Advanced LIGO

the Laser Interferometer Gravitational-wave Observatory

Development and Status

Brian Lantz, Stanford University
for the LIGO Scientific Collaboration
(40+ institutions and hundreds of people...)

SESAPS Nov. 9, 2006

black hole image courtesy of LISA,
http://lisa.jpl.nasa.gov

LIGO-G060581-00-R

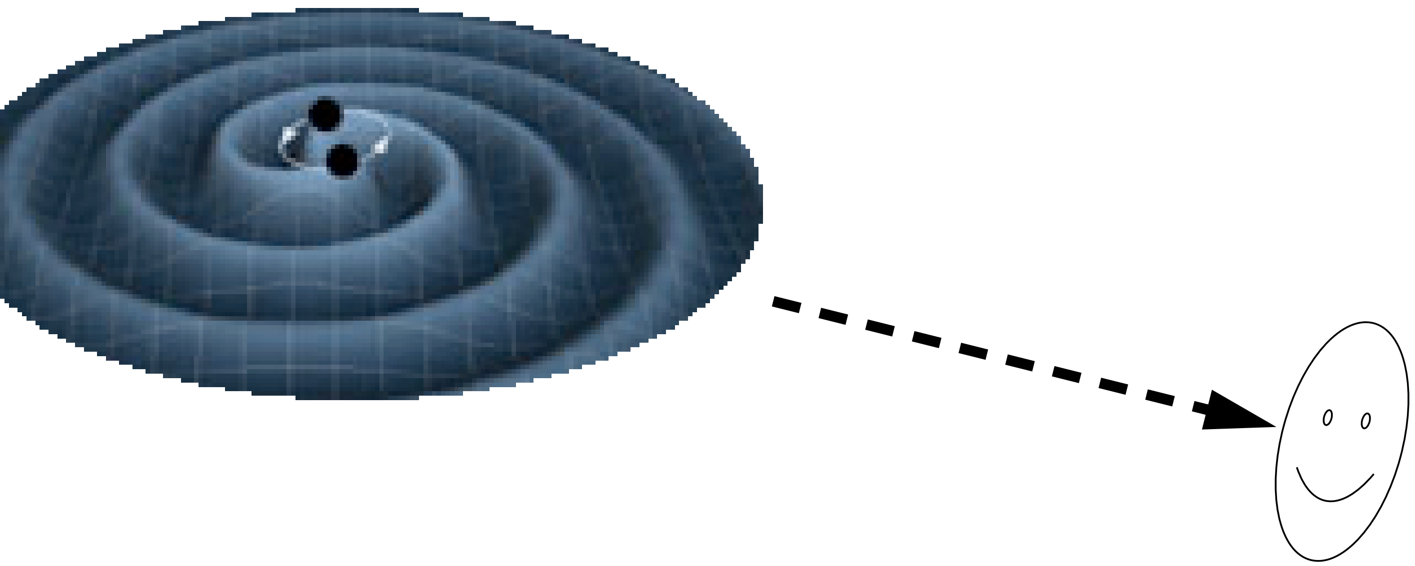
The Advanced LIGO *proposal*

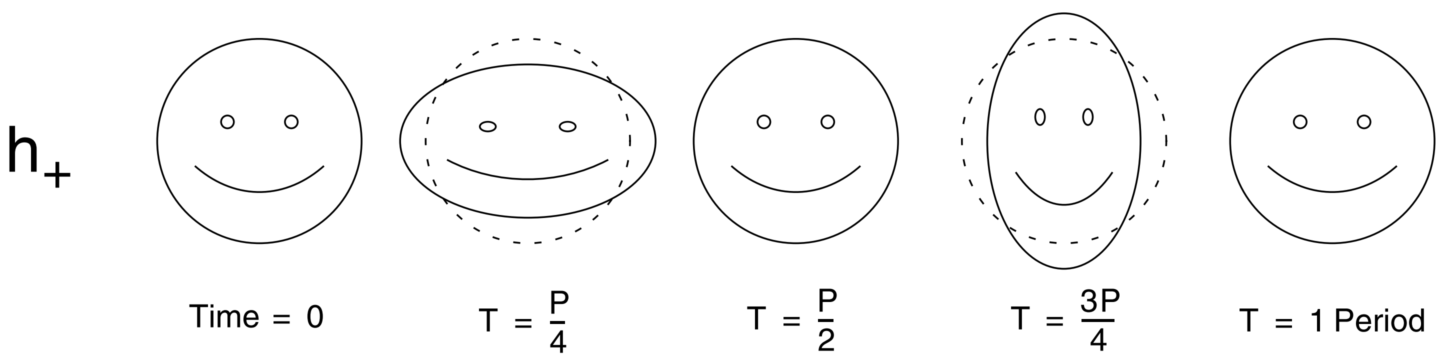
- Improve the sensitivity of existing observatories to dramatically enhance the astrophysics.
- Same facilities as Initial LIGO, but with new detectors.
- Development is very far along.
- Requested construction funding from NSF in FY2008.
- Project cost $186 M (US, 2006$)
  - NSF $172 M
  - AEI to supply the lasers.
    Already funded by Max Planck Gesellschaft for development and for $7.1M in 2006$ for fabrication.
  - UK/GEO for suspensions and core optics
    Already funded by PPARC for development and for $6.87M in 2006$ for fabrication.
  - ANU funding request submitted for ~$1.7M for output modecleaner.

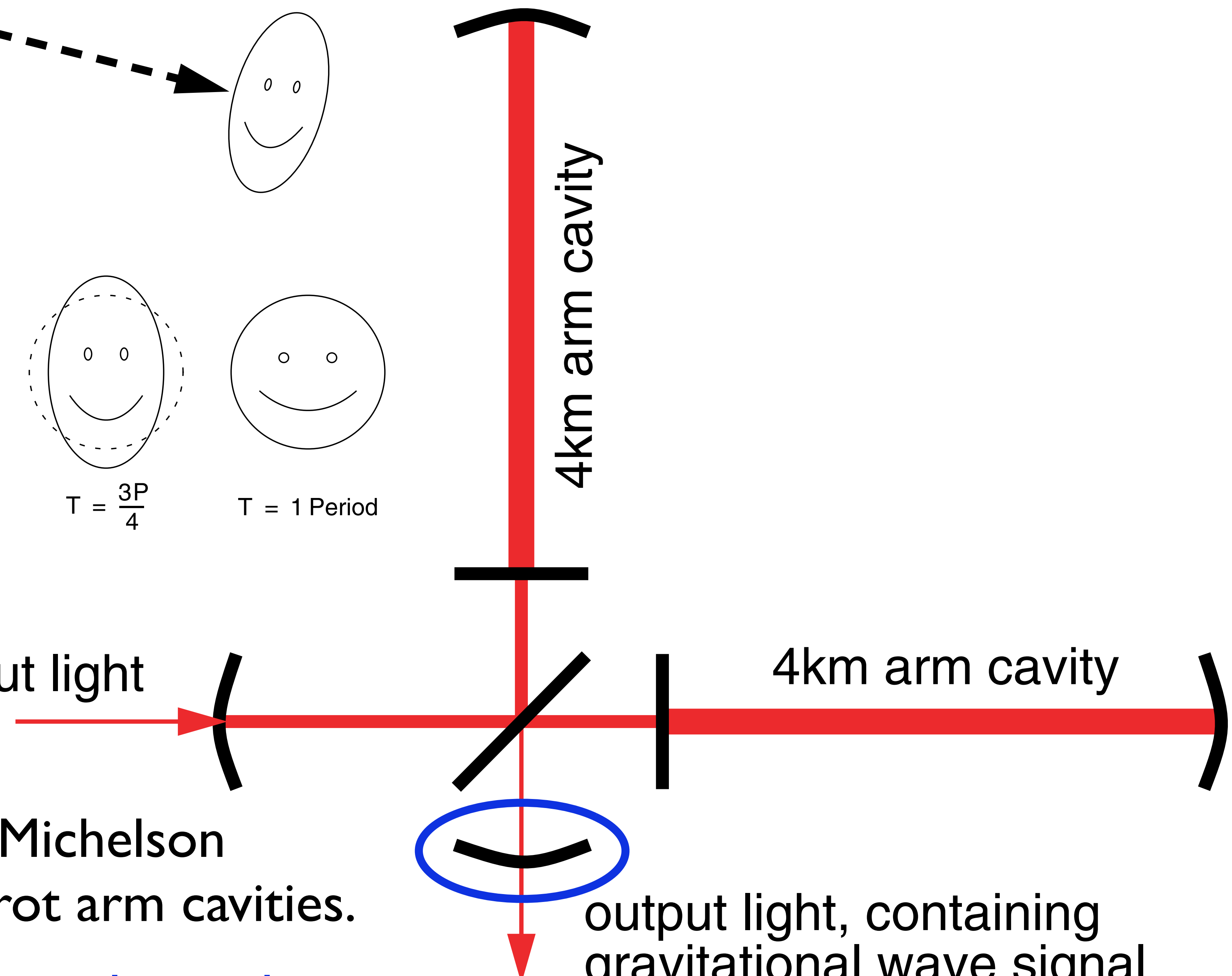
The Advanced LIGO *proposal*

- Milestones:
  - Advanced LIGO funding at start of FY2008; fabrication, assembly, and stand-alone testing of detector components
  - Advanced LIGO starts decommissioning initial LIGO instruments in early 2011, installing new detector components from stockpile.
  - First Advanced LIGO interferometer accepted in early 2013, second and third in mid-2014. Project completes!
  - Commissioning of instruments, engineering runs starting in 2014.

Detecting Gravitational Waves







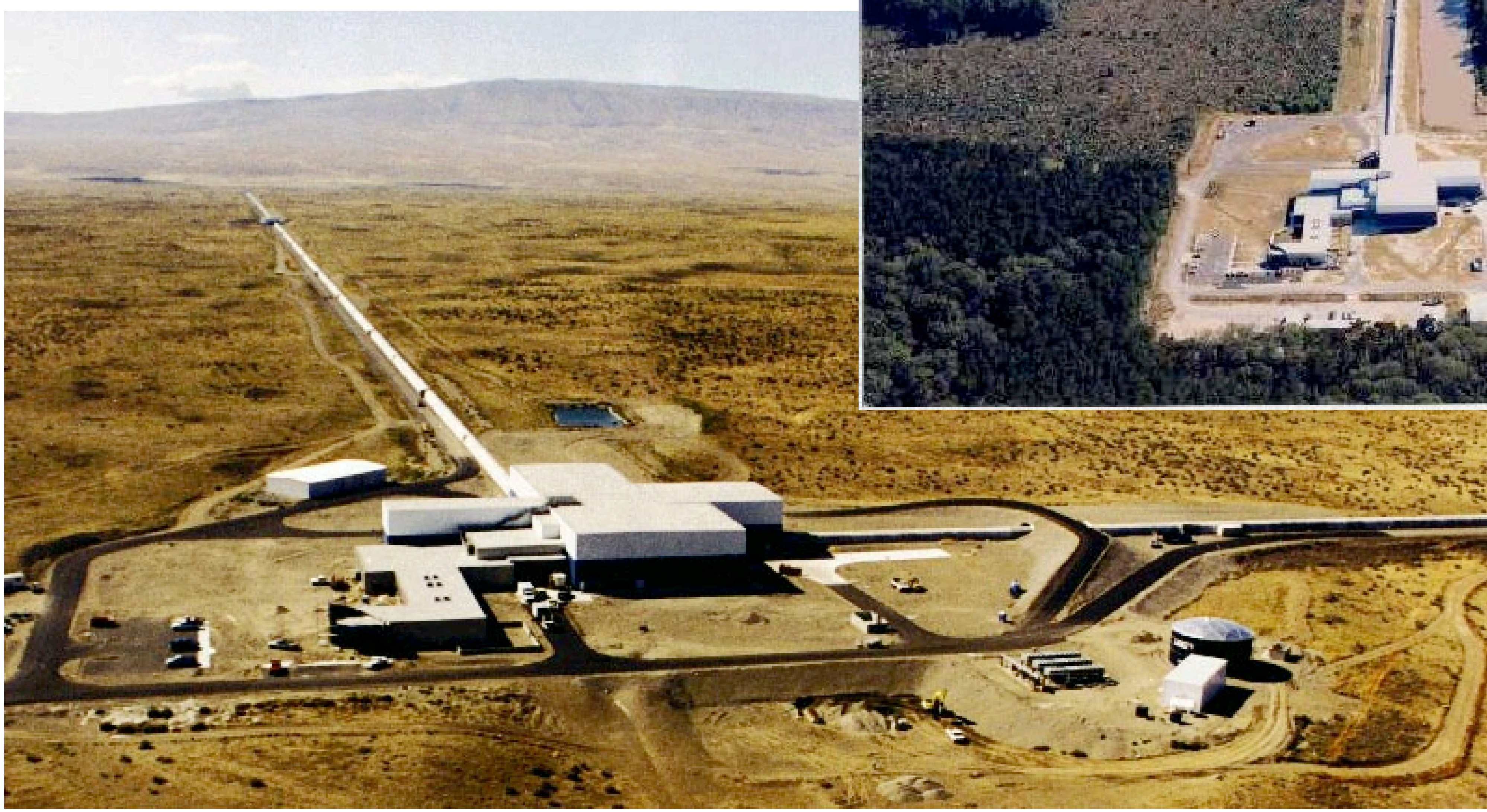
4km baseline power-recycled Michelson interferometer with Fabry-Perot arm cavities.

Advanced LIGO will also use signal-recycling

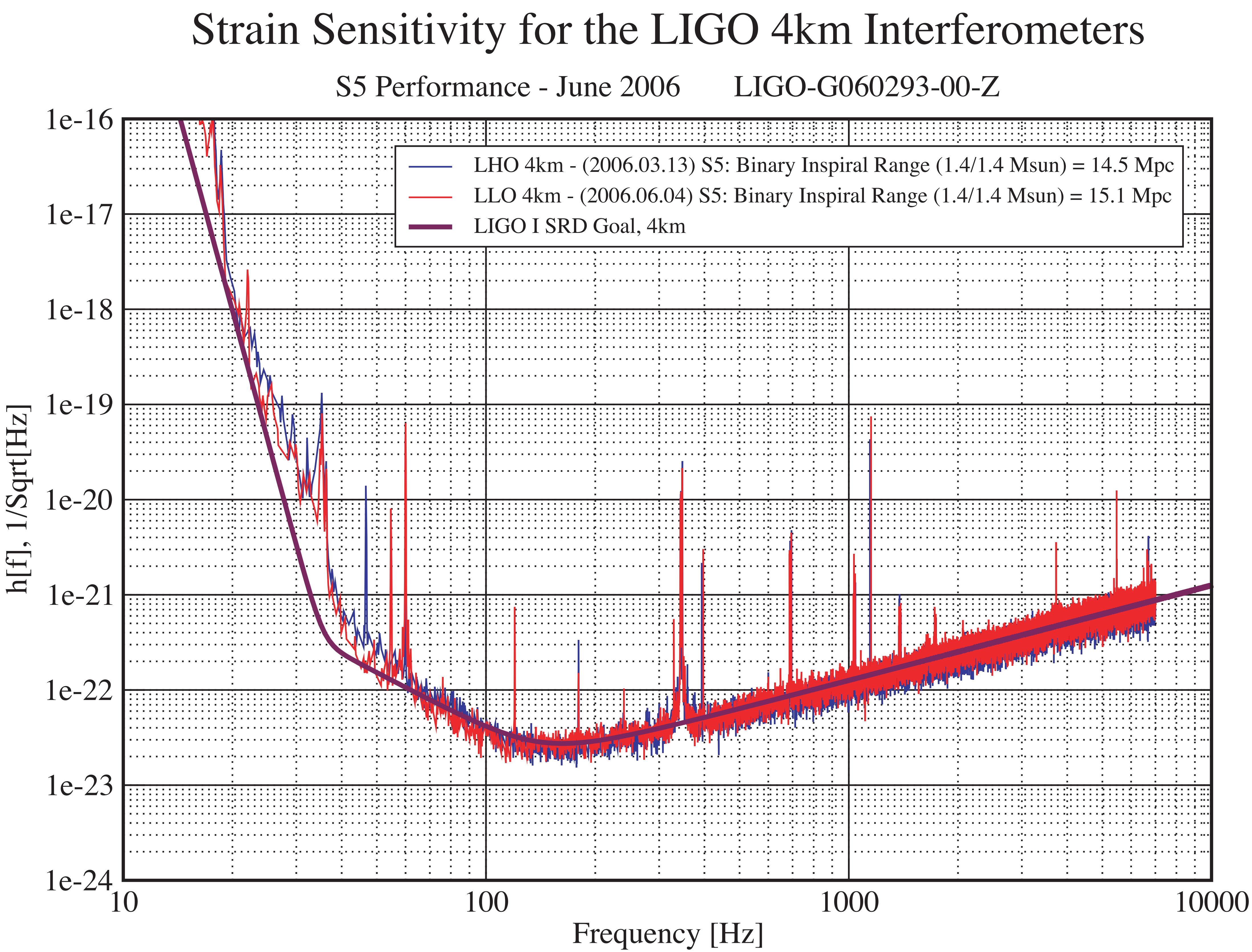
Initial LIGO

Observatories in Livingston LA and Hanford WA.

Science run 5 now underway at design sensitivity.



Initial LIGO Sensitivity



The Seeing

Initial LIGO NS/NS range ~15 MPc,
network range of ~22 MPc

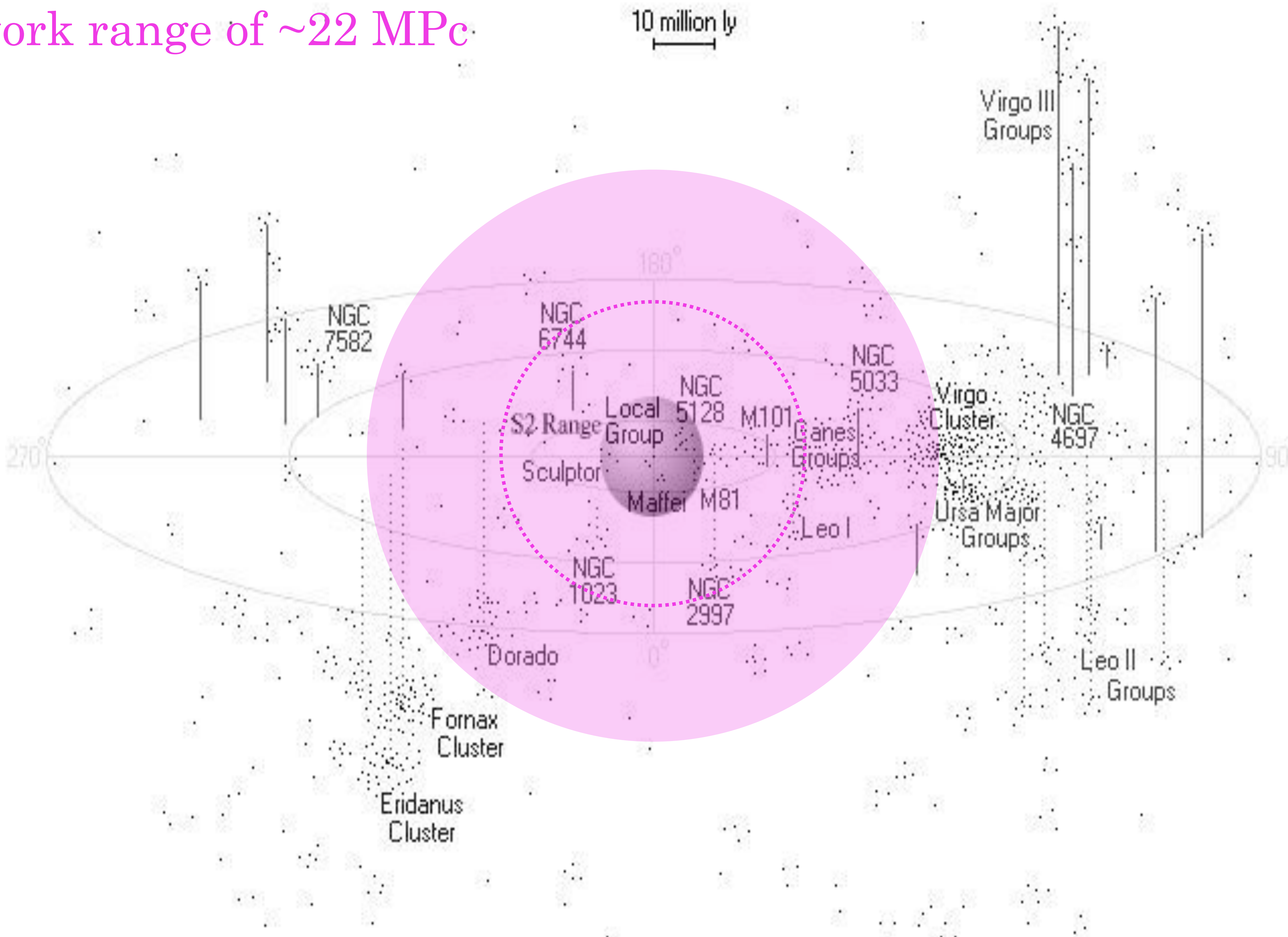


image by R. Powell

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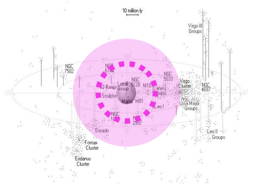


image by R. Powell

3 detector network range for NS/NS of 300 MPc

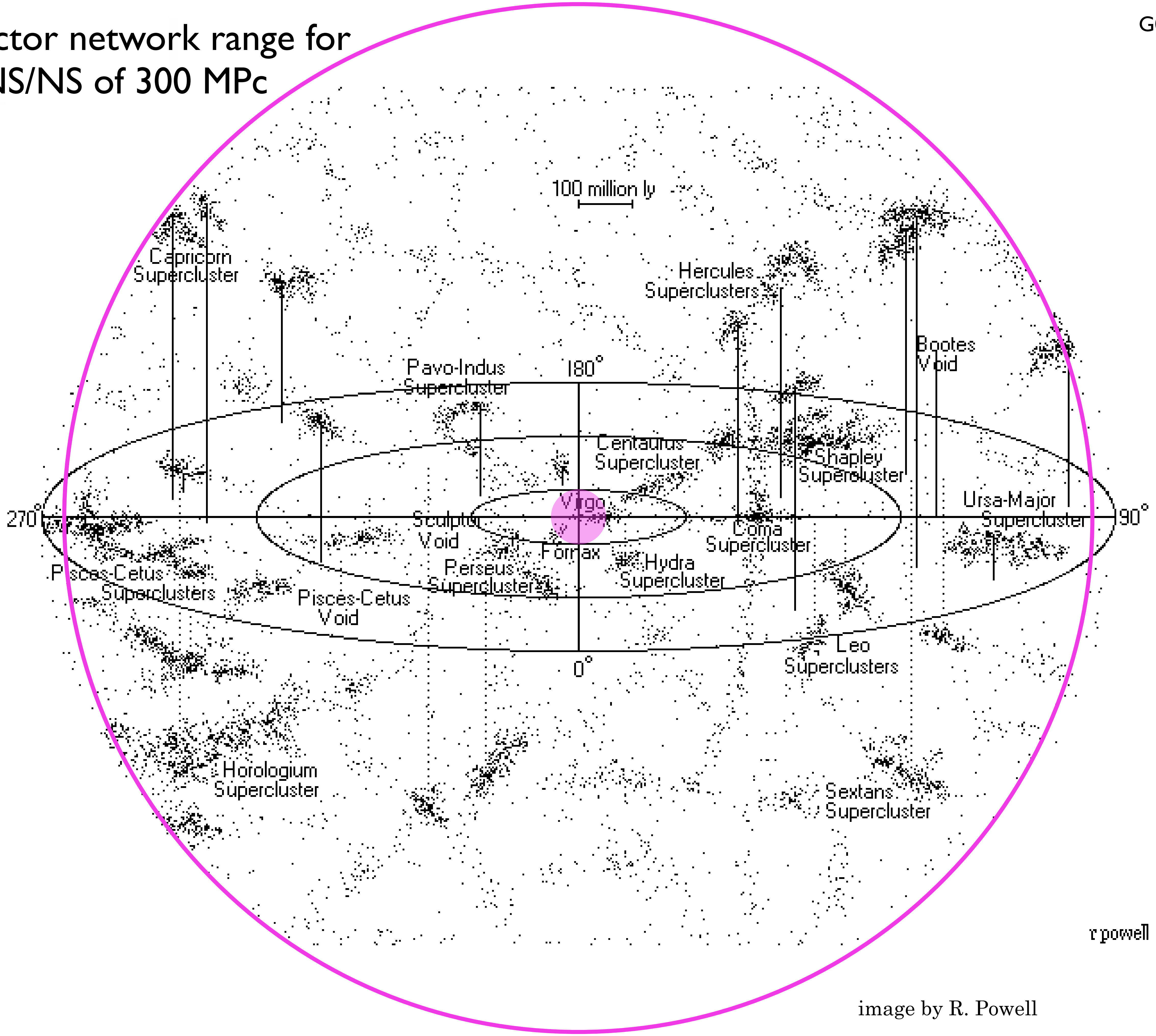


image by R. Powell

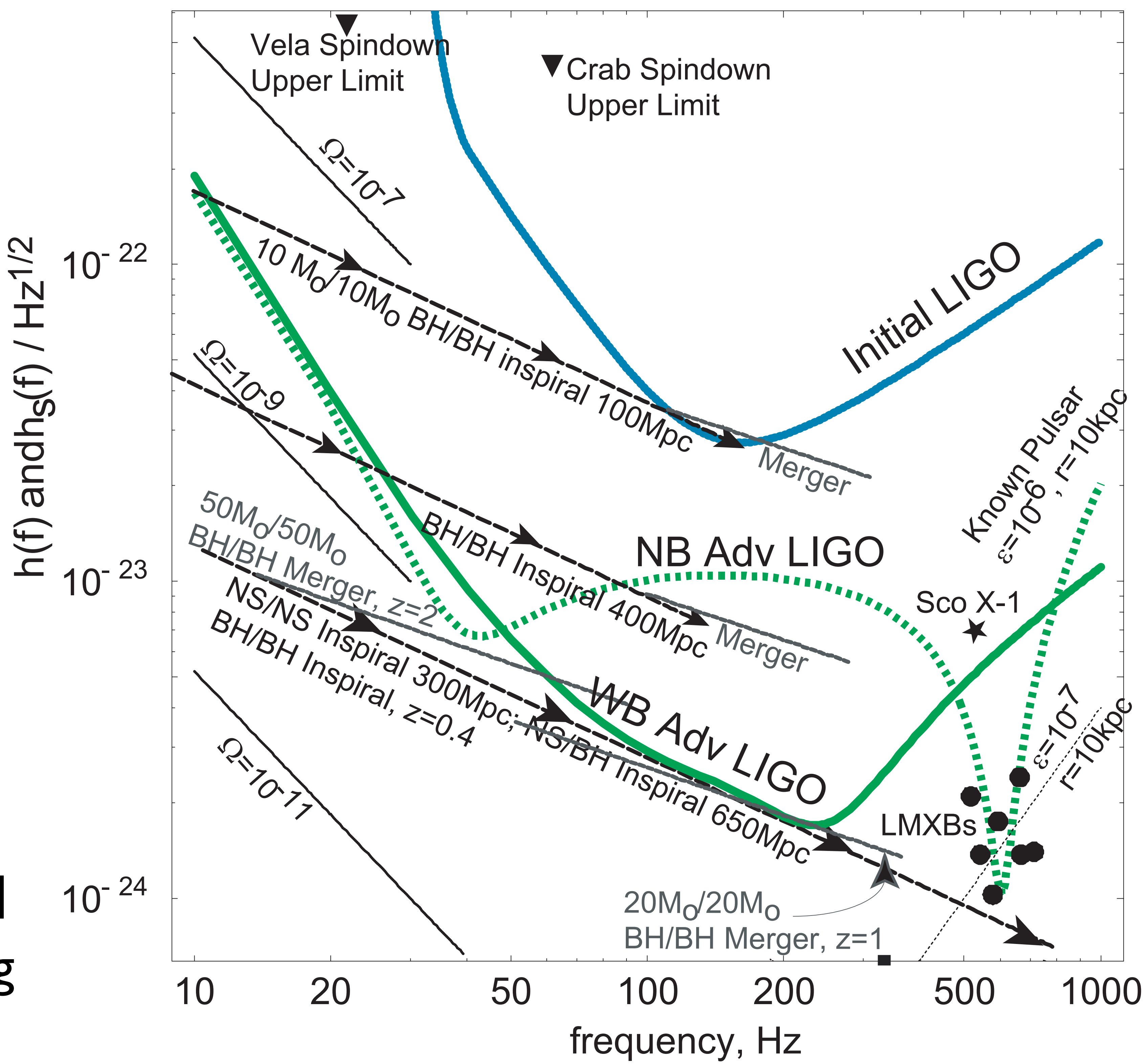
Advanced LIGO - Sources

Neutron star and
Black hole binaries
- inspiral
- merger
- GRBs?

Spinning NS's
- LMXB
- known pulsars
- unknown?

Birth of NS
(supernovas)
- tumbling
- convection

Stochastic Background
- remnants of the big bang



Advanced LIGO - Technology

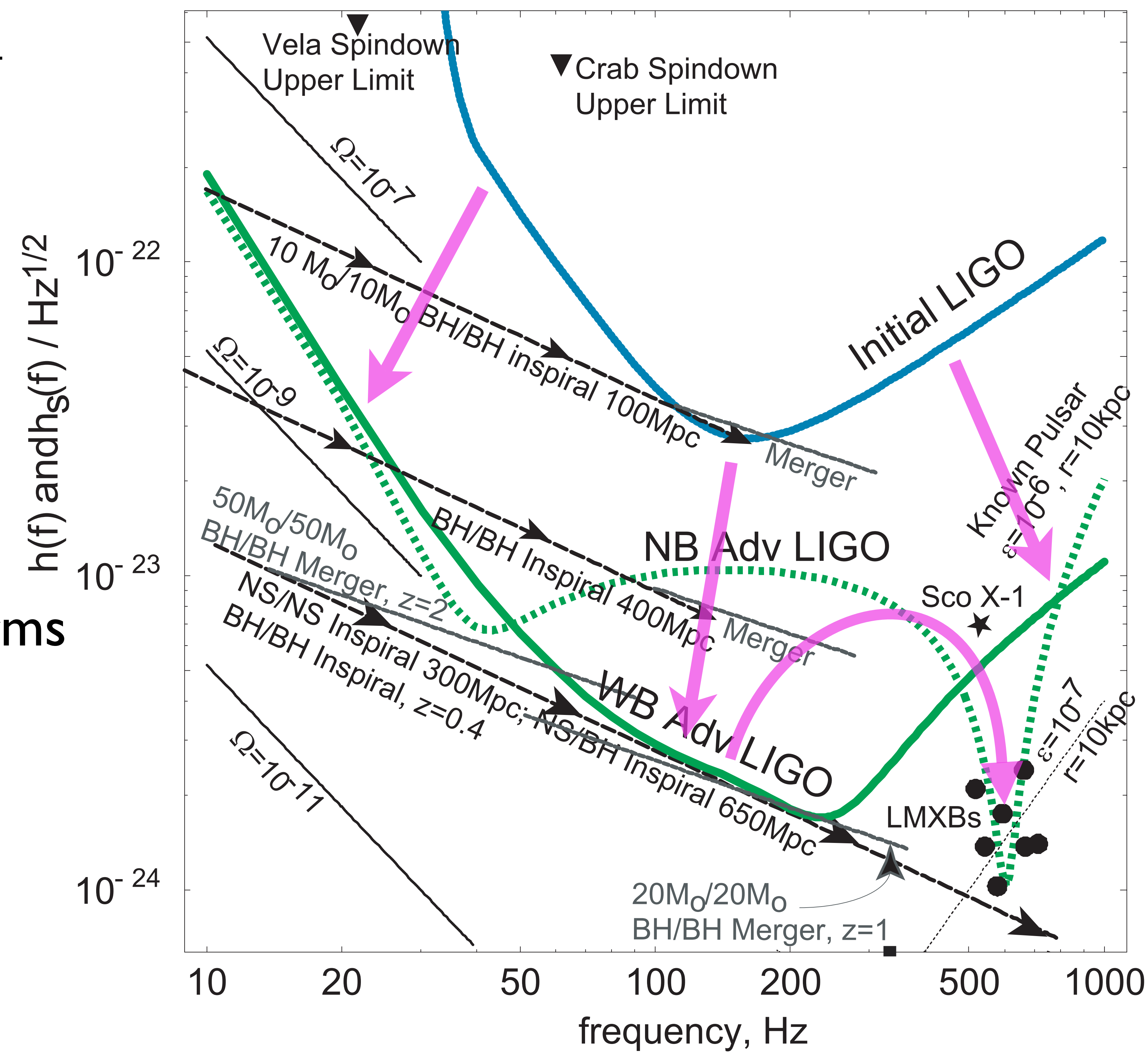
<u>Technical Improvements</u>

Environmental Isolation:
platforms & pendulums

Thermal Noise control:
suspensions & coatings

More Power
new 180 W laser
830 kW circulating in arms

Signal recycling
gives tunable response

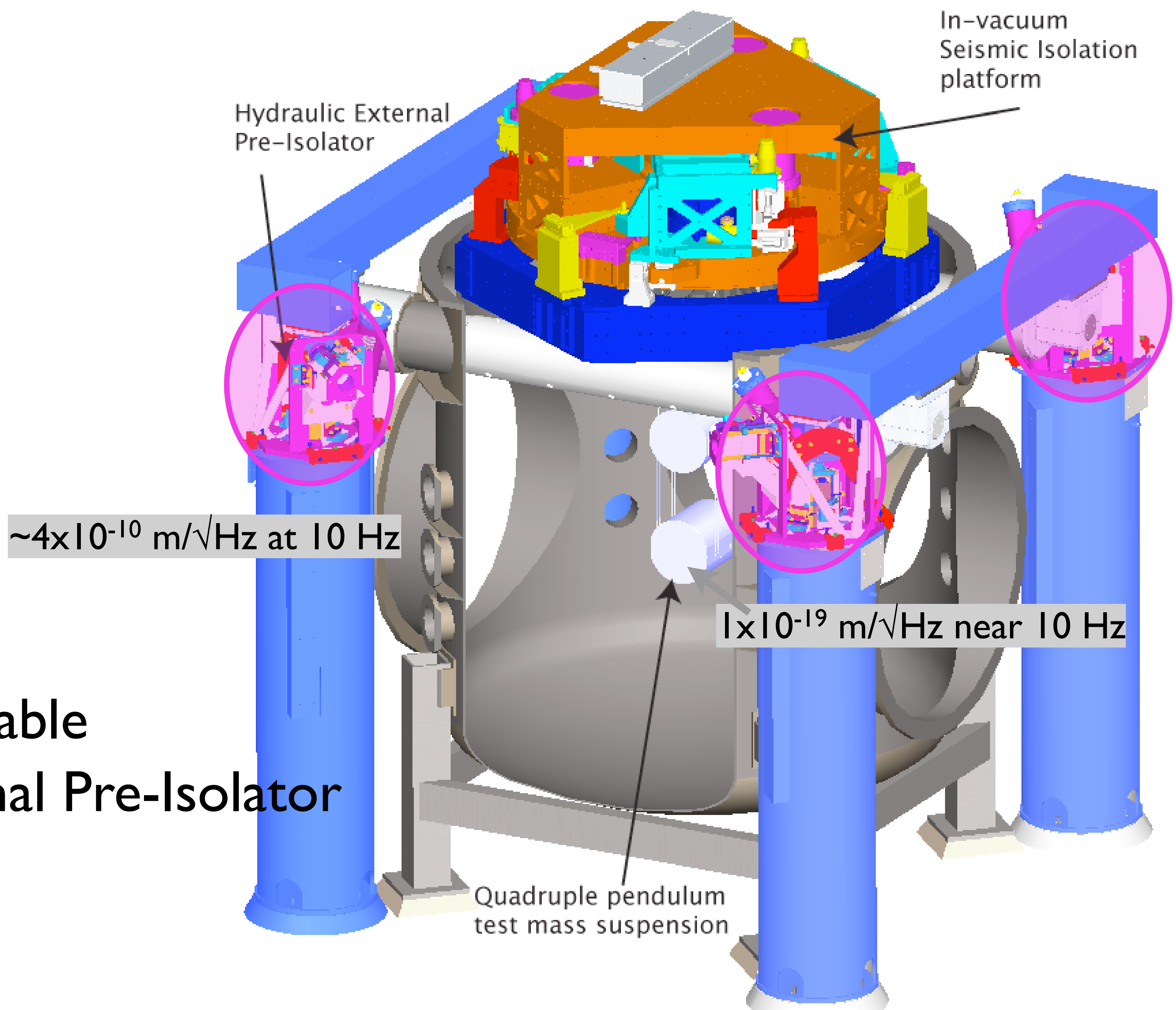


Seismic Isolation & Alignment

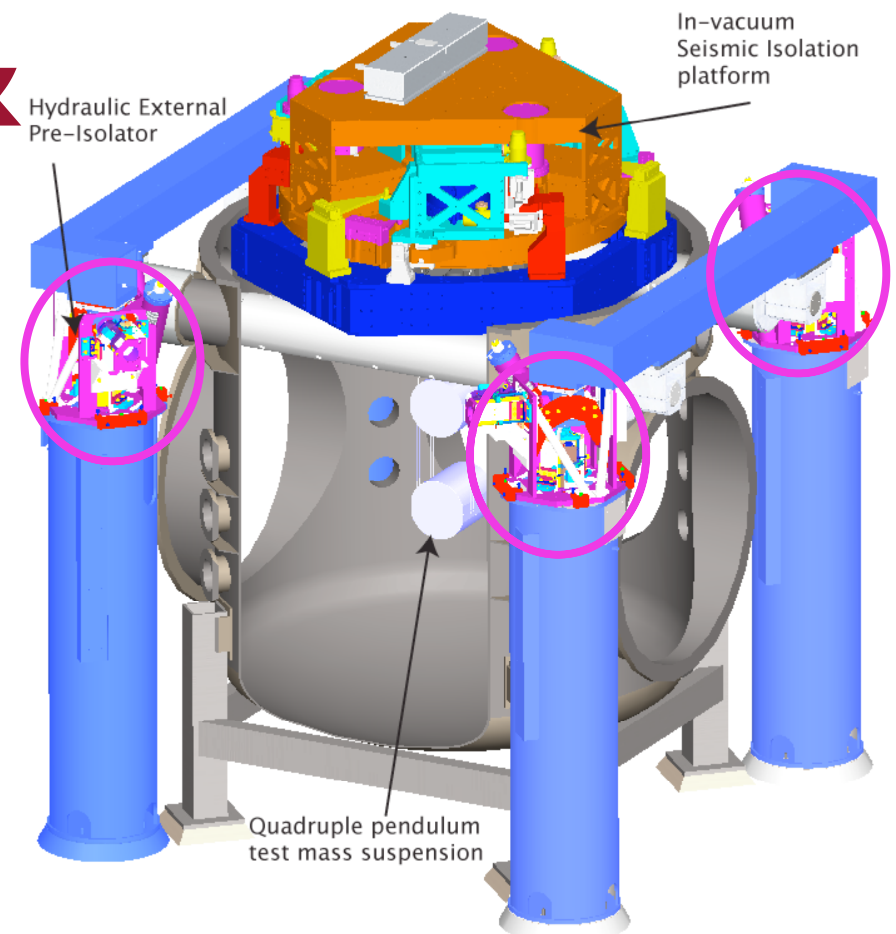
Isolation of the test mass
10 Hz motion
test mass 1×10^{-19} m/√Hz
ground ~4×10^{-10} m/√Hz

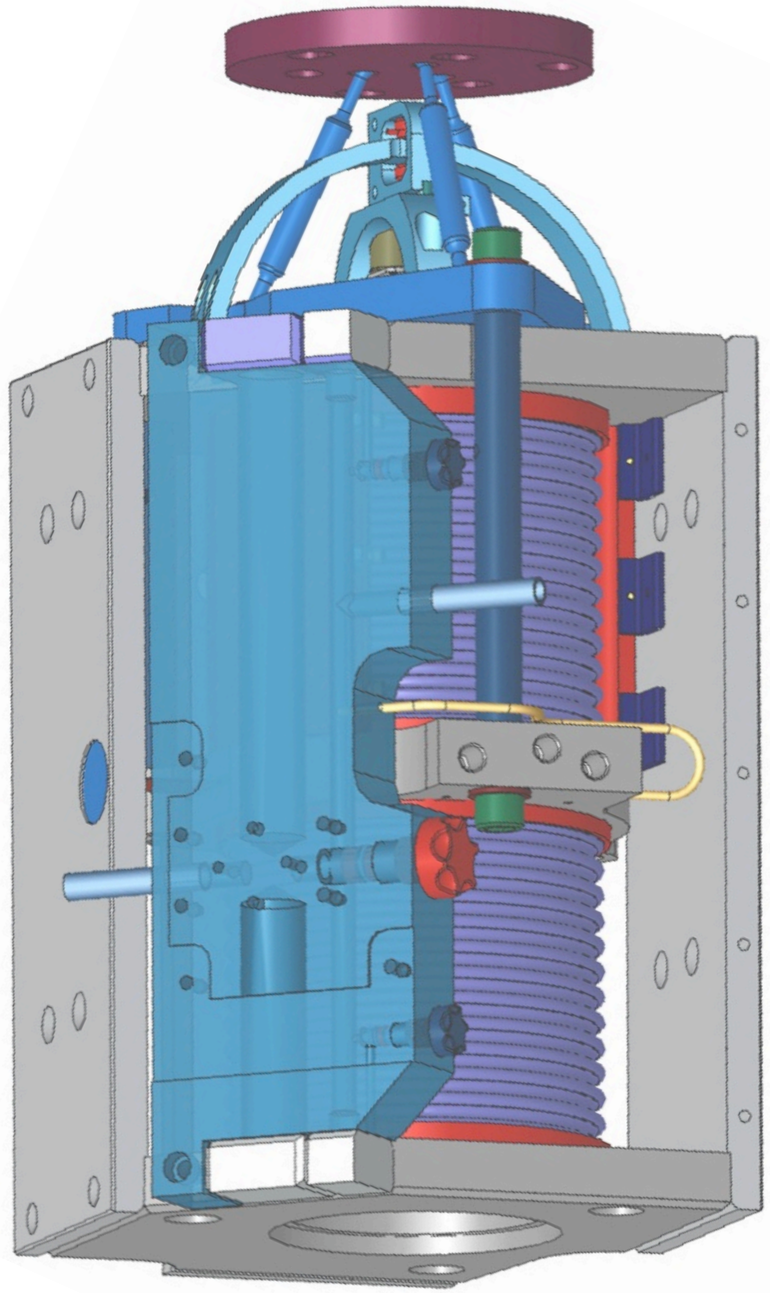
rms length variation
<1×10^{-14} m

<u>7 layers of isolation</u>
4 stage pendulum
2 stage active isolation table
1 stage Hydraulic External Pre-Isolator



Seismic Isolation & Alignment - HEPI





> Range of +/- 1 mm
> Easily holds 1e3 N (400 lbs) static offset
> Quiet (<1 nm/√Hz at 1 Hz)

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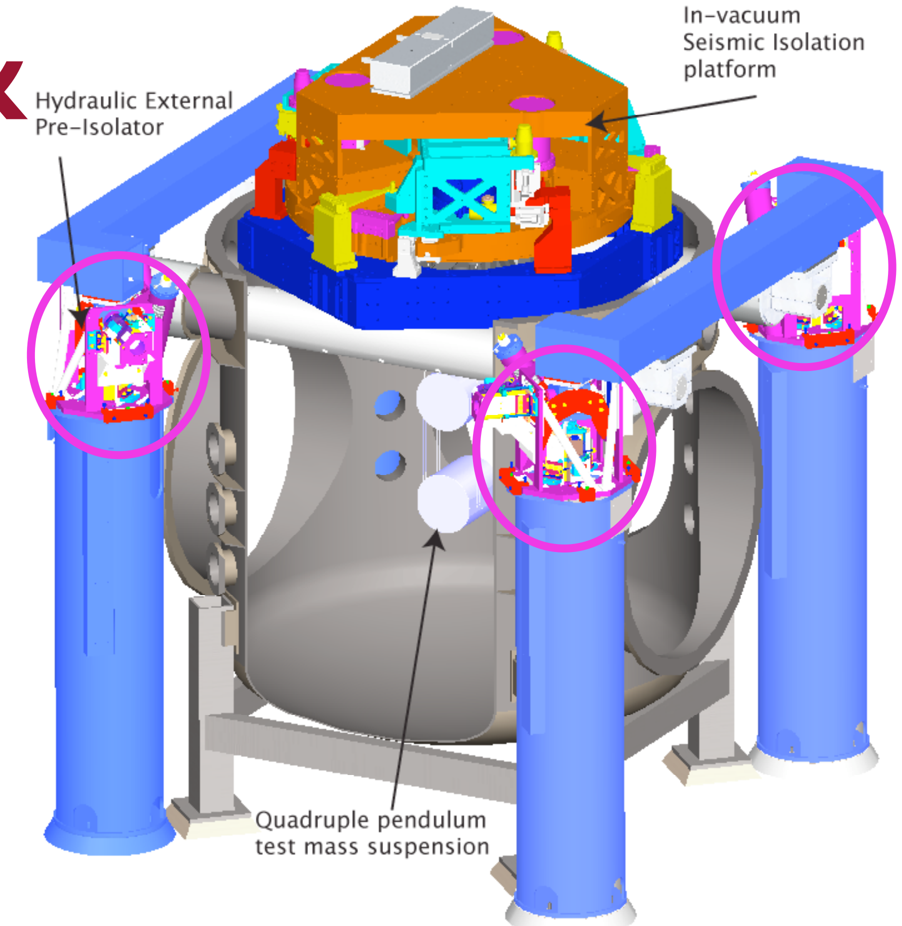

> Range of +/- 1 mm
> Easily holds 1e3 N (400 lbs) static offset
> Quiet (<1 nm/√Hz at 1 Hz)
> 1 Vert, 1 Horz per pier for full 6DOF control
> springs carry static load
> Feed-forward ground sensors and feed-back local sensors for alignment and isolation.
> Installed and running at LLO.

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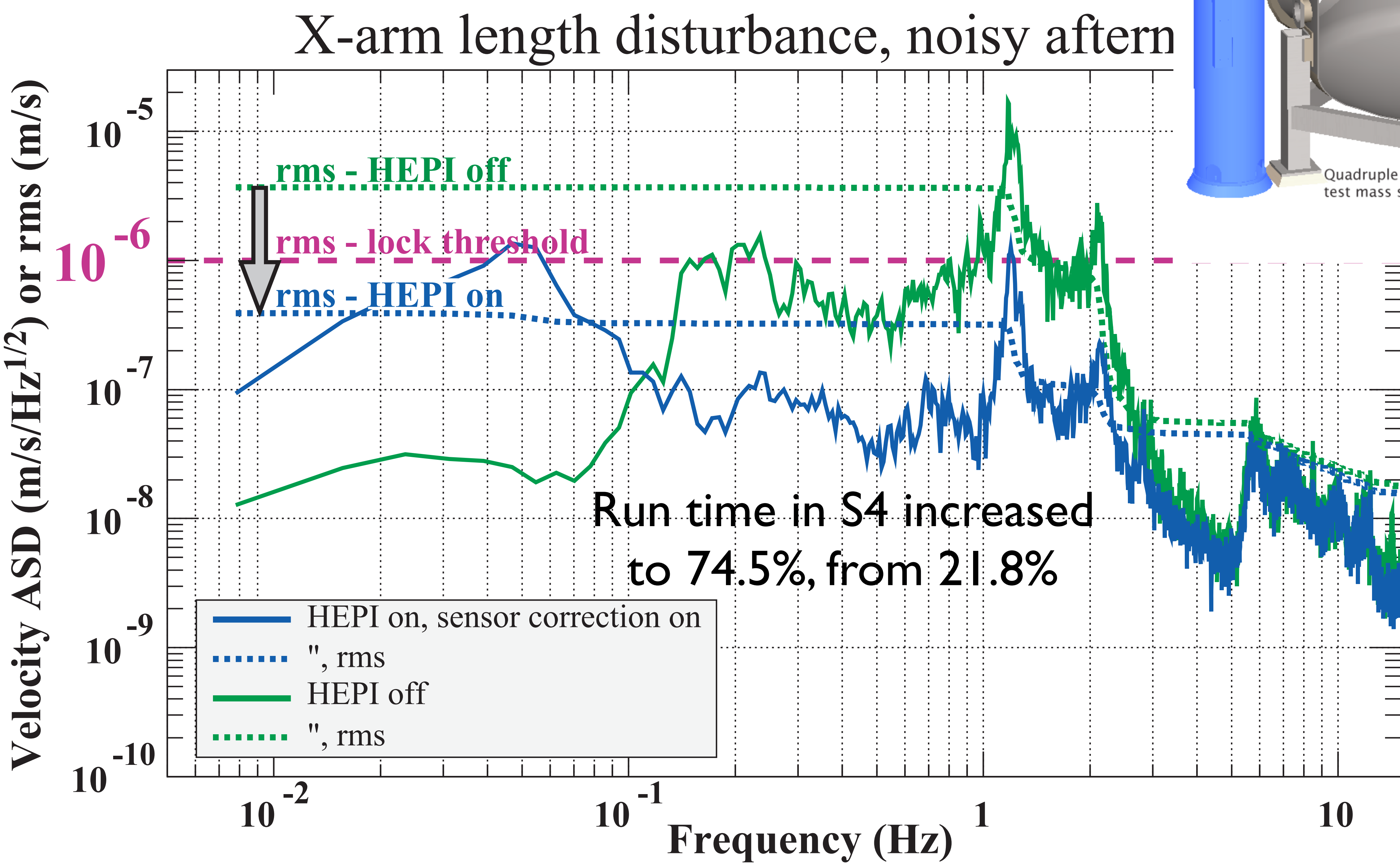
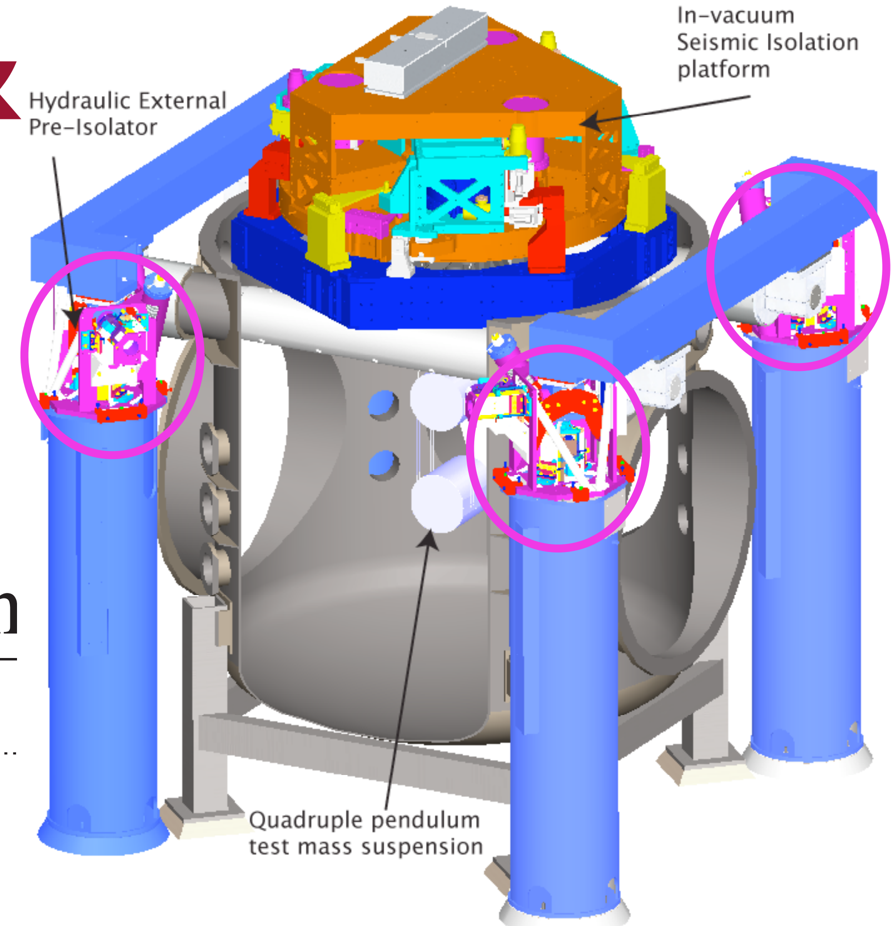
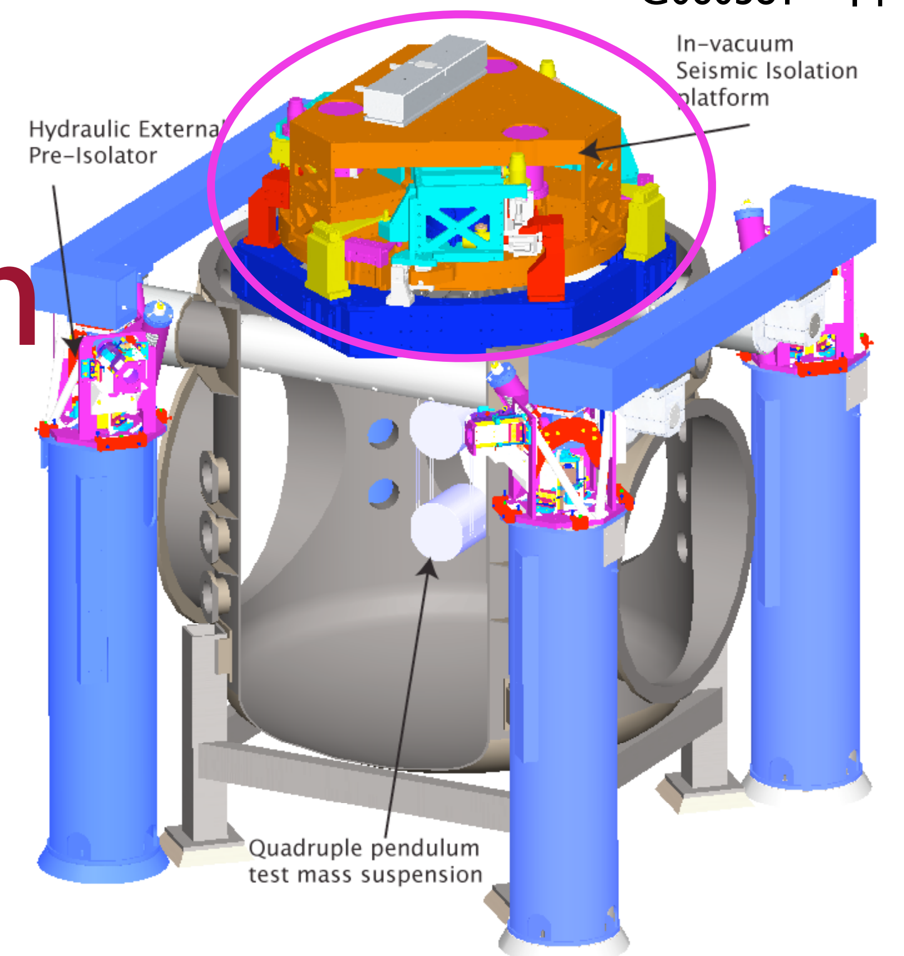
Seismic Isolation & Alignment - HEPI



Run time in S4 increased to 74.5%, from 21.8%

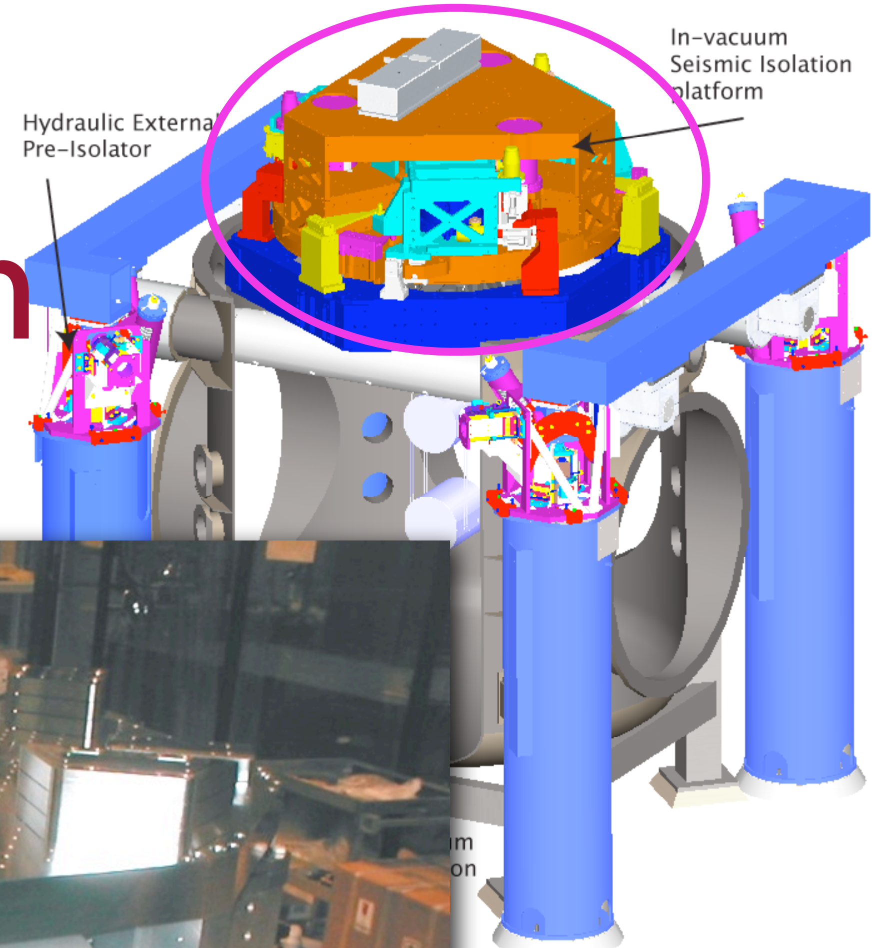


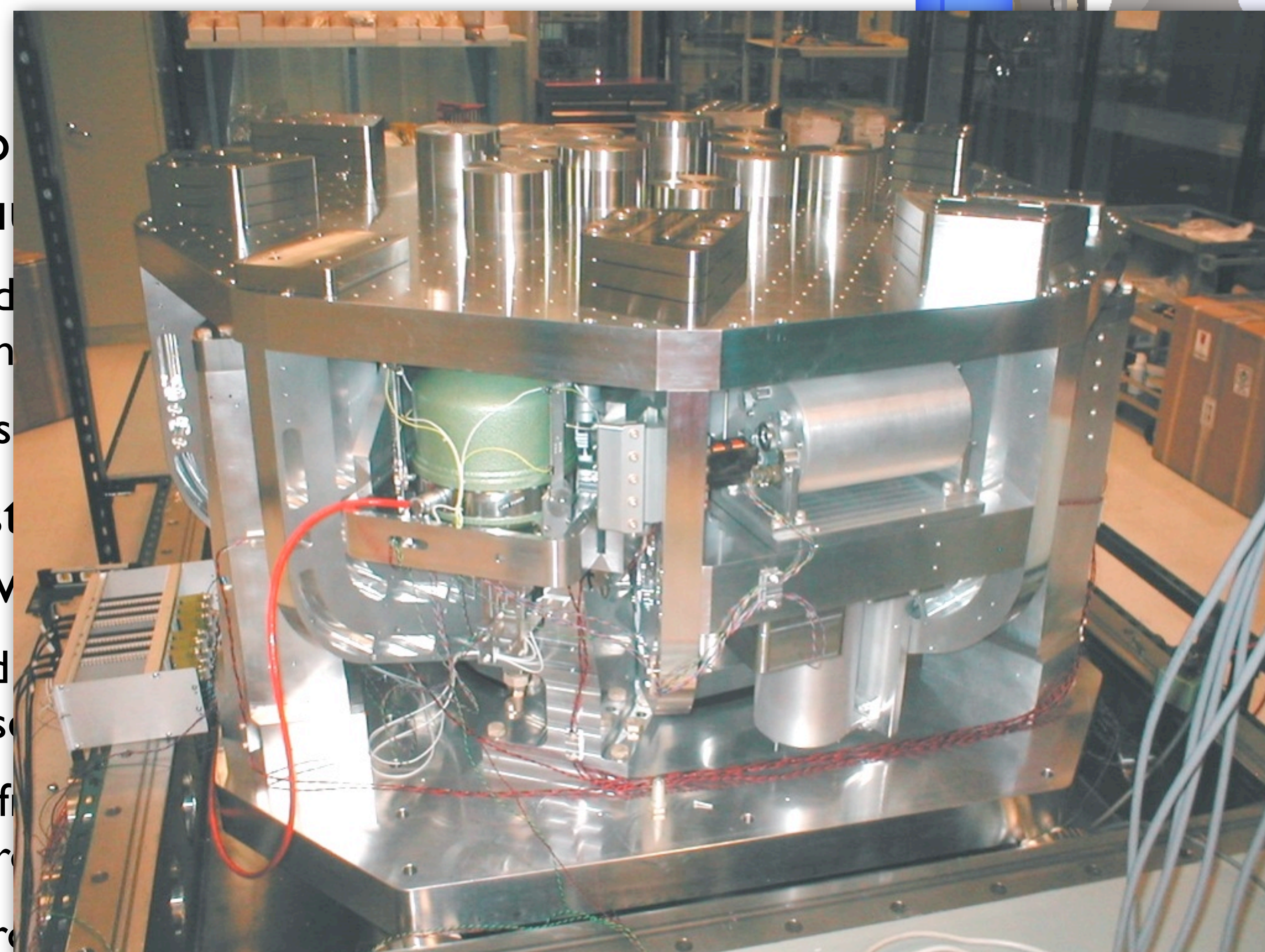
Seismic Isolation & Alignment - platform



- 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 being installed at MIT for full scale, UHV, tests with suspension systems.
  - modal frequencies designed to be > 150 Hz to accommodate ≈ 50 Hz servo unity-gain point.
  - modeling of 6 x 6 DOF stiffness at low frequencies. We design horizontal-tilt cross coupling < 1/500 rad/m.
  - new design for rigid and strong stops, to exactly position stages and restrict motion during earthquakes.
  - can accommodate ≈ 800 kg payload. Servo and mechanical design need to tolerate mechanically reactive massive payload

Seismic Isolation & Alignment - platform





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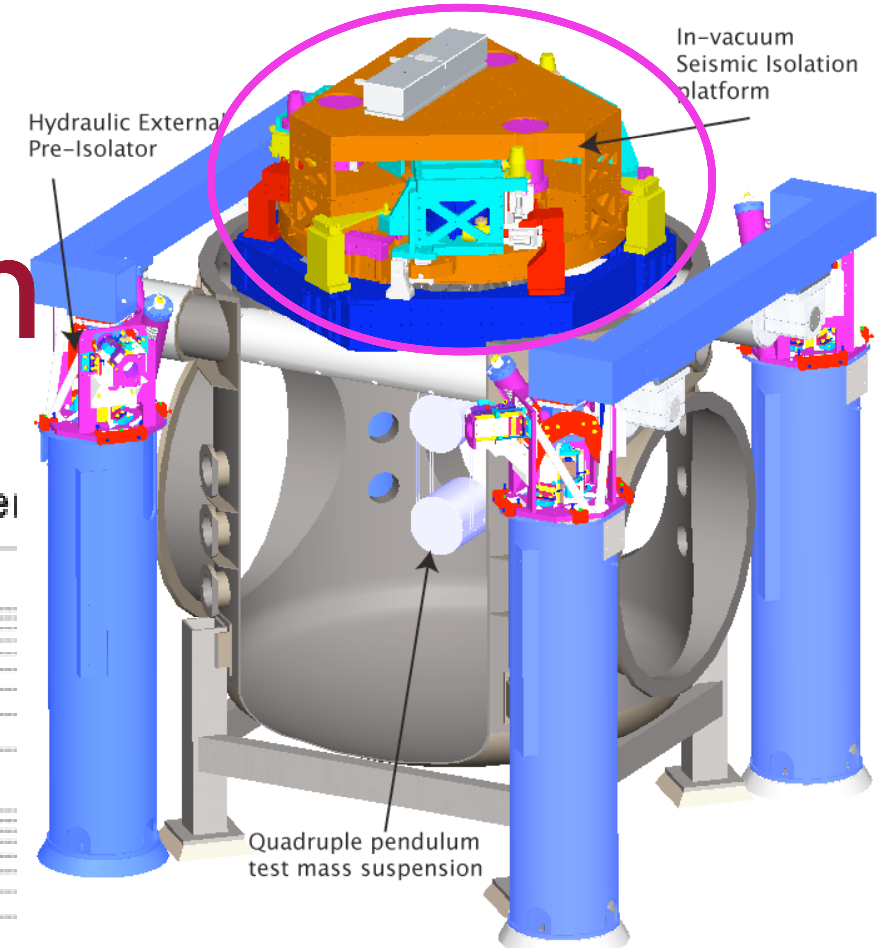
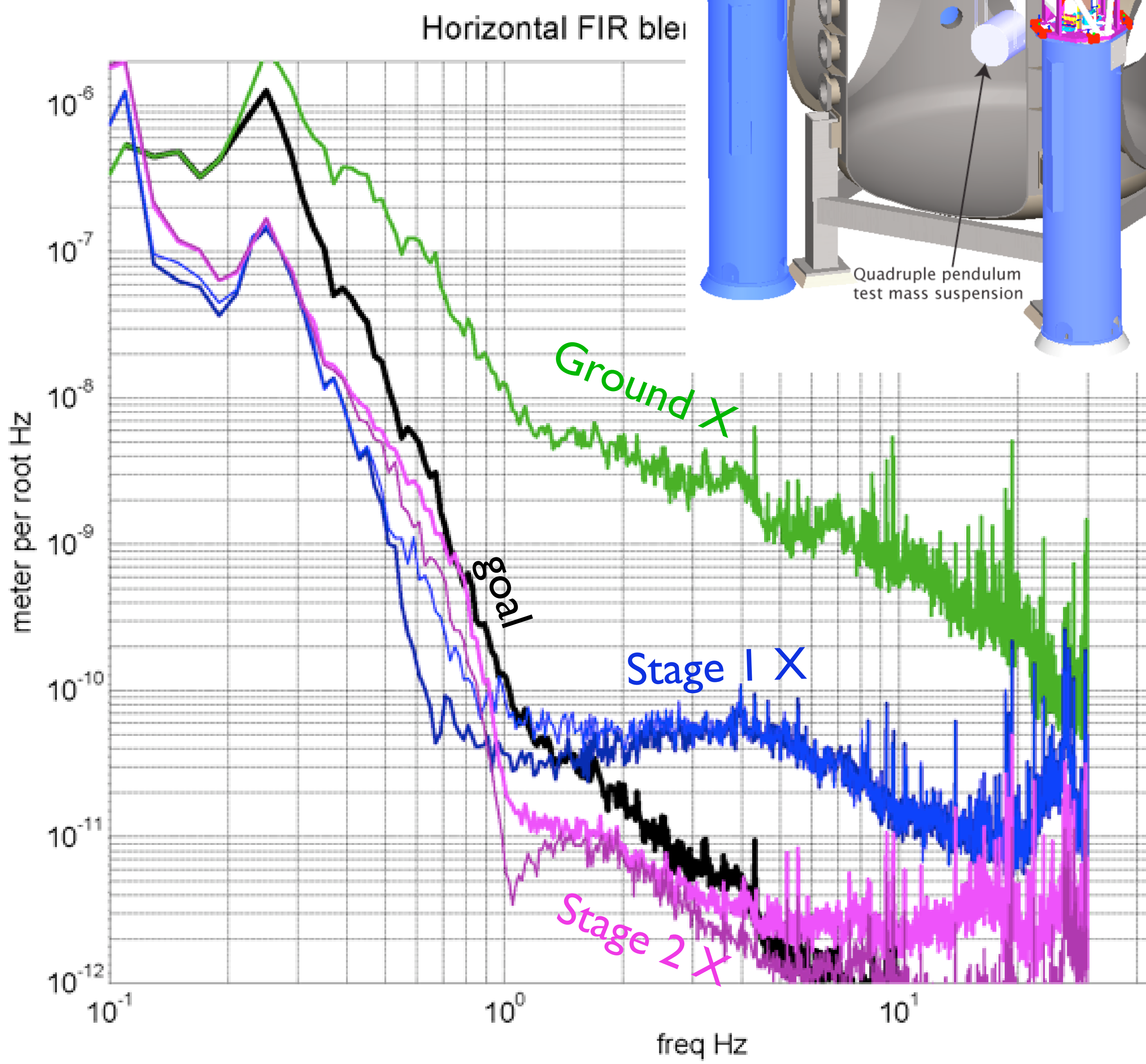
Seismic Isolation & Alignment - platform

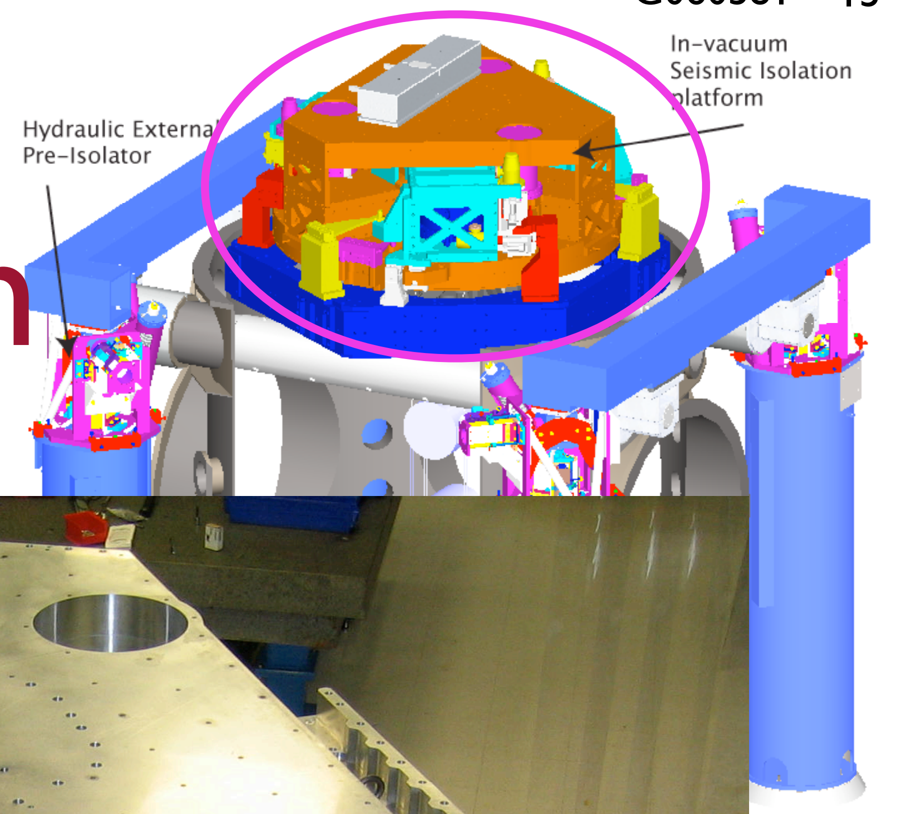
- Isolation requirement:
  100 at 1 Hz (met!)
  3000 at 10 Hz (design mod)

- We modified the LASTI prototype to increase vertical passive isolation at 10 Hz, based on these tests.





Seismic Isolation & Alignment - platform



- Isolation requirement:
  100 at 1 Hz (met!)
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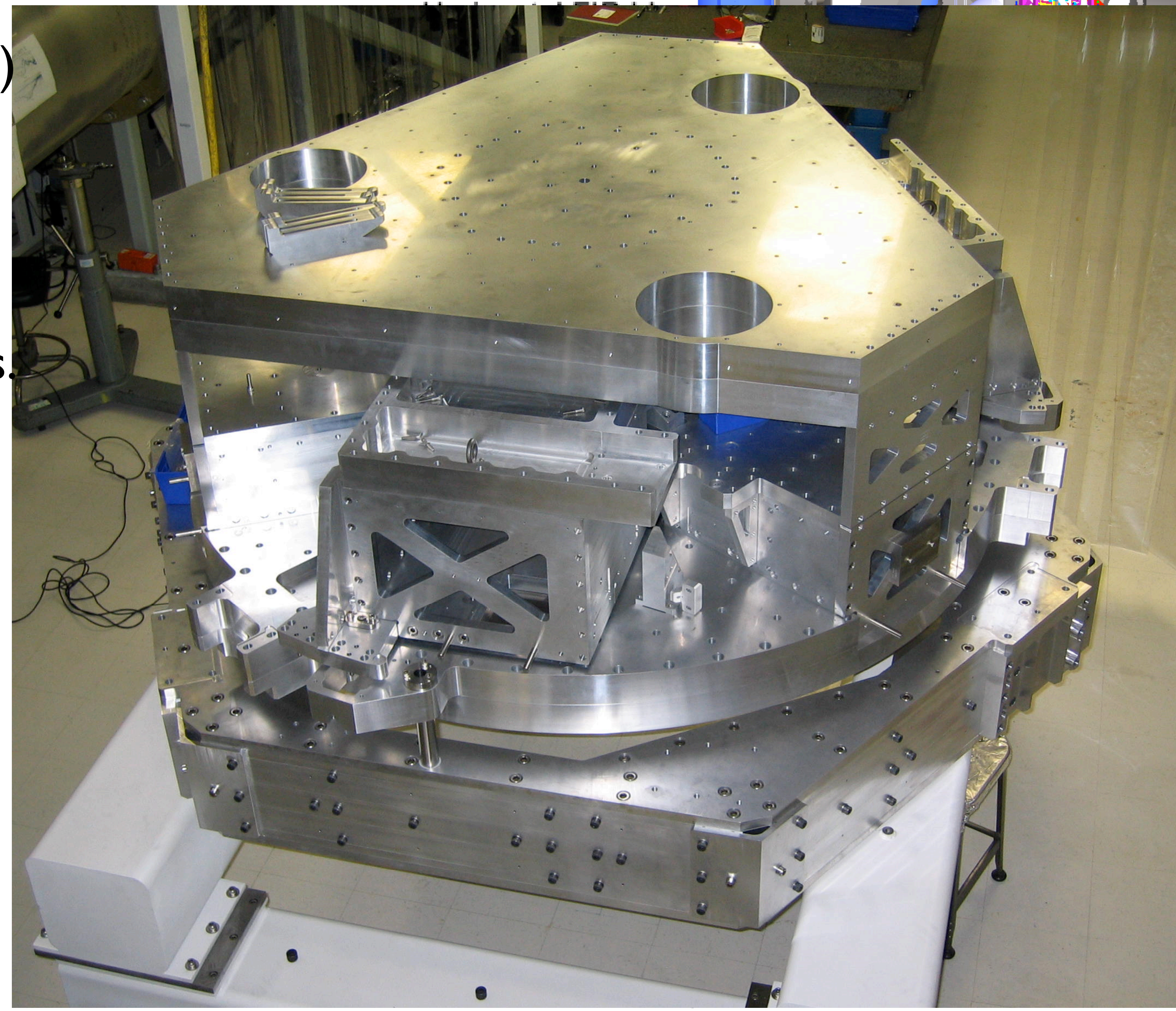
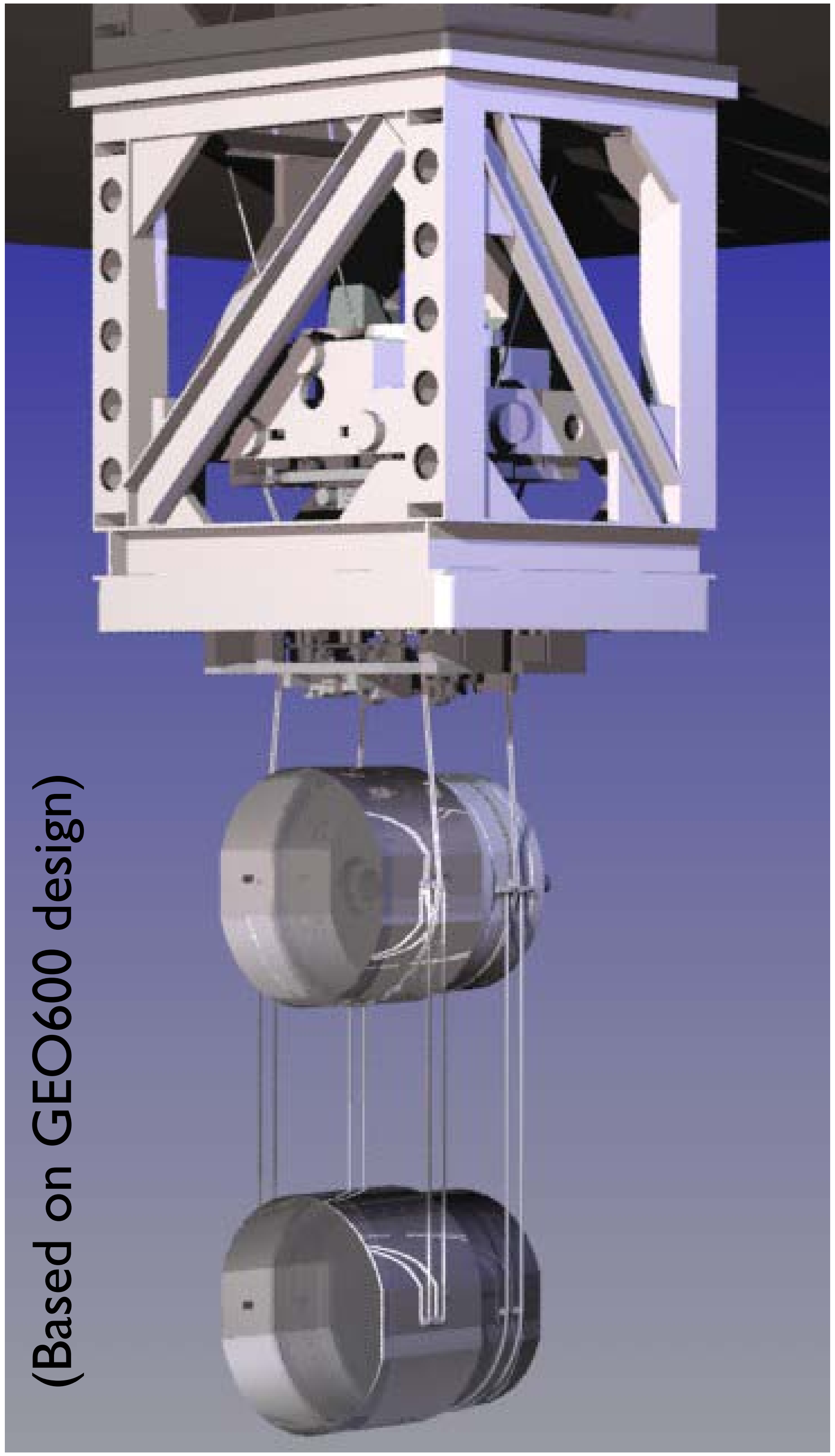
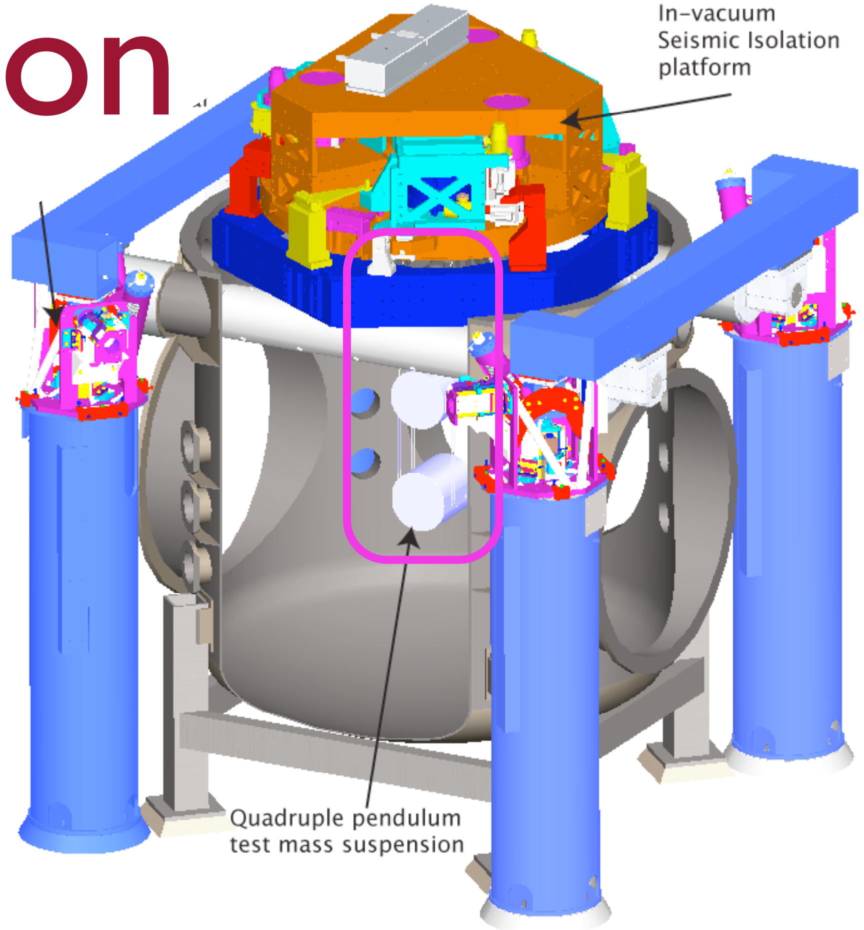
- We modified the LASTI prototype to increase vertical passive isolation at 10 Hz, based on these tests.
- LASTI prototype now being assembled at MIT. Testing to commence forthwith.



Pendulum Suspension



Drawings courtesy of Calum Torrie and GEO600



Multiple-pendulums
for control flexibility &
seismic attenuation

Test masses:
Synthetic fused silica,
40 kg, 34 cm dia.

» Q ≥ 1e7
» low optical absorption

Final suspensions are fused silica,
joined to form monolithic final stages.

Thermal vibrations at the optical surface
set the performance limit of the
suspension.

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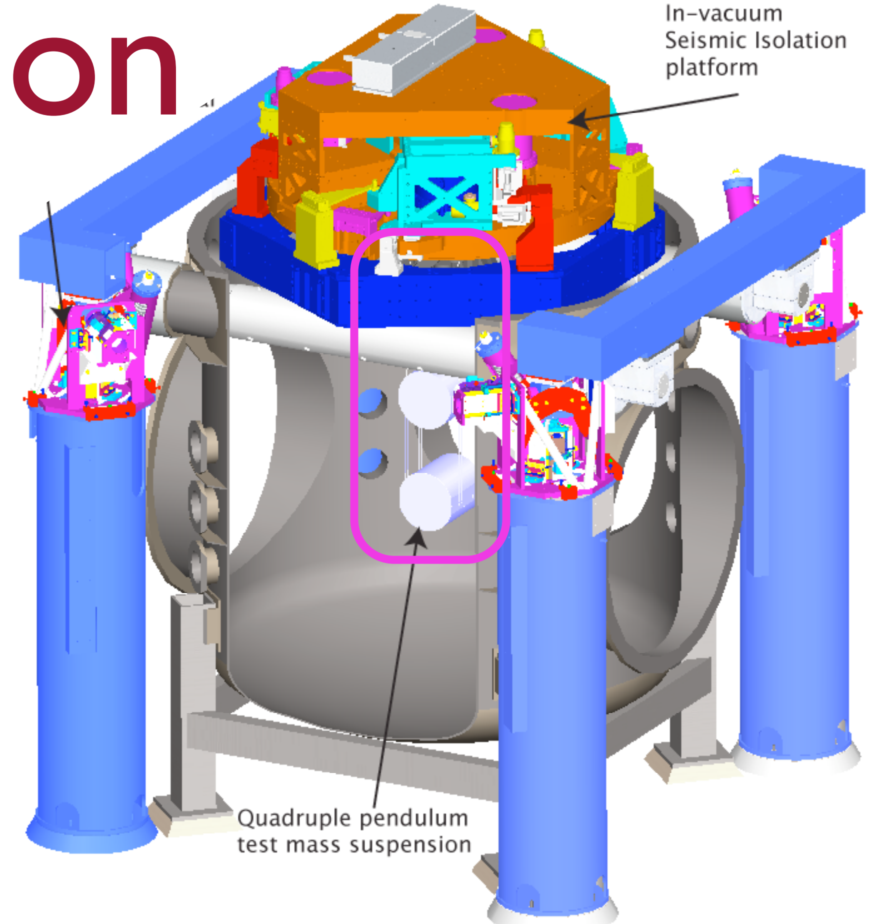
Pendulum Suspension



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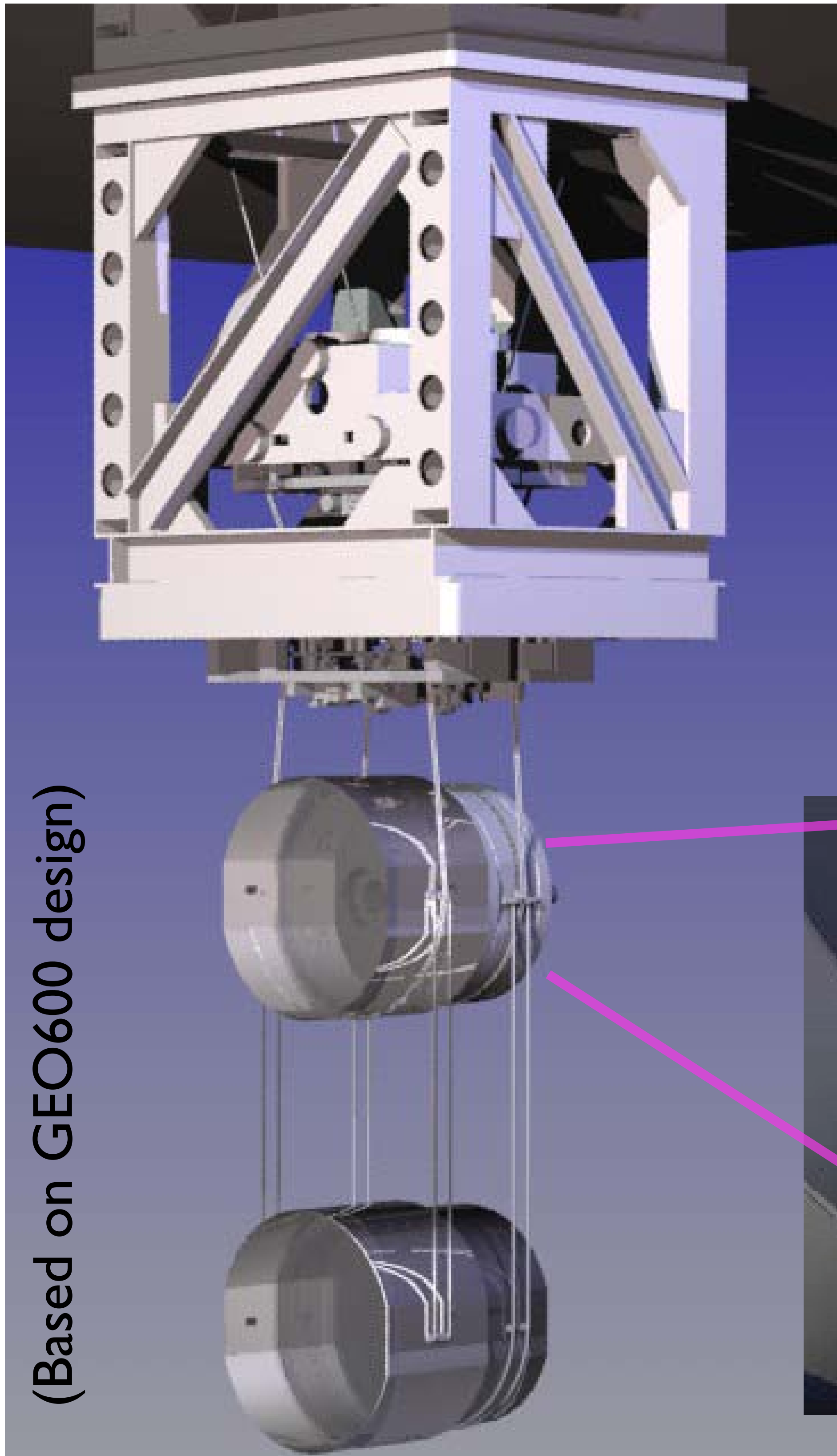

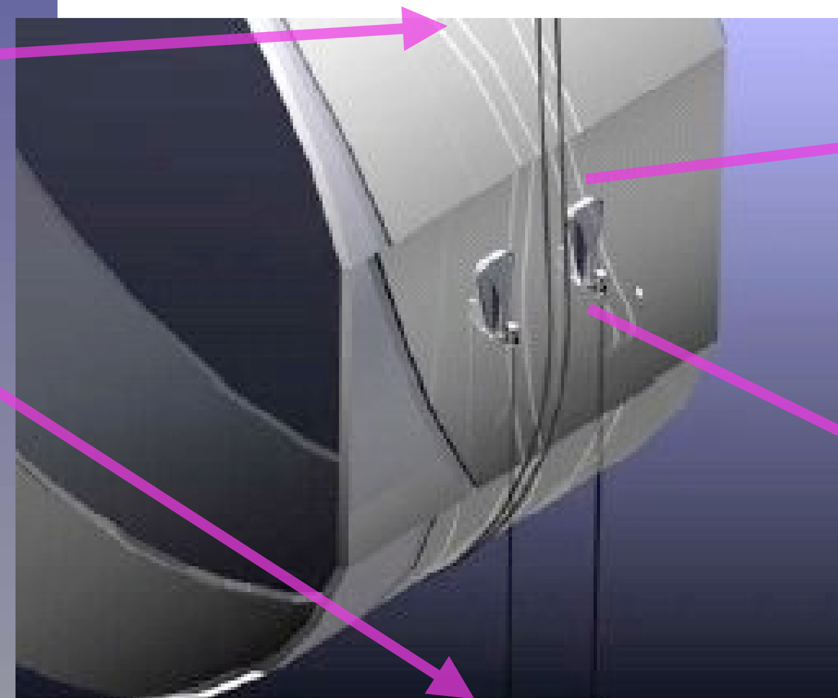

Drawings courtesy of Calum Torrie and GEO600

silicate bonding creates a monolithic final stage

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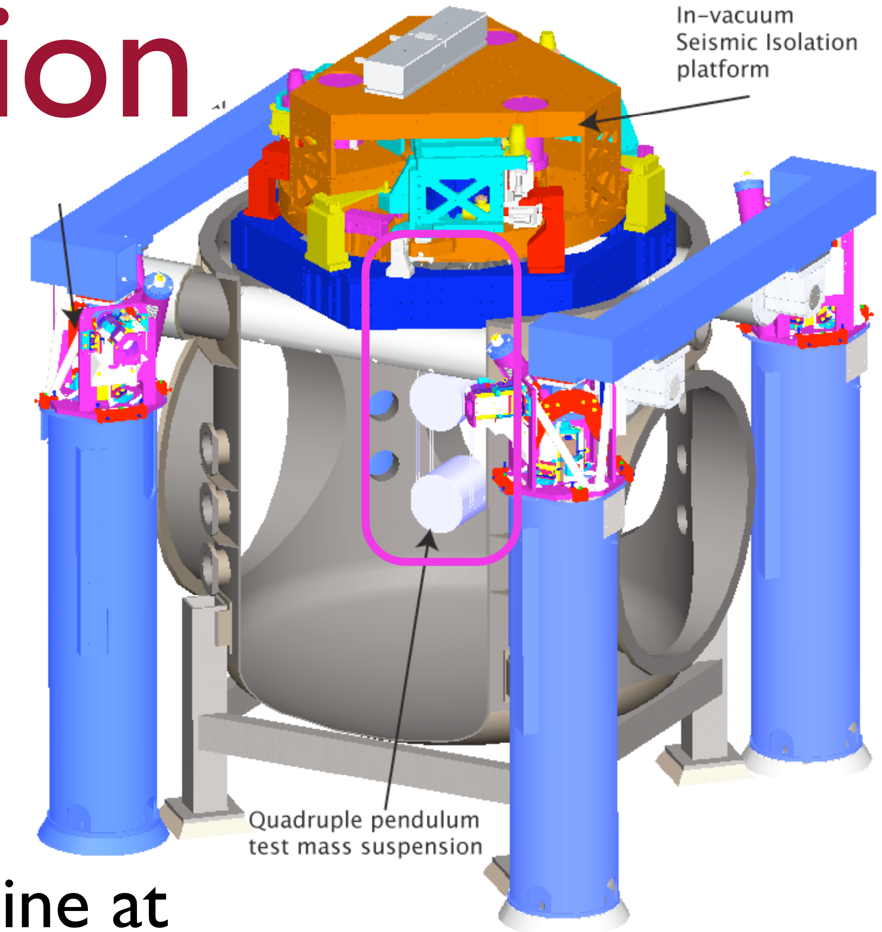

Installing 'controls prototype' at MIT
(metal masses, metal wires)

'Noise prototype' due in early 2007
(glass optics, silica ribbon suspensions)

Ribbon pulling machine at
the University of Glasgow

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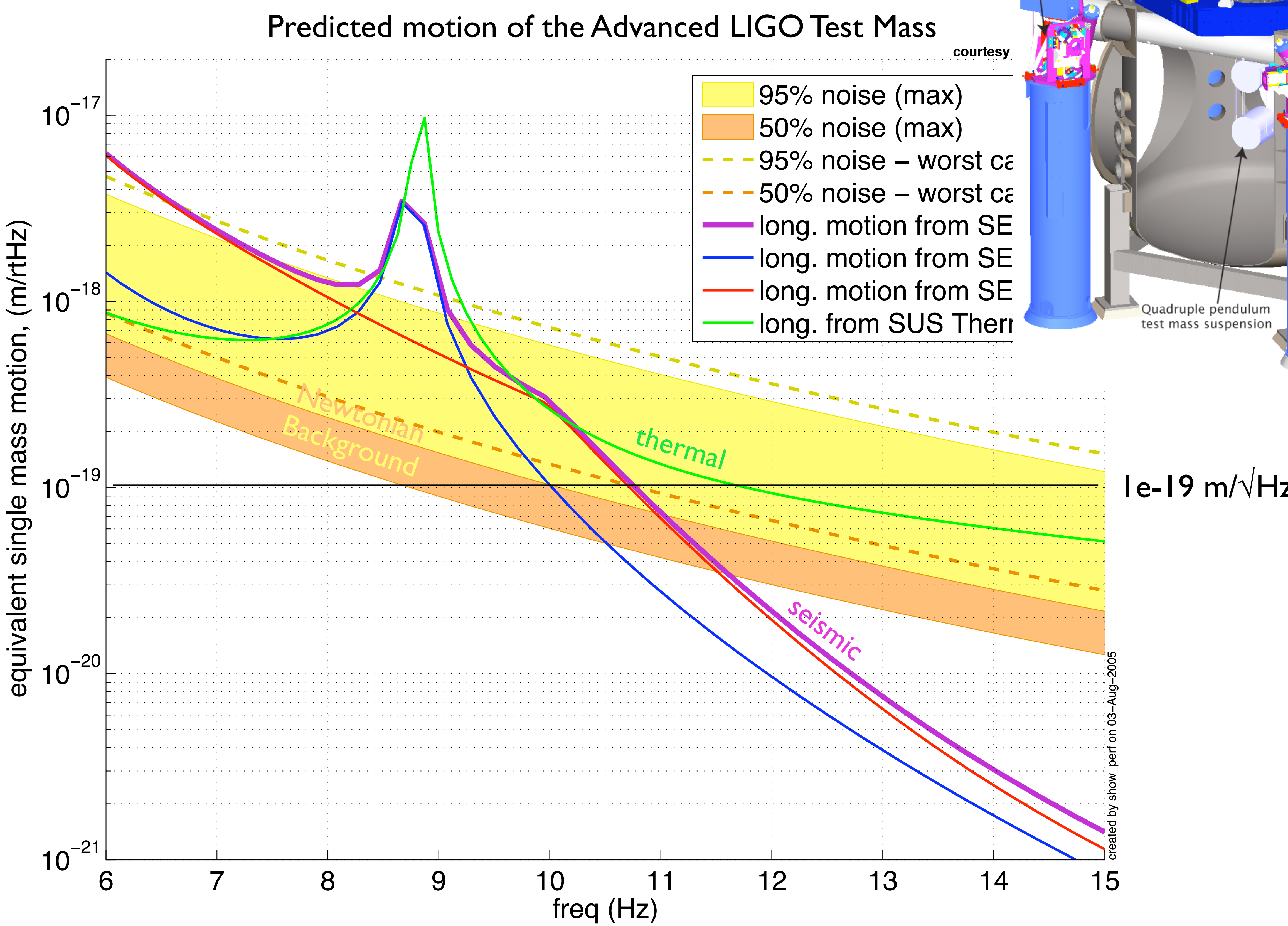
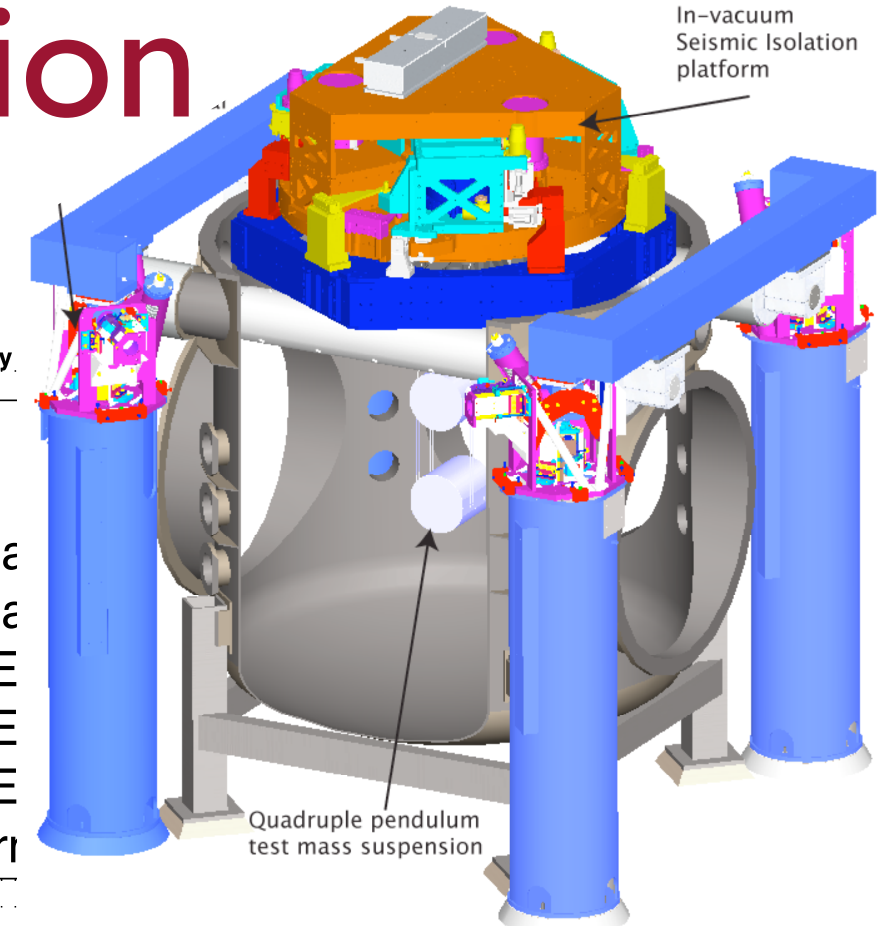
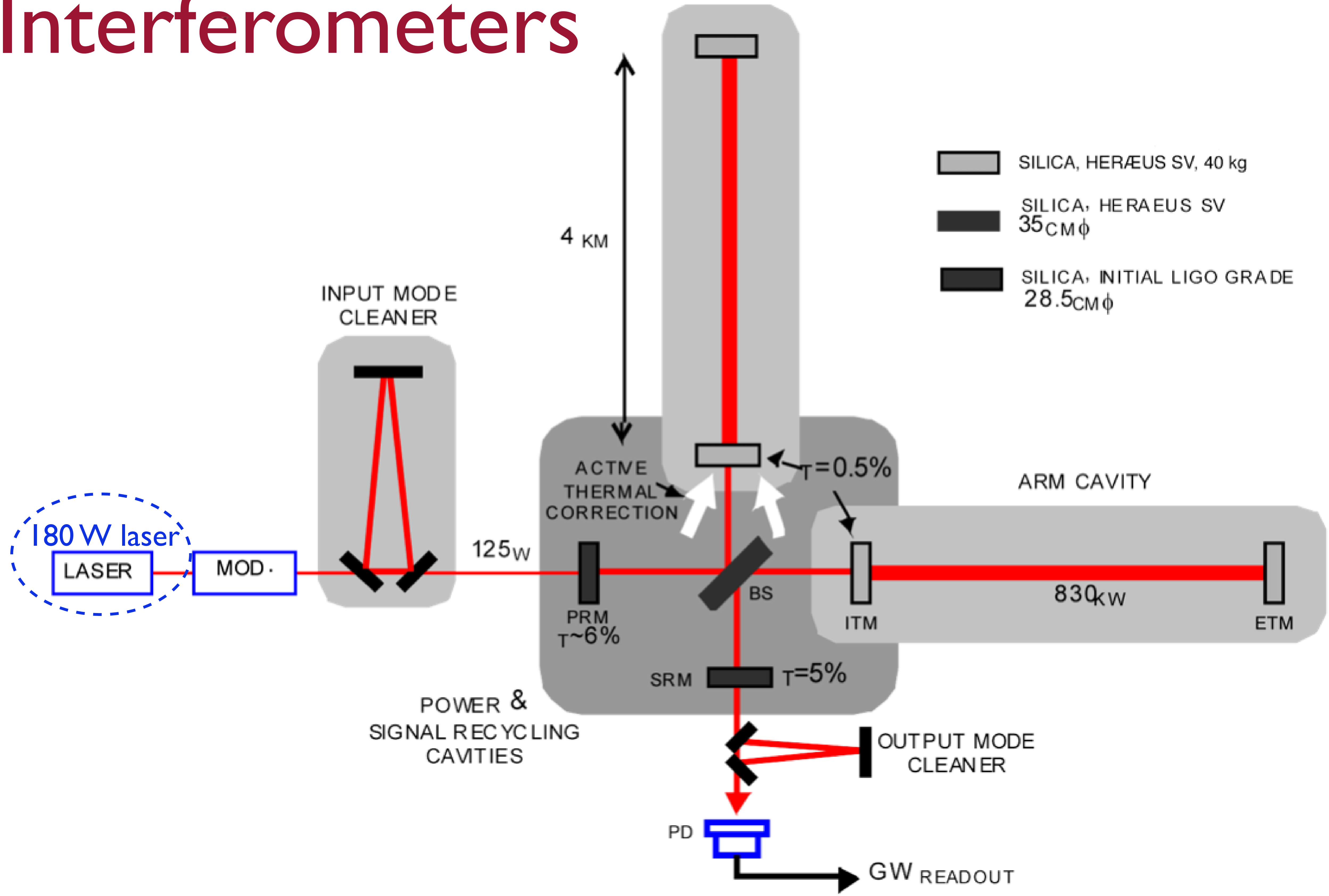
Pendulum Suspension





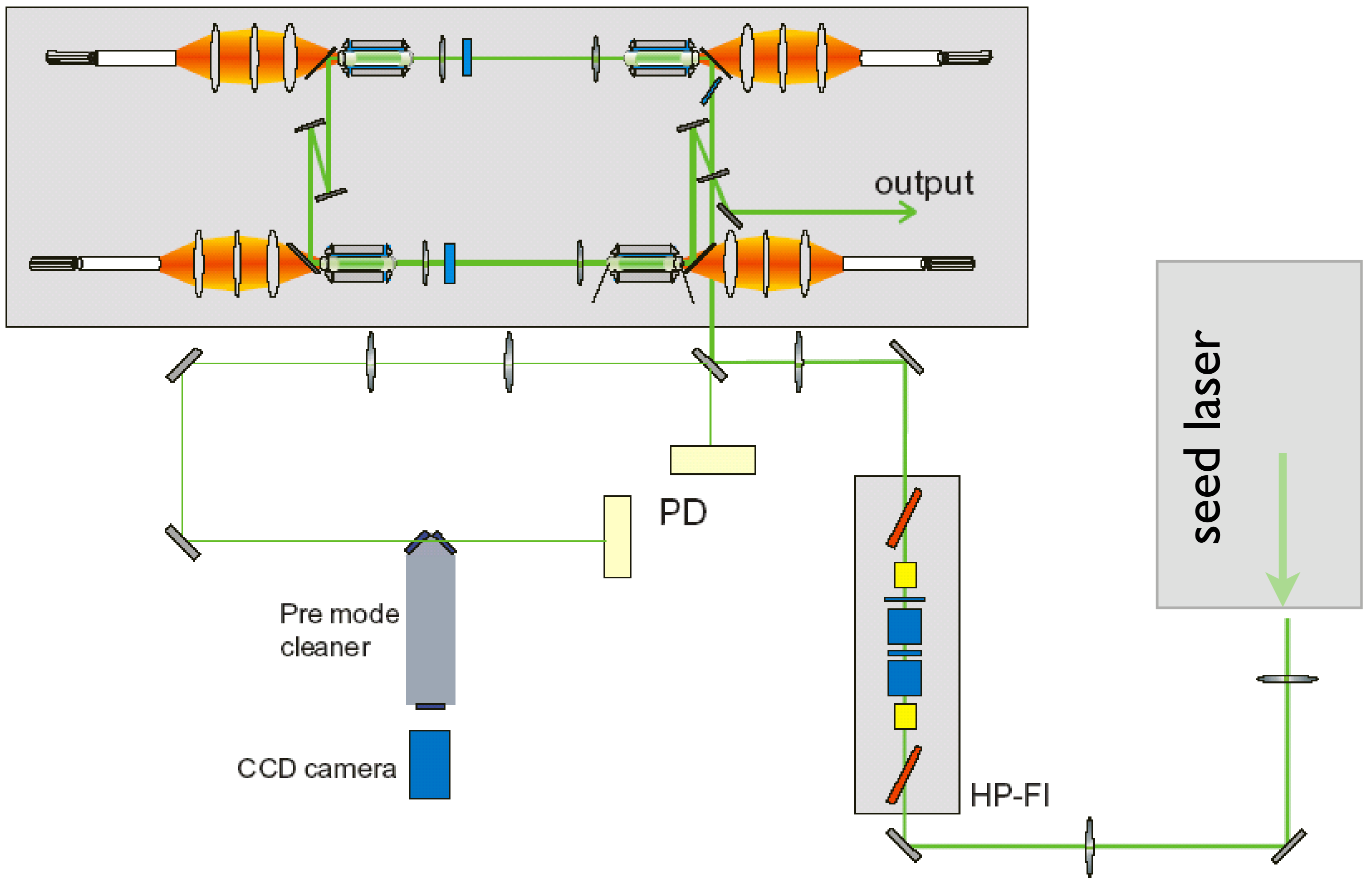
Power, Optics, and Interferometers

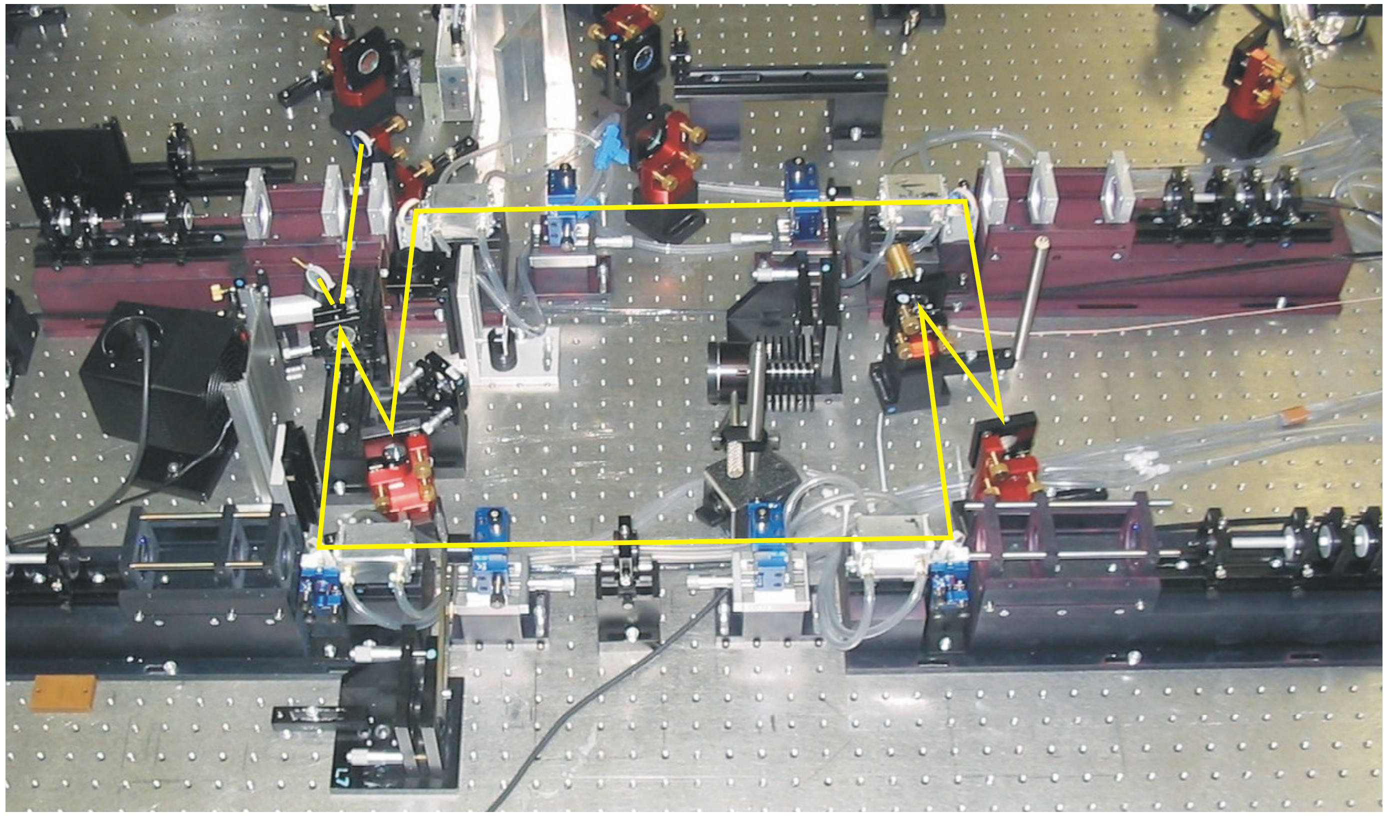


High Power Laser

- 180 W with good beam shape
- 1064 nm (YAG)
- very low intensity and frequency noise
- Developed by Max-Planck Institute, Hanover & Laser Zentrum Hanover
- stable front end determines laser frequency and frequency fluctuations.
- high power stage, Injection seeded ring oscillator determines power, power fluctuations, and beam shape.

high-power injection-locked oscillator





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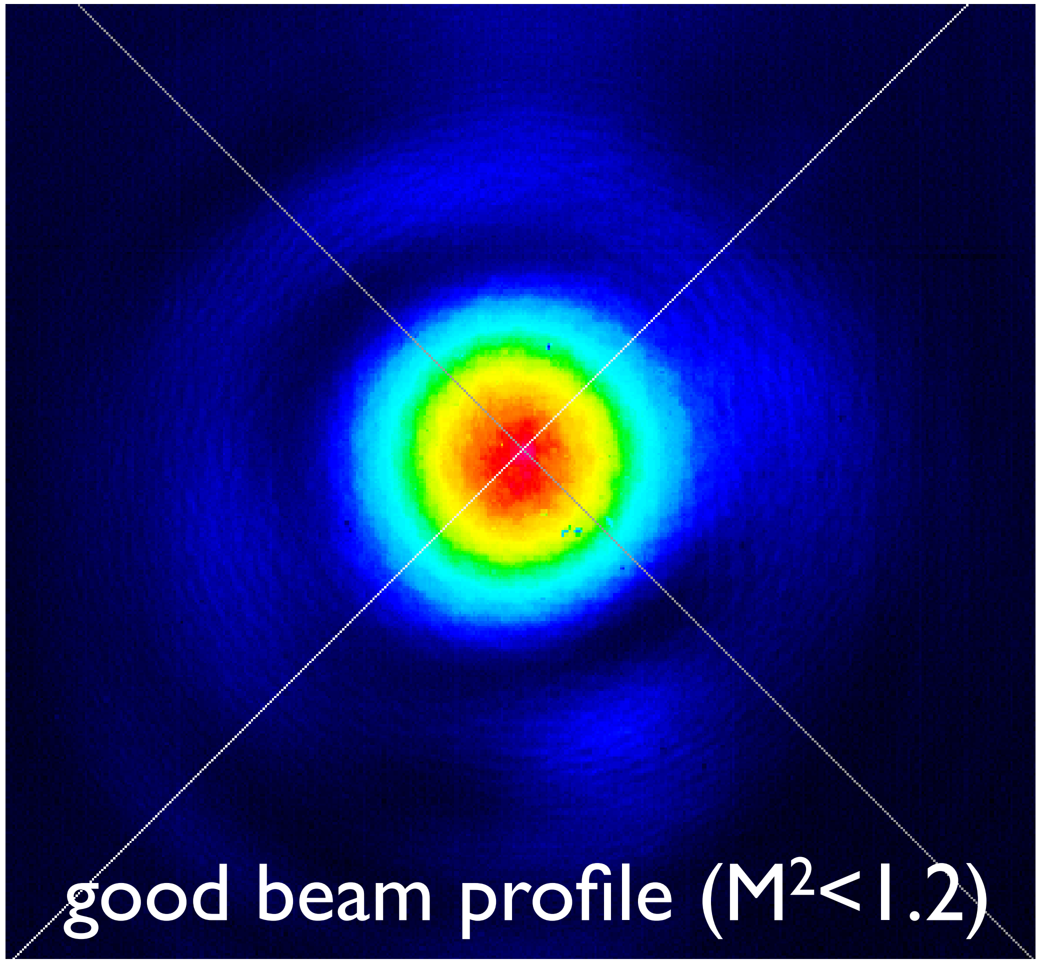
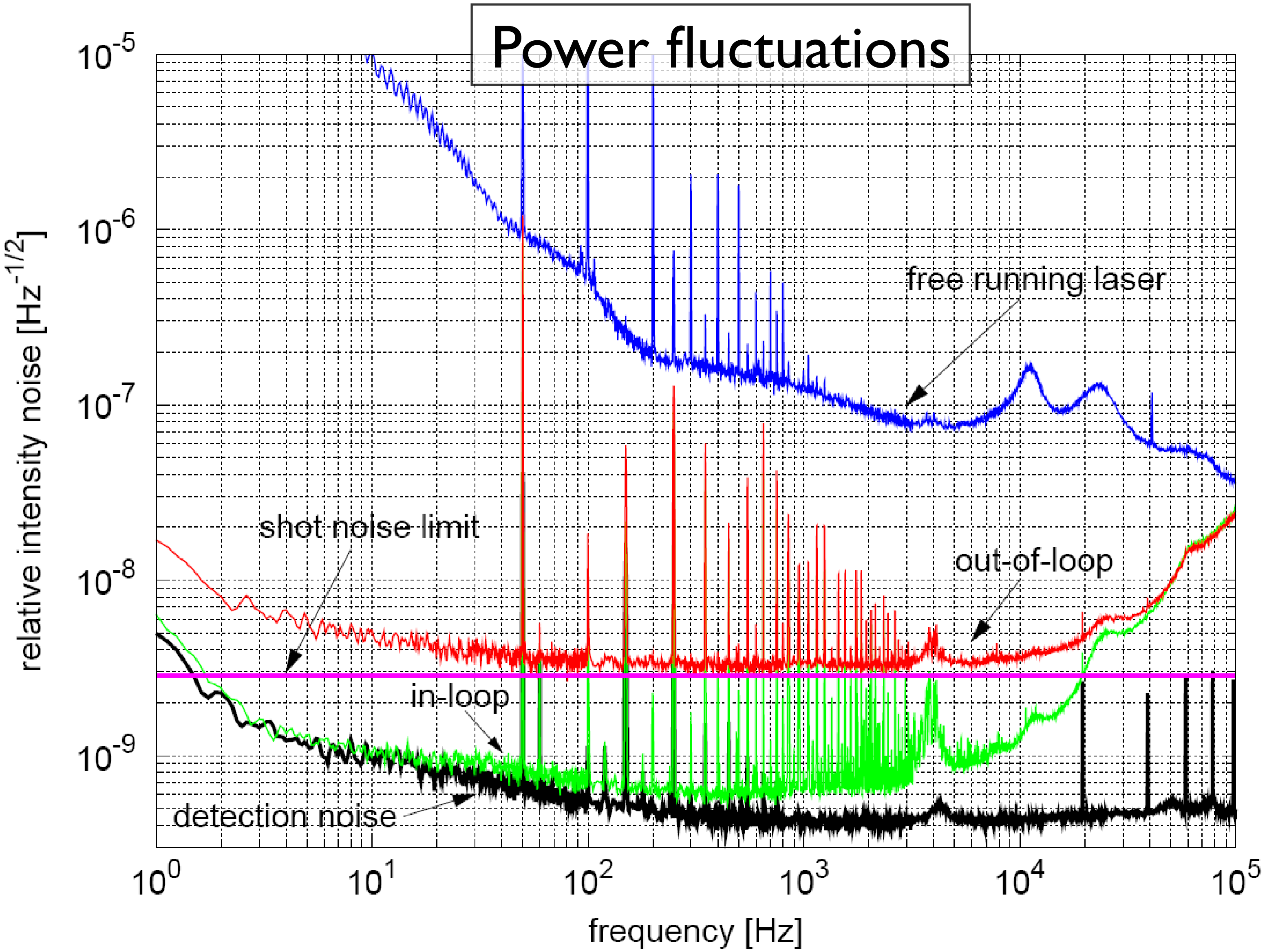
High Power Laser



Achieved:

- 180 W output power
- good spatial profile
- power fluctuations close to requirement.



Still to Verify:

- RIN at modulation freq.
- higher order mode content
- pointing fluctuations

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Test Mass Requirements

Mass	40 kg, fused silica	
Dimensions	340 mm x 200 mm	
Surface figure	< 1 nm rms	
Micro-roughness	< 0.1 nm rms	
Double-pass optical homogeneity	< 20 nm rms,	
Bulk absorption	< 3 ppm/cm	good enough for Thermal Comp. System
Bulk mechanical loss	$< 3\times10^{-9}$	
Optical coating: Titania doped Tantala/ silica		
Optical coating absorption	< 0.5 ppm(required) < 0.2 ppm(goal)	small samples OK
Optical coating mechanical loss	$< 2\times10^{-4}$ (required) $< 3\times10^{-5}$ (goal)	measured 8.5×10^{-5}
Optical coating scatter	< 2 ppm(required) < 1 ppm(goal)	not yet...
Arm cavity optical loss / round trip	< 75 ppm	

courtesy of Gregory Harry

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Test Mass Requirements

Mass	40 kg, fused silica
Dimensions	340 mm x 200 mm
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Micro-roughness	< 0.1 nm rms
Double-pass optical homogeneity	< 20 nm rms, good enough for Thermal Comp. System
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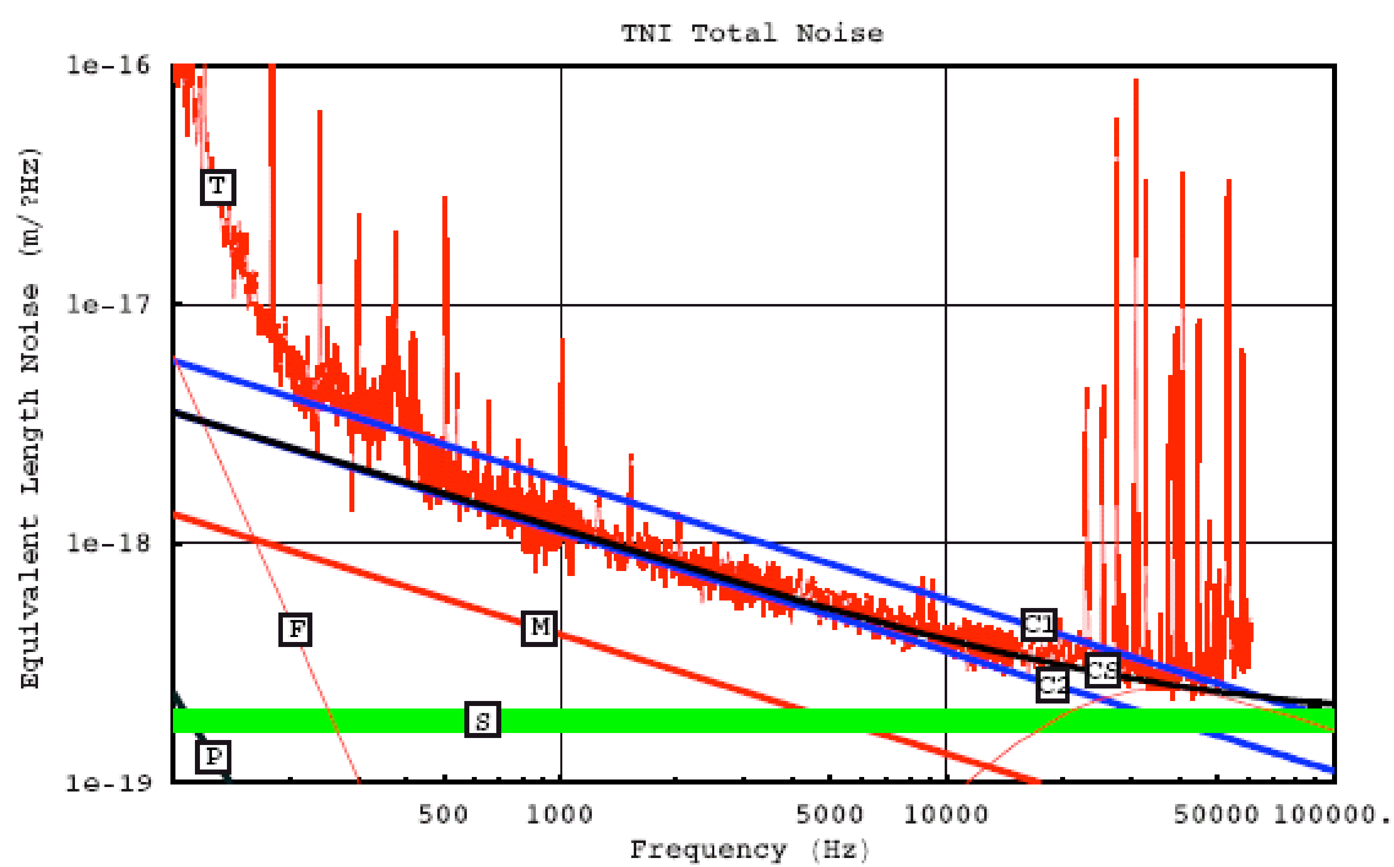


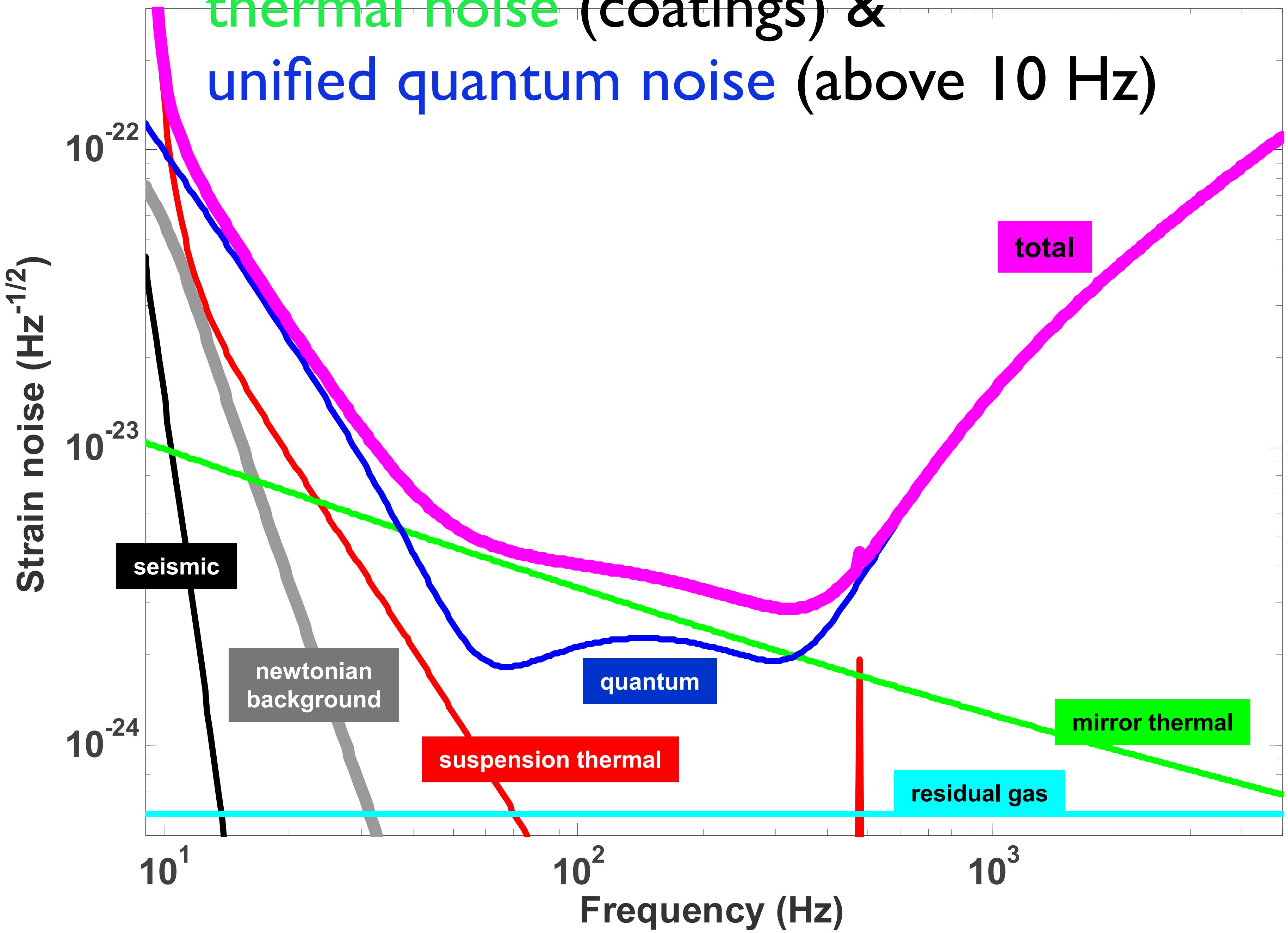
courtesy of Gregory Harry

and more...

- End-to-end model
- Sensing and control for all length and angle DOFs
- Big computing pipeline for both instrument control and for data analysis.
- output mode cleaner (CIT 40 meter lab)
- high power input optics (Univ. Florida)
- 40 m lab & Thermal noise interferometer at Caltech, LASTI at MIT, high-power test facility at Gingin, 10 meter lab at Univ. Glasgow, ETF at Stanford, the LIGO and GEO observatories...

Tuning

Instrument noise floor set by
thermal noise (coatings) &
unified quantum noise (above 10 Hz)



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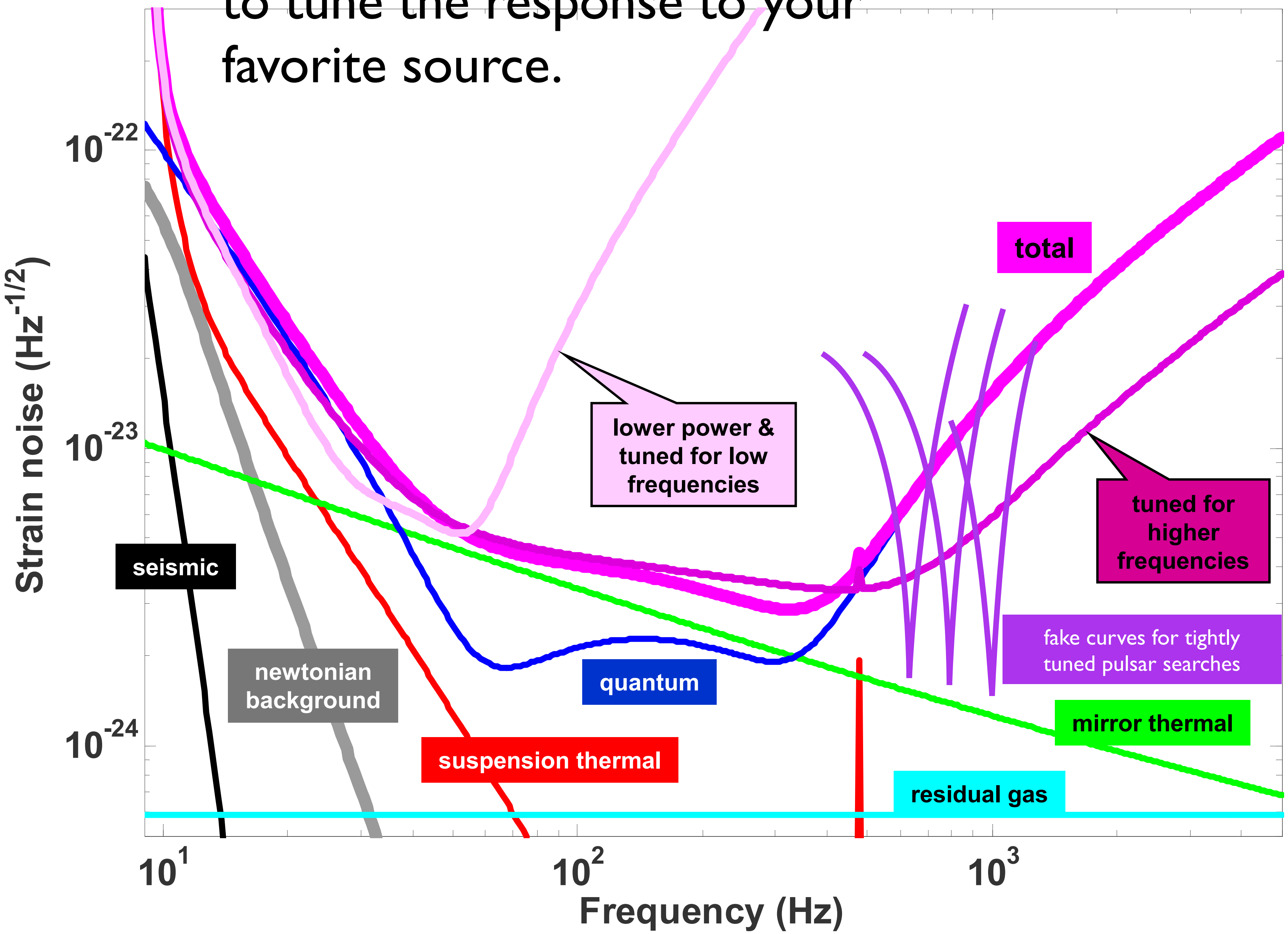
Tuning

Signal recycling mirror makes it possible to tune the response to your favorite source.



When we start measuring gravitational waves, this flexible instrument can be directed towards many different astrophysical goals.

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in Conclusion...

- LIGO science collaboration is large and active,
- We've developed a tremendous amount of new technology,
- We now have the technology in hand to make a fantastic new instrument, and
- We'll be ready to start construction next fall.

The astrophysics will be great!