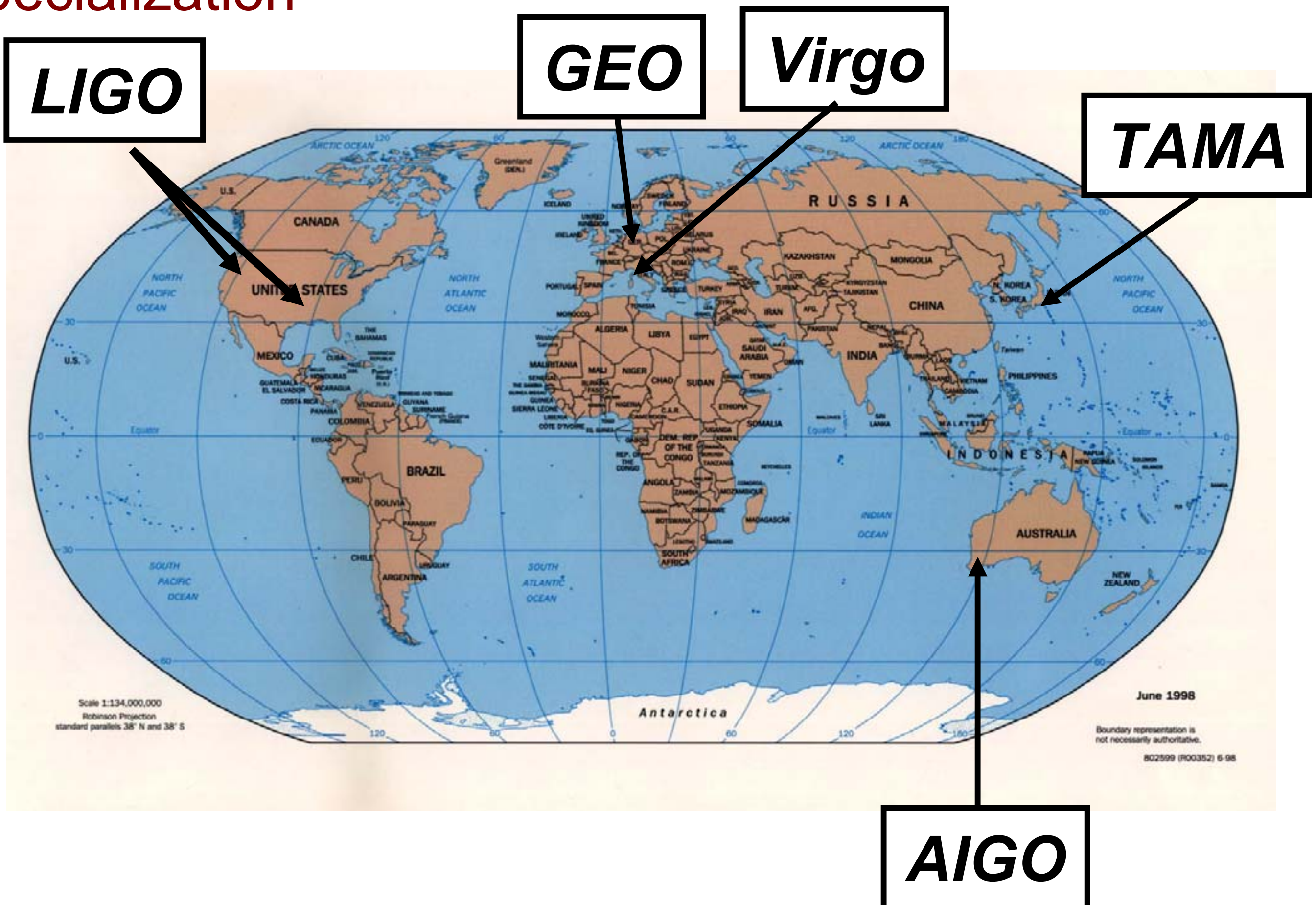
- Recovery of both polarizations
  - » Greater overlap with other networked detectors
- Diagnostics, auxiliary signals (as for LISA)
- Some loss in signal strength; recovery through combining signals from different ifow
- Potential for other physics
  - » Search for scalar GWs
  - » Sagnac studies



Ruediger

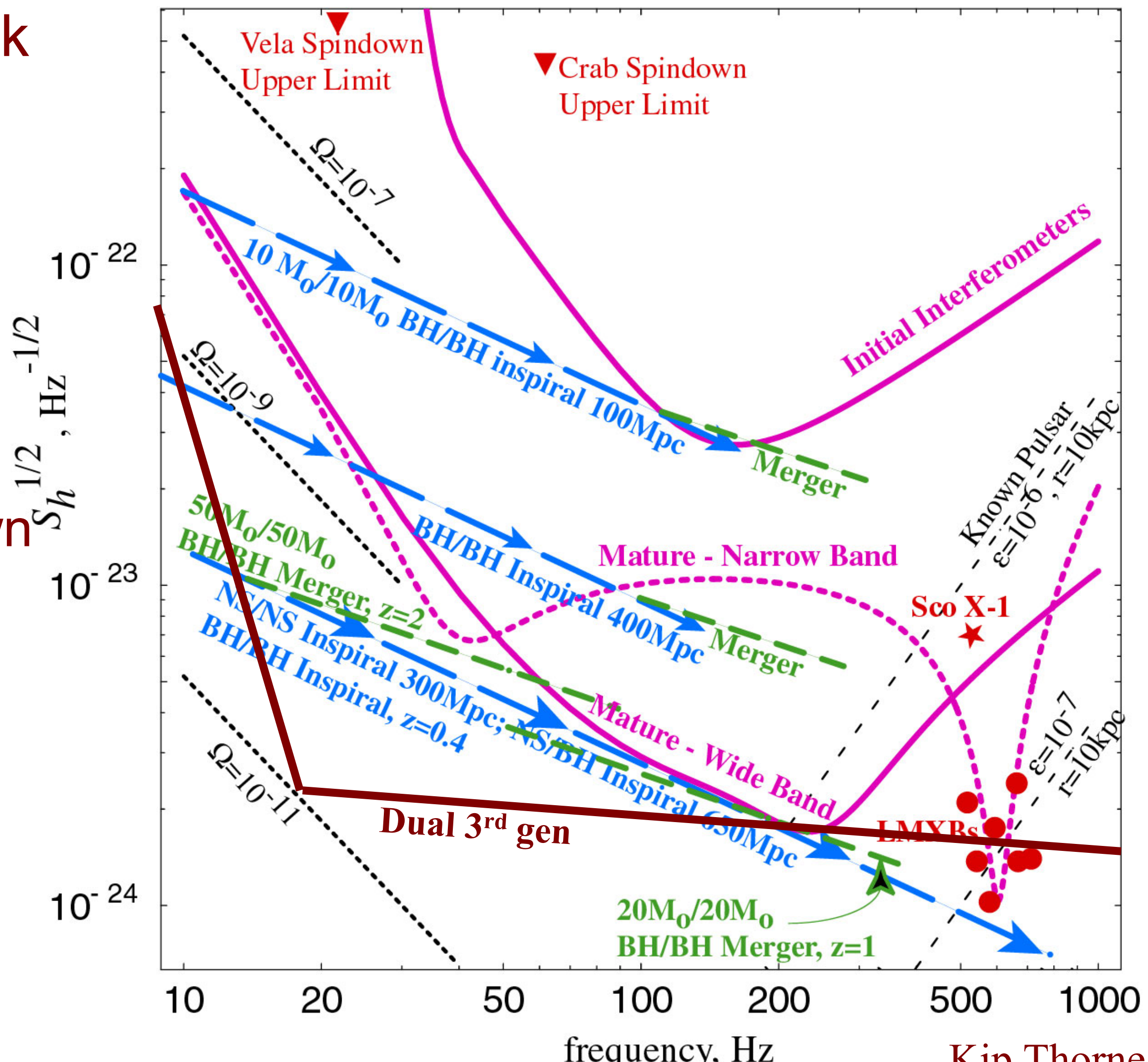
Multiple interferometers distributed around the world: the Network

- Detection confidence
- Extraction of polarization, position information
- Specialization



Astrophysical Reach

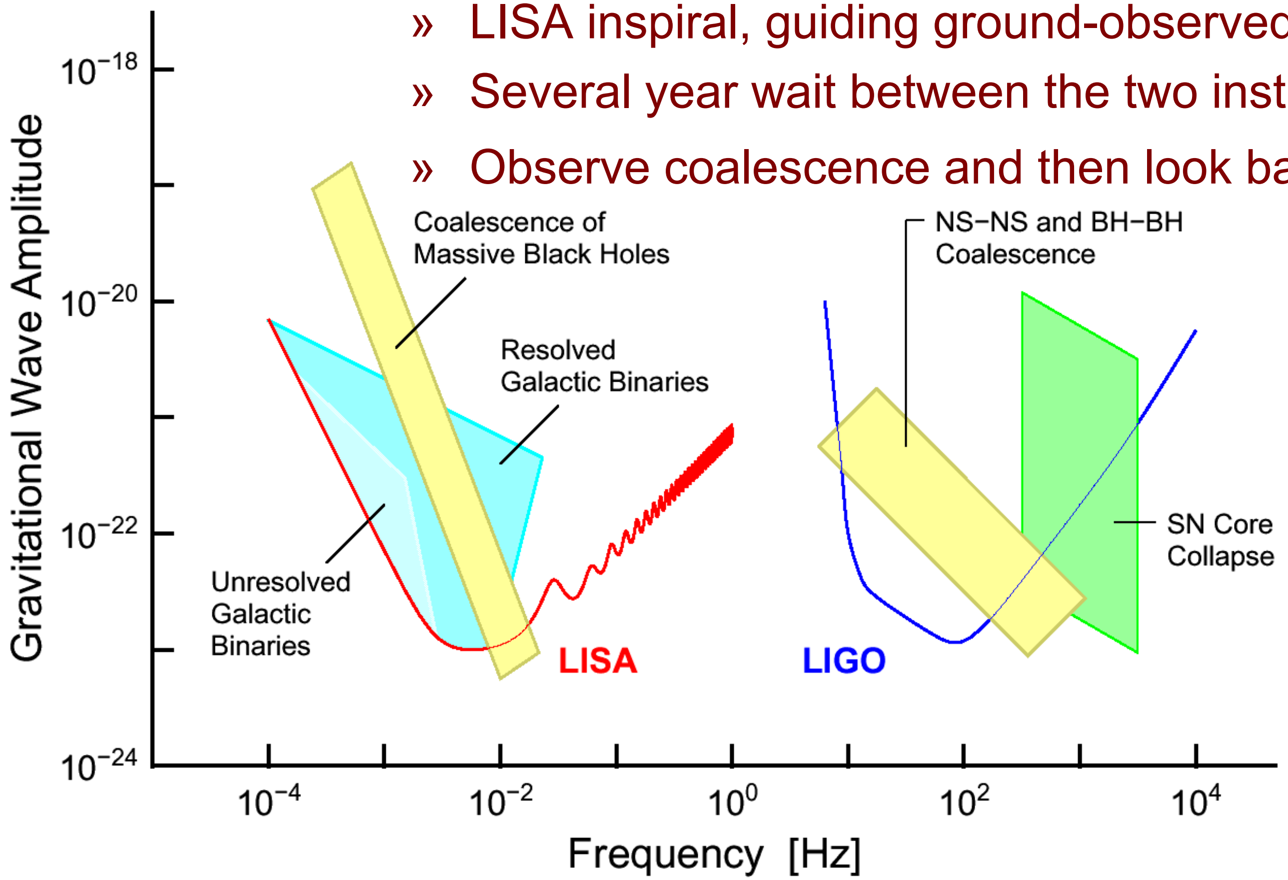
- Neutron Star & Black Hole Binaries
  - » inspiral
  - » merger
- Spinning NS's
  - » LMXBs
  - » known pulsars
  - » previously unknown
- NS Birth
  - » tumbling
  - » convection
- Stochastic background
  - » big bang
  - » early universe



Kip Thorne

Linking space- and ground-observations

- Are there ways of taking advantage of simultaneous (or sequential) observation with space- and ground-based systems?
  - Inspirals – 10 + 100 M_{sun}
    - » LISA inspiral, guiding ground-observed coalescence, ringdown
    - » Several year wait between the two instruments
    - » Observe coalescence and then look back at old LISA data?



- Stochastic background
- Anything else sufficiently broad-band?
- …LISA II…

Choosing an upgrade path for ground-based systems

- Technical constraints
  - » Need a ‘quantum’ of technological improvement
    - – Adequate increment in sensitivity for 2nd generation
    - – Promise for the 3rd generation
  - » Must be responsible observers – try to maintain a continuous Network of instruments
- Wish to maximize astrophysics to be gained
  - » Must fully exploit initial instruments
  - » Any change in instrument leads to lost observing time at an Observatory
  - » Studies based on initial interferometer 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

Ground-based Interferometry

- Starting observations this summer
  - » TAMA, LIGO, GEO – and soon VIRGO
  - » New upper limits to GW flux
- 1st generation observing run → ~2008
  - » At a sensitivity that makes detection 'plausible'
- 2nd generation starting ~2008
  - » At a sensitivity which makes a lack of detection implausible
- 3rd generation starting around the time that LISA is launched
  - » Guided by the GW discoveries already made
  - » With an ever-growing network of detectors
  - » Using some technologies yet to be discovered
  - » …and a good partner to LISA in developing a new gravitational wave astronomy