The Advanced LIGO detector

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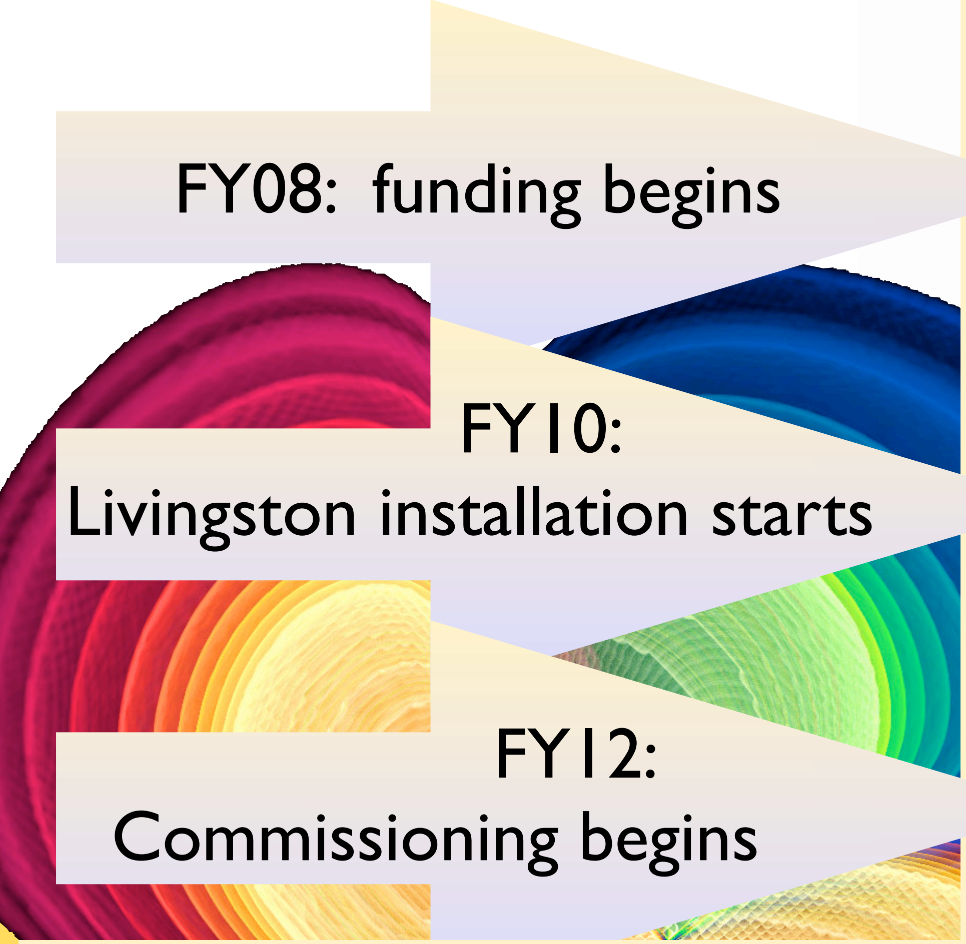
for the **LIGO Scientific Collaboration**

40+ institutions, hundreds of people ⇒ it is difficult to give credit where due …

AMALDI6 24 June, 2005 LIGO-G050315-00-D

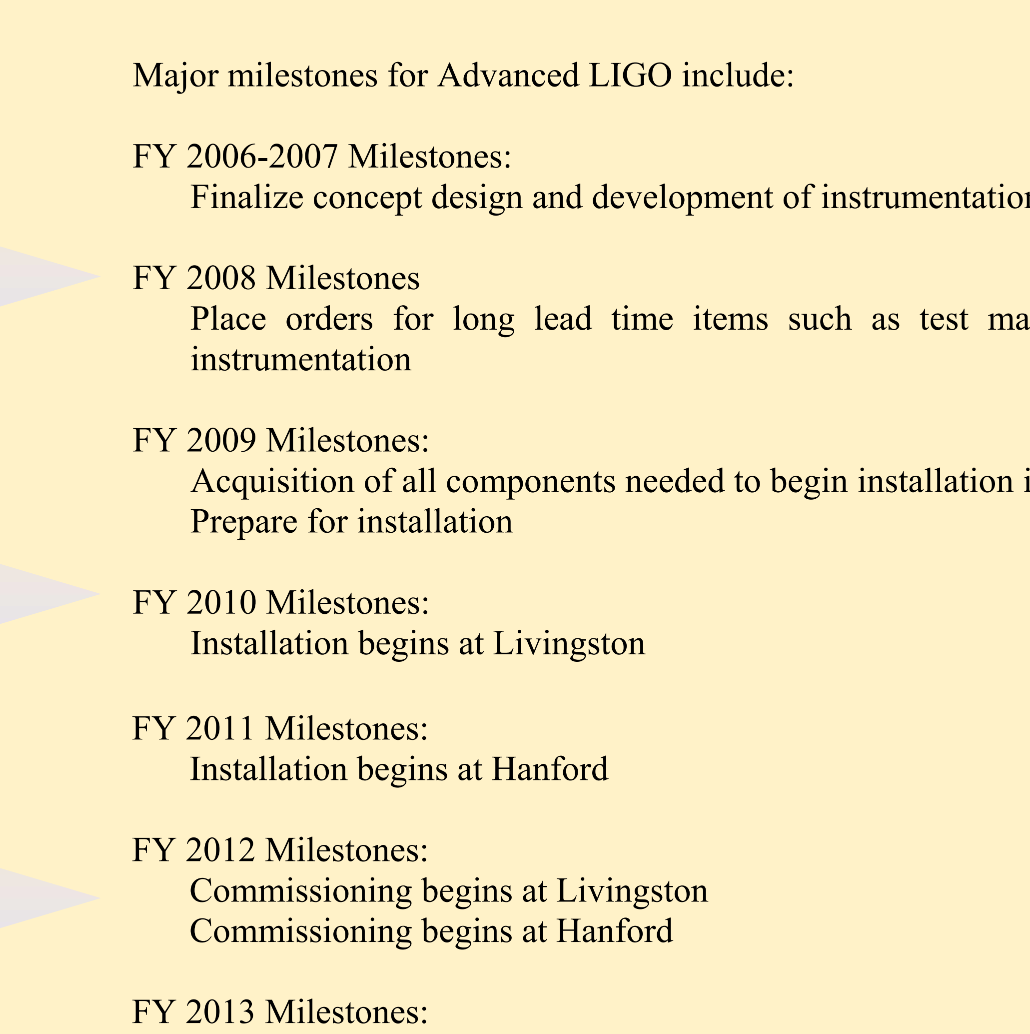
Clippings from the NSF FY ’06 budget *request* to the US Congress



FY08: funding begins

FY10:
Livingston installation starts

FY12:
Commissioning begins



Major milestones for Advanced LIGO include:

FY 2006-2007 Milestones:
Finalize concept design and development of instrumentation

FY 2008 Milestones
Place orders for long lead time items such as test mass optics; continue design of remaining instrumentation

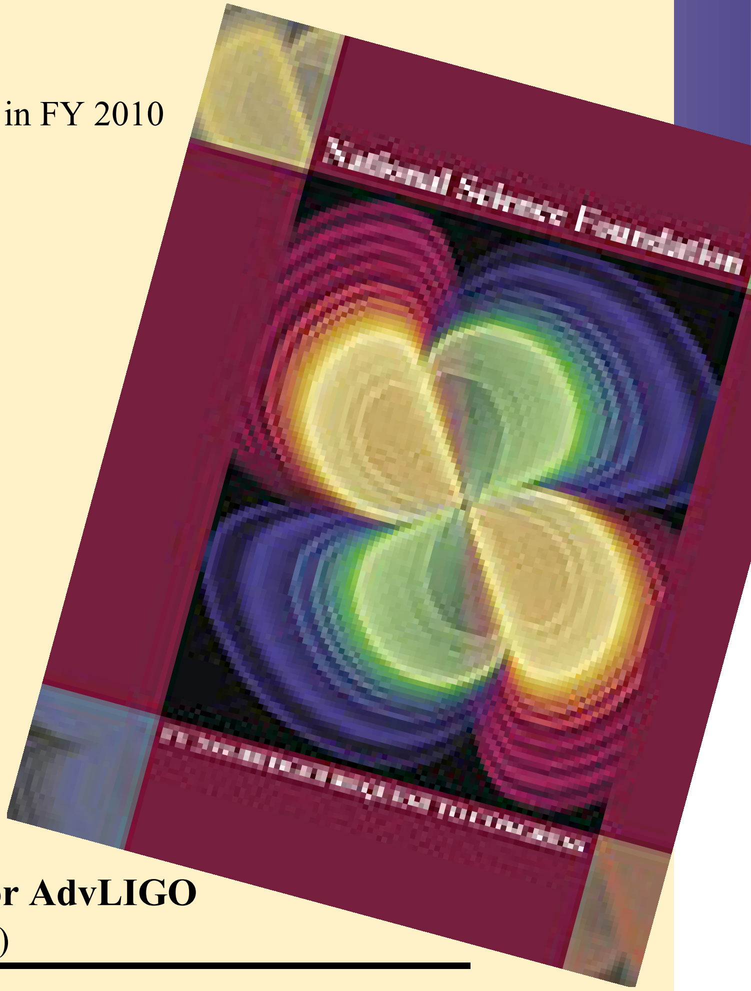
FY 2009 Milestones:
Acquisition of all components needed to begin installation in FY 2010
Prepare for installation

FY 2010 Milestones:
Installation begins at Livingston

FY 2011 Milestones:
Installation begins at Hanford

FY 2012 Milestones:
Commissioning begins at Livingston
Commissioning begins at Hanford

FY 2013 Milestones:



nds for AdvLIGO
illions)

1	FY 2012	FY 2013	Total
	$22.90	$7.60	$184.35

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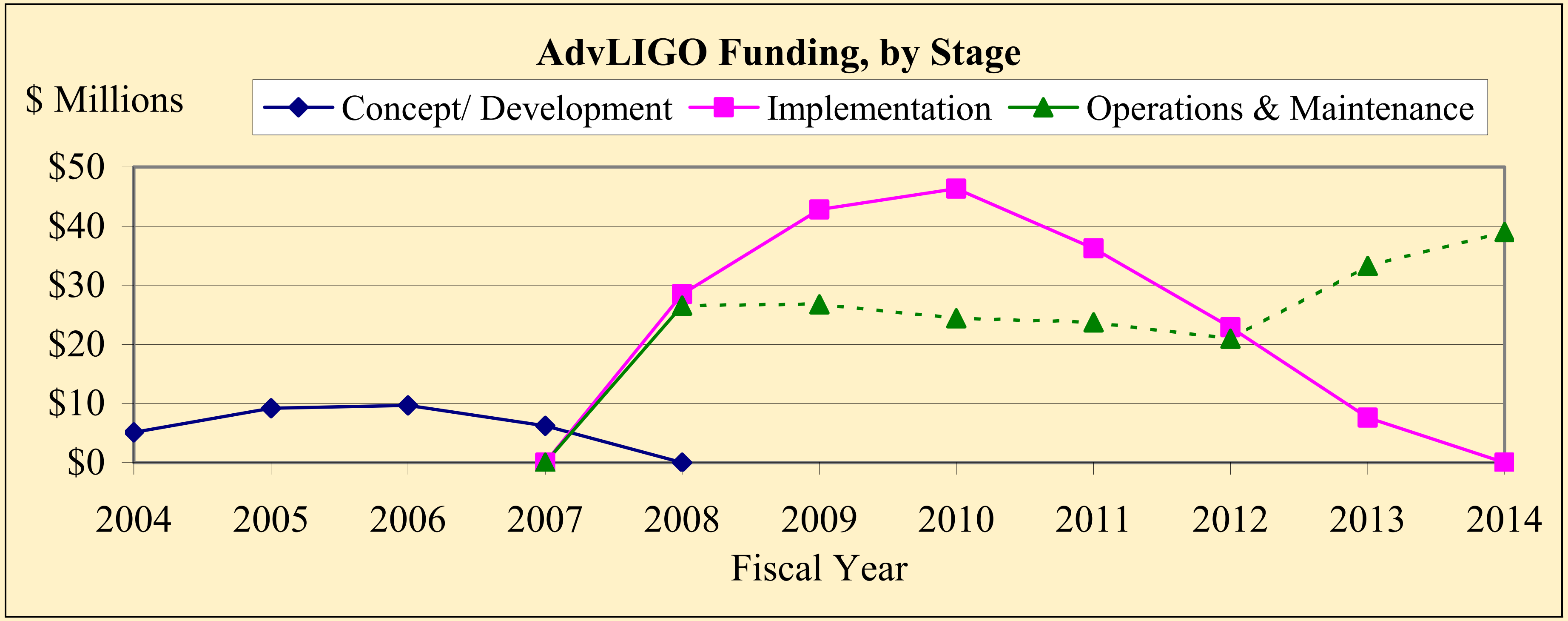
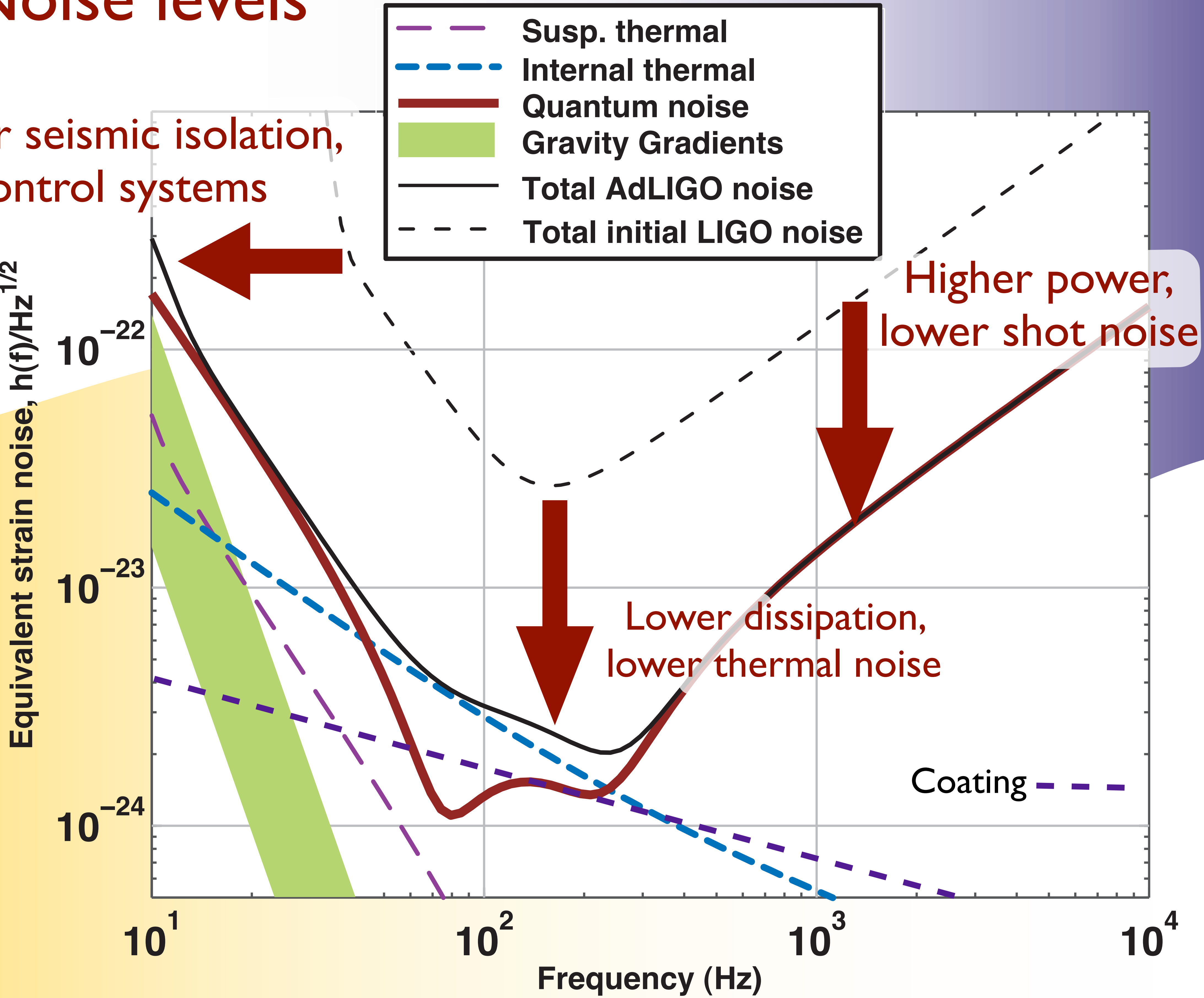


Partner contributions

- GEO/Germany
    - Presidential board of the Max Planck Society has endorsed Albert Einstein Institute (AEI) plans for Adv LIGO material contribution, the **Laser** etc.
- GEO/U.K.
    - U.K. PPARC approved (2003) approximately £ 8.8 M for
        - **Suspension** systems based on GEO technology
        - displacement sensors
        - one interferometer's test mass substrates.
- ACIGA
    - applied to ARC for funding to carry out (e.g.) parametric instability tests at Gingin, and development/production of output mode cleaner

Noise levels



Better seismic isolation, control systems

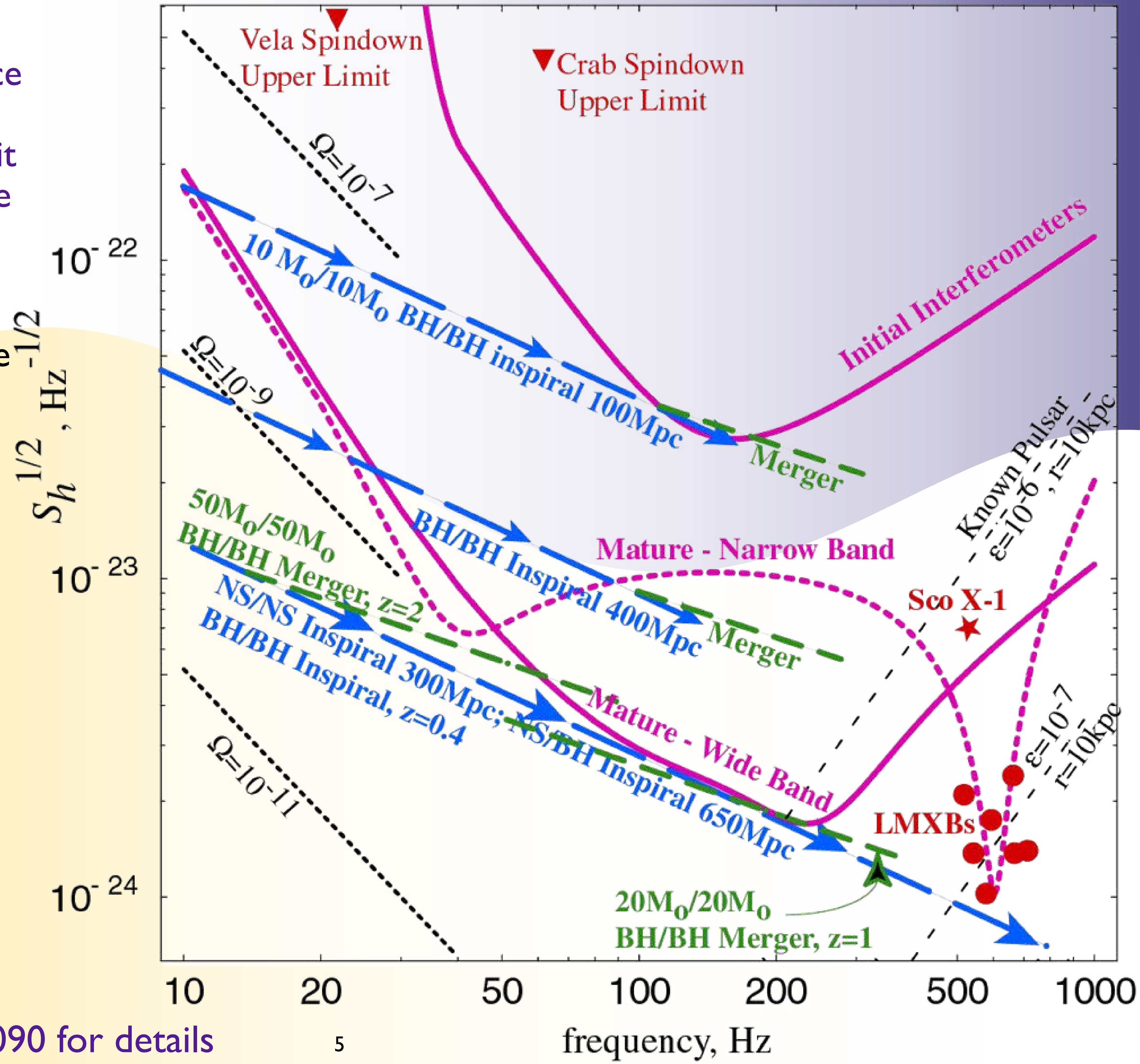
Higher power, lower shot noise

Lower dissipation, lower thermal noise

Sources for Advanced LIGO (Thorne)

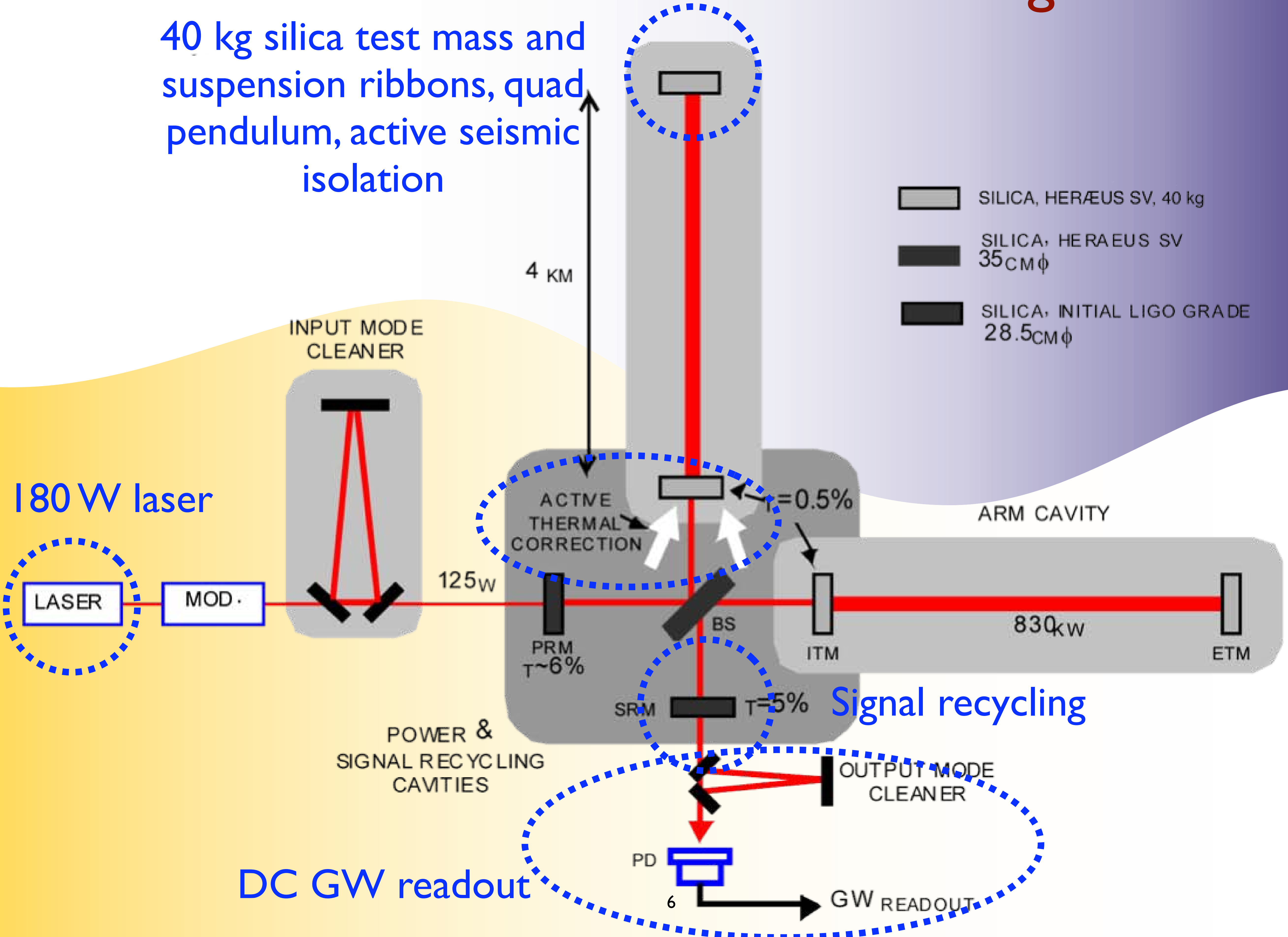
- "Kip" diagram: when source line coincides with that of interferometer sensitivity, it is detectable with 10^{-6} false alarm rate for reasonable observation time...

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



Please see gr-qc/0204090 for details

Advanced LIGO detector design



40 kg silica test mass and suspension ribbons, quad pendulum, active seismic isolation

180 W laser

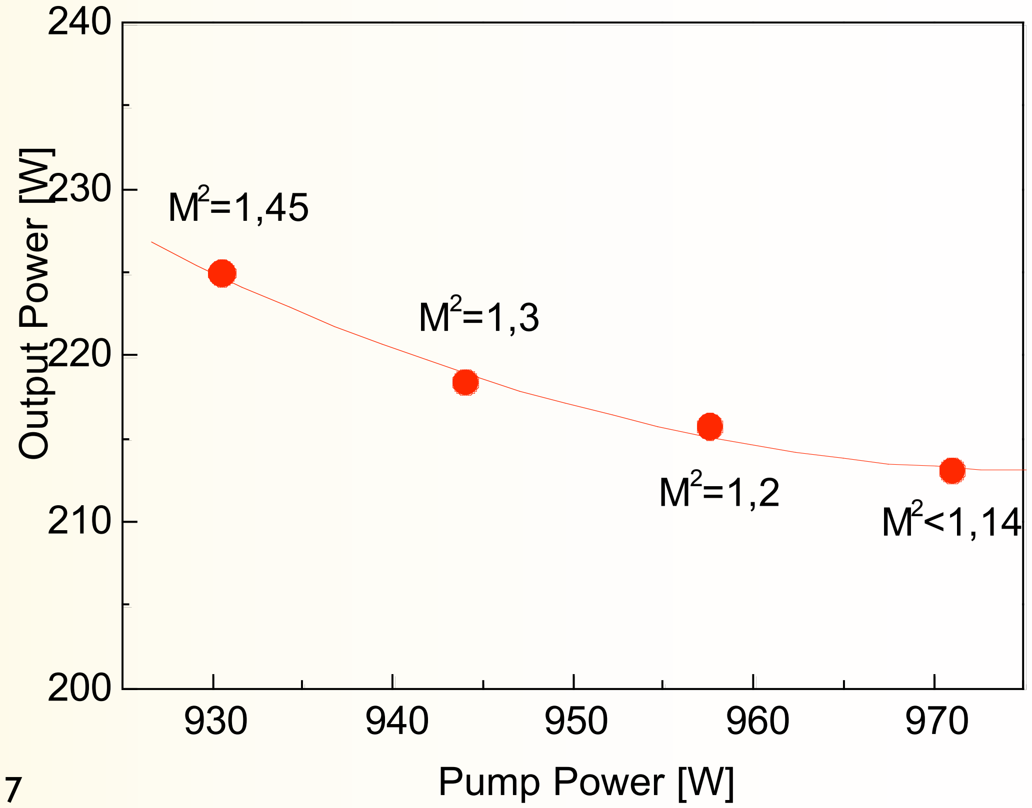
Signal recycling

DC GW readout

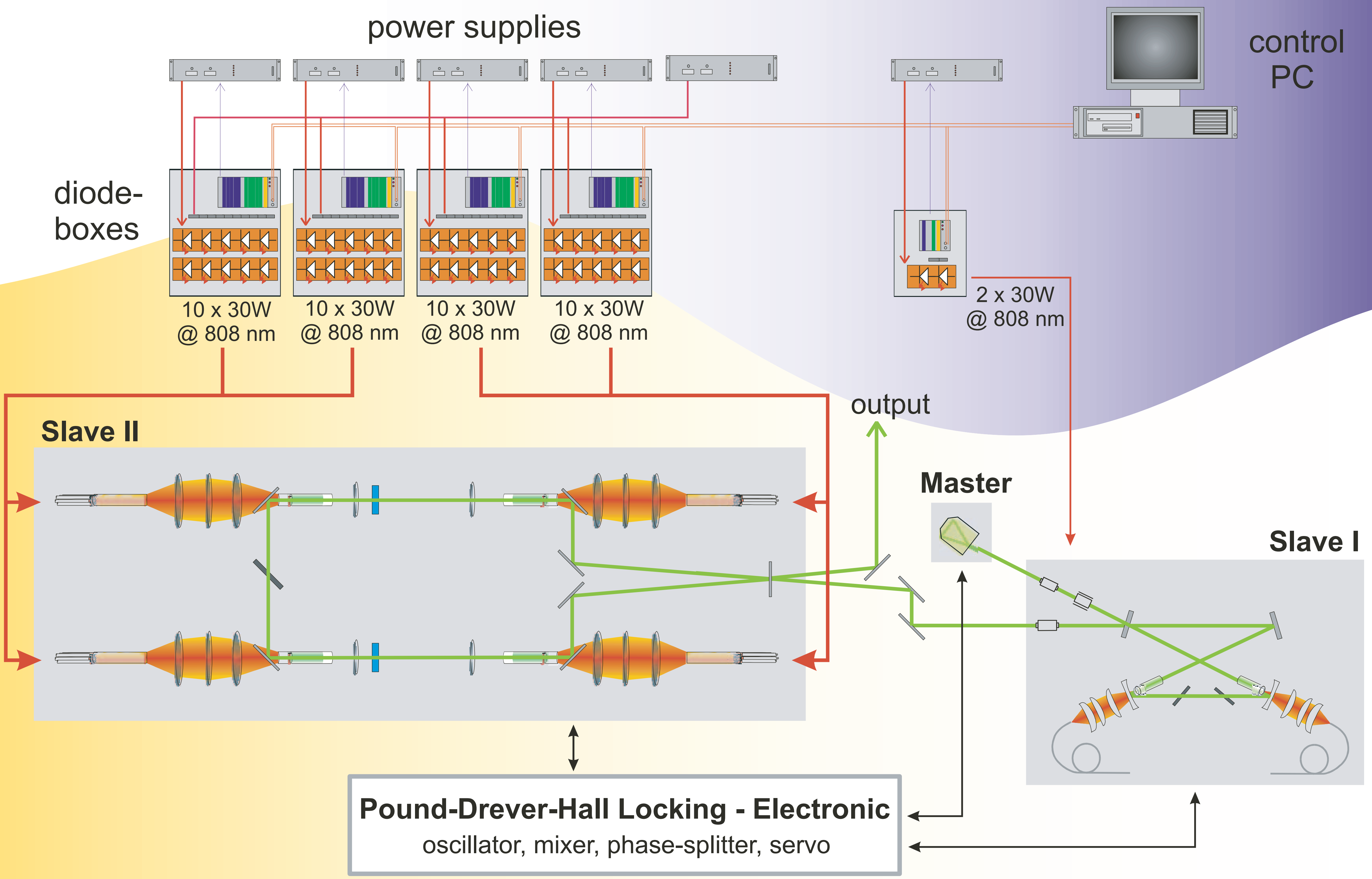
High power laser

- Front end similar to what is in service at GEO 600, monolithic ring oscillator, diode pumped, followed by injection-locked oscillator.
- New, high-power second injection-locked oscillator, 200 W
  - Conduction-cooled, end-pumped rods
  - Thermal compensation via symmetry in ring
- Active control of pump diode and laser rod temperatures.
- Design and production at Laser Zentrum Hannover. Please listen for Benno Willke's talk this afternoon.

Parameter	Specification
1. type of laser	Nd:YAG
2. wavelength	1064 nm
3. power in a circular TEM_{00} mode	>200 W
4. power in all other modes	< 20 W
5. polarization extinction ratio	100:1 in the vertical plane
6. relative power fluctuations	$<10^{-3}/\sqrt{\text{Hz}}$ between 0.1 Hz and 10 Hz $<10^{-5}/\sqrt{\text{Hz}}$ between 10 Hz and 10 kHz $<2\times10^{-9}/\sqrt{\text{Hz}}$ for $f>9$ MHz (3dB above shot noise of 50mA photocurrent)
7. frequency fluctuations	$<1\times10^{4}\ \text{Hz}/\sqrt{\text{Hz}}\times\left[1\ \text{Hz}/f\right]$ between 1 Hz and 10 kHz (same as NPRO free running)



Adv LIGO high-power Laser



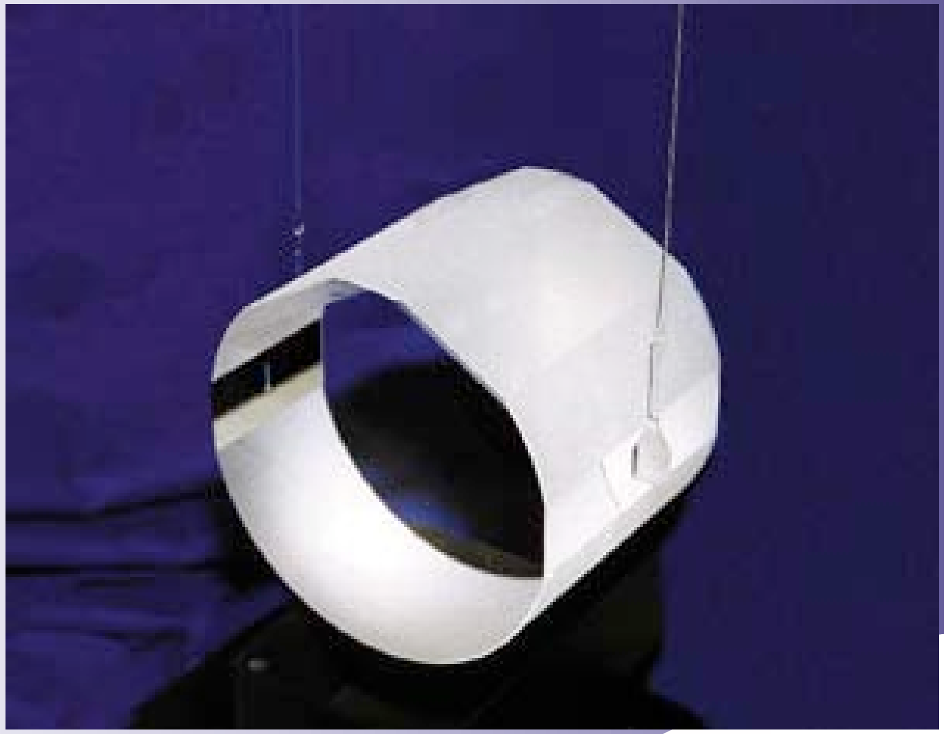
Pound-Drever-Hall Locking - Electronic

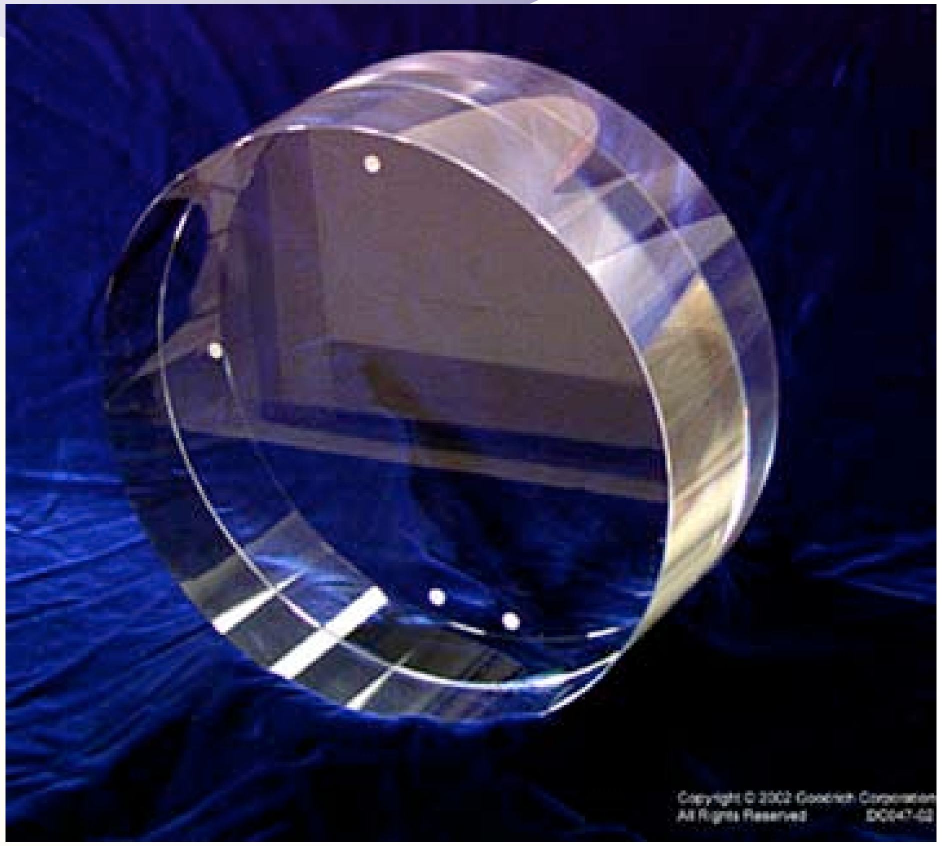
oscillator, mixer, phase-splitter, servo

Test mass material selection: **Silica**

- The decision between sapphire and Silica was very close.
  - Each substrate is believed to meet Adv LIGO's requirements.
- Sapphire:
  - *risks*: single vender for required size/properties, possible high or inhomogeneous optical loss.
  - *potential*: lower high-frequency thermal noise, *if* coating loss low enough, allowing deeper RSE.
- Silica:
  - *risks*: thermal noise (mechanical loss) likely dominated by coating. (noise from bulk loss thought to be lower)
  - *potential:* lower low-frequency thermal noise, which could open low-f end with squeezing or low laser power, an if we tackle the gravity gradients.

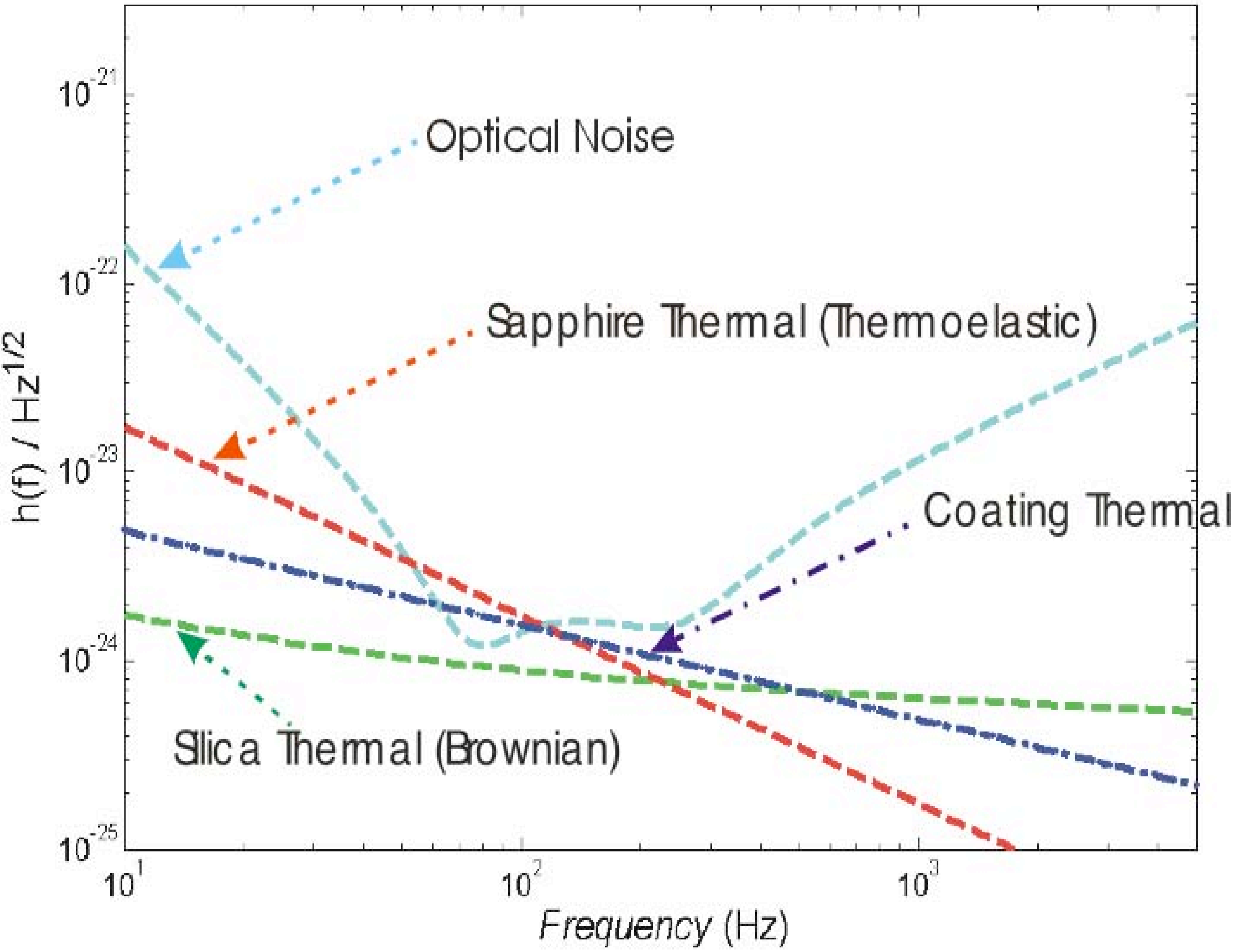
	Silica	**Sapphire**
NS/NS inspiral range	191 Mpc	191 Mpc
BH/BH inspiral range	1050 Mpc	920 Mpc
Stochastic Ω limit	2.6 X 10^{-9}	4.8 X 10^{-9}





Coating dissipation

- With Silica substrate choice, kT noise from mirror coatings will likely be our noise floor over part of the band.
- Coatings are being fabricated at LMA/Virgo and CSIRO to study methods to reduce mechanical loss.
- Results from LMA for titania doped tantila show reduction in loss angle from LIGO-1 coatings by factor of two, to φ ≈ 1.3 x 10^{-4}.
- Please see Geppo Cagnoli's poster.

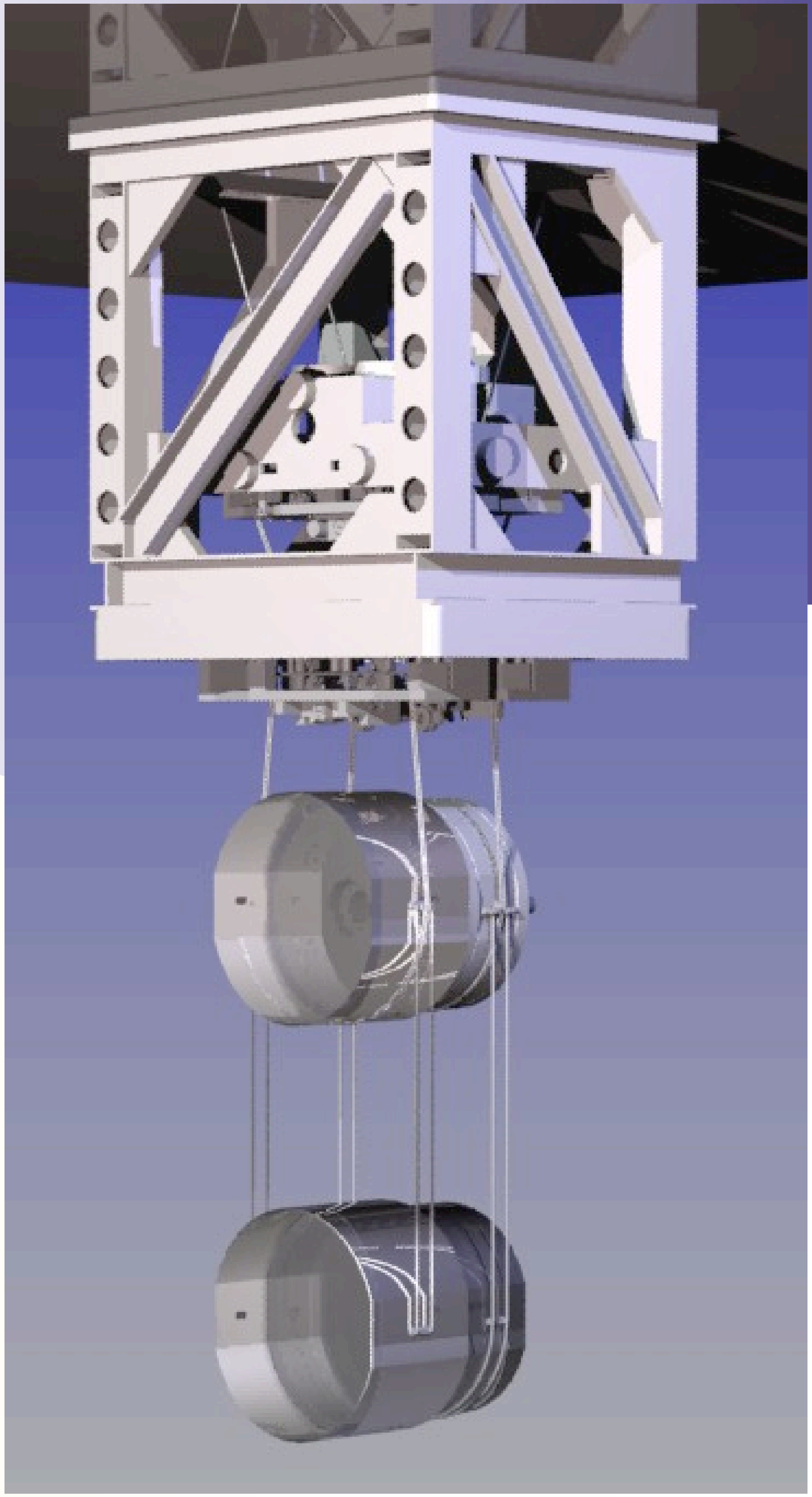


Input Optics R&D (U. of Fl. / LLO)

- Modulation
  - RTP-based electro-optic modulators tested for RFAM
    - currently looking at added phase noise
    - were using New Focus/UF hybrids; looking at all UF version for economy
  - Mach Zehnder modulation
    - noise analysis substantially complete for requirements on stability
    - prototype built and locked, currently undergoing characterization
- Mode Cleaner
  - optics design substantially complete
  - thermal modeling shows some degradation at reflected power mode at 180 W input
  - looking at alternative injection schemes
- Faraday Isolator
  - prototype AdvLIGO Faraday isolator tested up to 100 W
  - Need better thermal lens compensation, but performance adequate.
- Mode Matching Telescope
  - finished first generation table-top adaptive mode matching experiments
  - currently implementing table-top CO2 laser based adaptive telescope

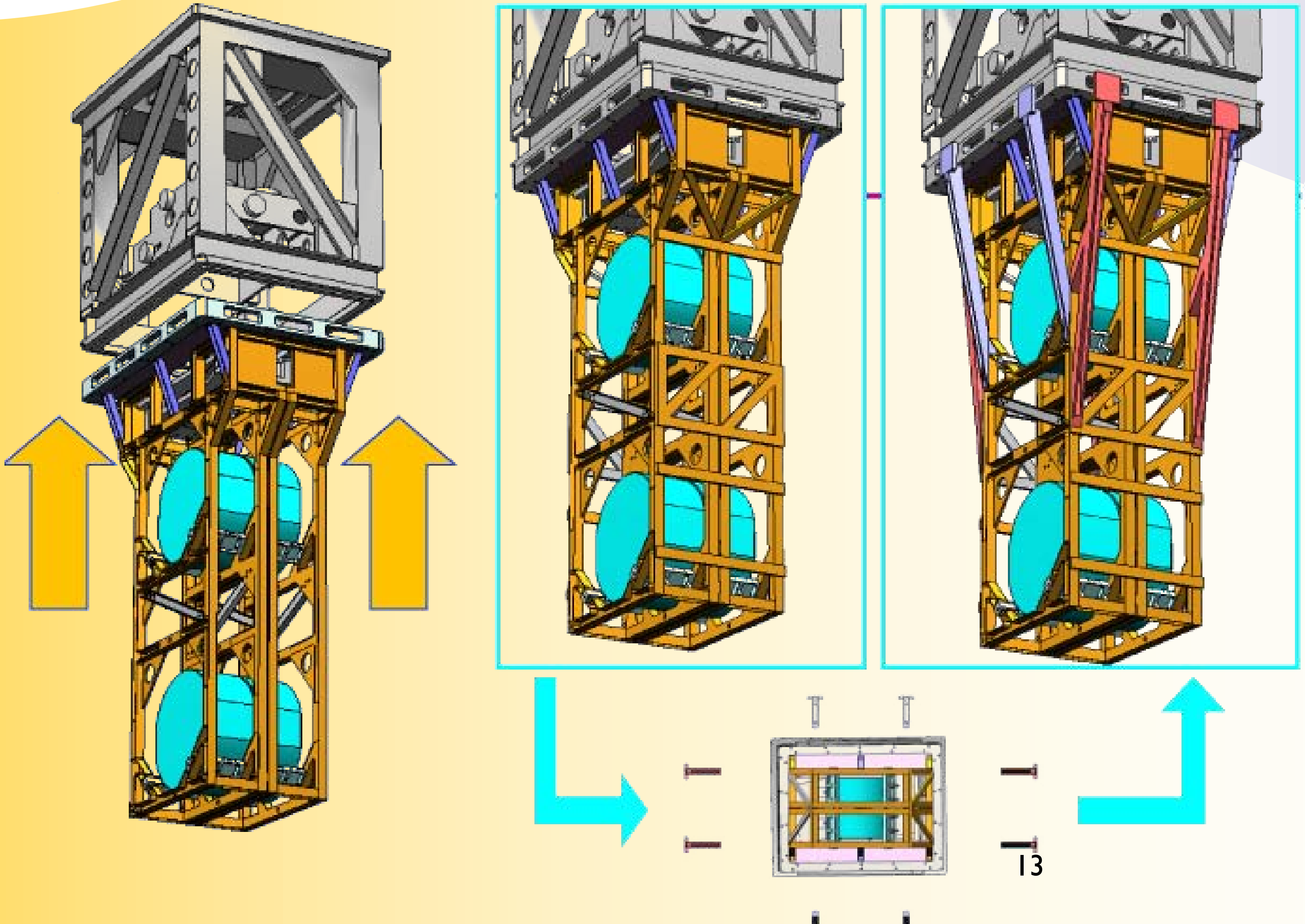
Test mass suspension design

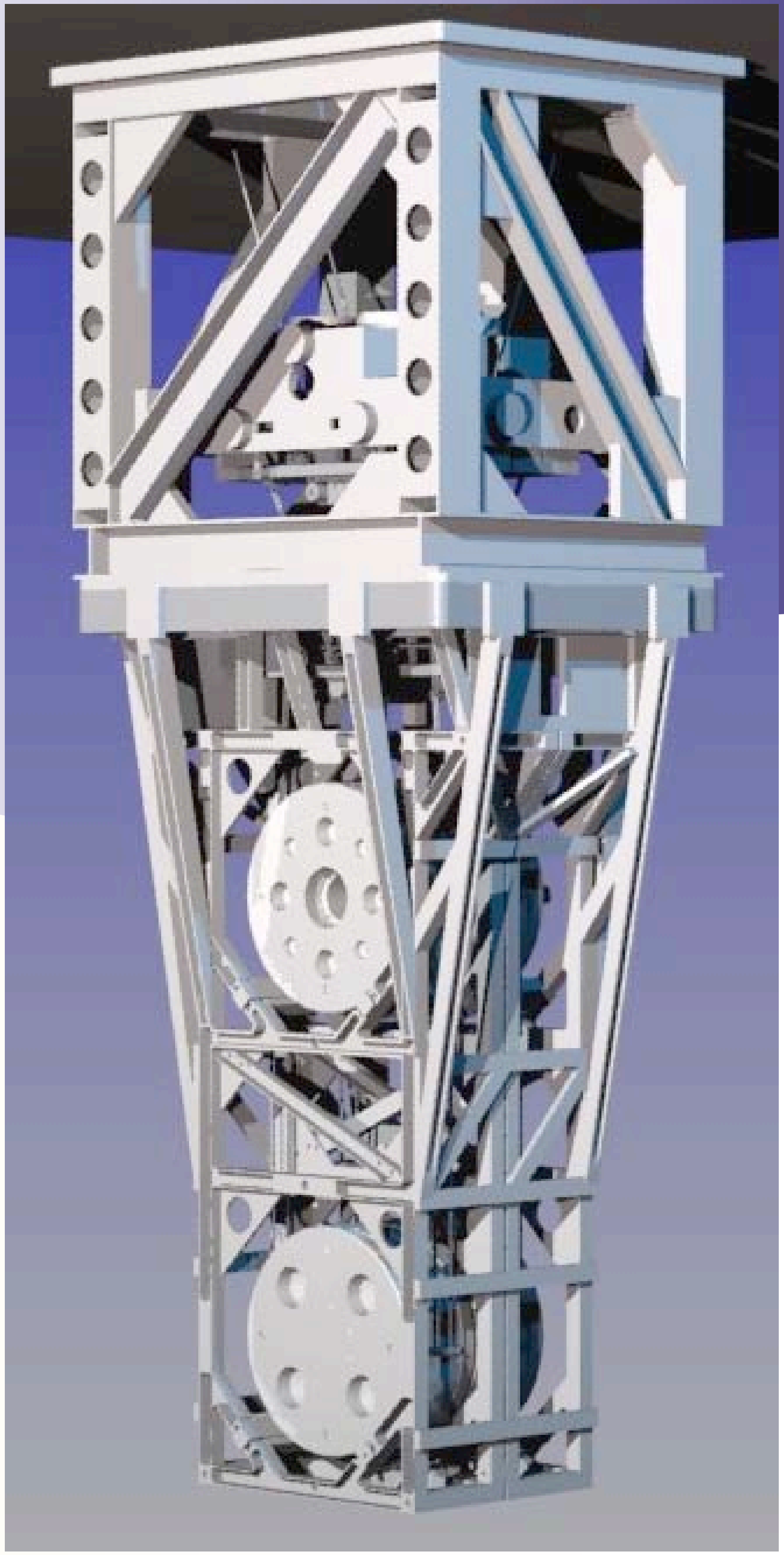
- 40 kg synthetic fused silica mirror suspended on silica ribbons
  - Silica ‘ears’ silicate-bonded to test and penultimate masses;
  - ribbons laser-welded to ears.
  - Upper stages connected using steel wires.
- four-stage pendulum with 3 stages of cantilever blade springs for vertical isolation
- Rigid-body modes at and below the 10 Hz end of the Adv LIGO detection band, damped at the top mass and by use of a reaction pendulum.
- Some violin-string modes damped using fiber coating.
- Target noise from suspension: 10^{-19} m/√Hz at 10 Hz
- Please see Norna Robertson’s poster



Test mass suspension R&D

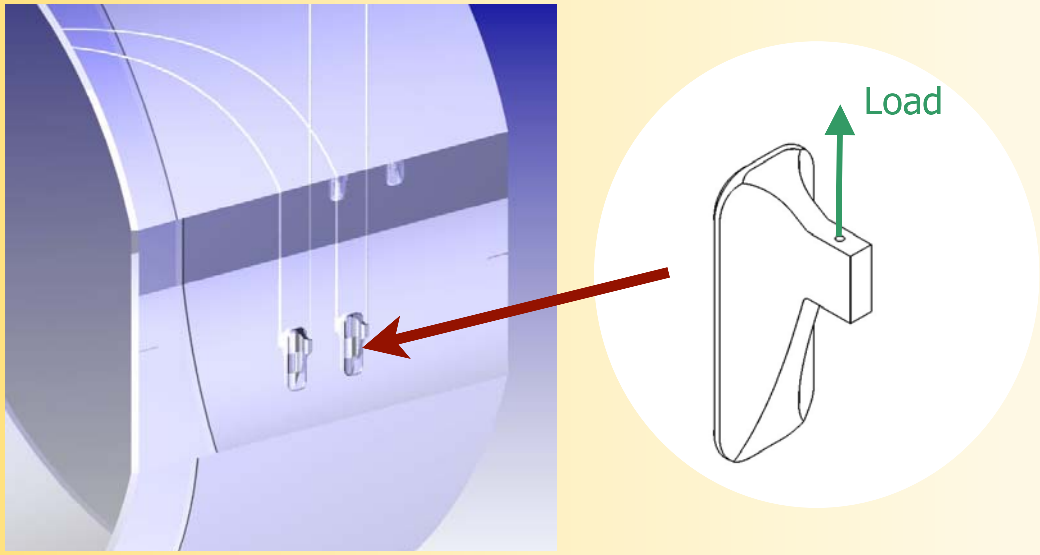
- Suspension cage design is a challenge
  - goal is that the elastic mode frequencies that are > 100 Hz. Present state is getting close, making use of careful light-weighting.
- Design allows ‘3+1’ assembly and installation
  - lower stages can be installed and serviced separately

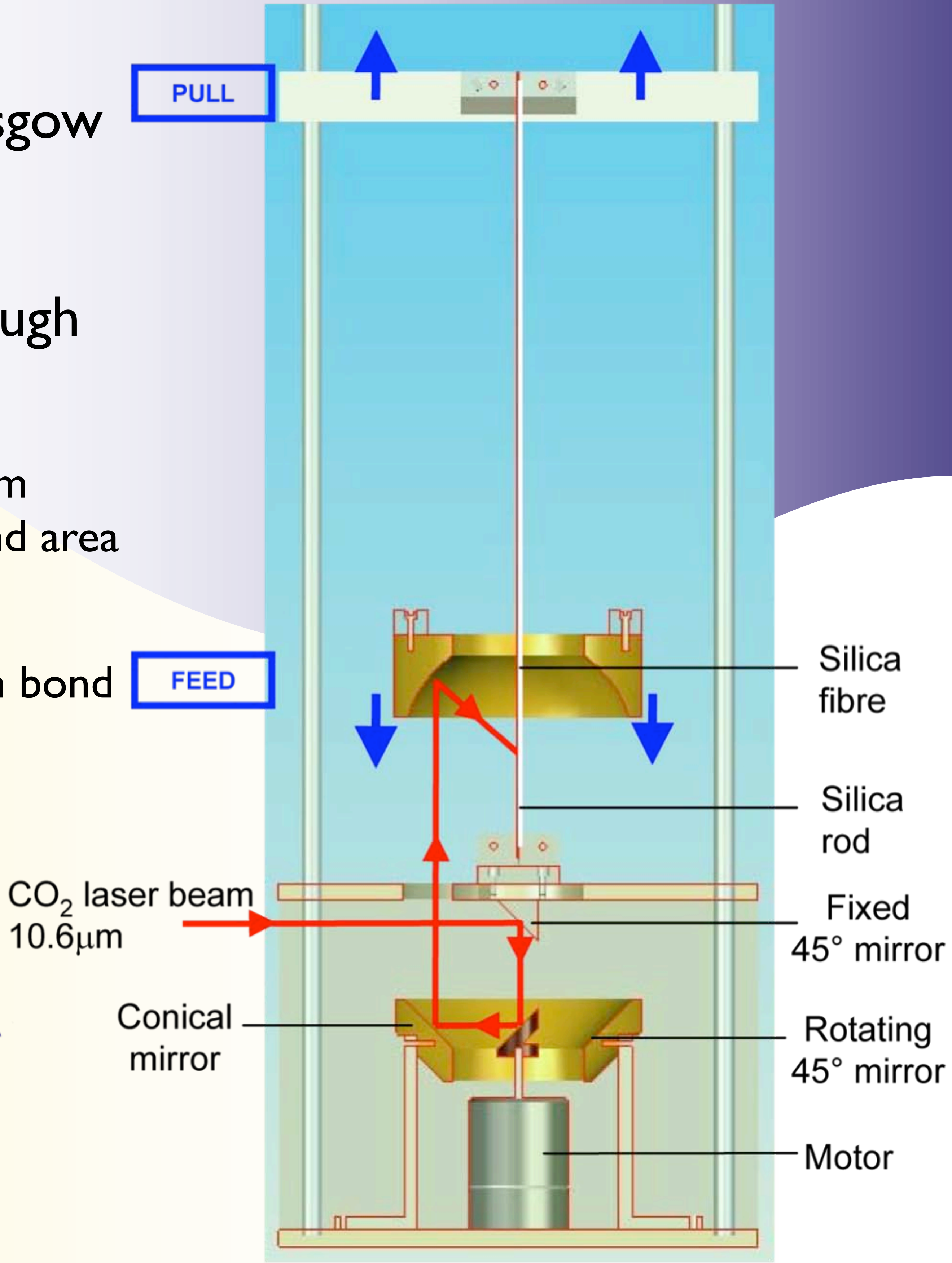




Fibers/ribbons & attachment

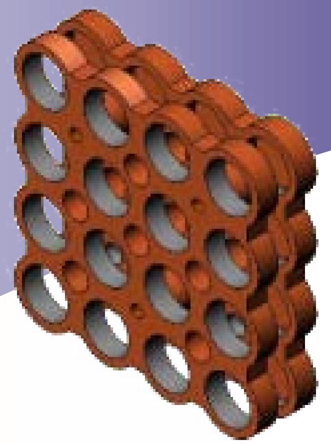
- Fiber/ribbon forming automation, Glasgow
  - CO_2 laser heat and CNC feed
- Fiber/ribbon connection to optic through ear will be using silicate-bonded ear.
  - 8 x 10^{-21} m/√Hz at 100 Hz 'contribution' from suspension thermal noise allows 7.1 cm^2 bond area per test mass.
  - This represents a factor of 6 safety margin in bond strength.

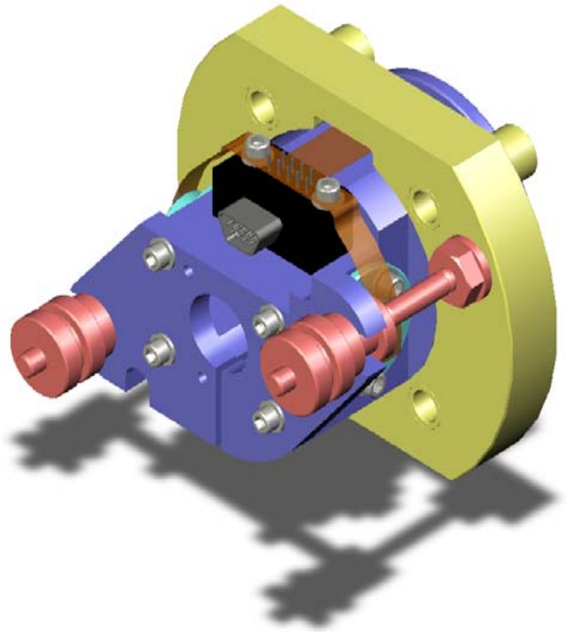




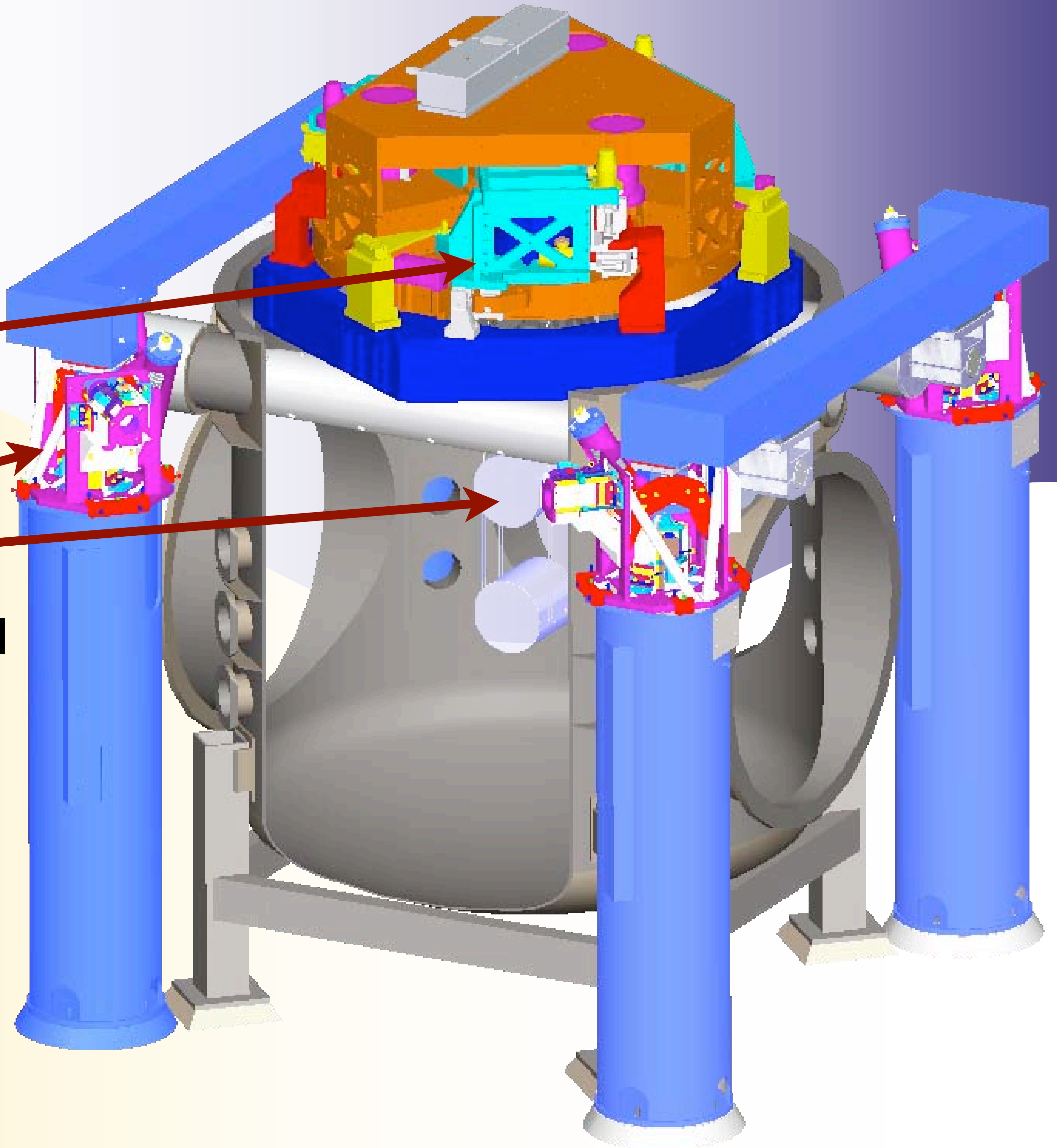
Suspension testing

- ‘Controls’ prototype:
  - correct geometry, masses and moments.
  - Metal mock-up optics
  - correct damping, sensing, actuation
  - to be installed at MIT’s ‘LASTI’ facility late summer ‘05.
- ‘Noise’ prototype:
  - concurrent design and manufacture by U.K. group
  - the real thing, to be tested at LASTI after seismic isolation in place.
- Triple-pendulum input optics controls prototype:
  - successfully tested at LASTI, used to refine dynamic models and control techniques.
- Damping and actuation:
  - Eddy current dampers fabricated and tested
  - Electrostatic actuation grid fabricated on penultimate mass
  - New displacement sensor/ actuator (‘osem’) design.

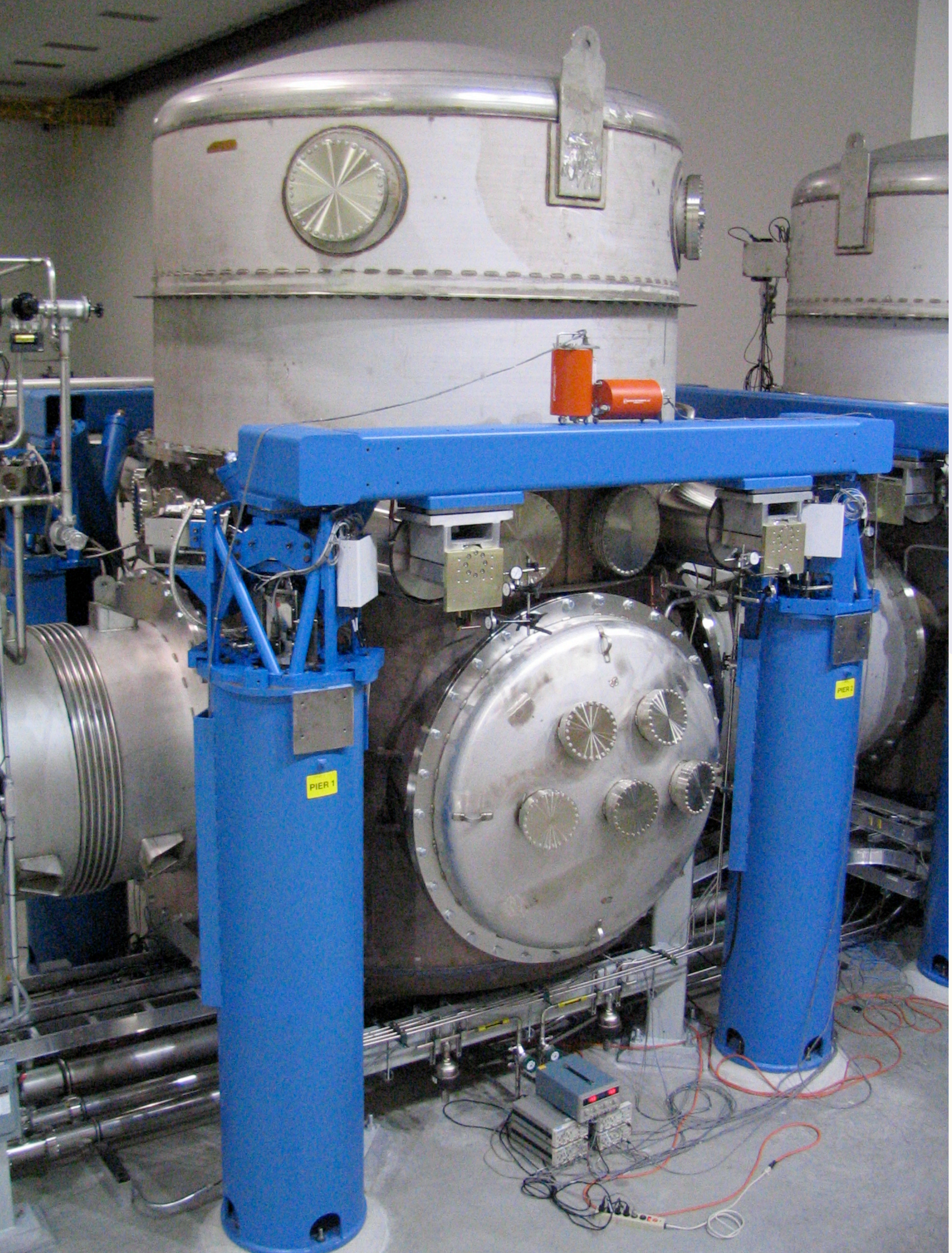




Seismic Isolation



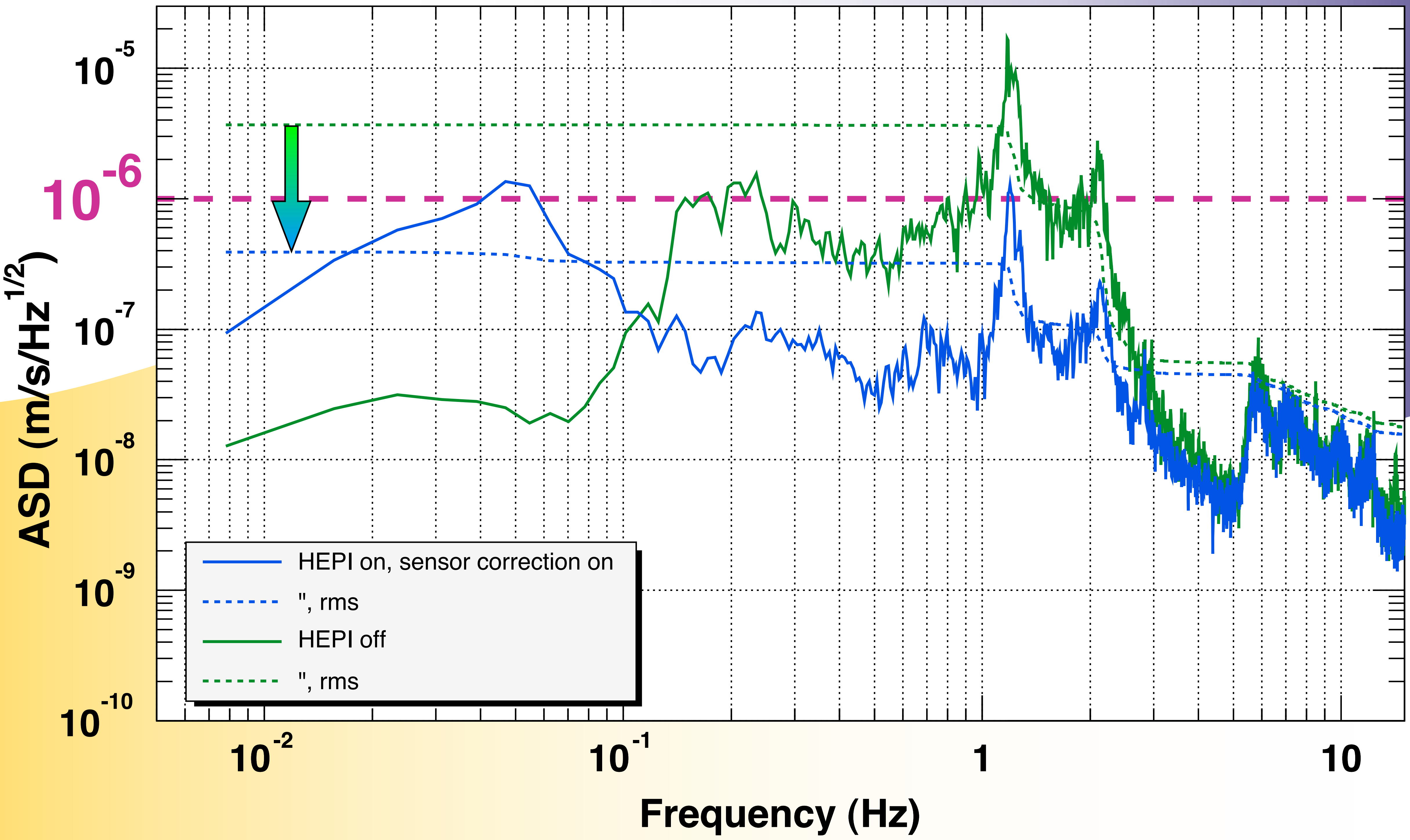
- Seismic isolation of the test mass occurs in:
  - A two-stage in-vacuum active platform
  - An external pre-isolation stage.
  - A quadruple pendulum
- R&D of seismic group focused on two-stage platform.



Hydraulic External Pre-isolation

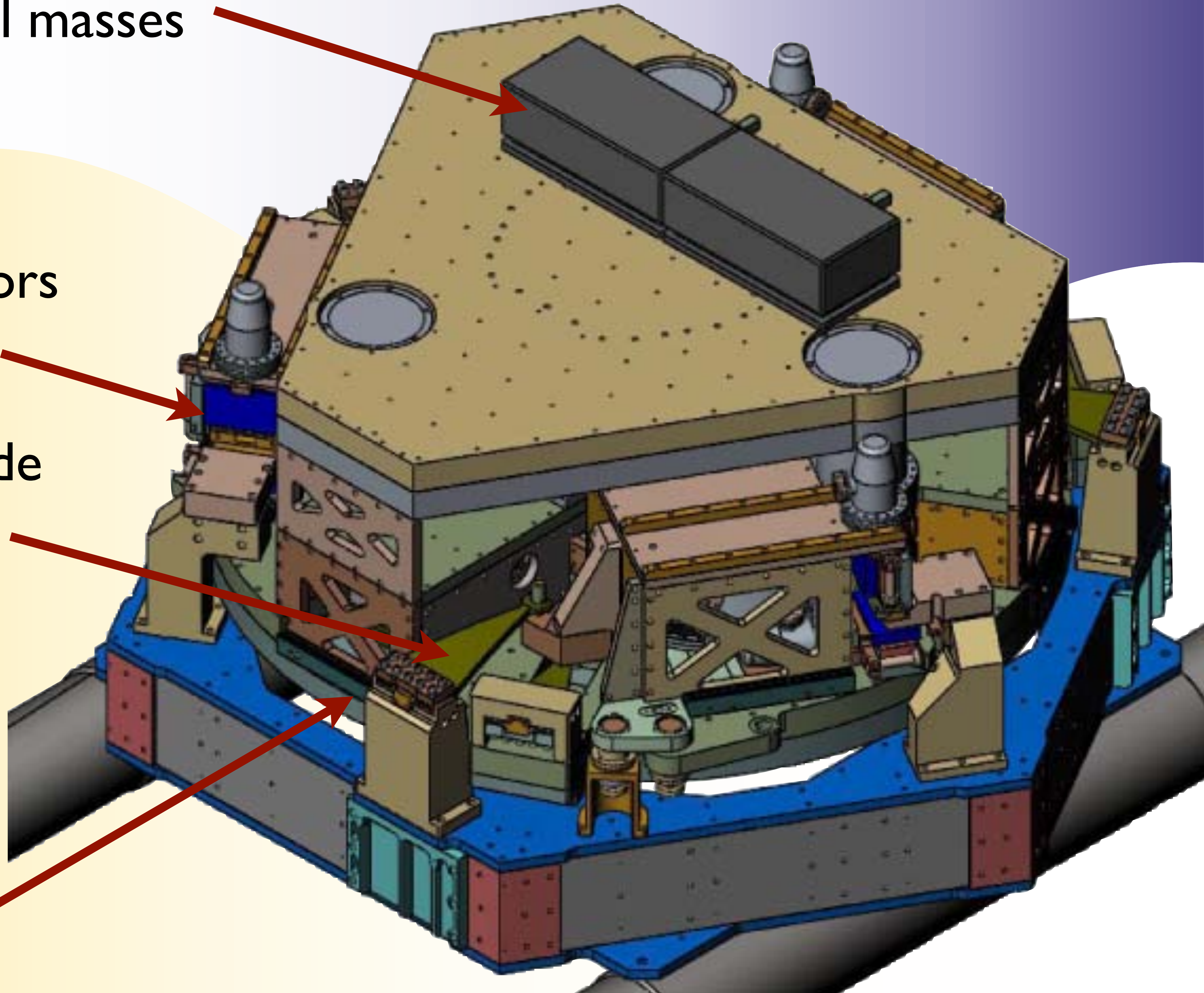
- The payload is supported by large coil springs, and actuated by quiet, high force hydraulic bridges.
- Vibration reduction is obtained by actively following inertial sensor signals from payload-mounted seismometers (L-4C) and by canceling floor vibrations measured by a broadband seismometer (Streckeisen STS-2).
- This is a 6 DOF system, though only x, y and z are quieted below 0.5 Hz.
- Already installed and commissioned at LIGO Livingston to overcome excess double-frequency microseism and local human-generated noise in the 0.1–2 Hz band.

X-arm length disturbance, noisy afternoon



- Noisy afternoon of Aug 10, 2004 had a BLRMS ground velocity 1–3 Hz monitor value between the 90th and 95th percentiles.
- The remaining RMS equivalent velocity is < 4 x 10^{-7} m/s, integrated down to 0.01 Hz.

In-vacuum active platform



relocatable
keel masses

collocated sensors
& actuators

stages supported by blade
springs and vertical
flexure rods

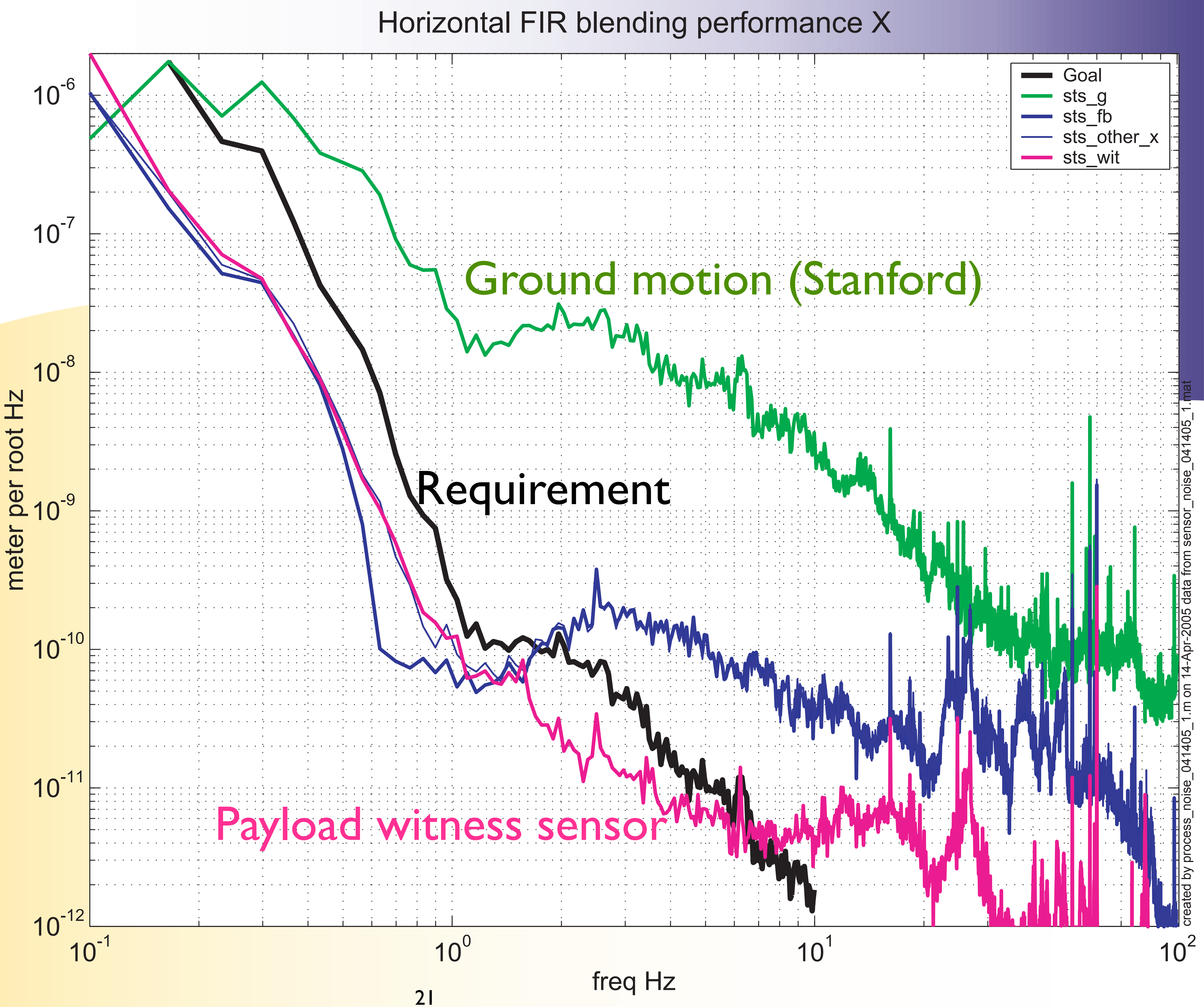
wide, matrix-drilled
optics table for payload

Active platform design

- Technology demonstrator designed and installed in Stanford vacuum system (ETF).
  - mechanical system designed for approximately LIGO size platform, with approx half-size payload capacity.
  - most sensors and actuators as final design.
- True prototype design has been prepared for fabrication and installation in LASTI (at MIT) for full scale, UHV, tests with suspension systems.
  - finite-element modeling of structural and rigid-body modes. we require modal frequencies to be > 150 Hz to accomodate ≈ 50 Hz servo unity-gain point.
  - modeling of 6 x 6 DOF stiffness at low frequencies. For example, we require horizontal-tilt cross coupling < 1/500 m.
  - new design for rigid and strong stops, to exactly position stages and restrict motion during earthquakes.
  - can accommodate ≈ 1 ton payload. Servo and mechanical design need to tolerate mechanically reactive massive payload.

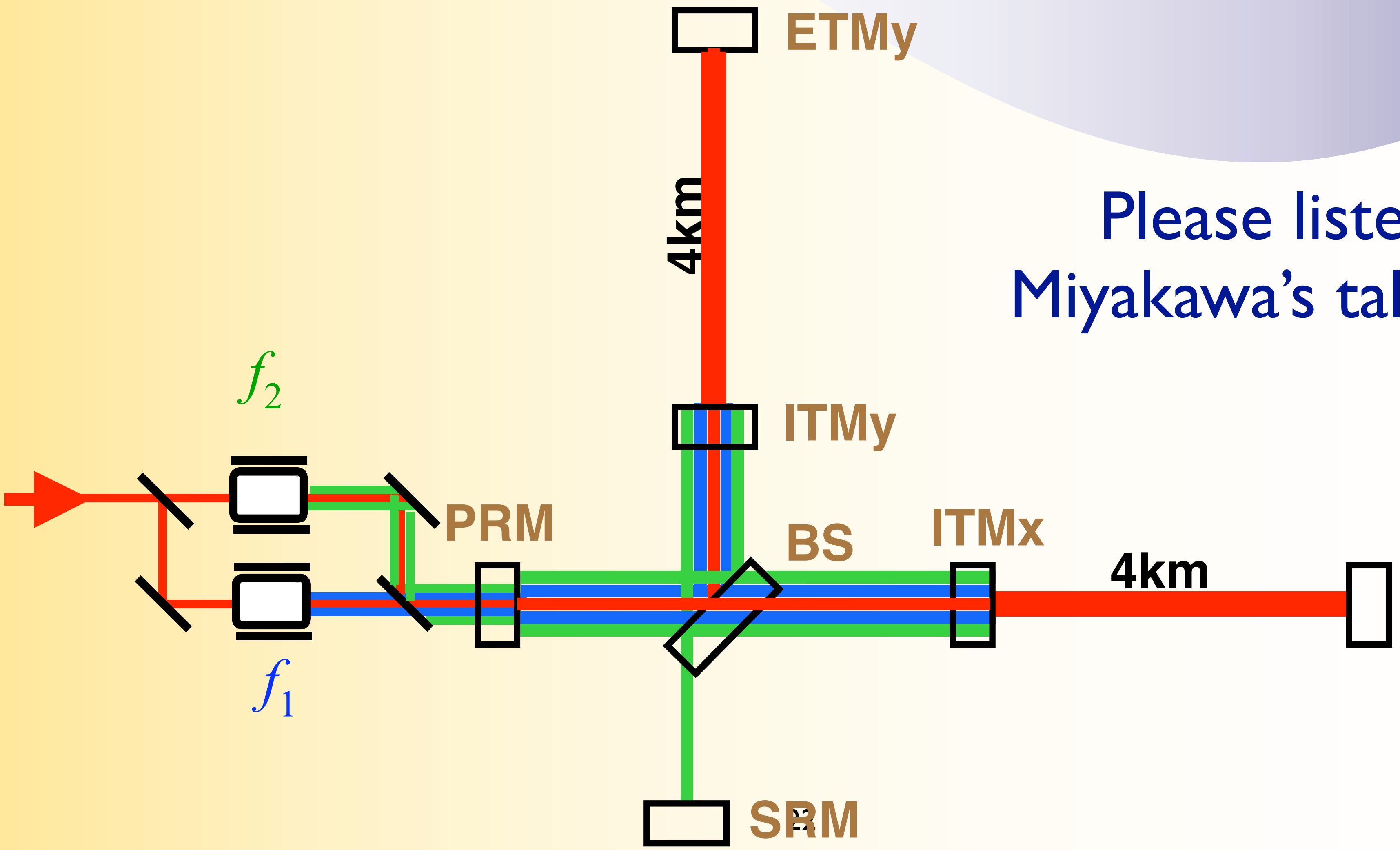
Technology demonstrator results

- Requirements: factor of 100 at 1Hz and factor of 1000 at 10 Hz.
- We are modifying the LASTI prototype mech. design to increase vertical passive isolation at 10 Hz, based on these tests.



Length sensing and control

- Baseline scheme is a narrowband-signal-recycled, and power recycled, Fabry-Perot Michelson.
    - Detuned resonant sideband extraction, with noise minimum tuned to make ‘the bucket’ deeper.
- Frontal RF modulation and synchronous demod used for all length (and angle) DOF’s, except differential arm.
- DC detection is the baseline design for the GW DOF.



Please listen for Osamu Miyakawa’s talk this afternoon

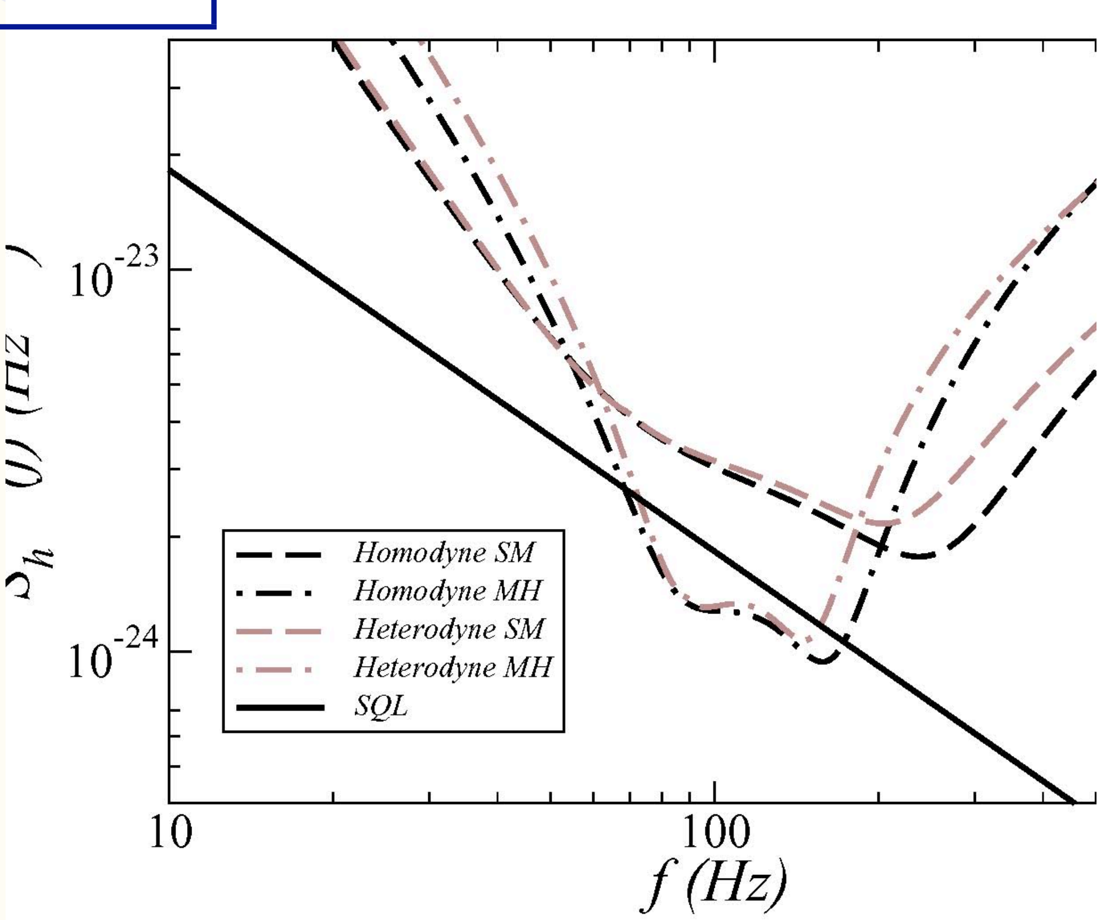
DC readout

- The ‘traditional’ RF detection method is to apply frontal RF phase modulation on the light, such that the sidebands are not resonant in the long FP arms.
    - The PM sidebands serve as an optical phase reference at the photodiode, converting the phase difference signal to an RF intensity.
    - RF detection requires that the output photodiodes have both high efficiency and high bandwidth. This usually means small size.
    - As we use detuned RSE, there will be an imbalance in the antisymmetric port PM sidebands.
- Using homodyne, or DC readout, we arrange to operate such that there is some carrier always incident on the photodiode.
    - The constant carrier light serves as the phase reference, and the phase difference signal is converted to an intensity signal at the baseband.
    - The phase reference light comes either from an arm loss imbalance or intentional servo offset from the dark fringe.
    - DC readout requires an output mode cleaner to prevent fake signals due to (e.g.) intensity noise in recycling cavity light higher-order modes.
    - Large-area, low-bandwidth photodiode is allowed.

DC readout

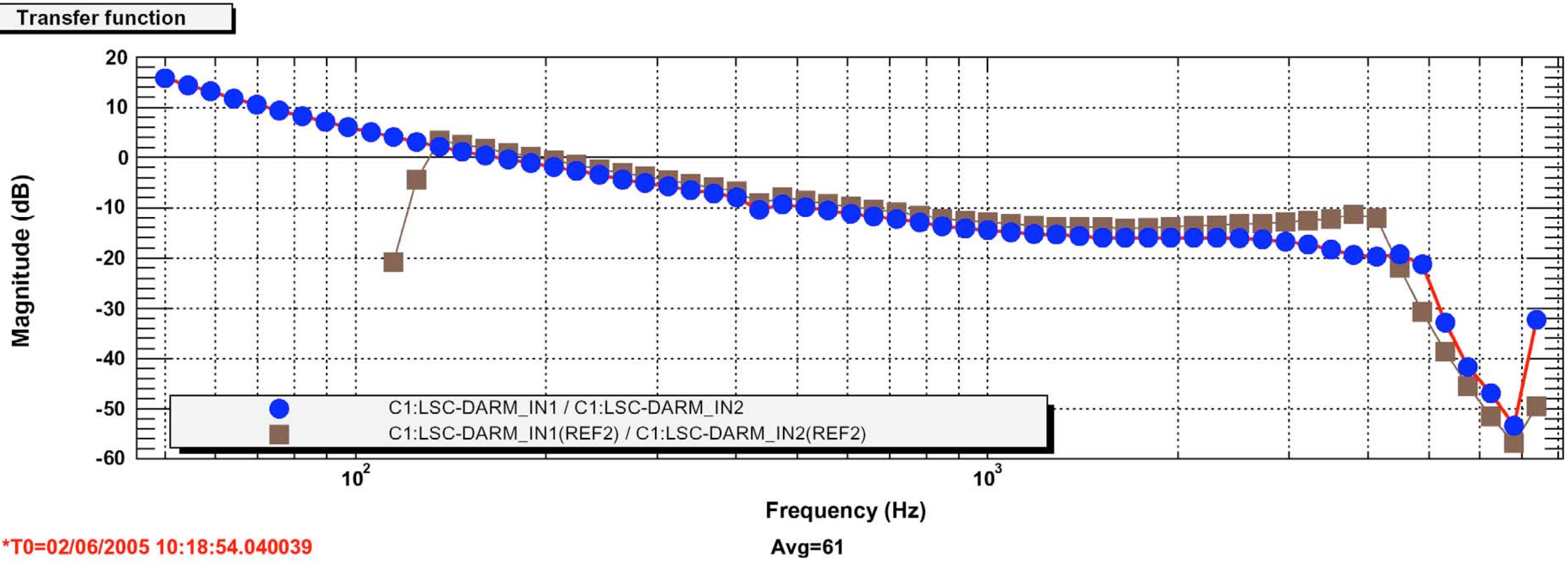
Noise Source	***RF readout***	***DC readout***
Laser frequency noise	~10x more sensitive	Less sensitive since carrier is filtered
Laser amplitude noise	Sensitivity identical for frequencies below ~100 Hz; both driven by technical radiation pressure	
	10–100x more sensitive above 100Hz	Carrier is filtered
Laser pointing noise	Sensitivity essentially the same	
Oscillator phase noise	-140 dBc/rtHz at 100 Hz	NA

- Buonanno & Chen model, parameters optimized for NS/NS binaries
- SNR for DC higher than RF by ≈ 5%.



40 m facility: Resonant sideband extraction

- Experiment underway at 40 m facility (Caltech) to develop and test a length sensing and control scheme for *detuned* resonant sideband extraction, using two frontal modulation frequencies. DRSE has been demonstrated, with a few loose ends (Please listen for Osamu Miyakawa’s talk this afternoon.)



And more …

- End-to-end detector model being re-built for Adv LIGO
- Thermal noise interferometer facility tests.
- Data pathways and analysis computing resources to be augmented.
- Installation planning for complex, fragile, heavy and large components.
- Continued R&D on substrate and coating technology.
- R&D on flat-top beams.
- R&D on squeezed light methods. Please see Nergis Mavalvala's poster.
- etc.