Pursuing Gravitational Wave Astrophysics with LIGO


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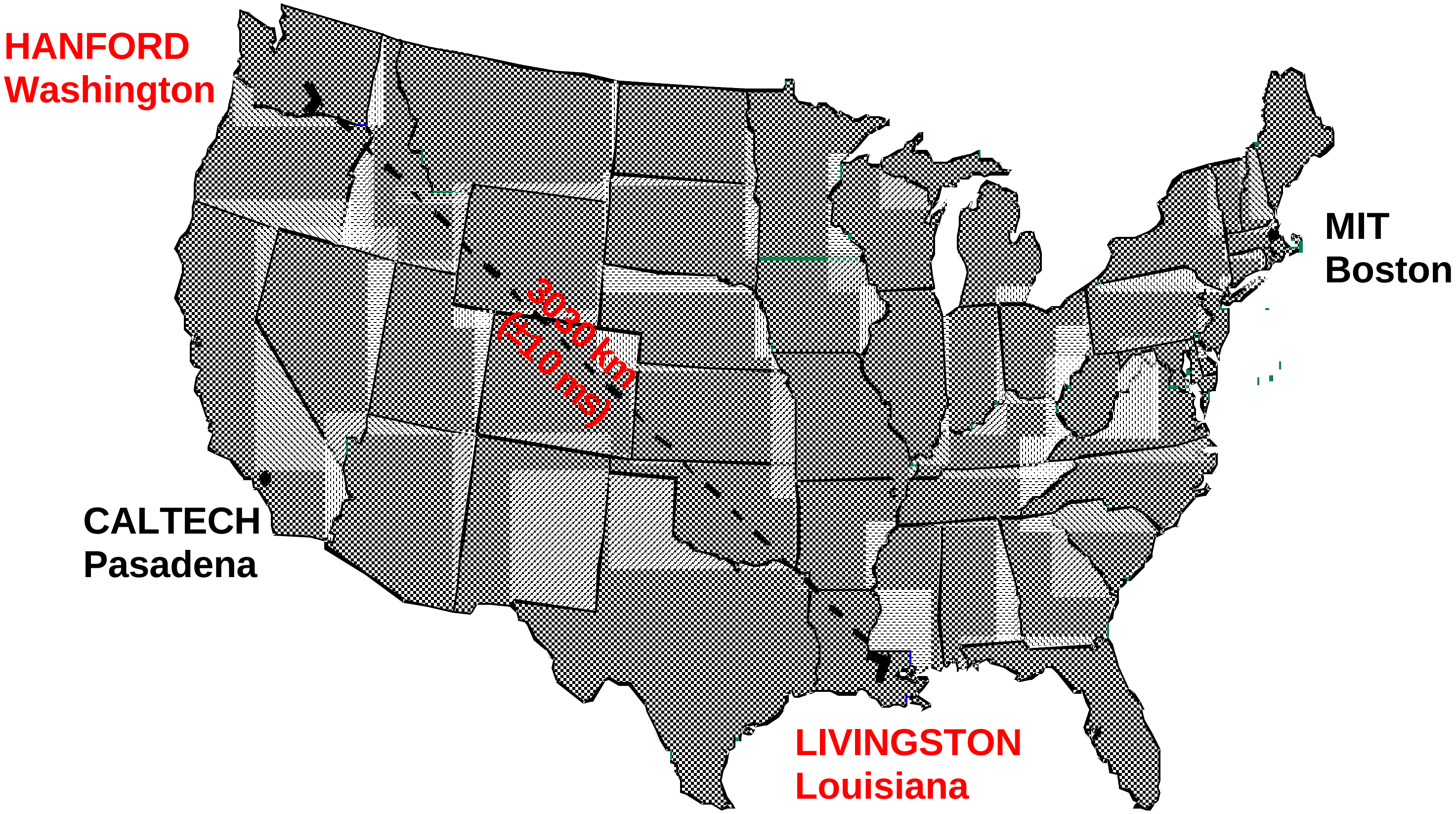
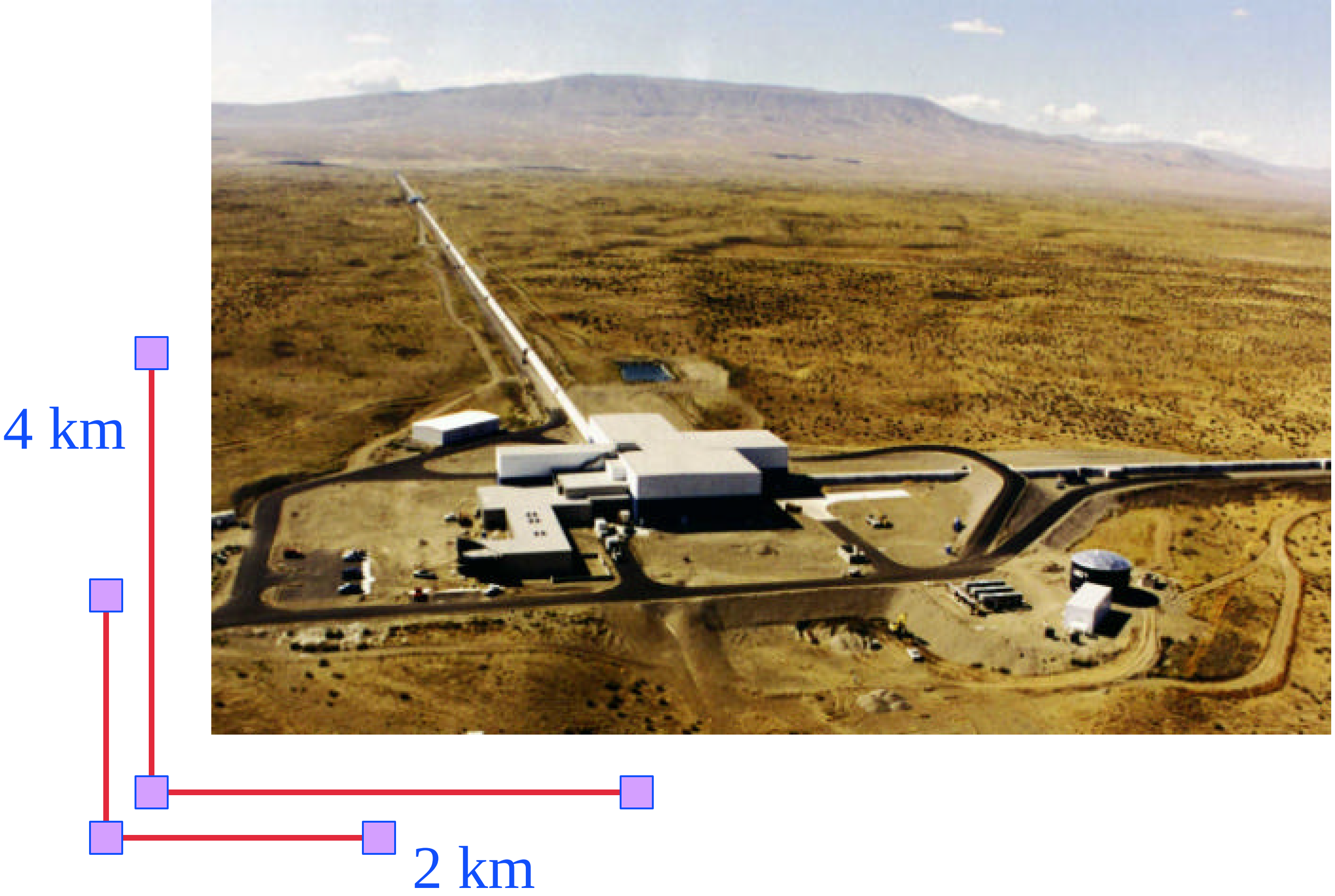
Outline of Talk

- ❑ Initial Detector Overview
  - Performance Goals
  - How do they work?
  - What do the parts look like?
- ❑ Very Current Status
  - Installation and Commissioning
- ❑ Advanced LIGO Detectors
- ❑ A Look At Sources

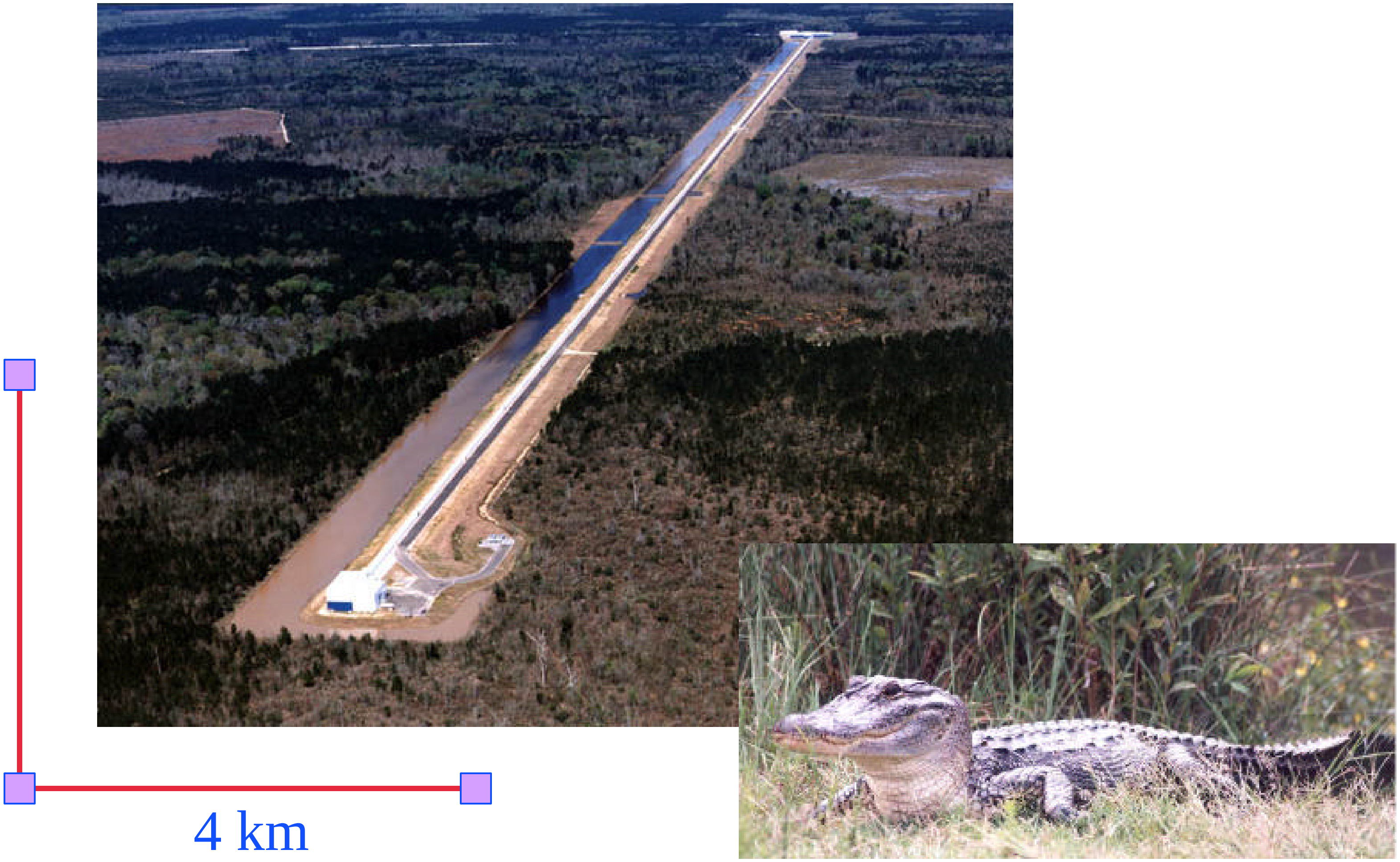
LIGO Observatories



Hanford Observatory



Livingston Observatory


4 km

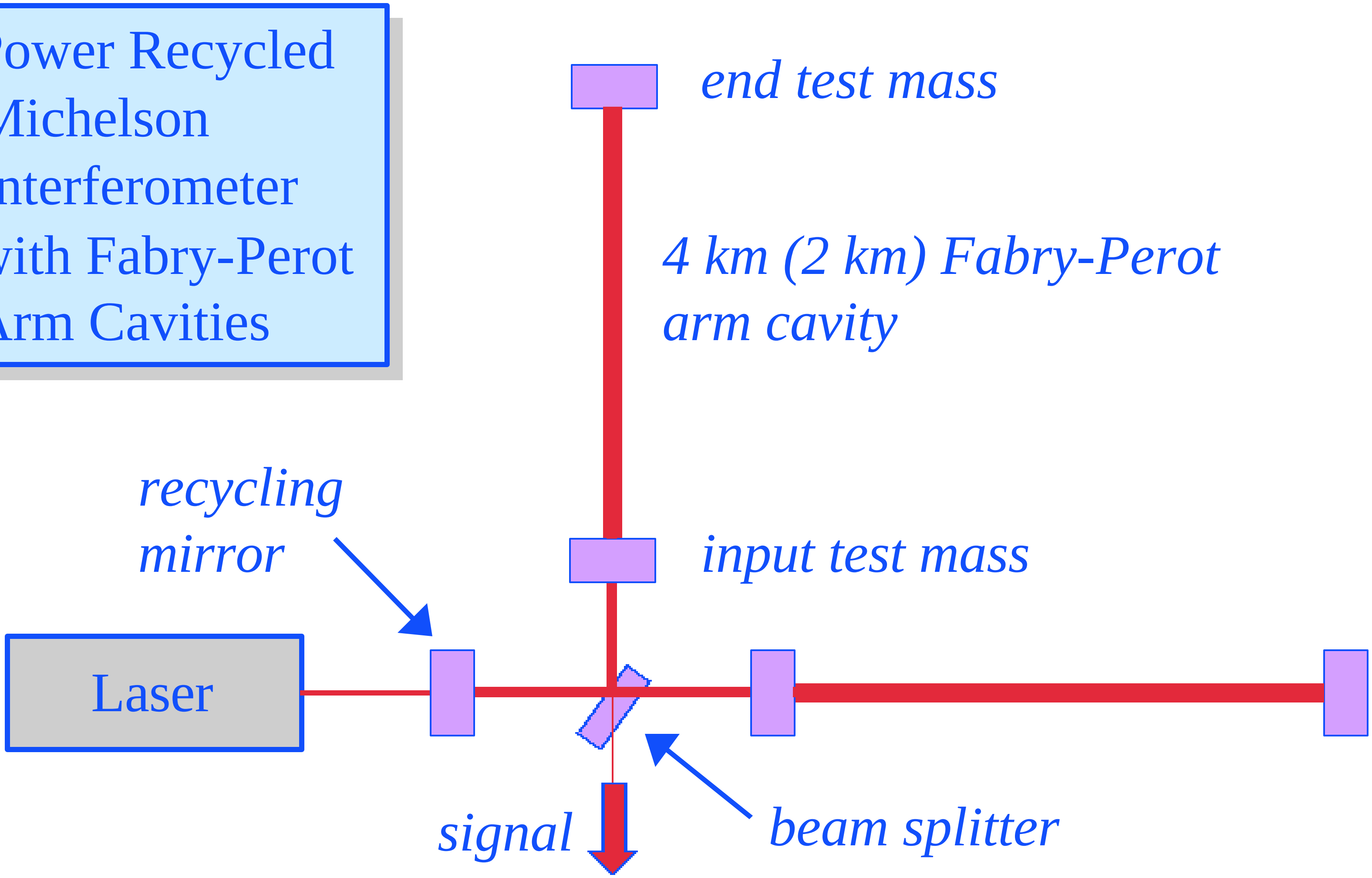
Initial Detectors—Underlying Philosophy

❑ Jump from laboratory scale prototypes to multi-kilometer detectors is already a BIG challenge

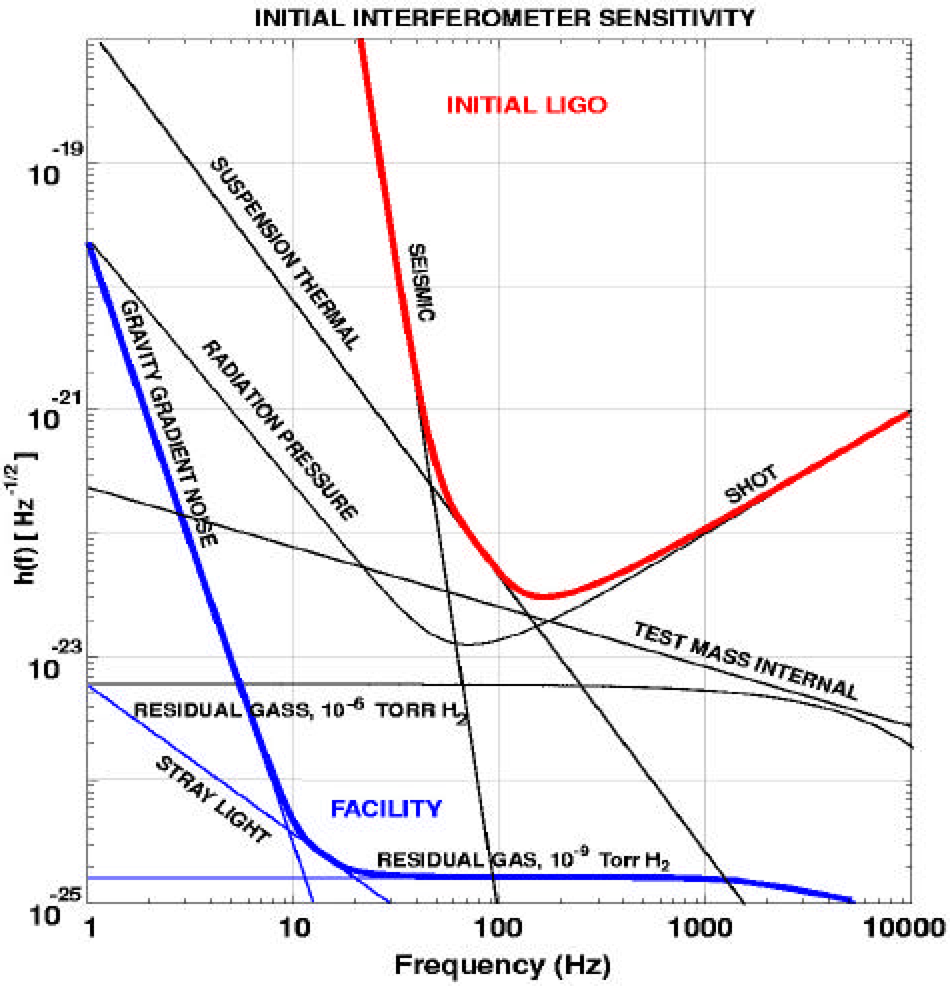
- Design should use relatively cautious extrapolations of existing technologies
  - » Reliability and ease of integration should be considered in addition to noise performance
    - – "The laser should be a light bulb, not a research project" Bob Byer, Stanford
  - » All major design decisions were in place by 1994
- Initial detectors would teach us what was important for future upgrades
- Facilities (big $) should be designed with more sensitive detectors in mind
- Expected 1000 times improvement in sensitivity is enough to make the initial searches interesting even if they only set upper limits

Initial LIGO Interferometers

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



Initial LIGO Sensitivity Goal



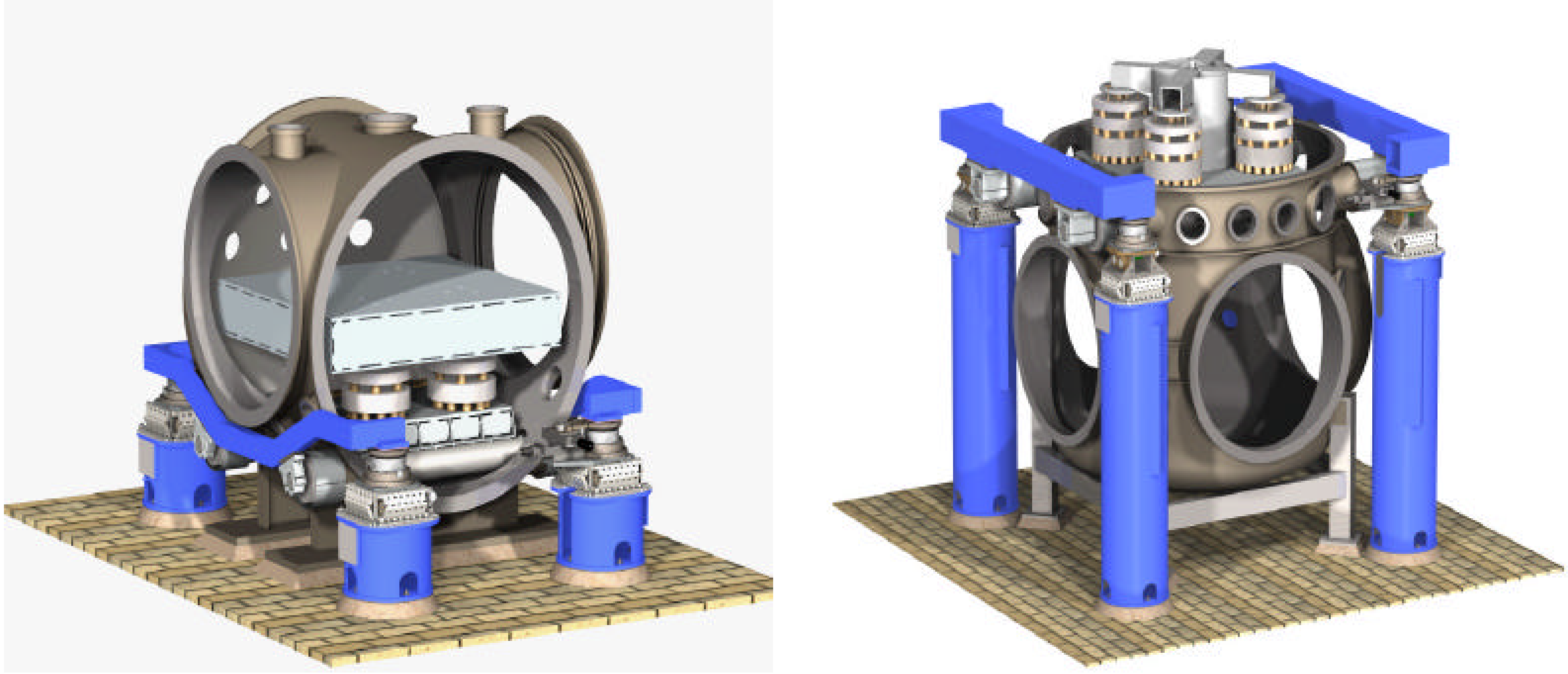
- ☐ Strain sensitivity $<3\times10^{-23}\ 1/\mathrm{Hz}^{1/2}$ at 150 Hz
- ● Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- ● Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

Initial LIGO Detector Status

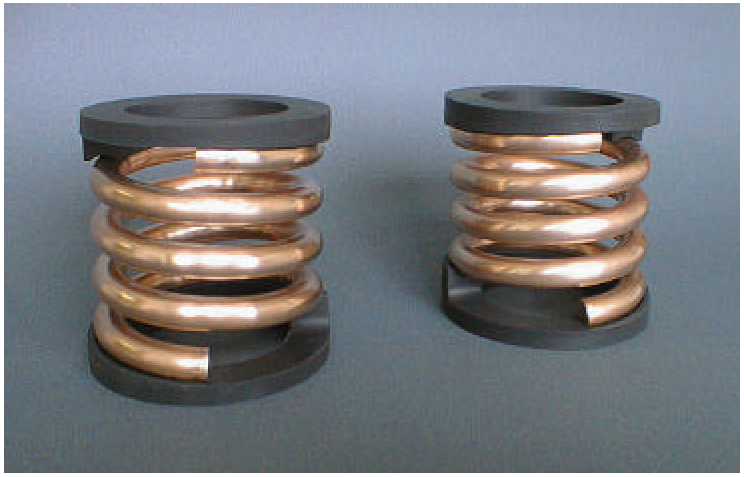
- ☐ Construction project - Finished
  - Facilities, including beam tubes complete at both sites
- ☐ Detector installation
  - Washington 2k interferometer complete
  - Louisiana 4k interferometer complete
  - Washington 4k interferometer in progress
- ☐ Interferometer commissioning
  - Washington 2k full interferometer functioning
  - Louisiana 4k individual arms being tested
- ☐ First astrophysical data run - 2002

Vibration Isolation Systems

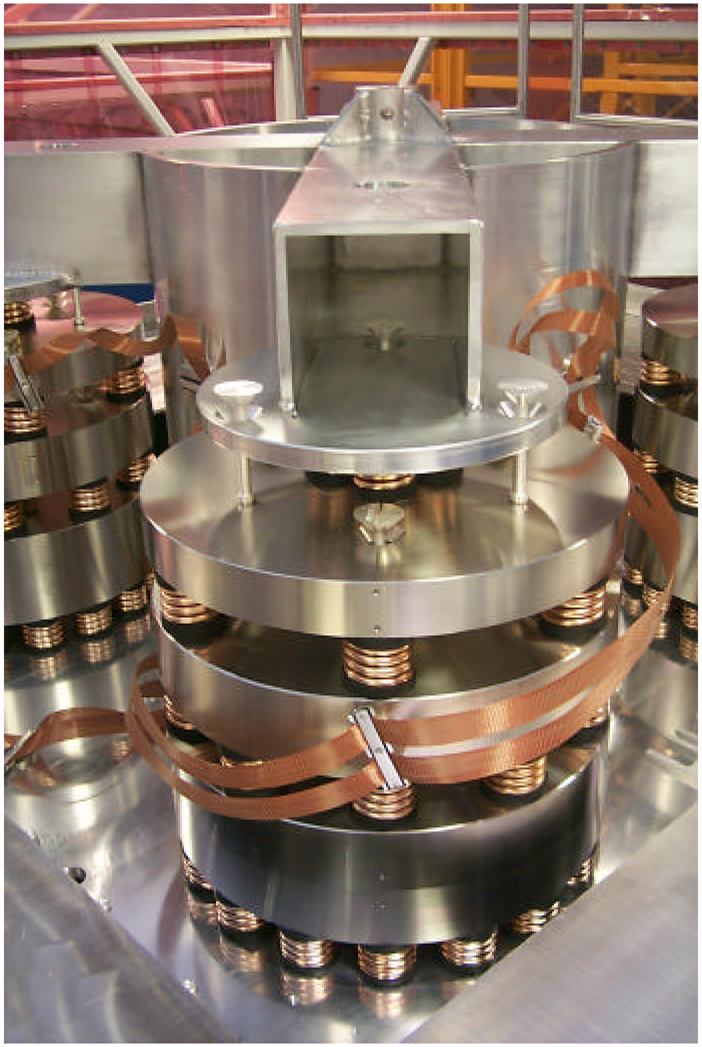
- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Large range actuation for initial alignment and drift compensation
- Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation



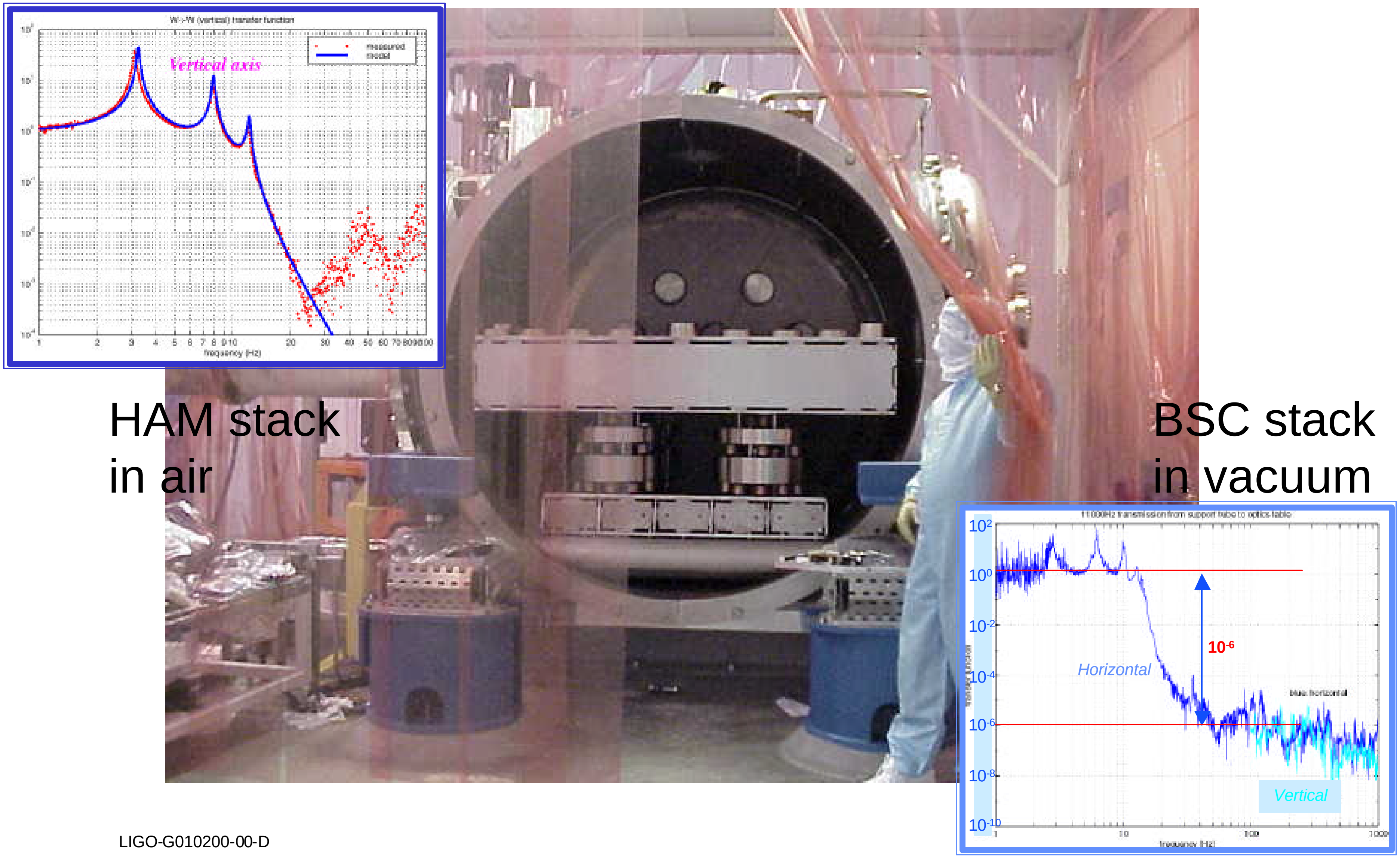
Seismic Isolation – Springs and Masses



damped spring
cross section



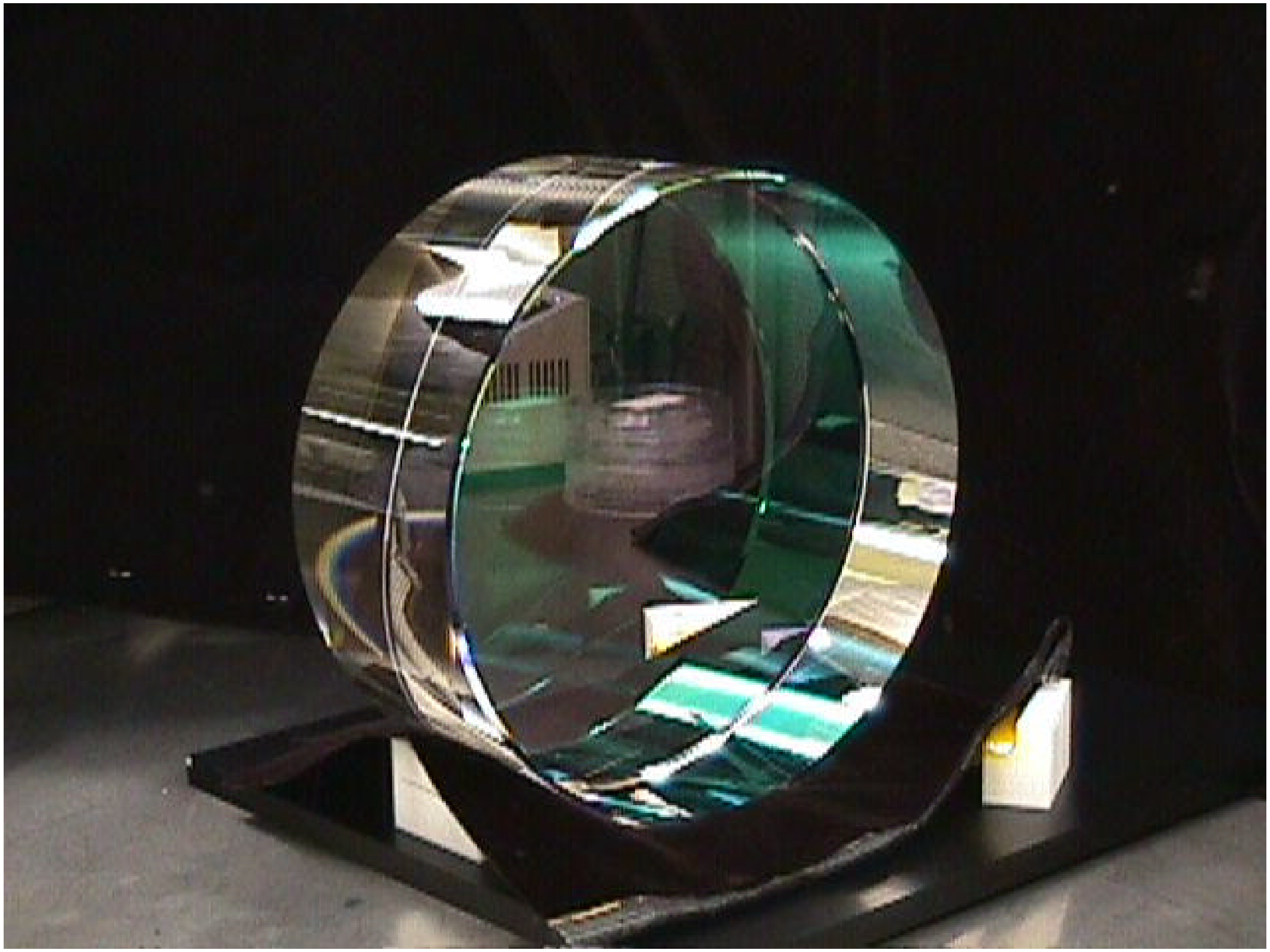
Seismic System Performance



HAM stack
in air

BSC stack
in vacuum

Core Optics

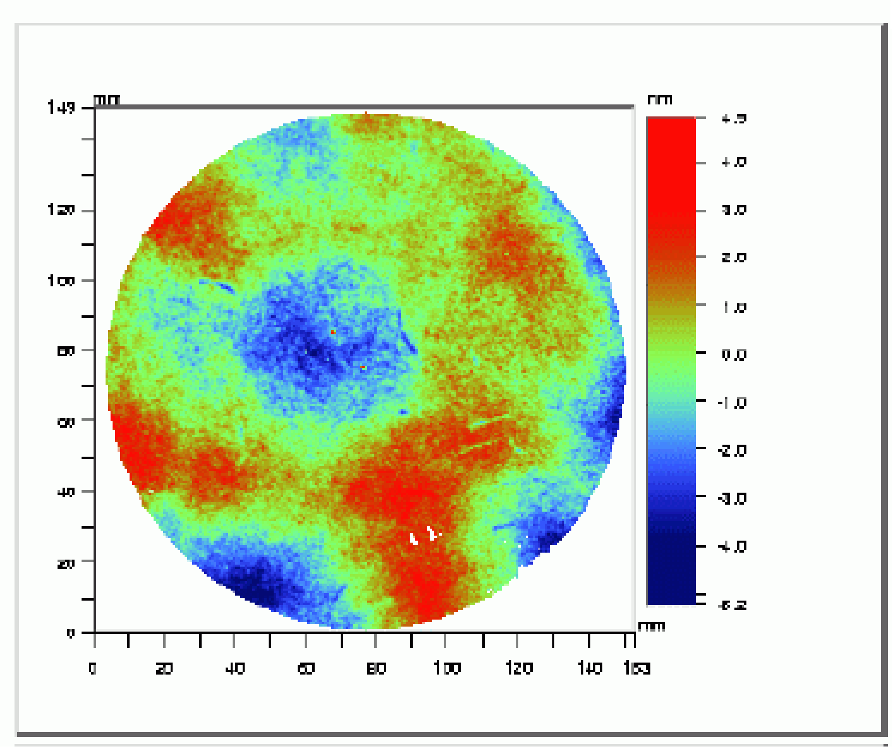


Core Optics Requirements

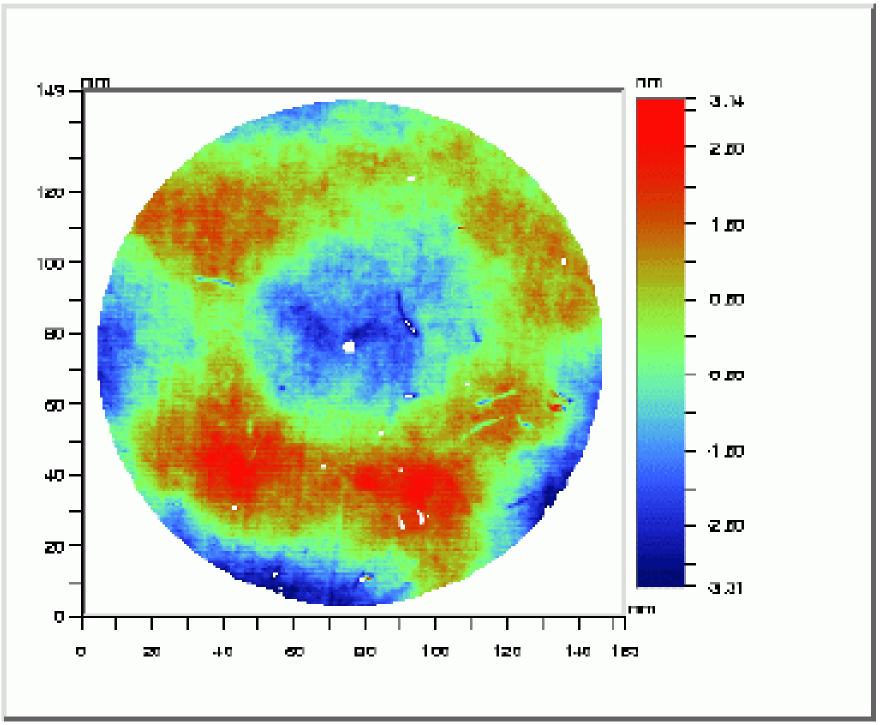
- Substrates
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - ROC matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Successful production eventually involved 6 companies, NIST and the LIGO Lab

Core Optic Metrology

- ❑ Current state of the art: 0.06-0.2 nm repeatability



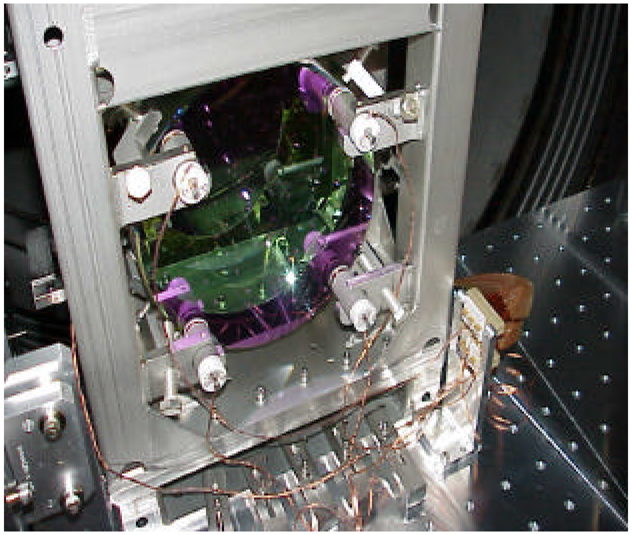
LIGO data (1.2 nm rms)

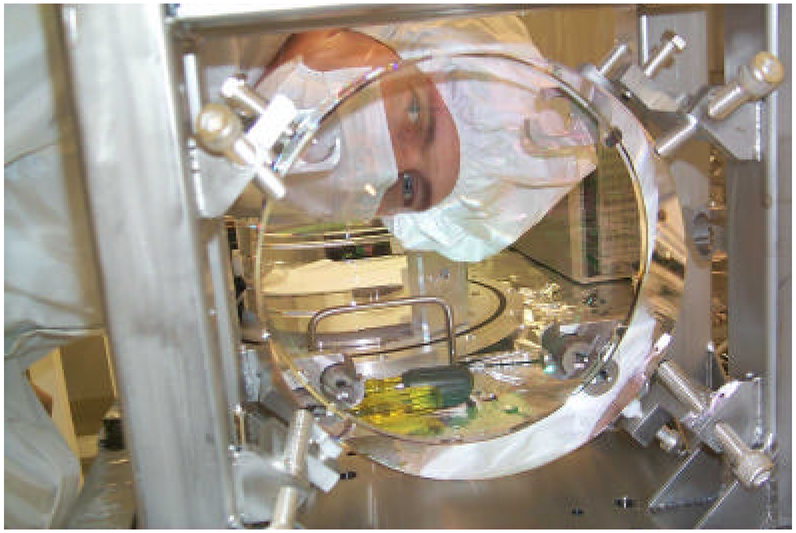


CSIRO data (1.1 nm rms)

➢***Best mirrors are l /6000 over the central 8 cm diameter!***

Core Optics Suspension and Control

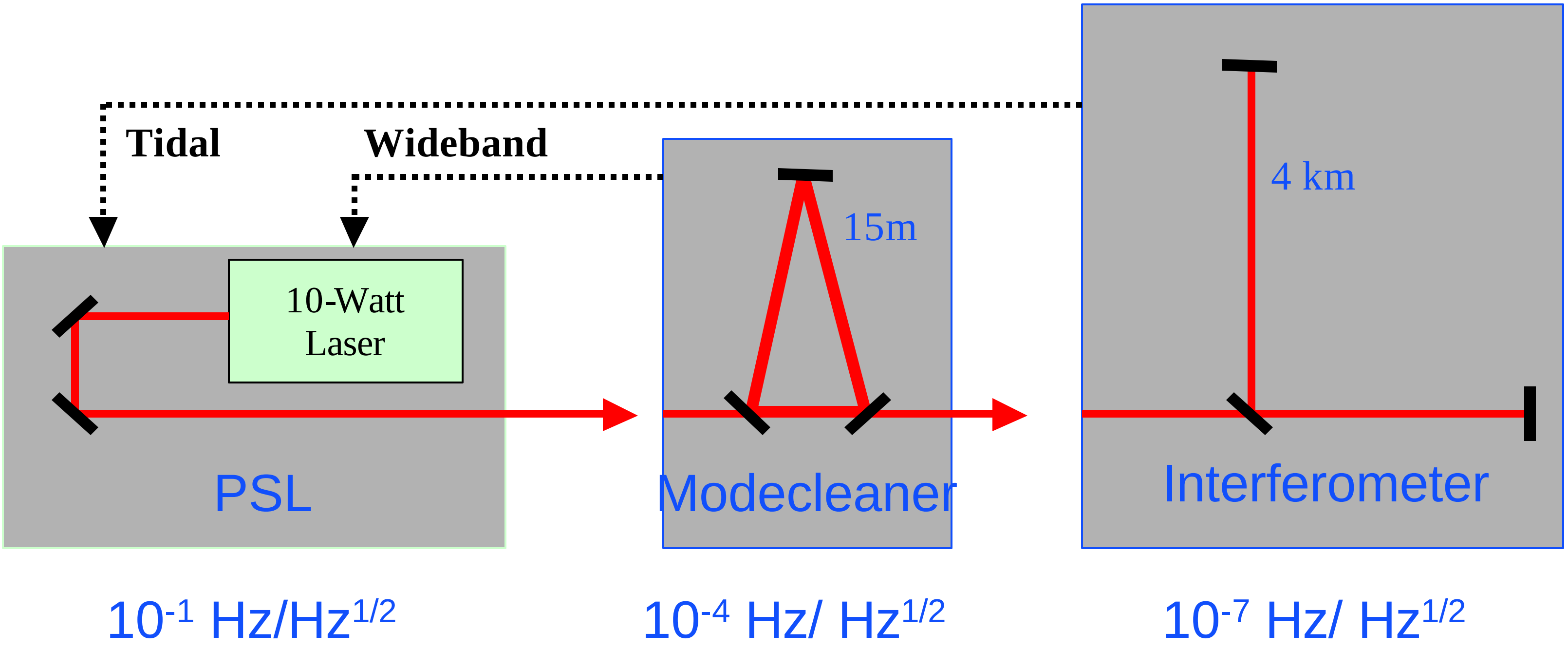




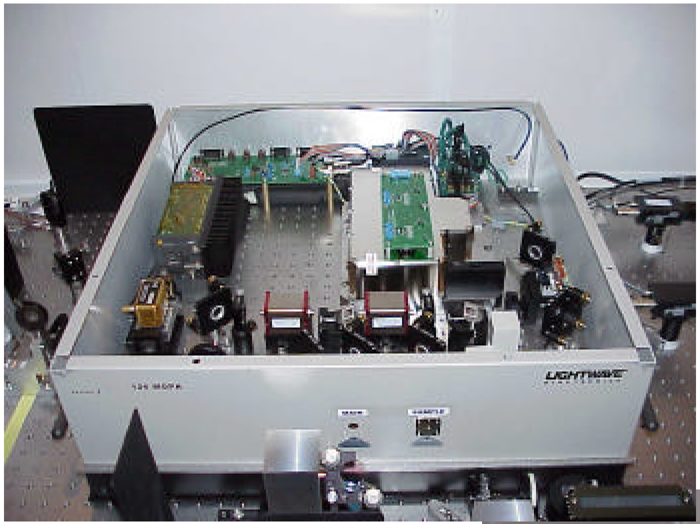
Core Optics Installation and Alignment

Pre-stabilized Laser

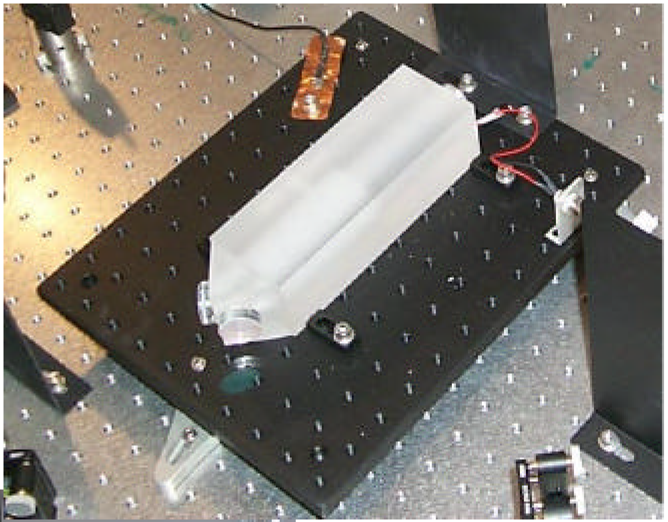
- ❑ Deliver pre-stabilized laser light to the 15-m mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**



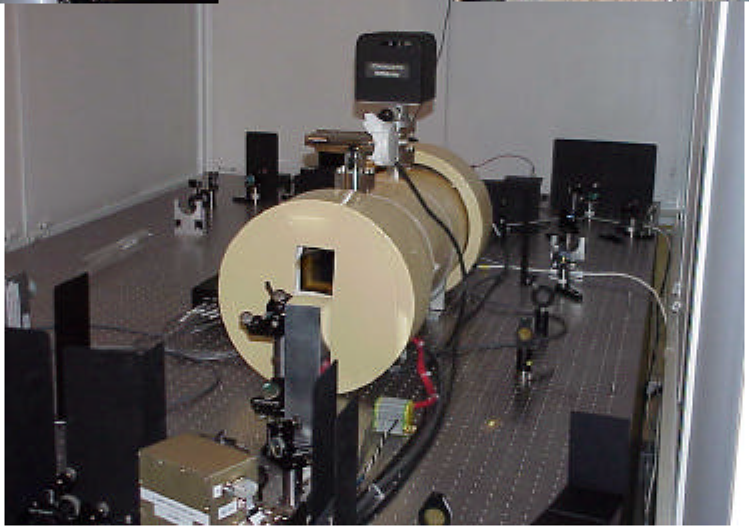
Washington 2k Pre-stabilized Laser



Custom-built
10 W Nd:YAG
Laser

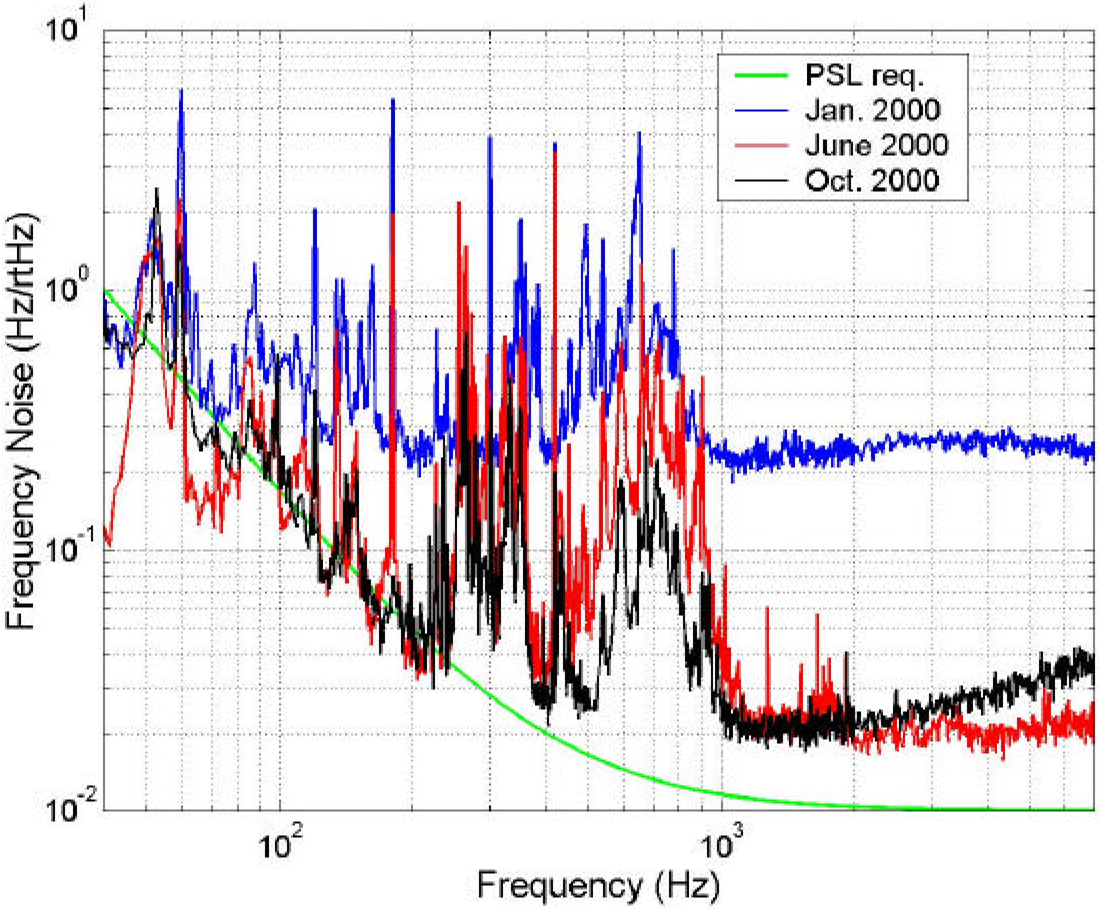


Stabilization cavities
for frequency
and beam shape



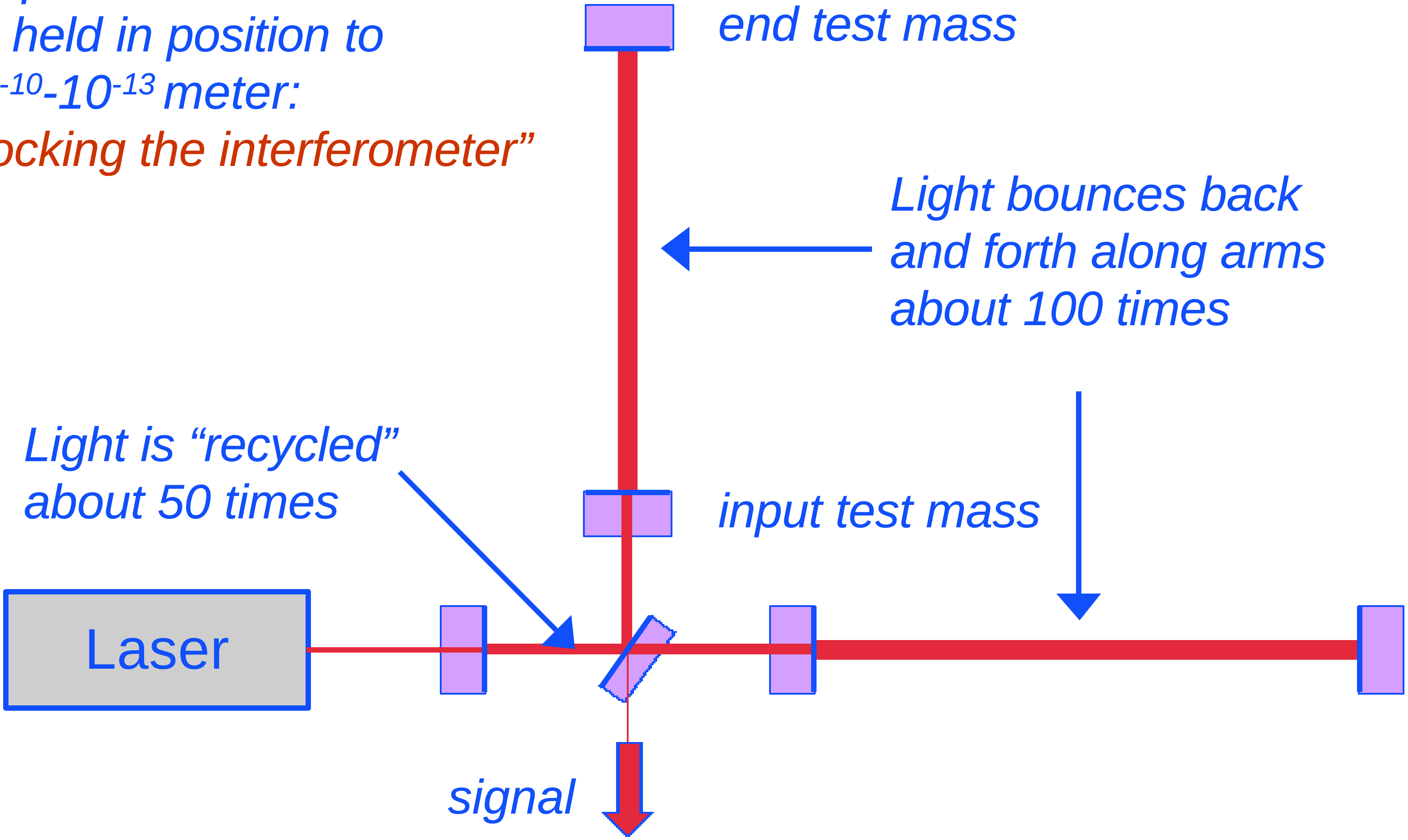
WA 2k Pre-stabilized Laser Performance

- > 20,000 hours continuous operation
- Frequency lock very robust
- TEM$_{00}$ power >8 W delivered to input optics
- Non-TEM$_{00}$ power < 10%
- Improvement in noise performance
  - » electronics
  - » acoustics
  - » vibrations



Interferometer Controls

Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
"Locking the interferometer"



end test mass

Light bounces back and forth along arms about 100 times

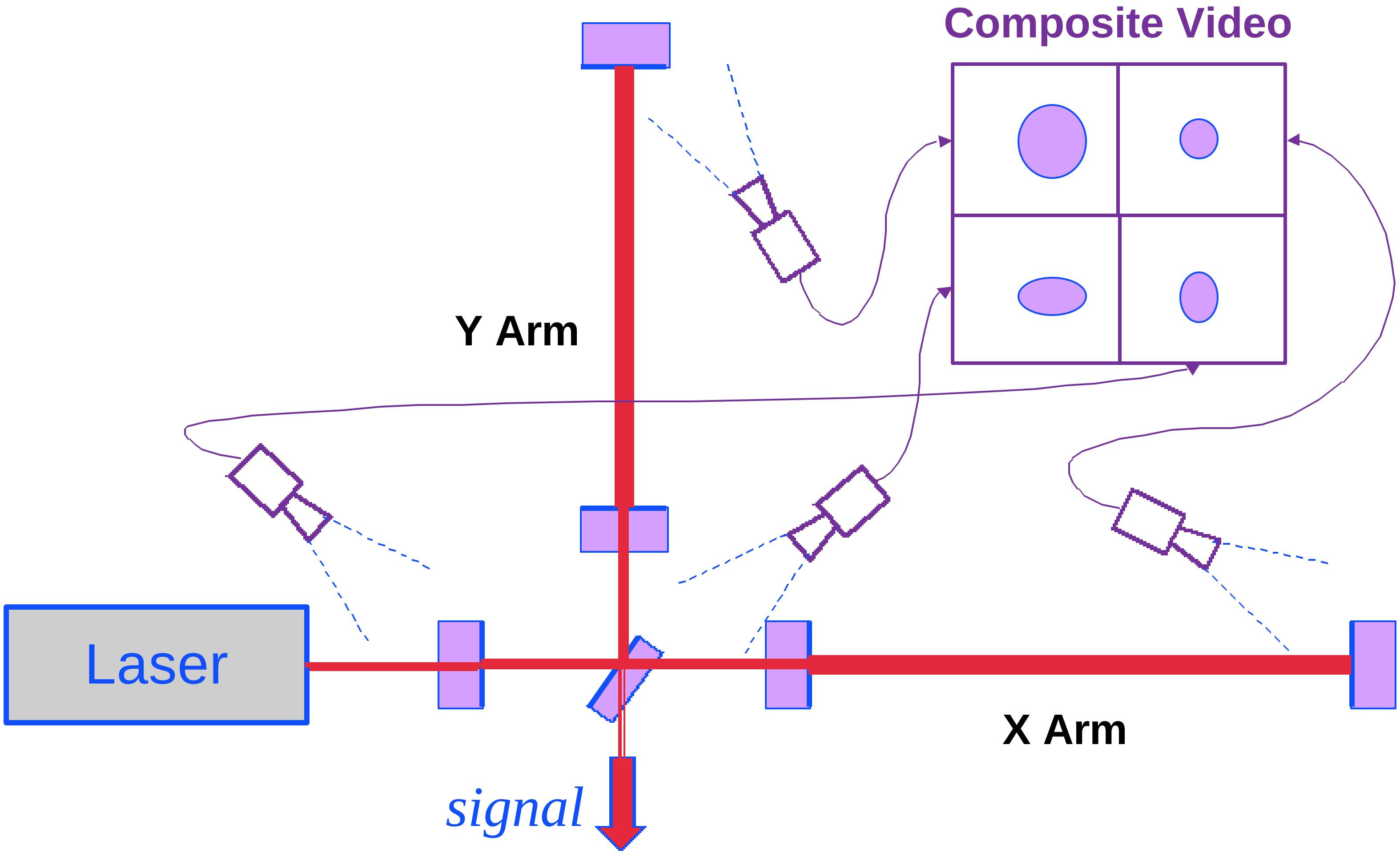
Light is "recycled" about 50 times

input test mass

Laser

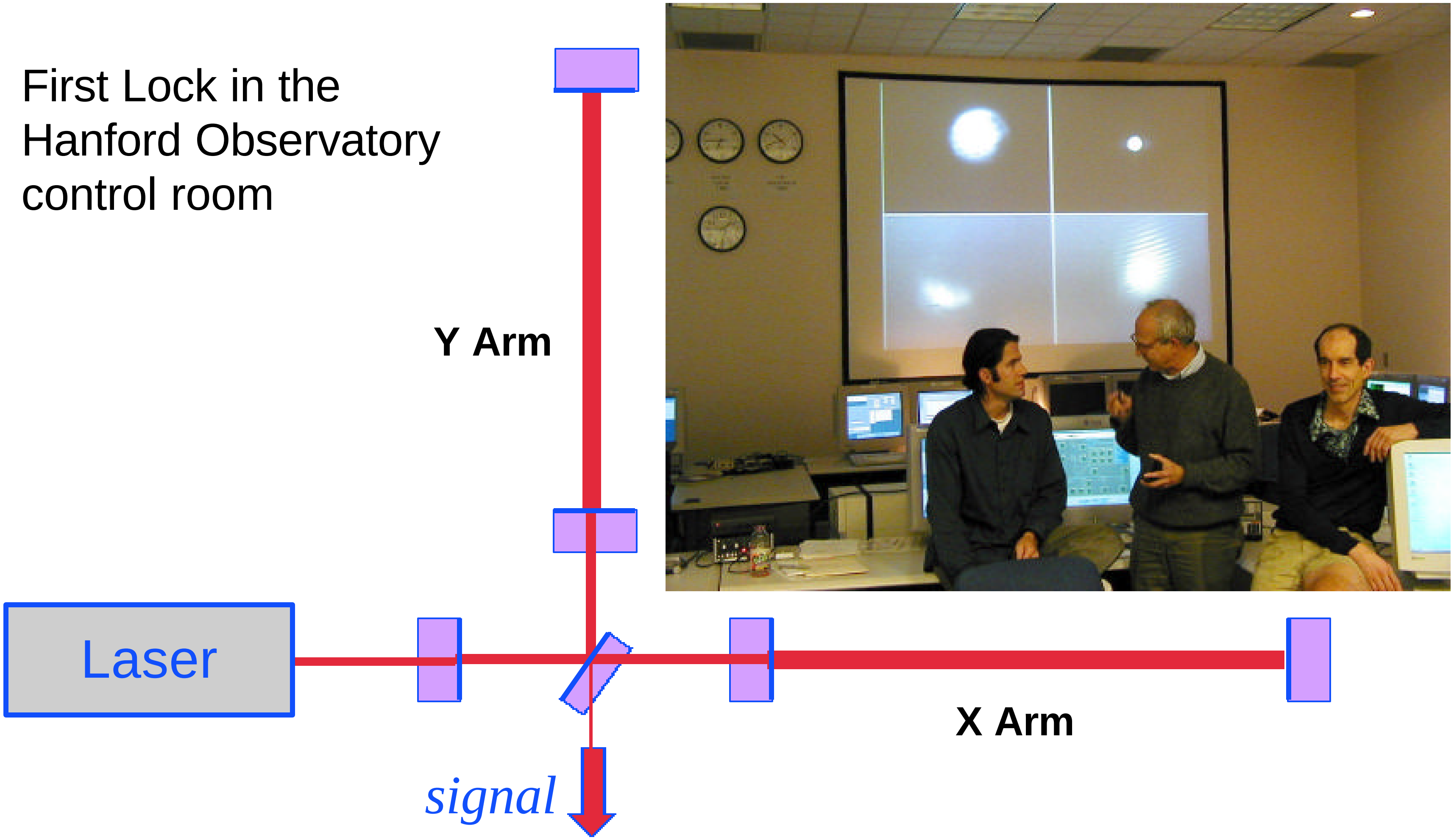
signal

Steps to Locking an Interferometer

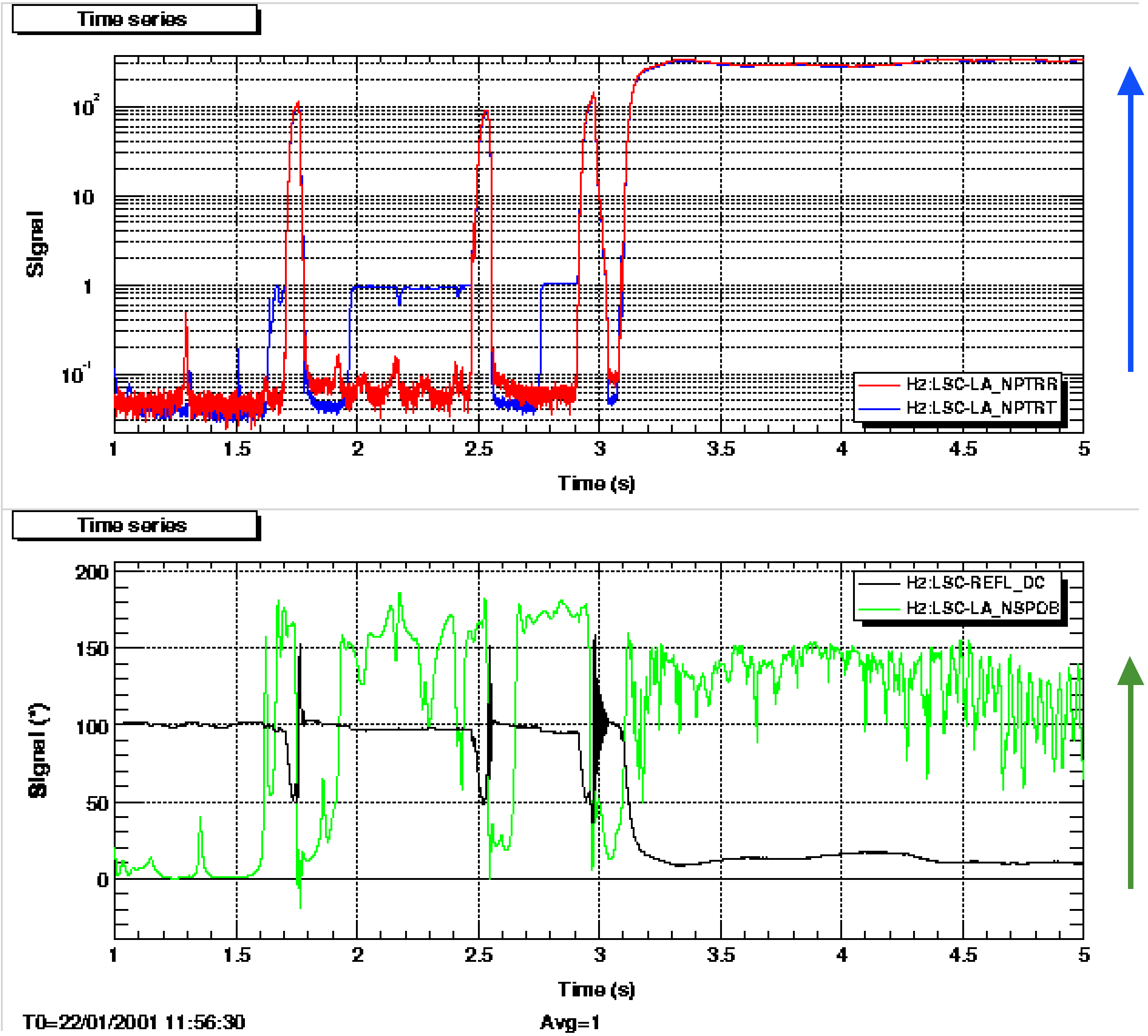


Watching the Interferometer Lock

First Lock in the
Hanford Observatory
control room



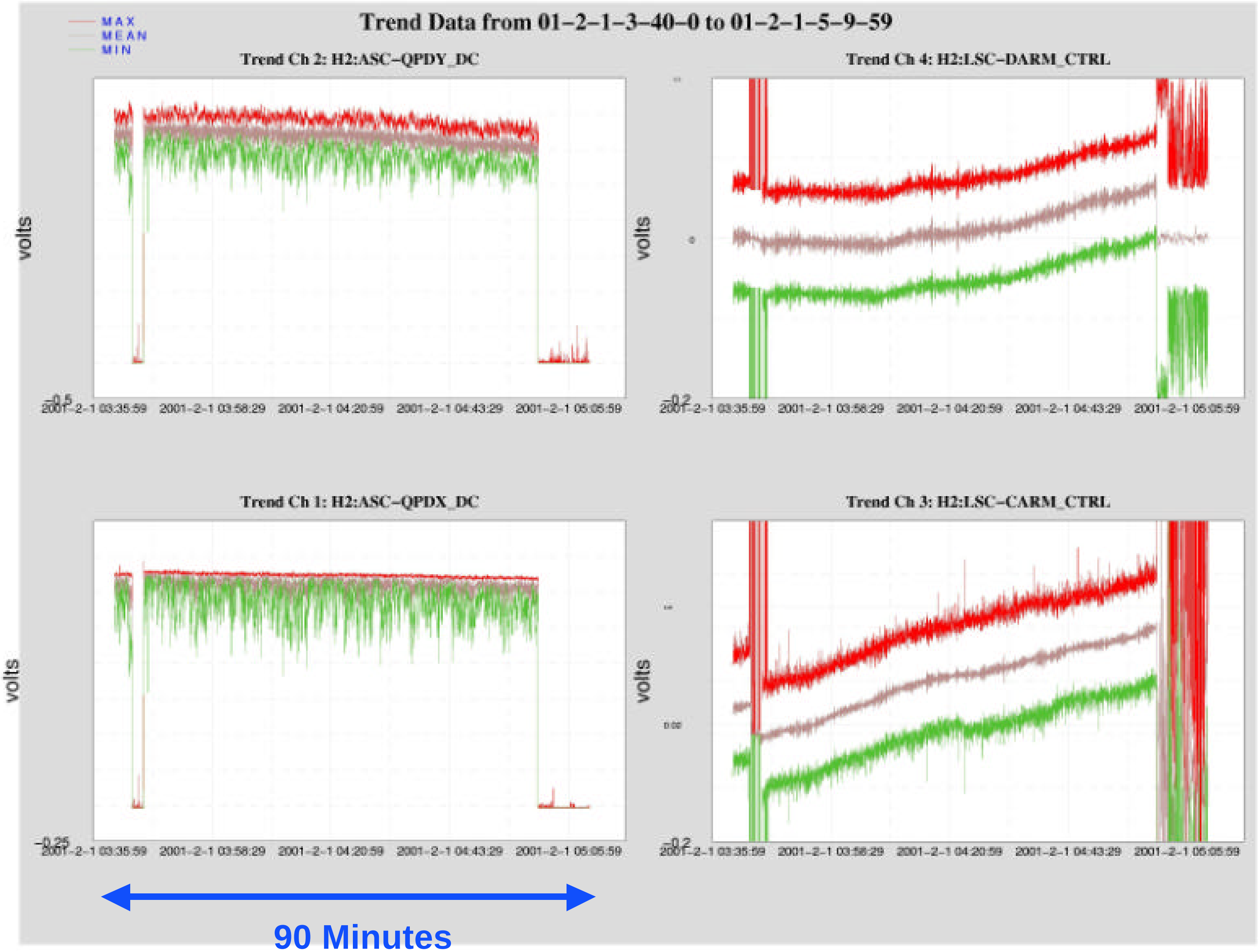
Lock Acquisition Example



Carrier
Recycling
Gain ~10

Sideband
Recycling
Gain ~5

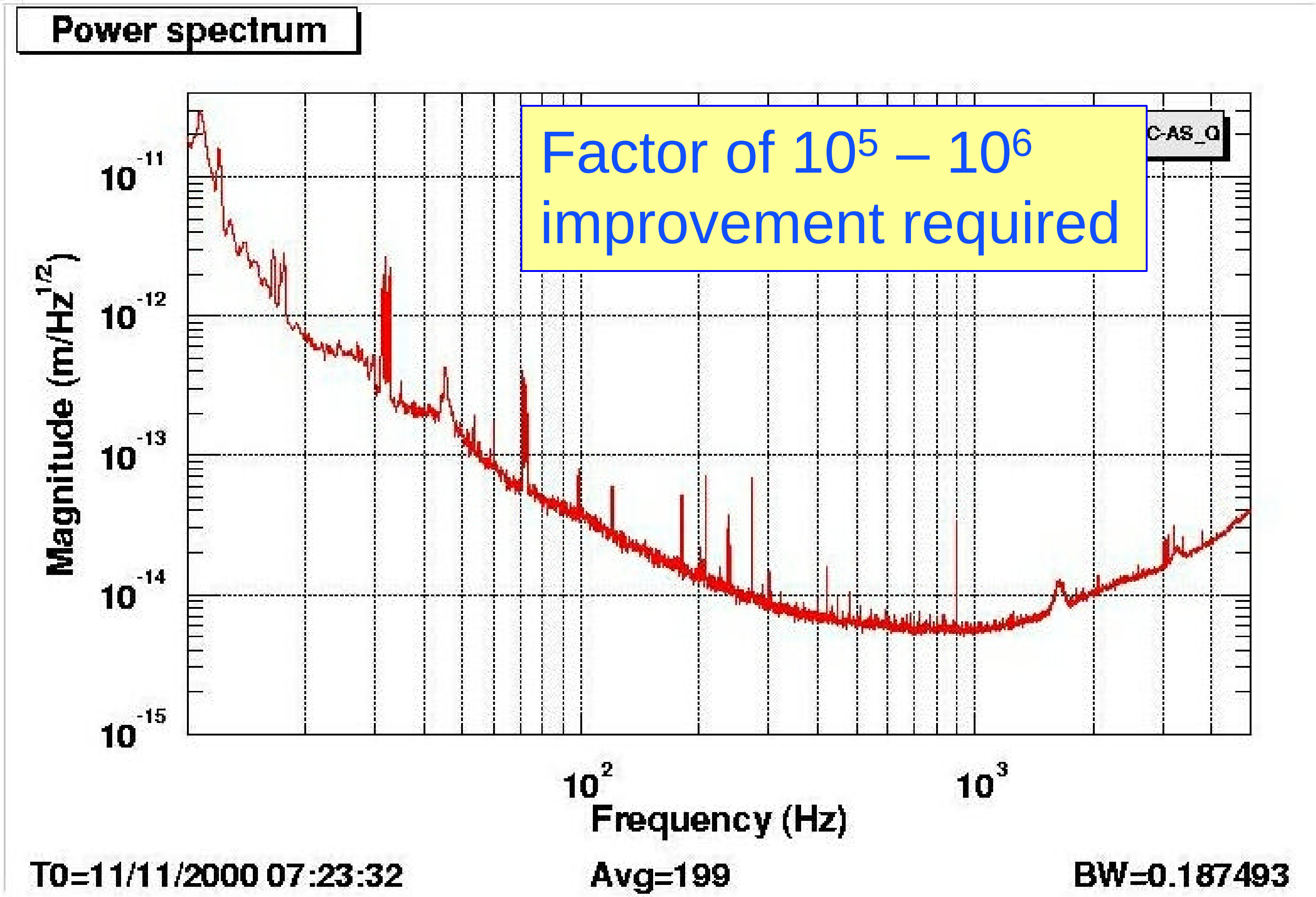
Full Interferometer Locking



90 Minutes

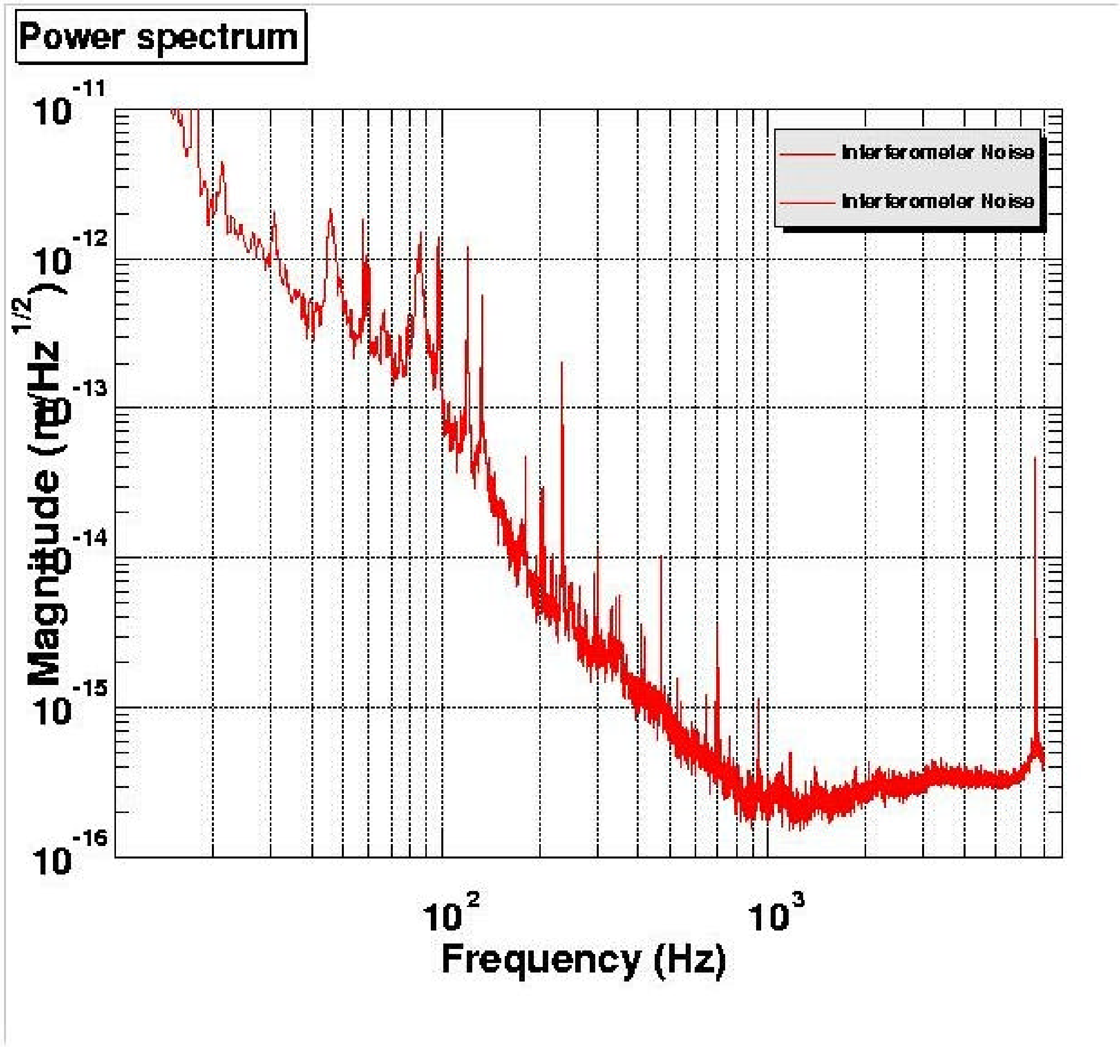
First Interferometer Noise Spectrum

Recombined Michelson with F-P Arms (no recycling) – November 2000



Factor of 10^5 – 10^6 improvement required

Improved Noise Spectrum

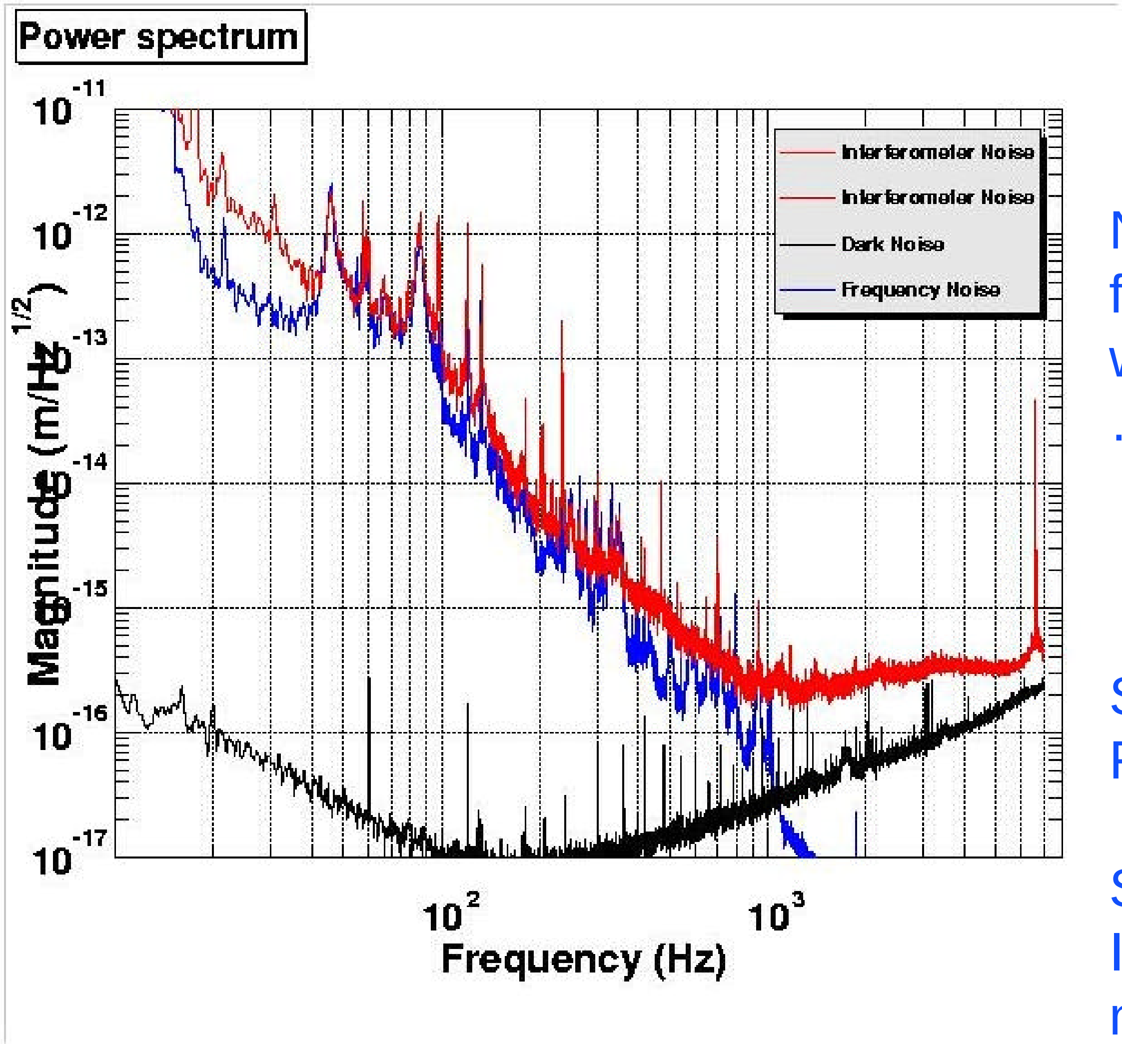


9 February 2001

Improvements due to:

- Recycling
- Reduction of electronics noise
- Partial implementation of alignment control

Known Contributors to Noise



New servo to improve frequency stabilization was being installed, when …

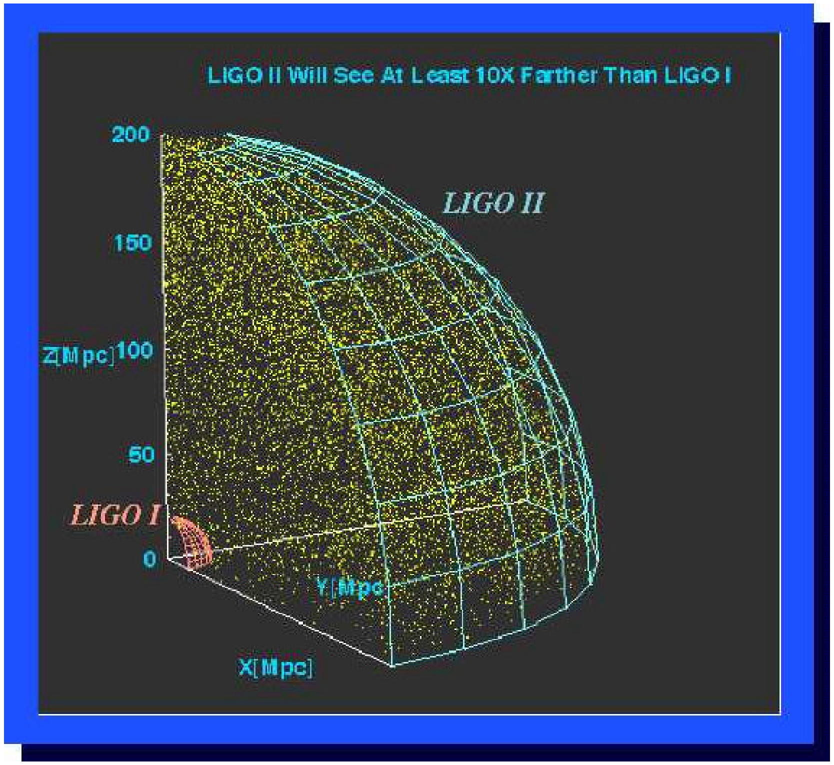
EARTHQUAKE !

Struck Olympia, WA, February 28th

Shook up Hanford 2km Interferometer, forced much repair, now nearly complete

Advanced LIGO

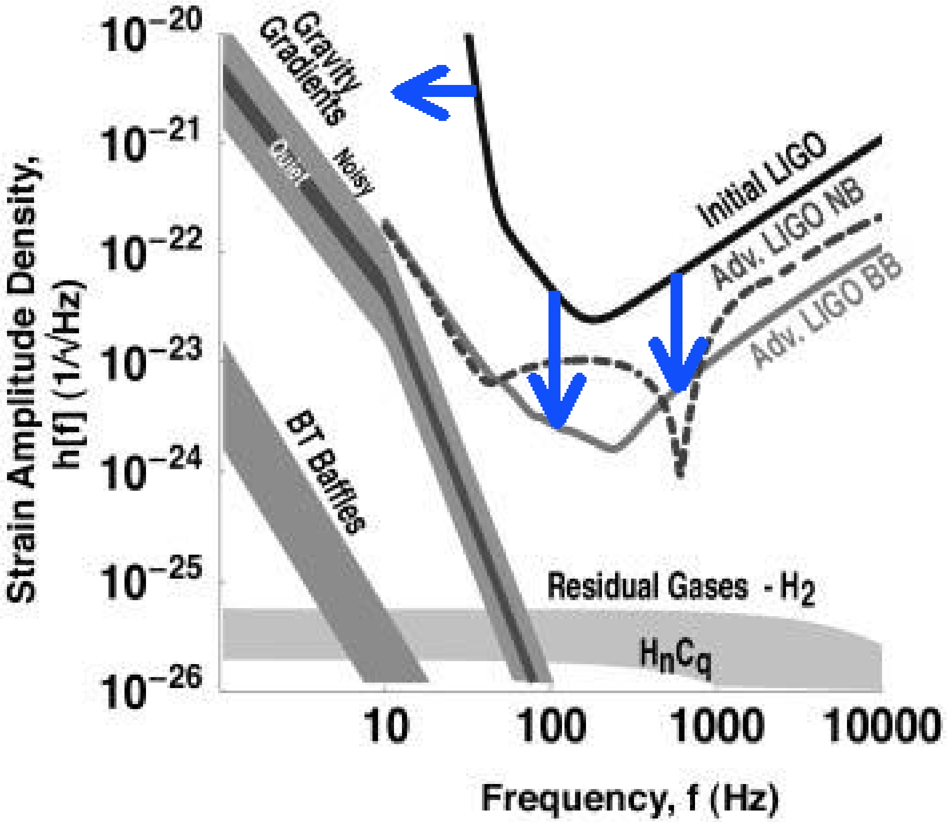
- Now being designed by the LIGO Scientific Collaboration (~25 institutions)
- Goal:
  - » Quantum-noise-limited interferometer
  - » Factor of ~ten increase in sensitivity
- Schedule:
  - » Begin installation: 2006
  - » Begin data run: 2008



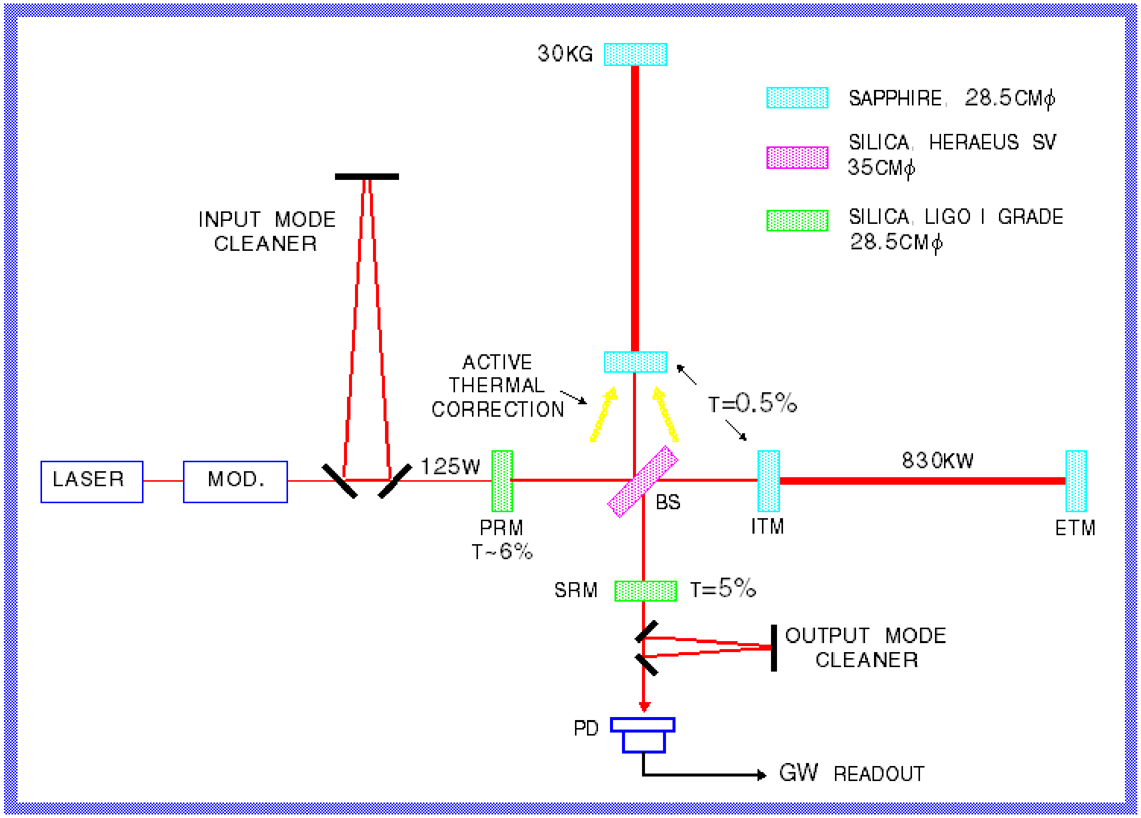
➢ ***First 2-3 hours of Advanced LIGO is equivalent to initial LIGO's 1 year science run***

Present and future limits to sensitivity

- ❑ Facility limits
  - Gravity gradients
  - Residual gas
  - (scattered light)
  - Leaves lots of room for improvement
- ❑ Advanced LIGO
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15
  - Shot noise 1/10, tunable
- ❑ Beyond Adv LIGO
  - Thermal noise: cooling of test masses
  - Quantum noise: quantum non-demolition



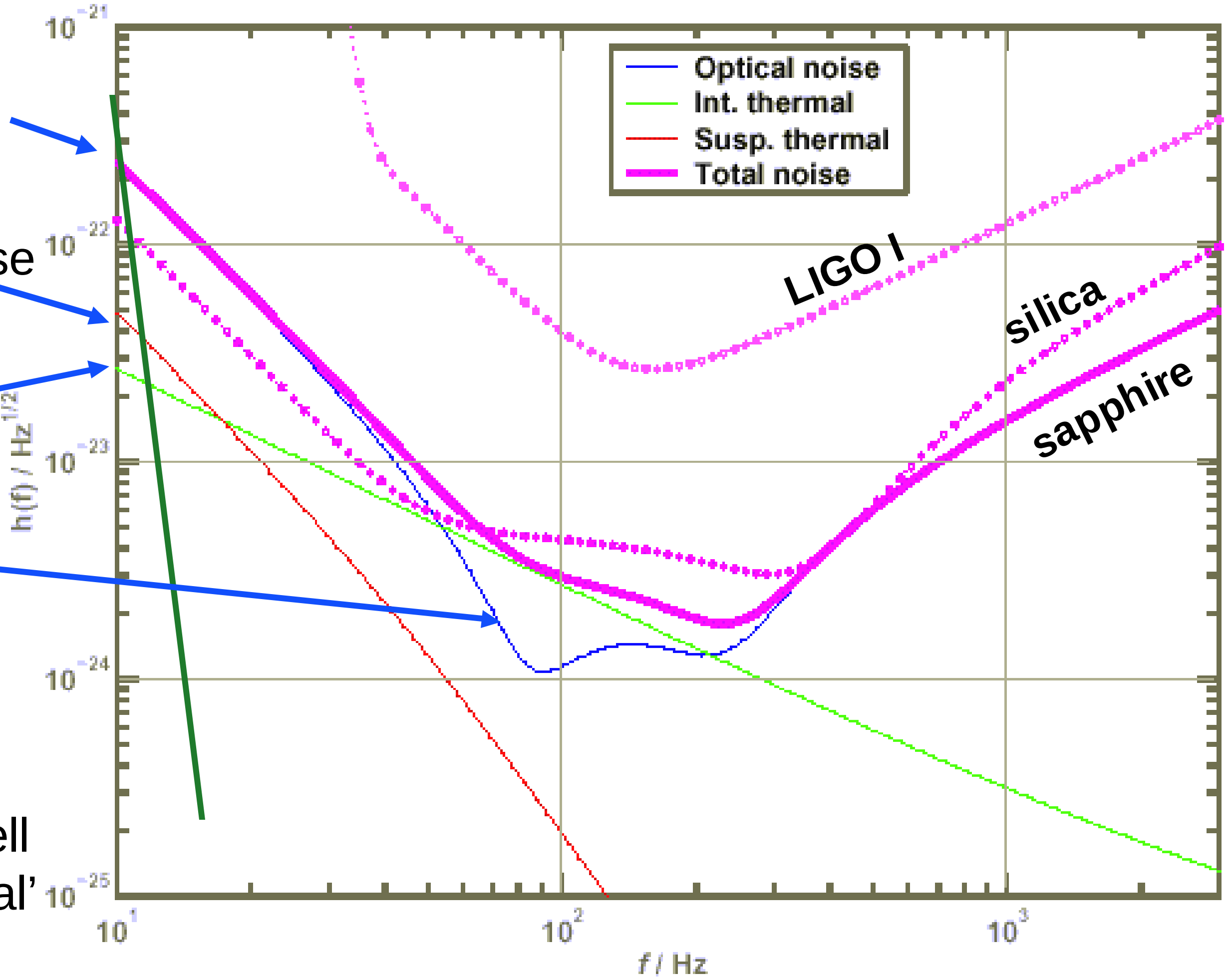
Advanced Interferometer Concept



- » Signal recycling
- » 180-watt laser
- » Sapphire test masses
- » Quadruple suspensions
- » Active seismic isolation
- » Active thermal correction

Anatomy of Projected Performance

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



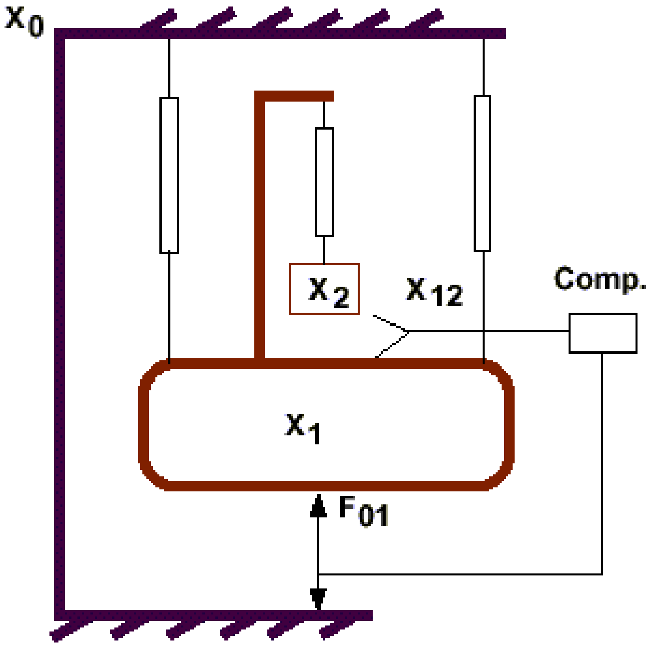
From Initial to Advanced LIGO

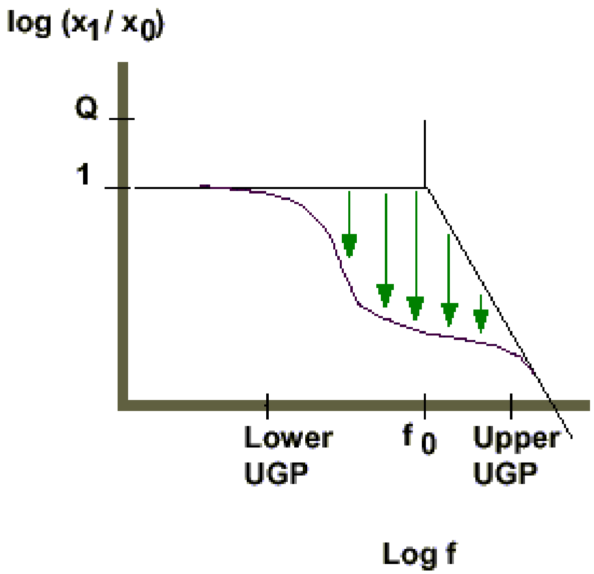
Parameter	LIGO I	LIGO II
Equivalent strain noise, minimum	$3x10^{-23}$/rtHz	$2x10^{-24}$/rtHz
Neutron star binary inspiral range	19 Mpc	285 Mpc
Stochastic backgnd sens.	$3x10^{-6}$	$1.5\text{-}8x10^{-9}$
Interferometer configuration	Power-recycled Michelson w/ FP arm cavities	LIGO I, plus signal recycling
Laser power at interferometer input	6 W	120 W
Test masses	Fused silica, 11 kg	Sapphire, 40 kg
Suspension system	Single pendulum, steel wires	Quad pendulum, silica fibers/ribbons
Seismic isolation system, type	Passive, 4-stage	Active, 2-stage
Seismic wall frequency	40 Hz	10 Hz

Advances in Seismic Isolation

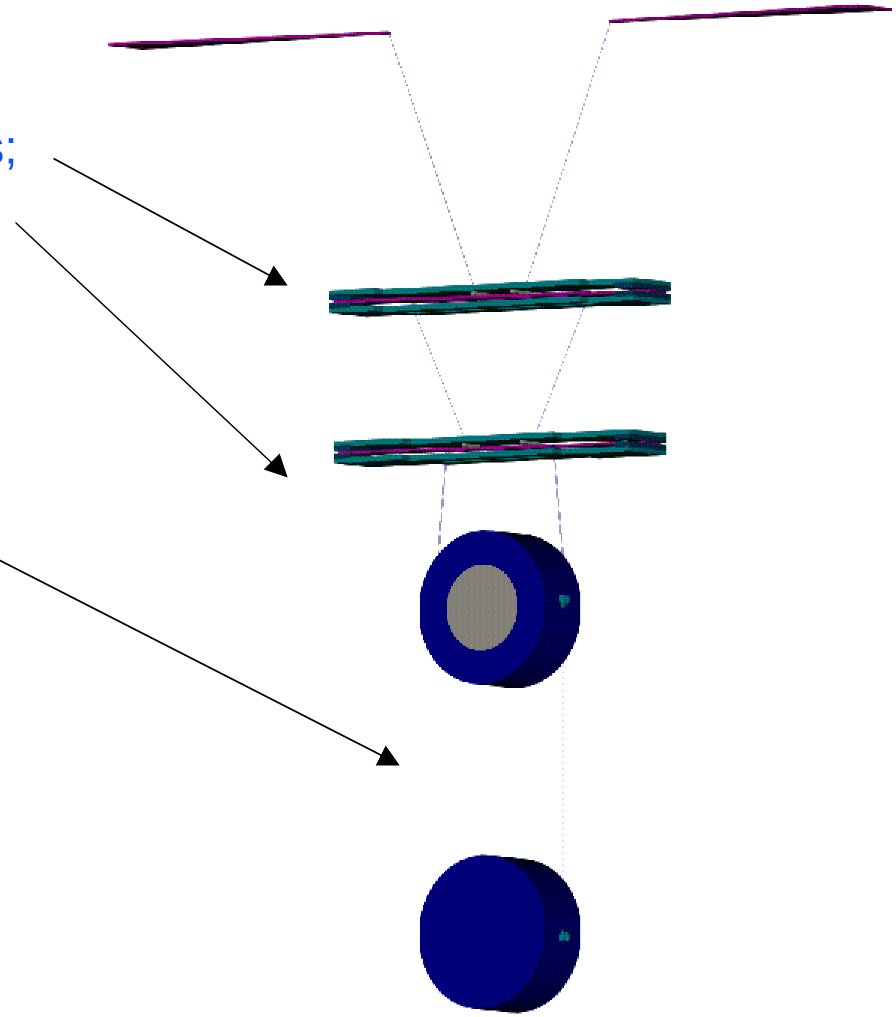
- ❑ Goal taken as 10^{-19} m/rtHz at 10 Hz
  - Corresponds to level of suspension thermal noise
  - Very close to gravity-gradient noise around 10 Hz
  - Ground noise attenuation of 10^{10} required
- ❑ Active seismic isolation

- 2 in-vacuum stages, each w/ sensors & actuators for 6 DOF
- provides ~1/3 of the required attenuation
- provides ~10^3 reduction of rms at lower frequencies, crucial for controlling technical noise sources





Advances in Suspensions



- ❑ Quadruple suspension:
  - ~10^7 attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses
- ❑ Fused silica fiber
  - Welded to 'ears', hydroxy-catalysis bonded to optic
- ❑ Seismic isolation and suspension together:
  - 10^{-20} m/rtHz at 10 Hz
  - Factor of 10 margin

Advances in Thermal Noise

- ❑ Suspension thermal noise
  - Fused silica fibers, ~10^4x lower loss than steel wire
  - Ribbon geometry – more compliant along optical axis
- ❑ Internal thermal noise

Sapphire test masses:

- Much higher Q: 2e8 vs 2-3e6 for LIGO I silica
- BUT, higher *thermoelastic damping* (higher thermal conductivity and expansion coeff); can counter by increasing beam size
- Requires development in size, homogeneity, absorption

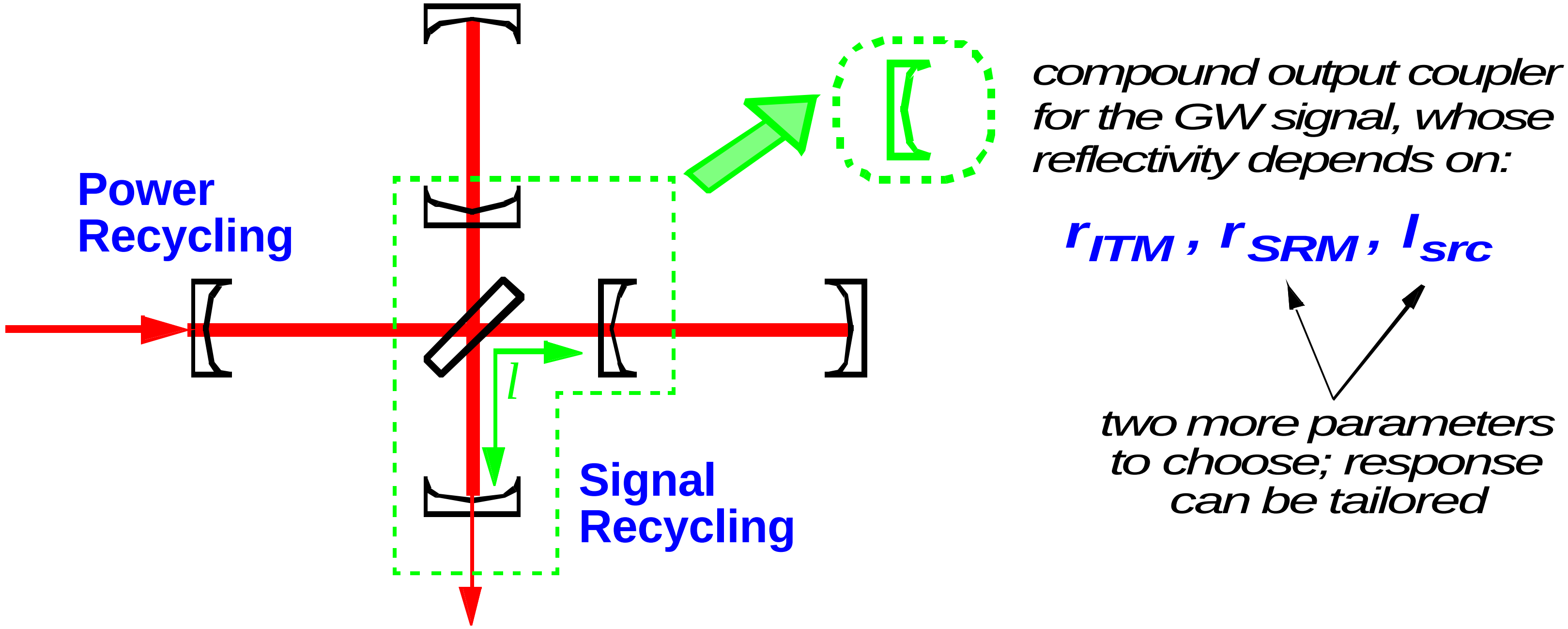
Fused silica test masses:

- Intrinsic Q can be much higher: ~5e7 (avoid lossy attachments)
- Low absorption and inhomogeneity, but expensive

Both materials: mechanical loss from polishing and dielectric coatings must be studied and controlled

Advances in Sensing

- Input laser power: 120 W
  - Incremental progress in laser technology
  - Thermal management in the interferometer become a big issue!
- Optimizing interferometer response

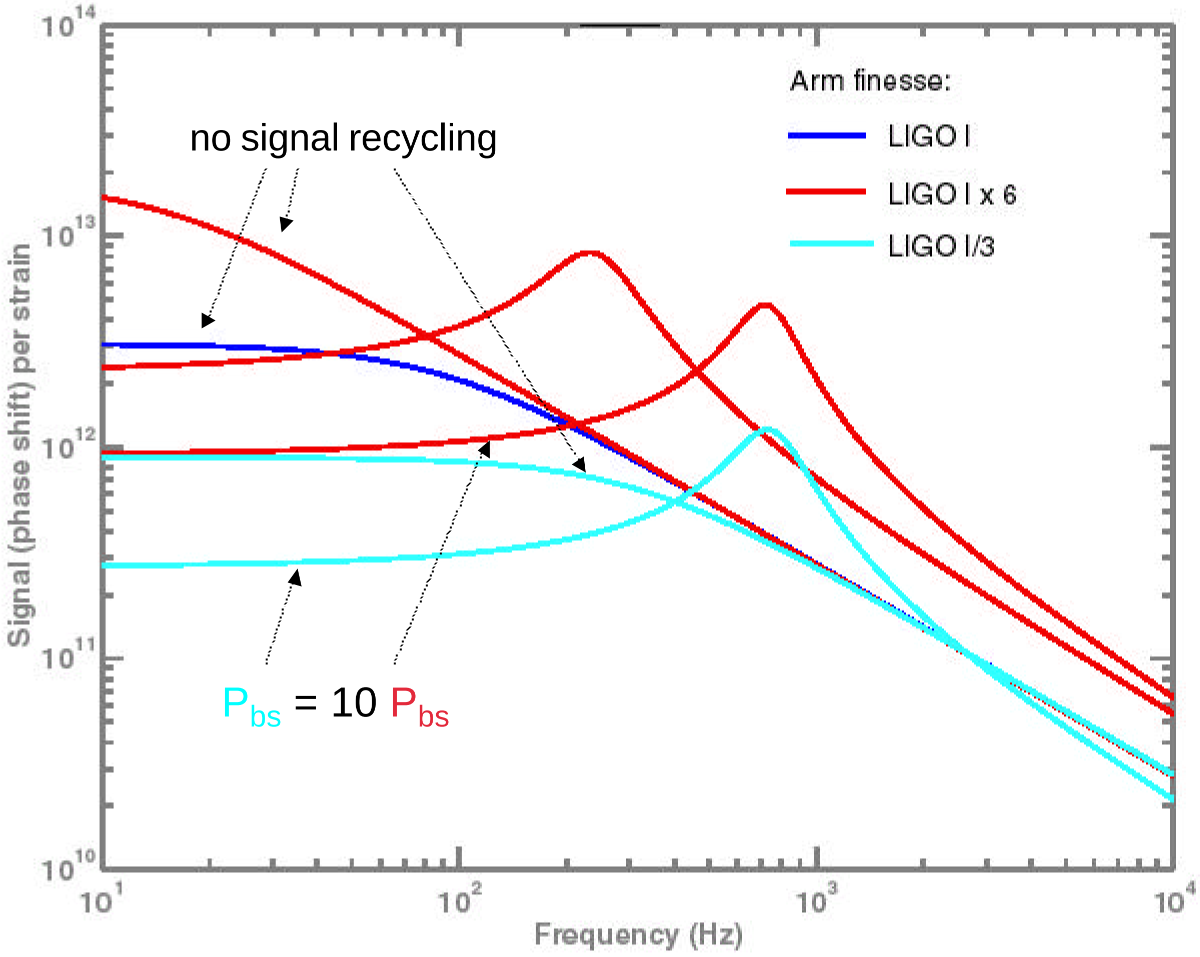


compound output coupler for the GW signal, whose reflectivity depends on:

$r_{ITM}\,,\; r_{SRM}\,,\; l_{src}$

two more parameters to choose; response can be tailored

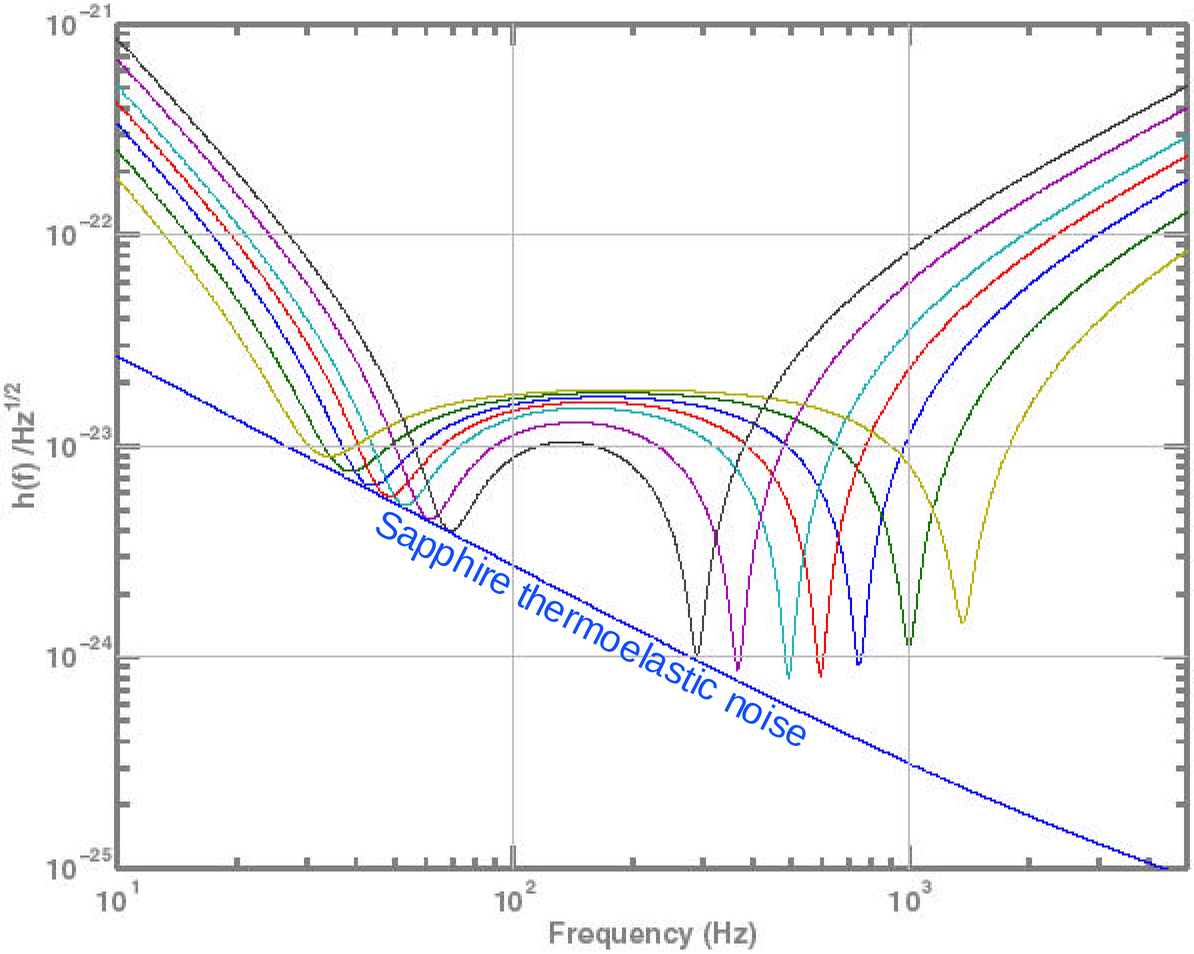
Response functions



no signal recycling

$P_{bs} = 10\ P_{bs}$

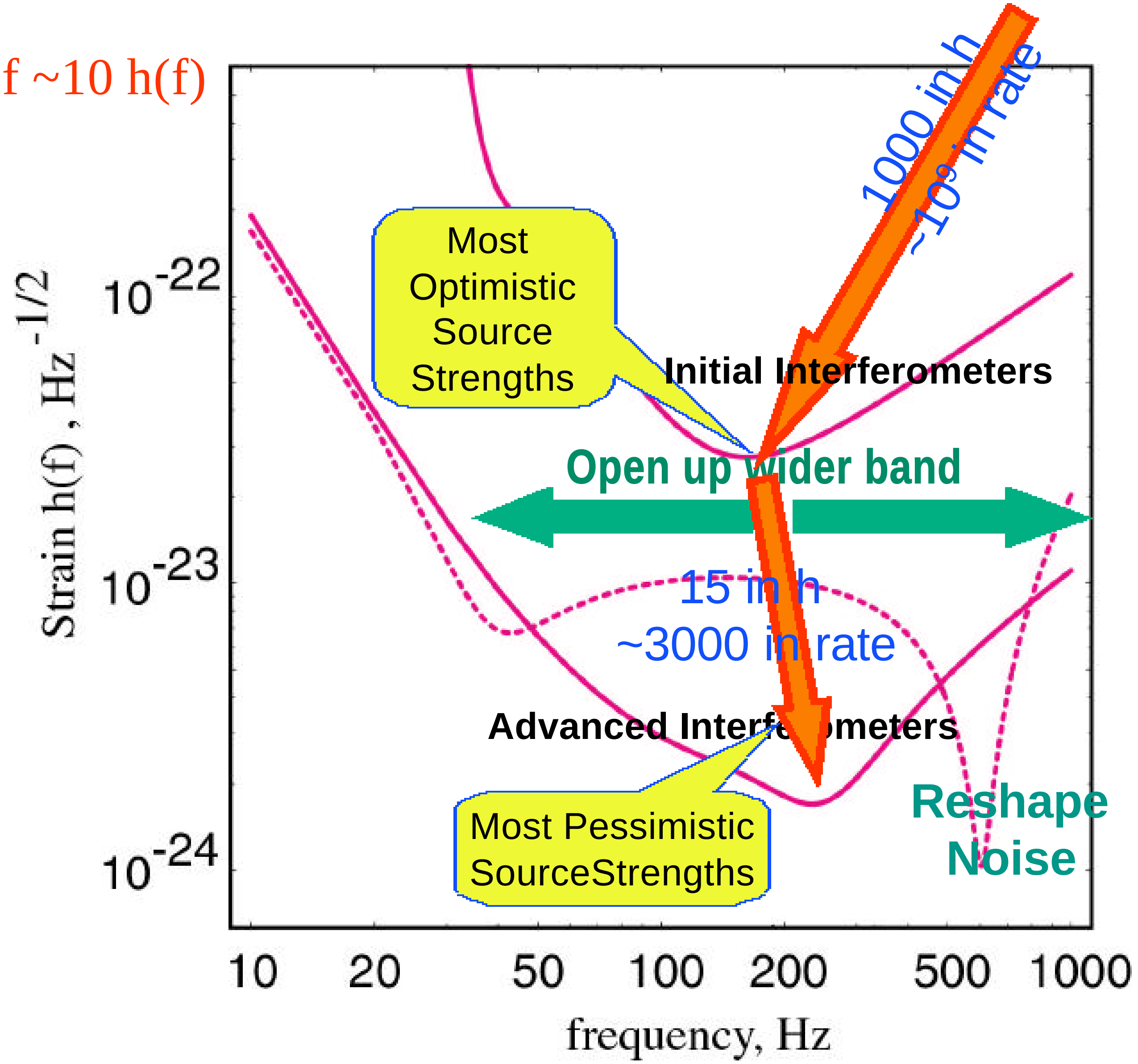
A Narrowband Interferometer



Example tuning curves for a fixed transmission signal recycling mirror

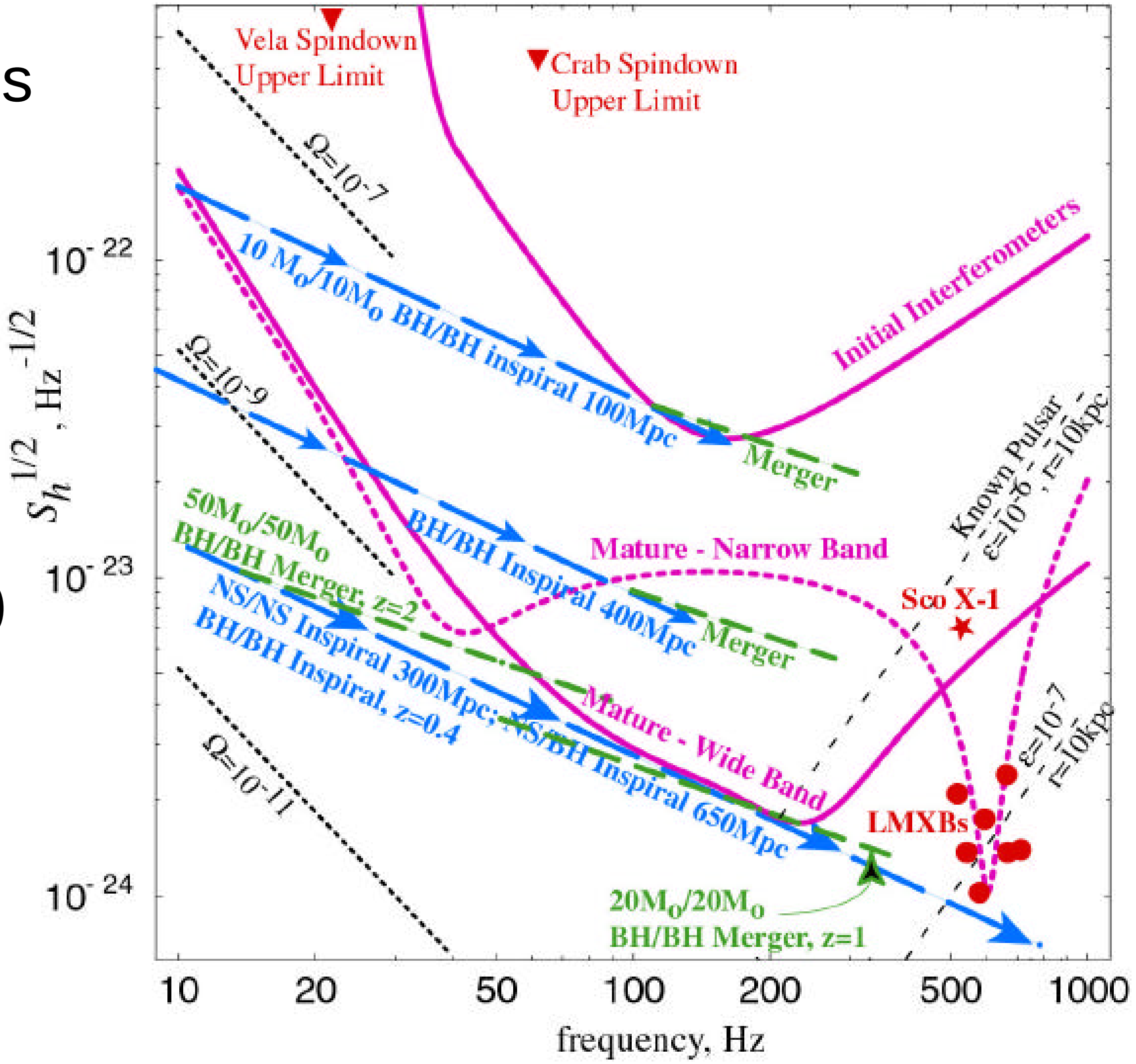
Source Detection: from Initial Interferometers to Advanced

$h_{rms} = h(f) \sqrt{f} \sim 10\ h(f)$



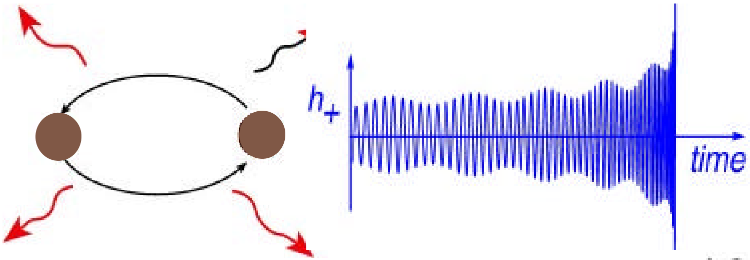
Overview of Sources

- Neutron Star & Black Hole Binaries
  - inspiral
  - merger
- Spinning NS’s
  - LMXBs
  - known pulsars
  - previously unknown
- NS Birth (SN, AIC)
  - tumbling
  - convection
- Stochastic background
  - big bang
  - early universe



Neutron Star / Neutron Star Inspiral

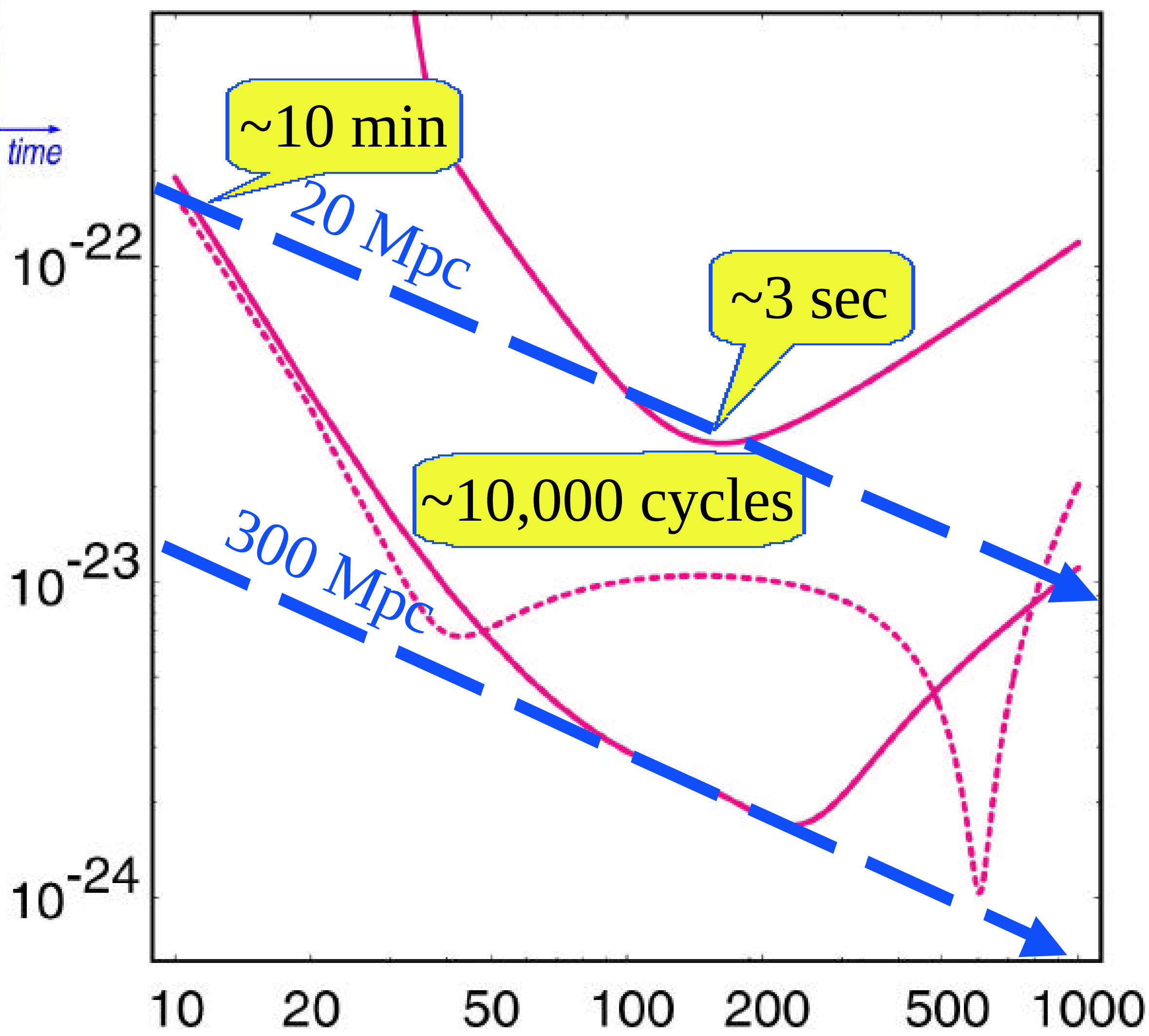
(our most reliably understood source)



- 1.4 Msun / 1.4 Msun NS/NS Binaries

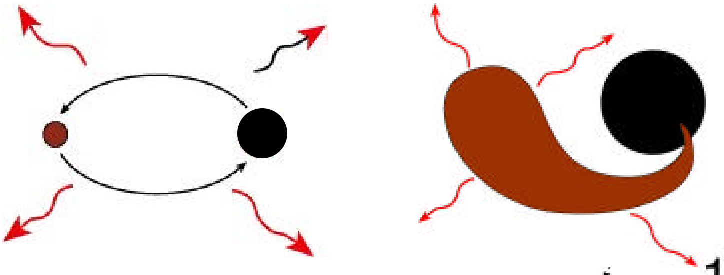
Event rates:*

- Initial IFOs
  - Range: 20 Mpc
  - 1 / 3000 yrs to **1 / 3yrs**
- Advanced IFOs -
  - Range: 300Mpc
  - **1 / yr to 2 / day**



*V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor, astro-ph/0012038

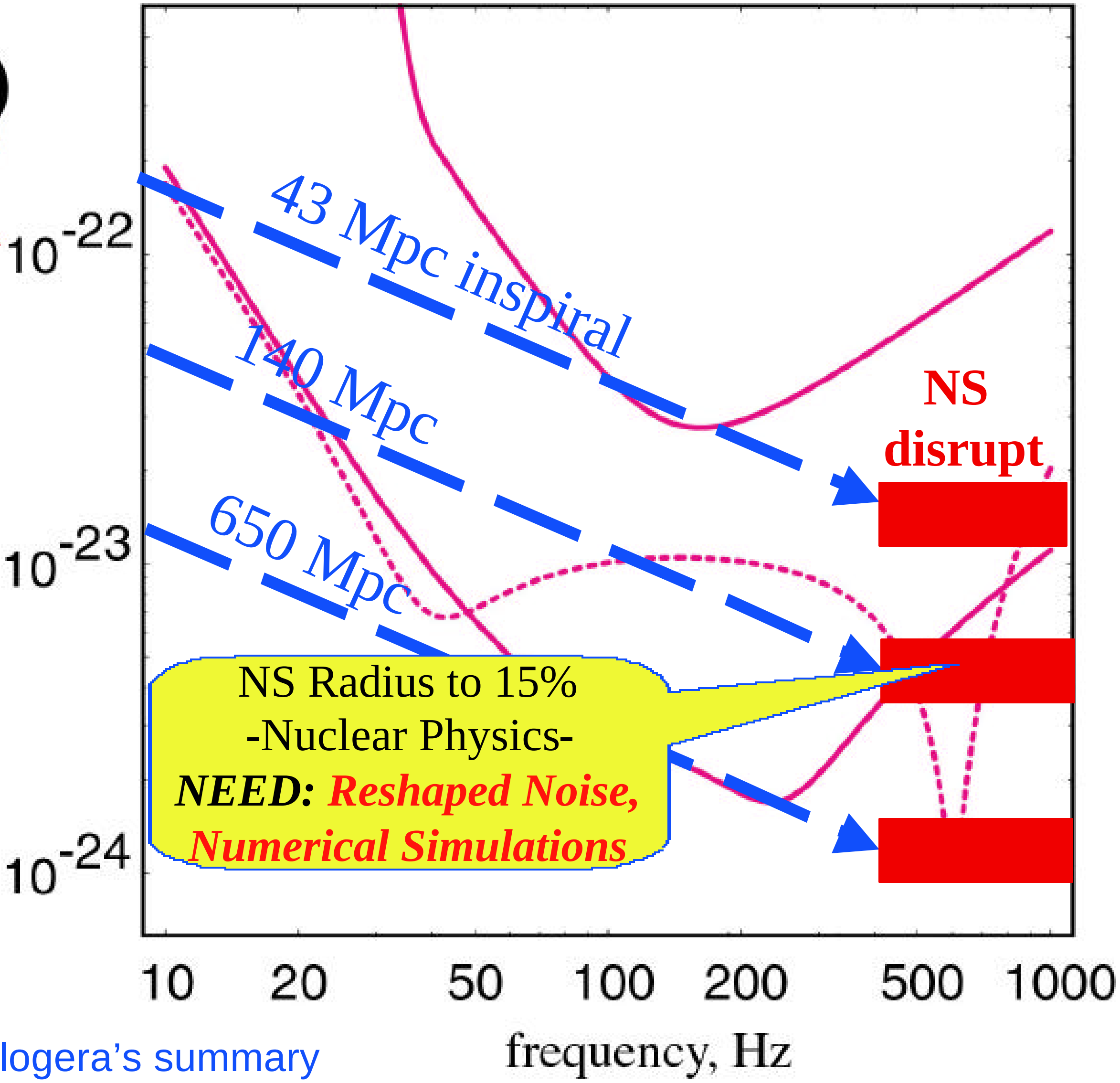
Neutron Star / Black Hole Inspiral and NS Tidal Disruption



- 1.4Msun / 10 Msun NS/BH Binaries

Event rates:*

- Initial IFOs
    - Range: 43 Mpc
    - ≲1 / 2500 yrs to **1 / 2yrs**
- Advanced IFOs
    - Range: 650 Mpc
    - ≲ **1 / yr to 4 / day**

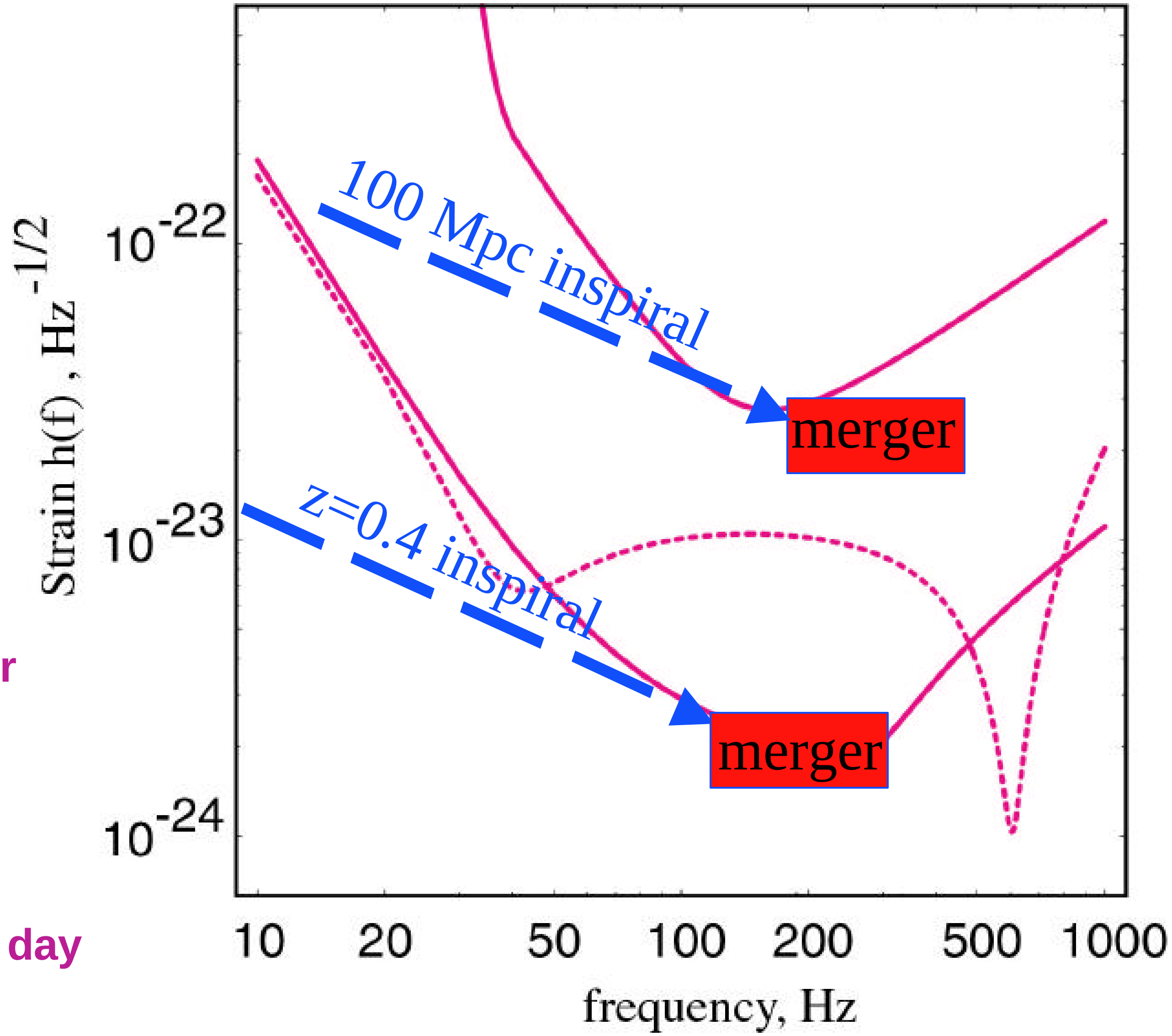


NS Radius to 15%
-Nuclear Physics-
NEED:* *Reshaped Noise, Numerical Simulations

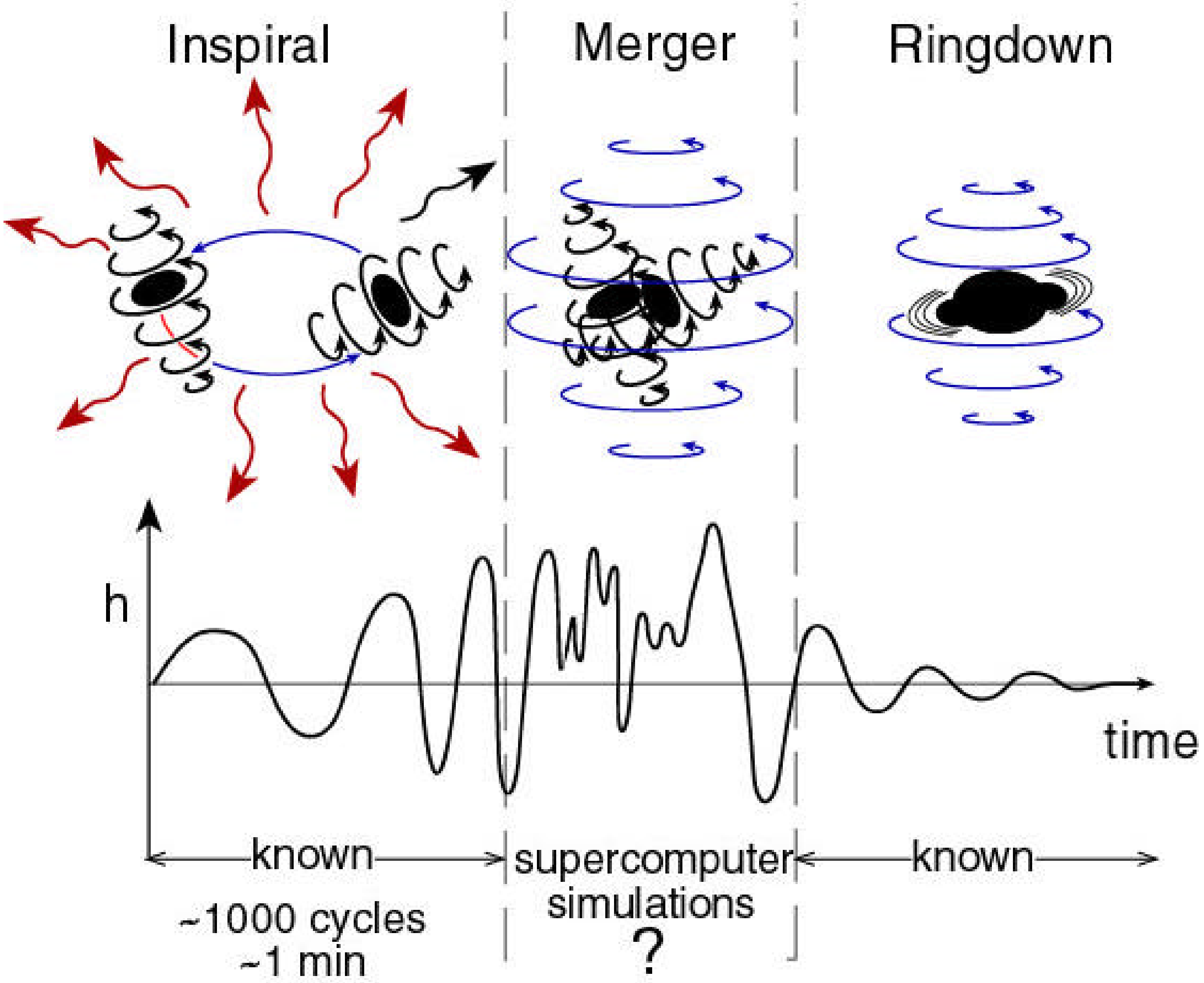
*Kalogera's summary

Black Hole / Black Hole Inspiral and Merger

- ❑ 10Msun / 10 Msun BH/BH Binaries
- ❑ Event rates
  - Based on population synthesis [Kalogera’s summary of literature]
- ❑ Initial IFOs
  - Range: 100 Mpc
  - ≲ 1 / 300yrs to **~1 / yr**
- ❑ Advanced IFOs -
  - Range: z=0.4
  - **≲ 2 / month to ~10 / day**



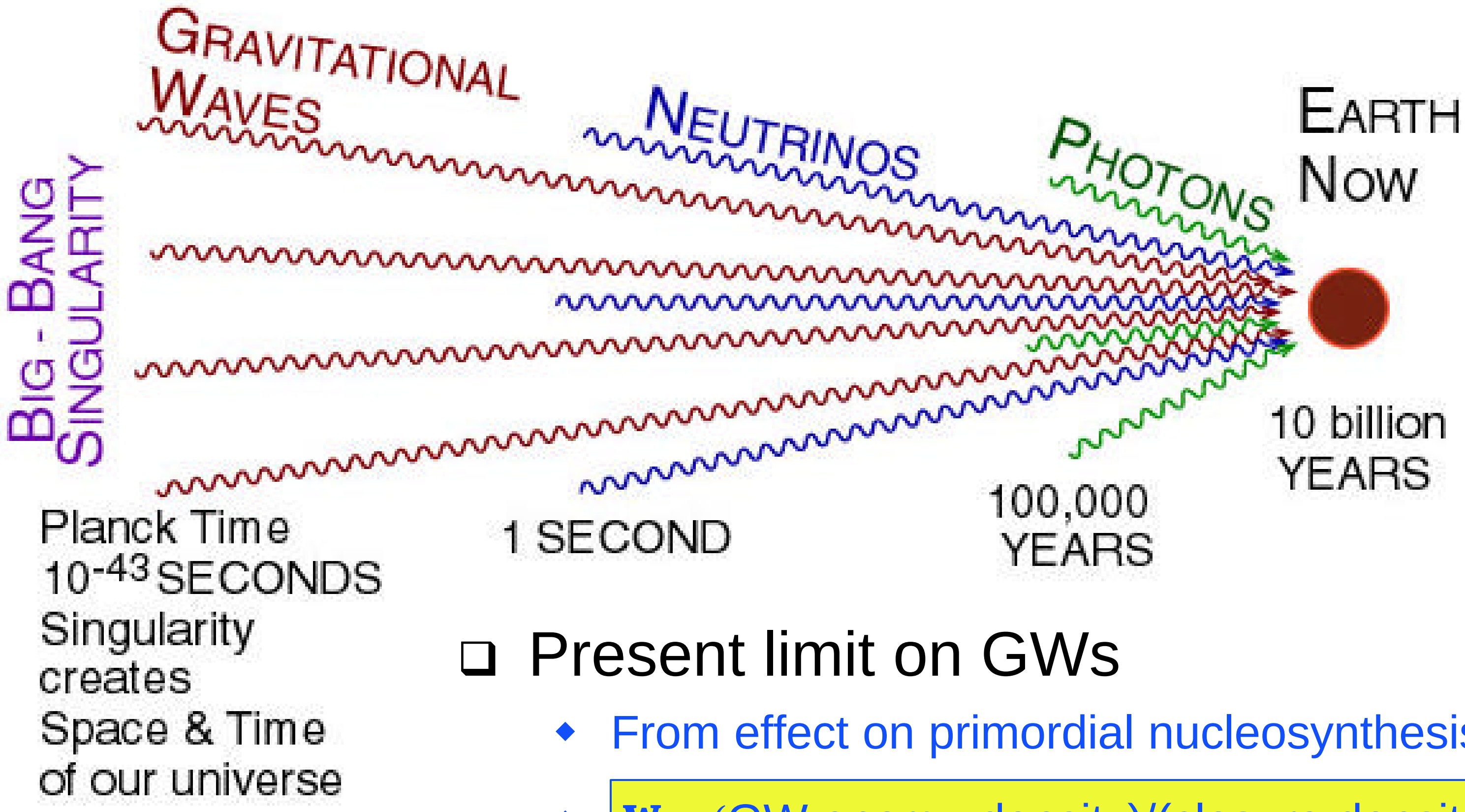
BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



Numerical Relativity Simulations Are Badly Needed!

Stochastic Background from Very Early Universe

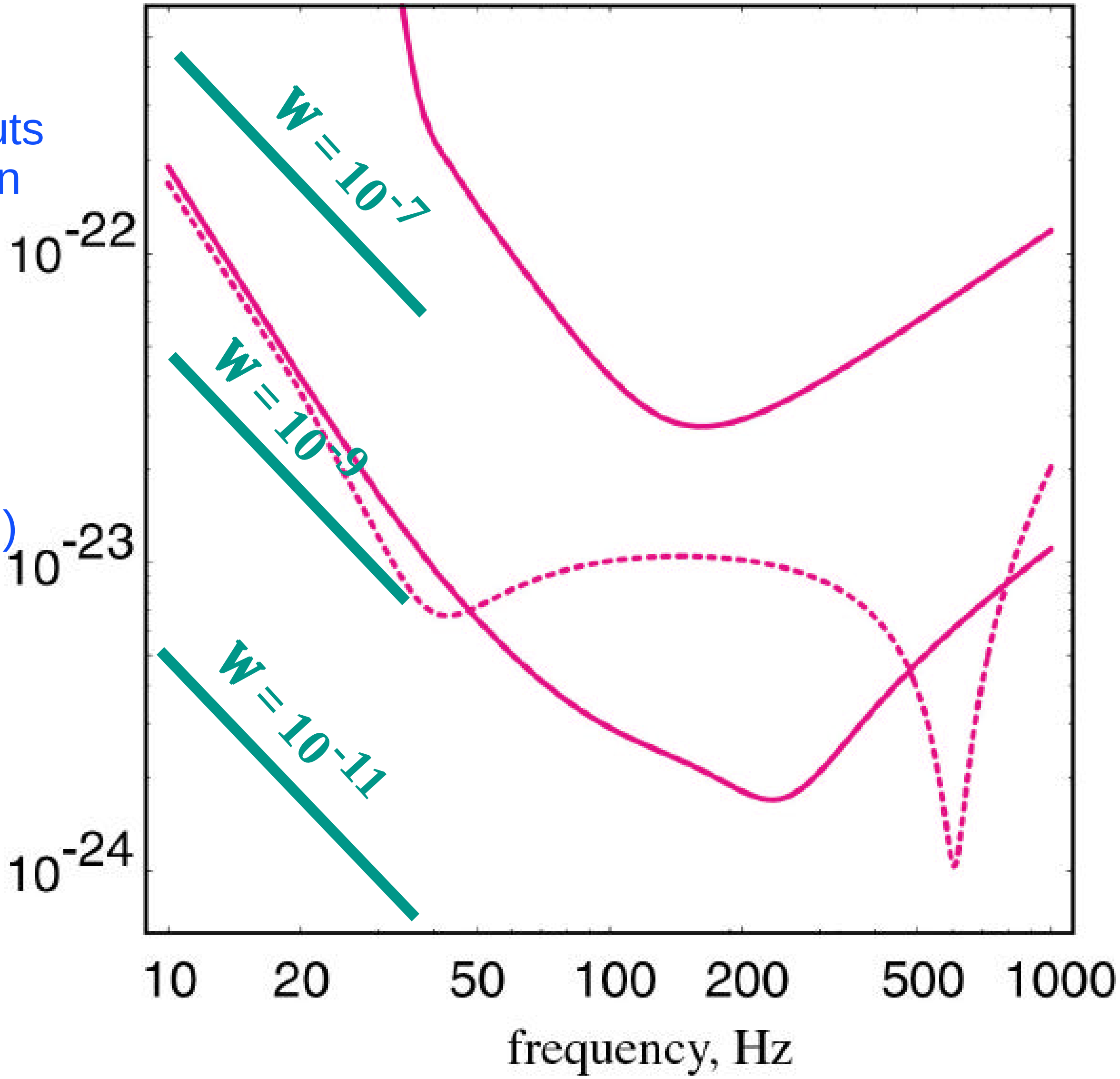
- ☐ GW's are the ideal tool for probing the very early universe



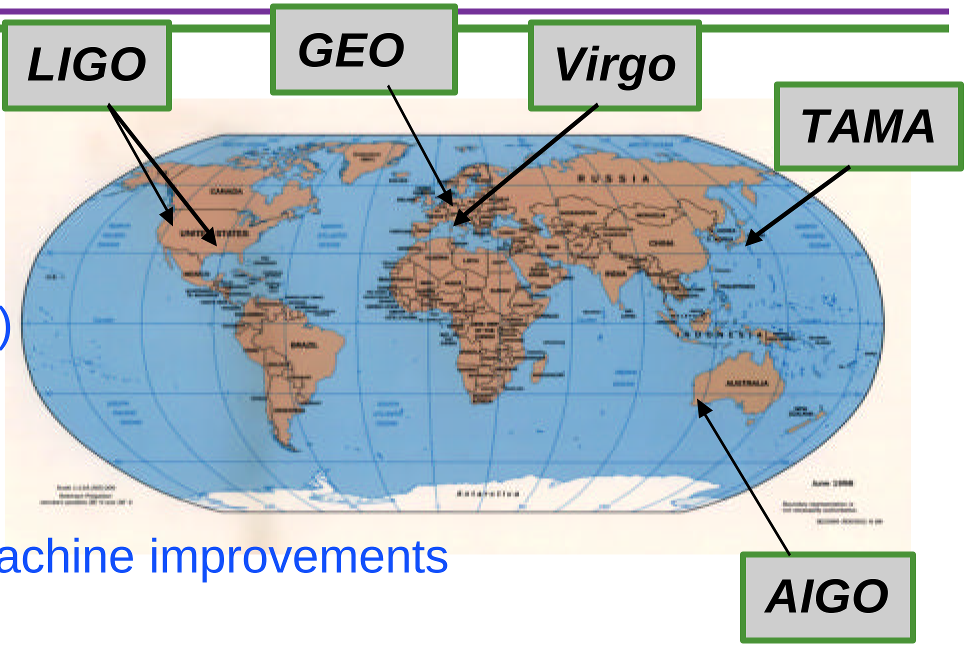
- ☐ Present limit on GWs
  - From effect on primordial nucleosynthesis
  - **W** = (GW energy density)/(closure density) $\lesssim \mathbf{10^{-5}}$

Stochastic Background from Very Early Universe

- ☐ Detect by
  - cross correlating outputs of Hanford & Livingston 4km IFOs
- ☐ Good sensitivity requires
  - (GW wavelength) ≳ **2x**(detector separation)
  - $f \lesssim 40$ Hz
- ☐ Initial IFOs detect if
  - **W ≳ 10^{-5}**
- ☐ Advanced IFOs:
  - **W ≳ 5×10^{-9}**



Where do we go from here?



- ❑ 2001
  - Detector commissioning
  - Improve sensitivity/ reliability
  - Initial data run (“upper limit run”)
- ❑ 2002
  - Begin Science Run
  - Interspersed data taking and machine improvements
- ❑ Advanced LIGO R&D

- ➢ *LIGO’s Initial Interferometers bring us into the realm where it is plausible to begin detecting GW’s*
- ➢ *With LIGO’s Advanced Interferometers we can be confident of detecting waves from a variety of sources, and gaining major new insights into the universe and the nature of spacetime curvature*