Advanced LIGO

the Laser Interferometer Gravitational-wave Observatory

The Next Gravitational-Wave Observatory

Brian Lantz, for the LSC
(40+ institutions, hundreds of people)
SLAC Instrumentation Series, Feb 20, 2008

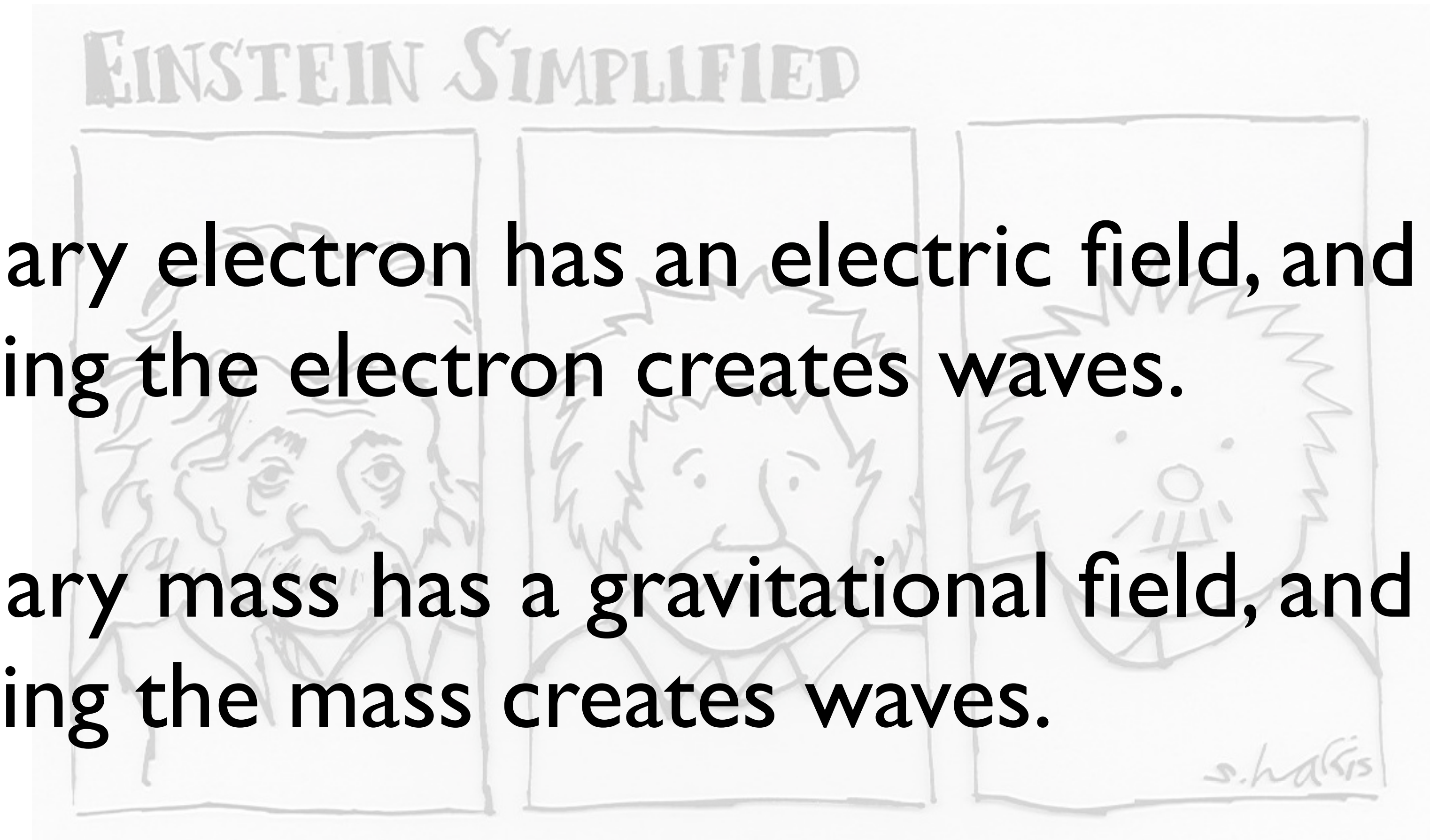
black hole image courtesy of LISA,
http://lisa.jpl.nasa.gov

A LIGO Instrument Overview

This afternoon:

- Introduction to Gravitational waves and their detection.
- Performance of Initial LIGO (amazing, but...),
  plans for Enhanced LIGO, and
  predictions for Advanced LIGO (regular detections?).
- Discussion of a few of the new instrument’s subsystems.
  optics, seismic isolation, laser,

What is a Gravitational Wave?



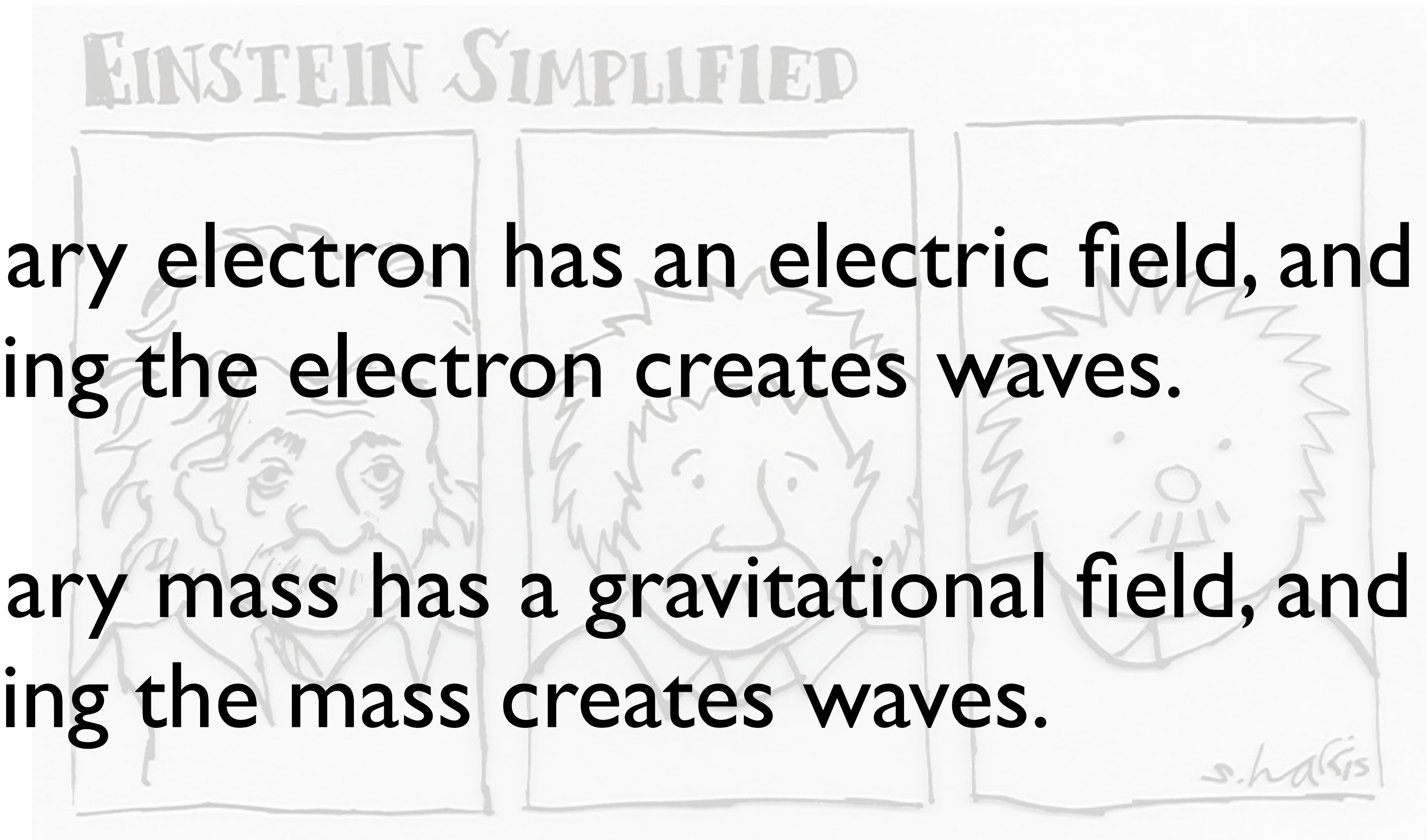
A stationary electron has an electric field, and accelerating the electron creates waves.

A stationary mass has a gravitational field, and accelerating the mass creates waves.

But, gravitational forces are relatively weak

$$(for\ electron\ and\ proton)\ \frac{electrical\, force}{gravitational\, force} \approx 2 \cdot 10^{39}$$

What is a Gravitational Wave?



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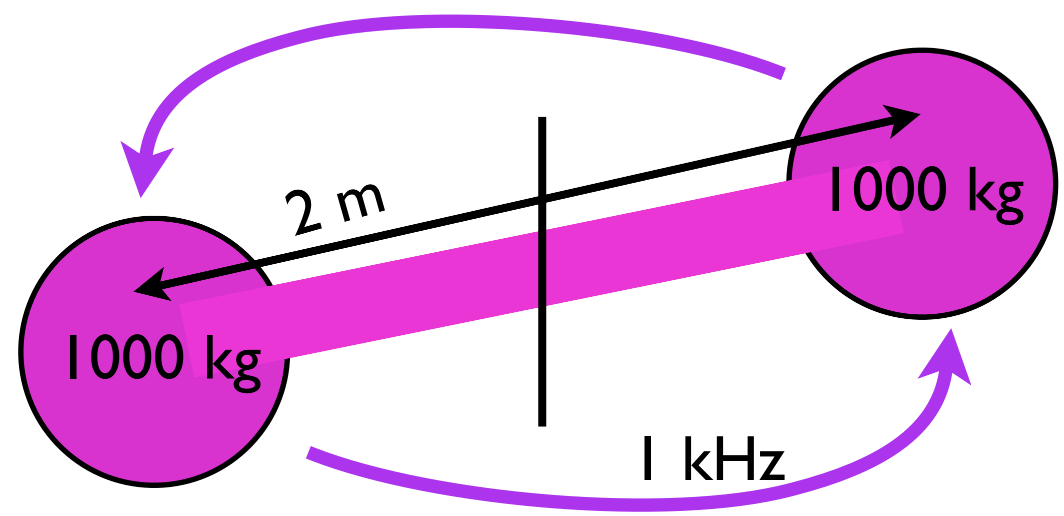
A stationary mass has a gravitational field, and accelerating the mass creates waves.

But, gravitational forces are relatively weak

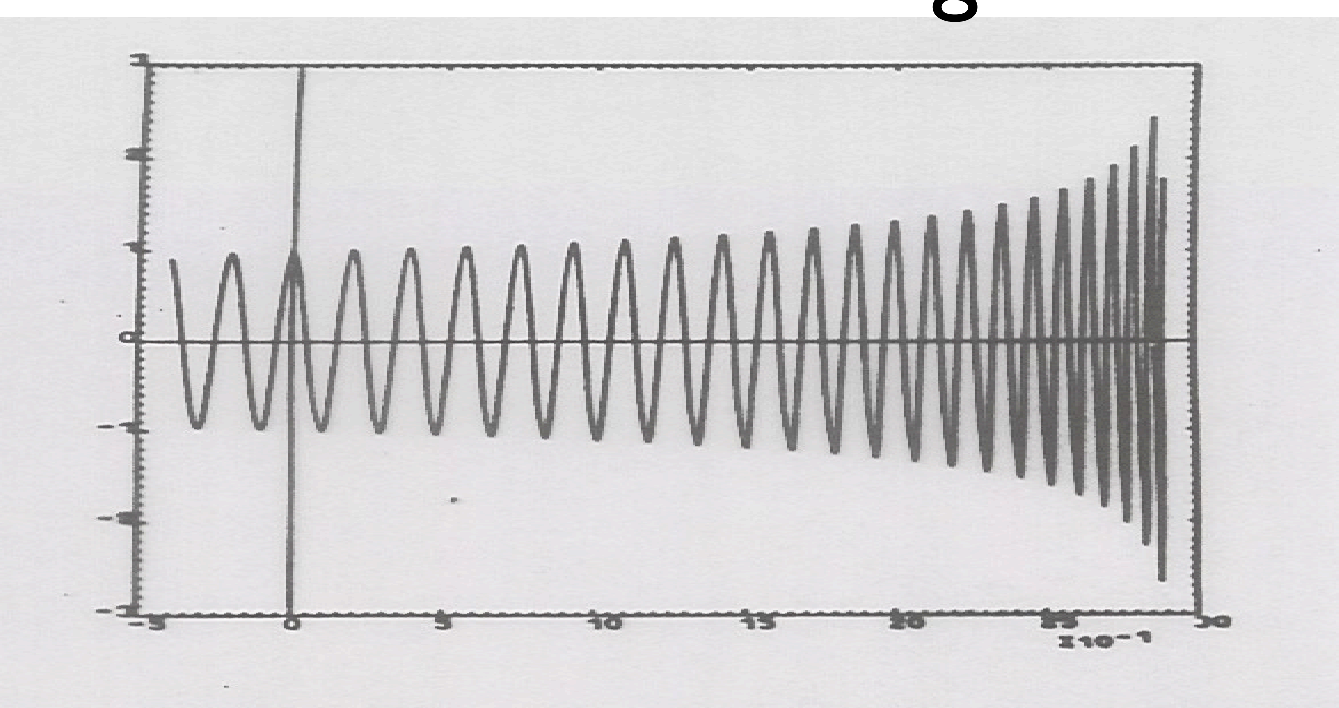
spinning a barbell in the lab is hopeless, $h \sim 10^{-38}$

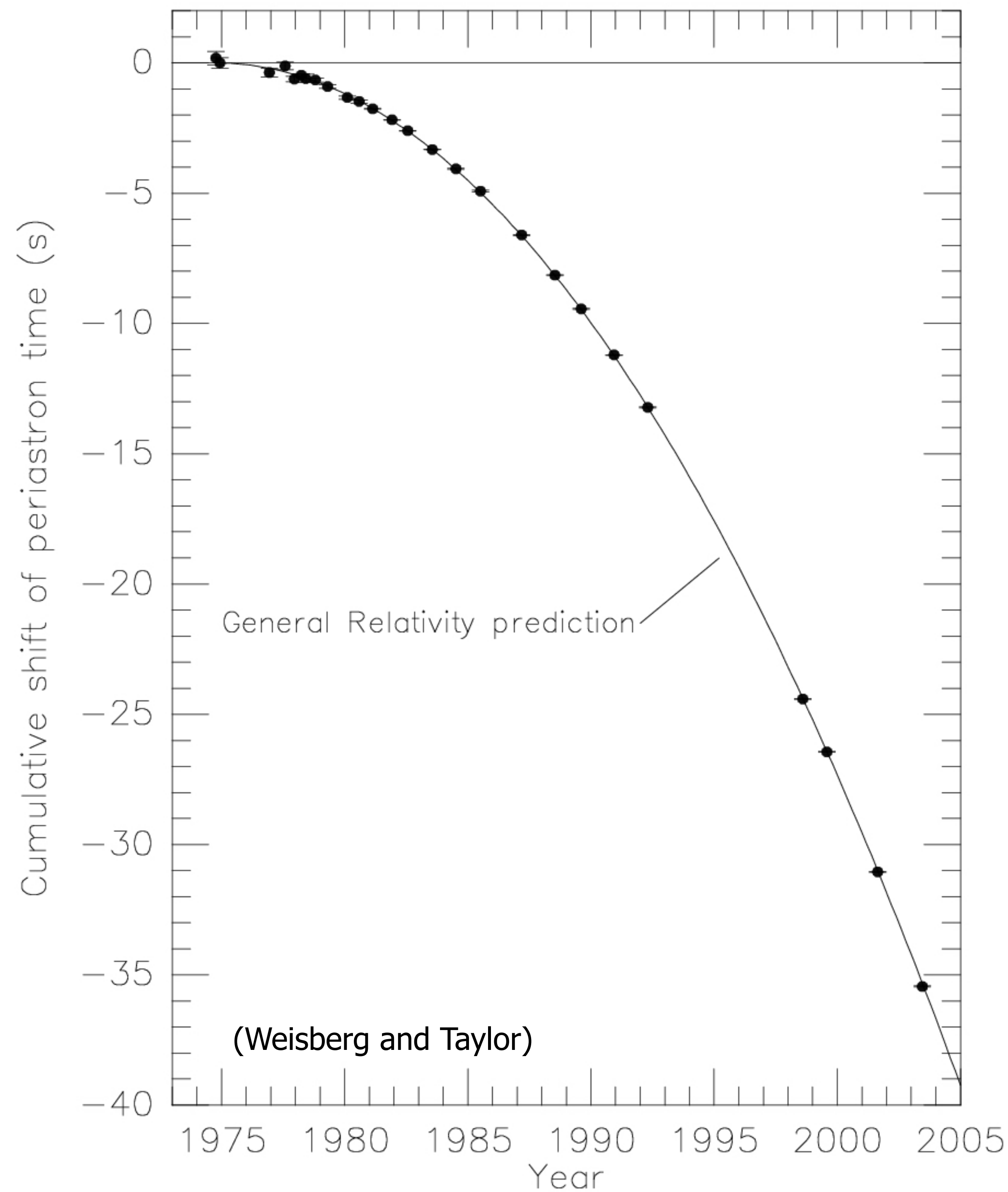


Astronomy!

- How about Neutron stars?
- Hulse and Taylor '93. (PSR 1913+16)
- and in 300 MYears...

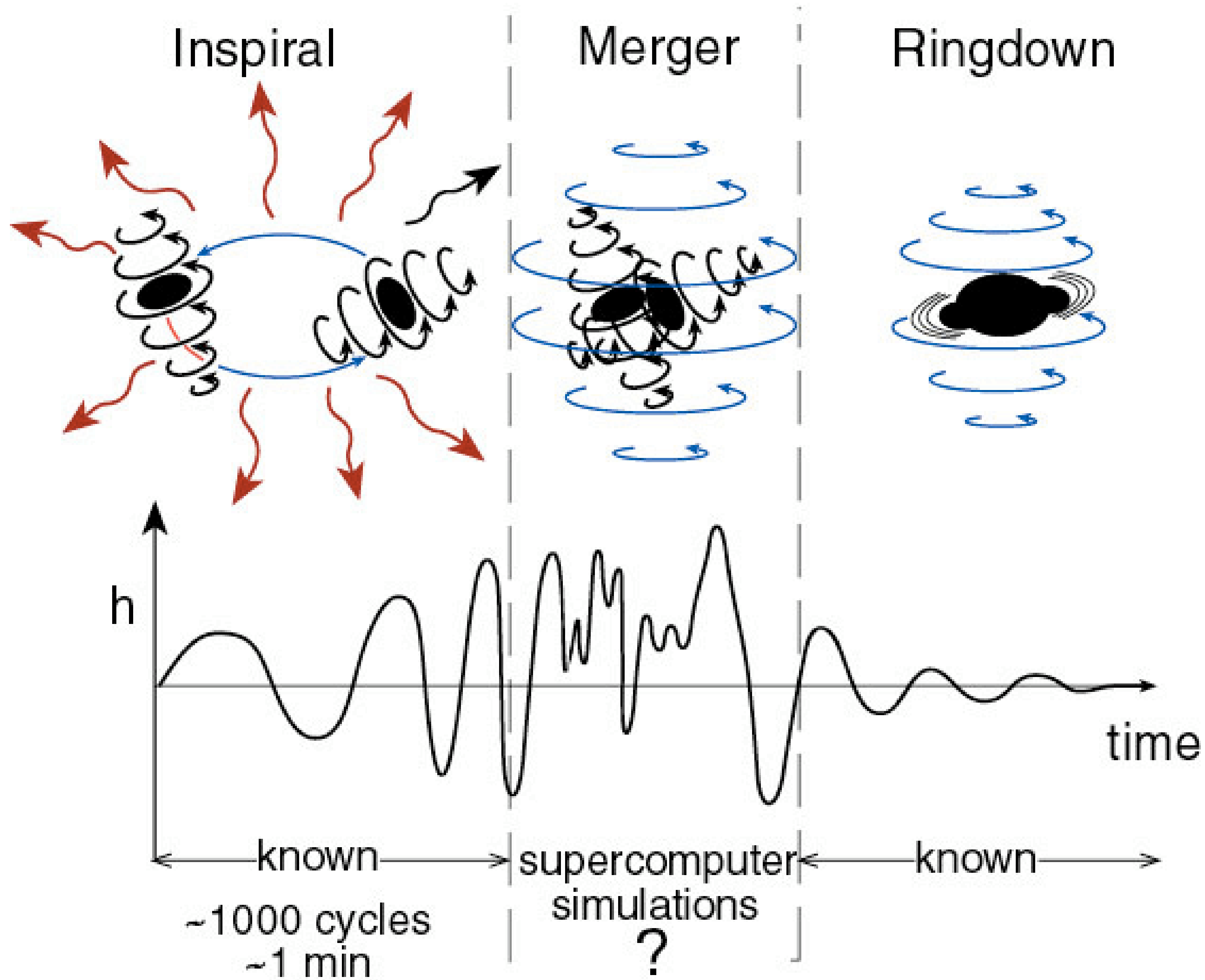
The Swan-song





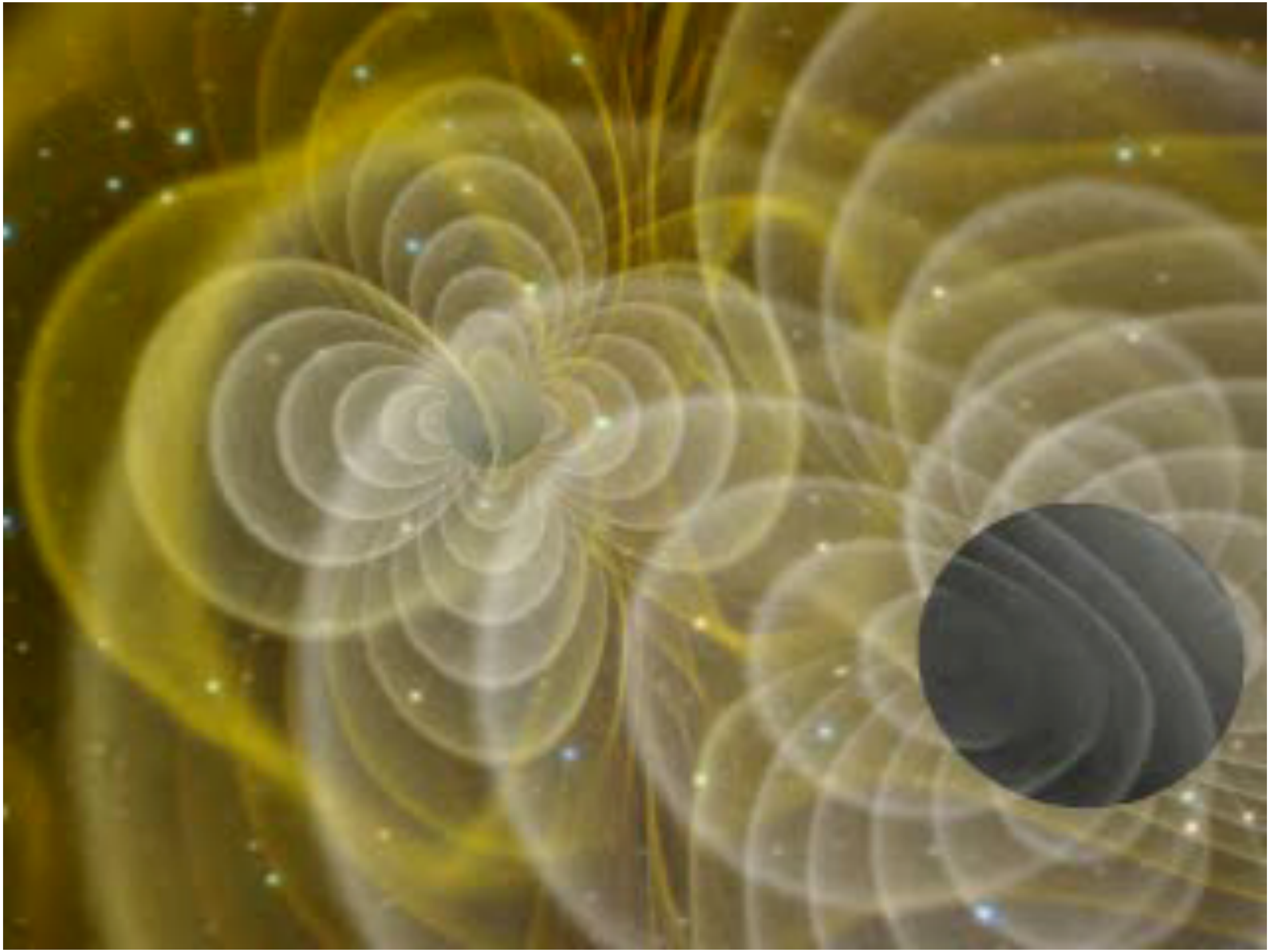
Black Hole Collisions

Black hole collisions



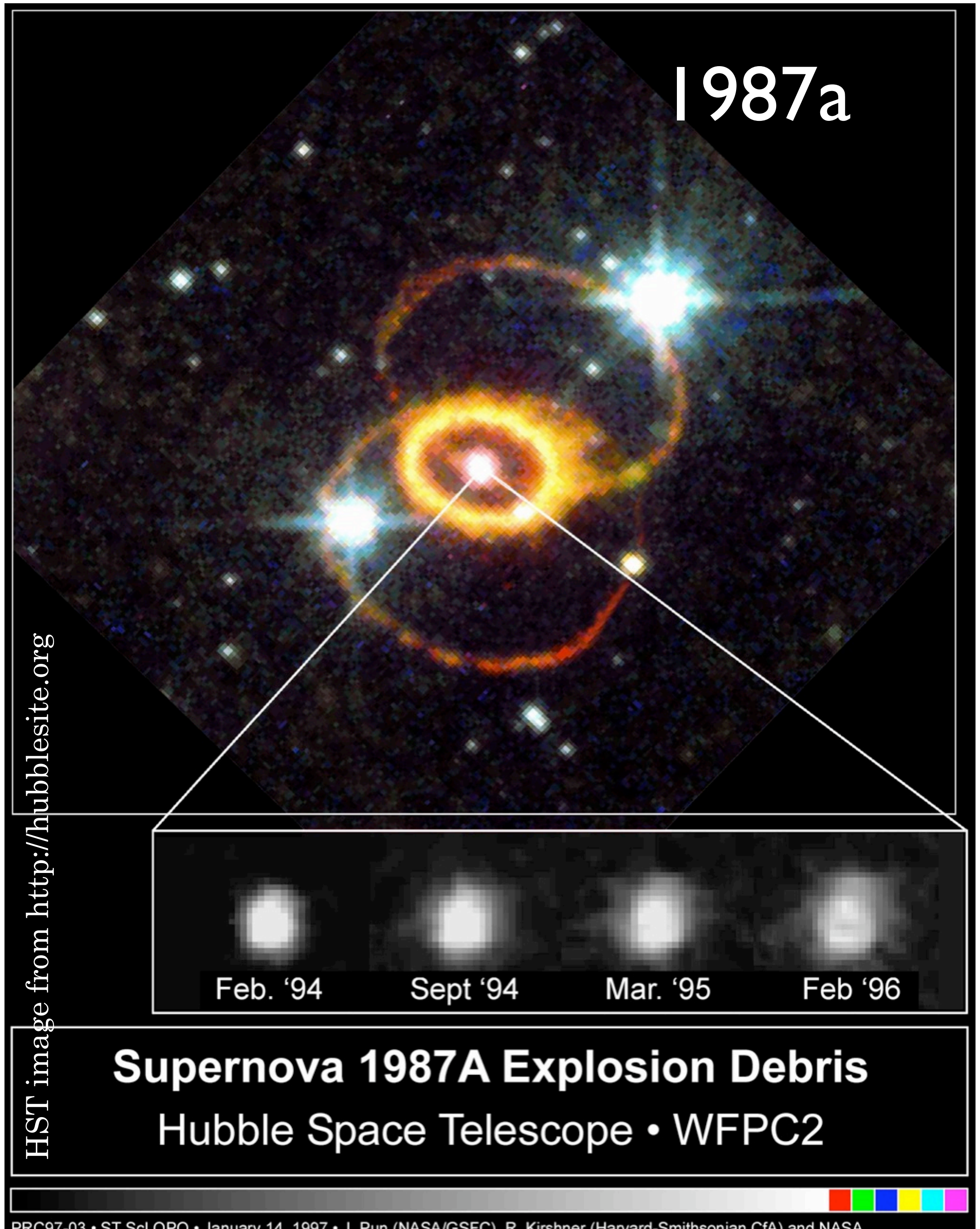
courtesy of Kip Thorne, G030311, June 2003

Binary black holes

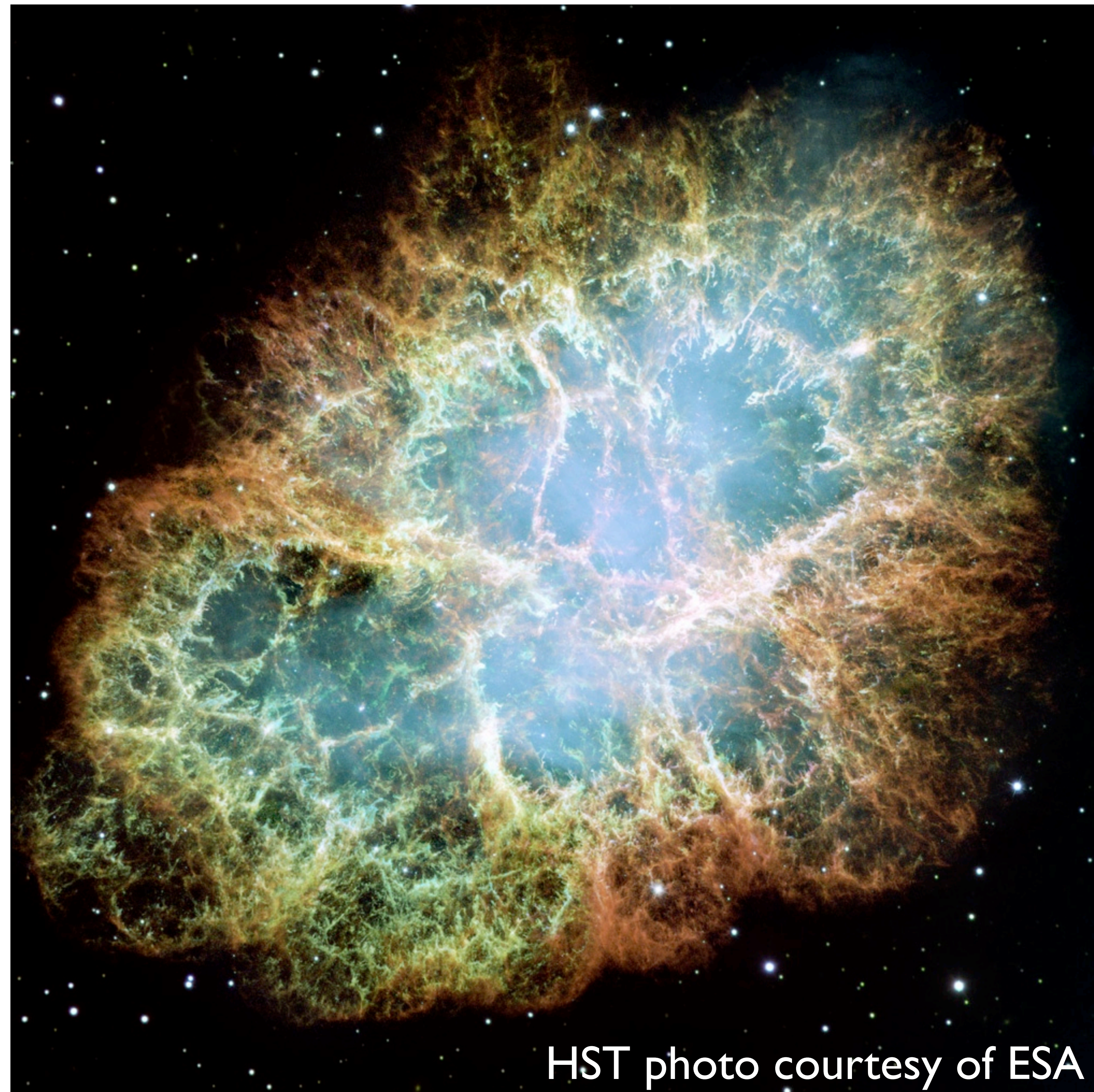


Centrella et. al, NASA Goddard Spaceflight center

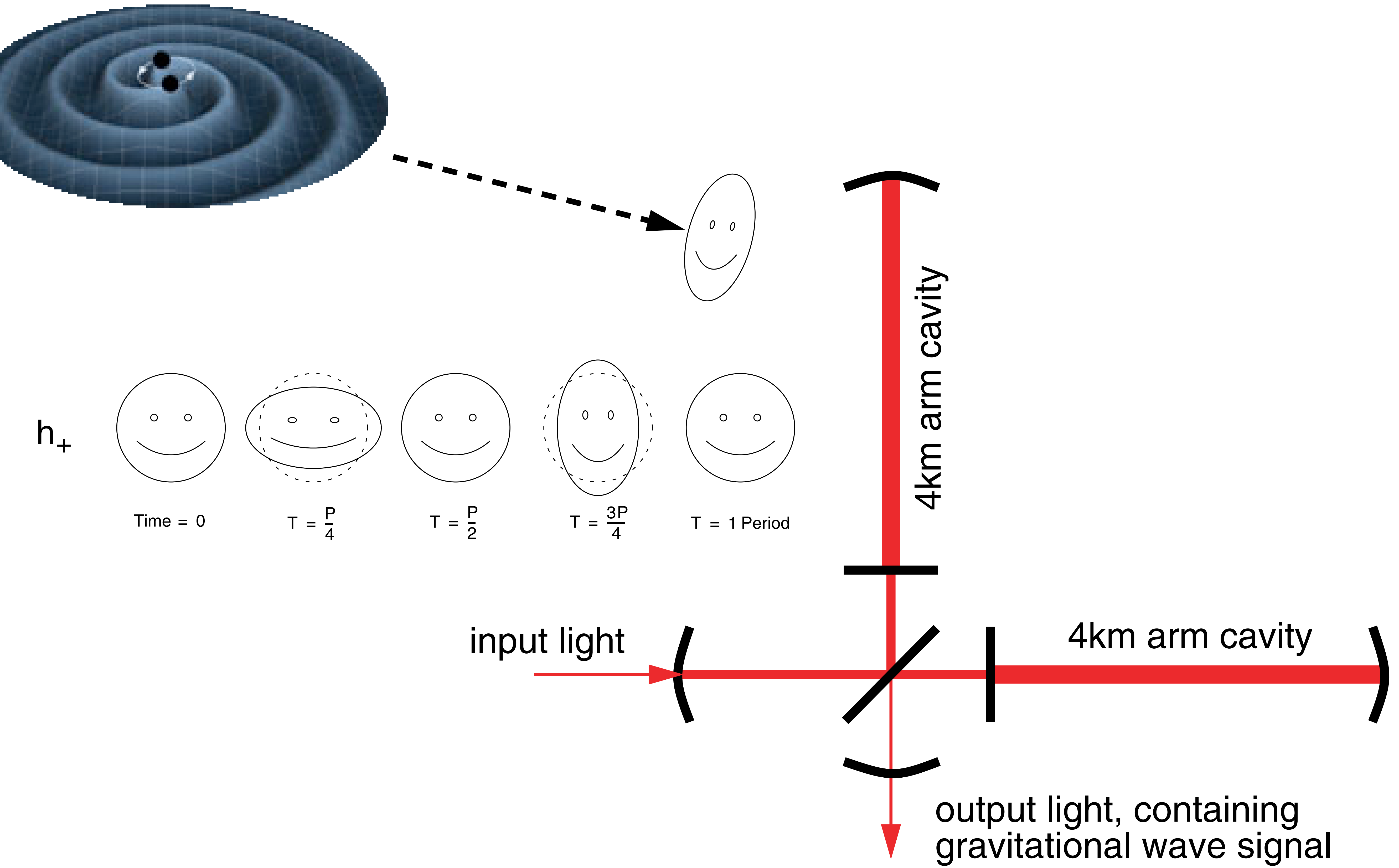
Supernovas and remnants



Crab Nebula, supernova in 1054, now a spinning neutron star



The LIGO concept



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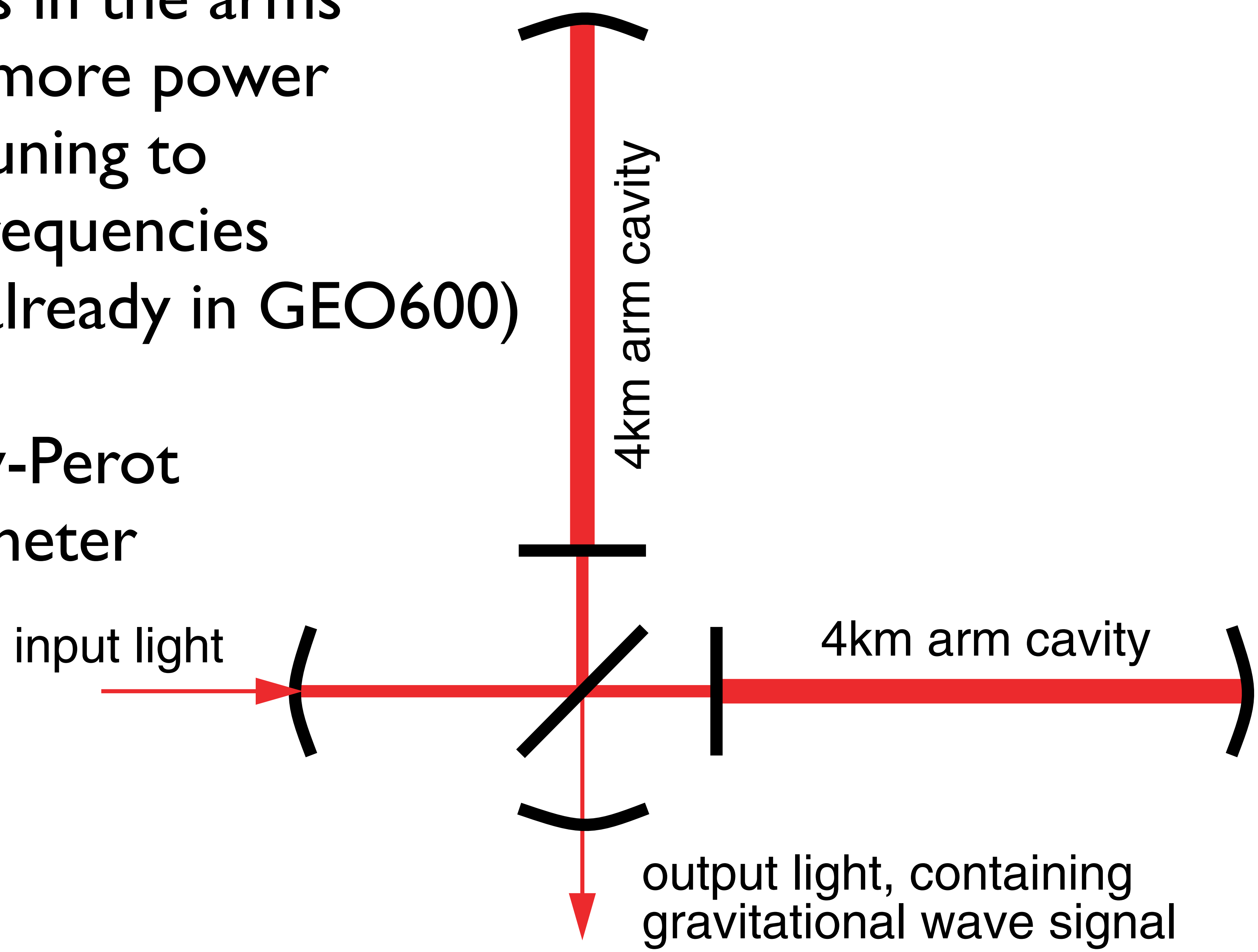
The LIGO concept

A few interferometer tricks:
- long arms, because h = dL/L
- Fabry-Perot cavities in the arms
- Power recycling = more power
- Signal recycling = tuning to enhanced certain frequencies (new for AdLIGO, already in GEO600)

=dual-recycled Fabry-Perot Michelson Interferometer



LIGO facilities

LIGO has 2 US sites, funded by NSF.

Part of international network, including GEO600, VIRGO, TAMA, ACIGA

photos from http://www.ligo.caltech.edu

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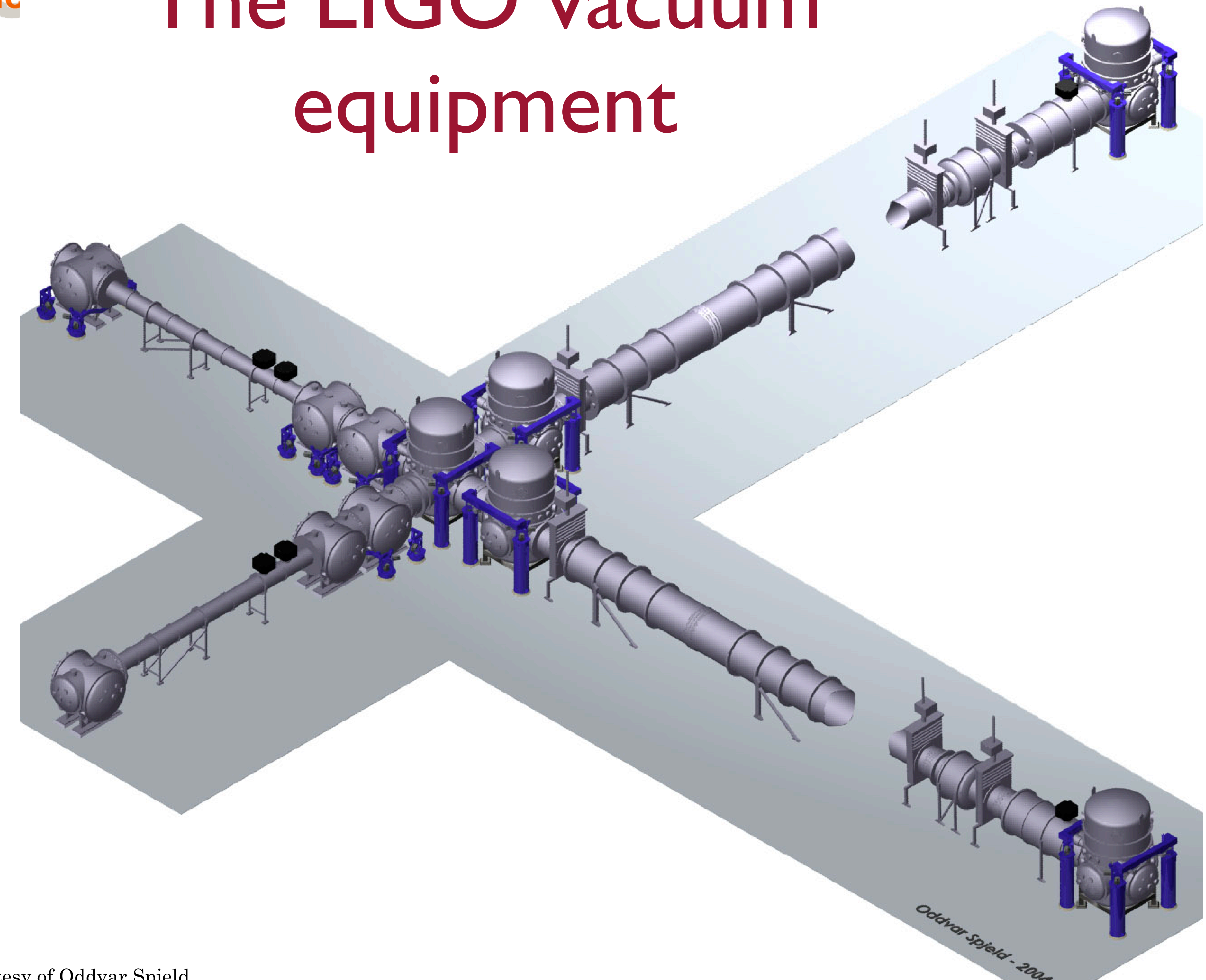
The LIGO vacuum equipment



drawing courtesy of Oddvar Spjeld

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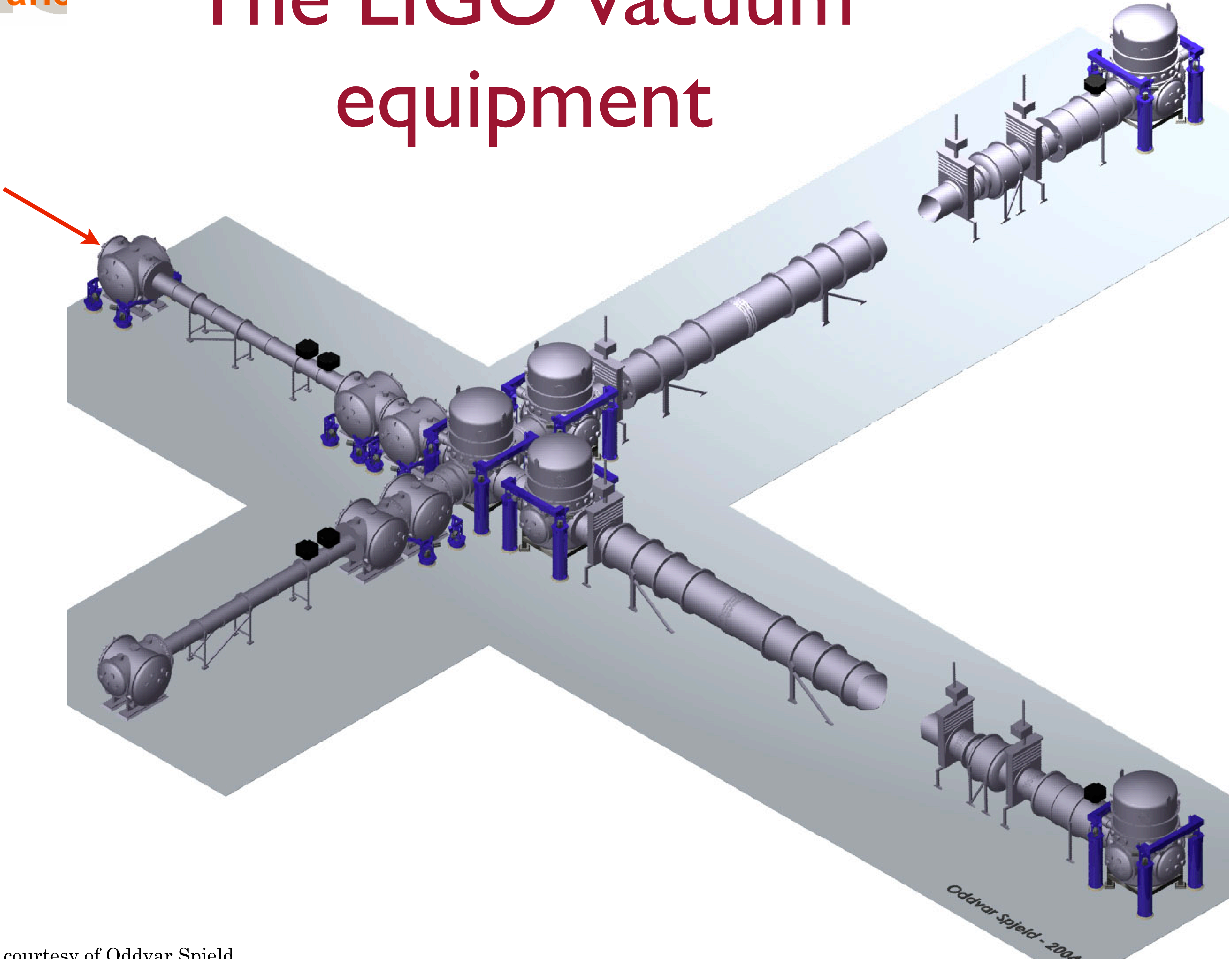
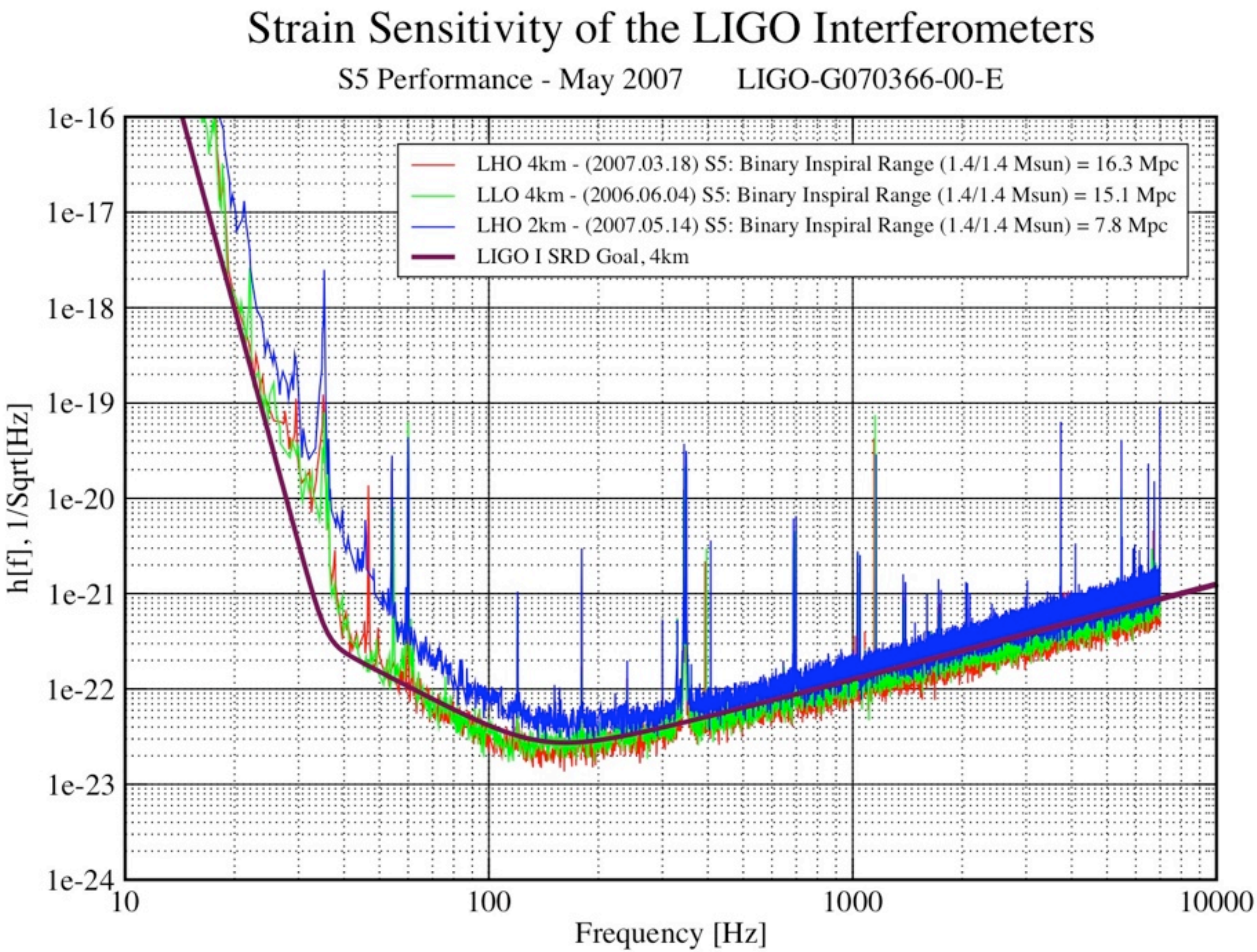


drawing courtesy of Oddvar Spjeld

Initial LIGO sensitivity



Finished "S5"

We recently completed Science run #5

1 year of triple coincidence data at design sensitivity completed on Sept 30, 2007, 2400 UTC!

Several "upper limit" papers on partial data exist.

Full data set is now being analyzed

No detections.

The Seeing

Initial LIGO NS/NS range ~15 MPc
(50e6 lightyears)

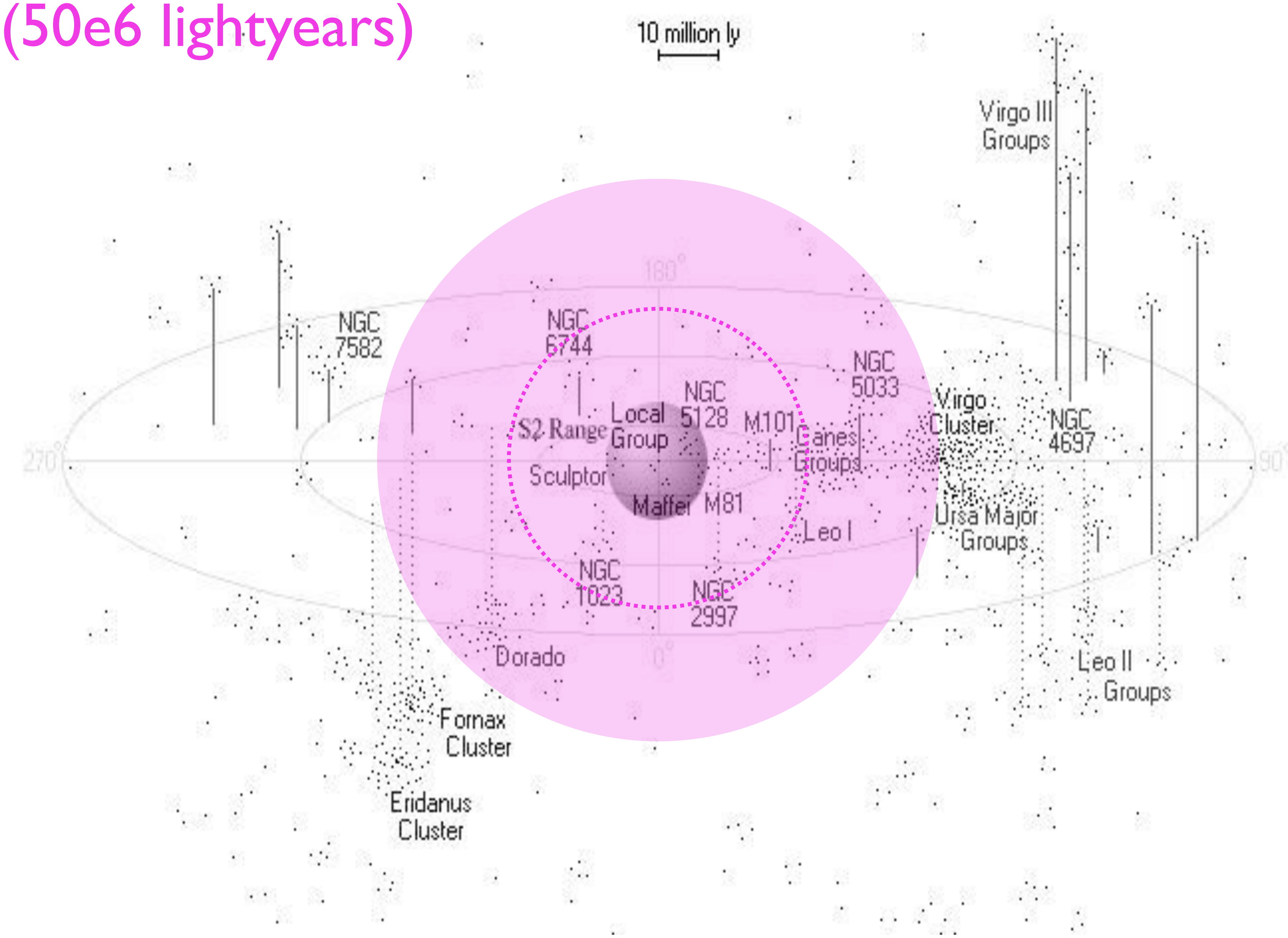


image by R. Powell

3 detector network range for NS/NS of 300 MPc

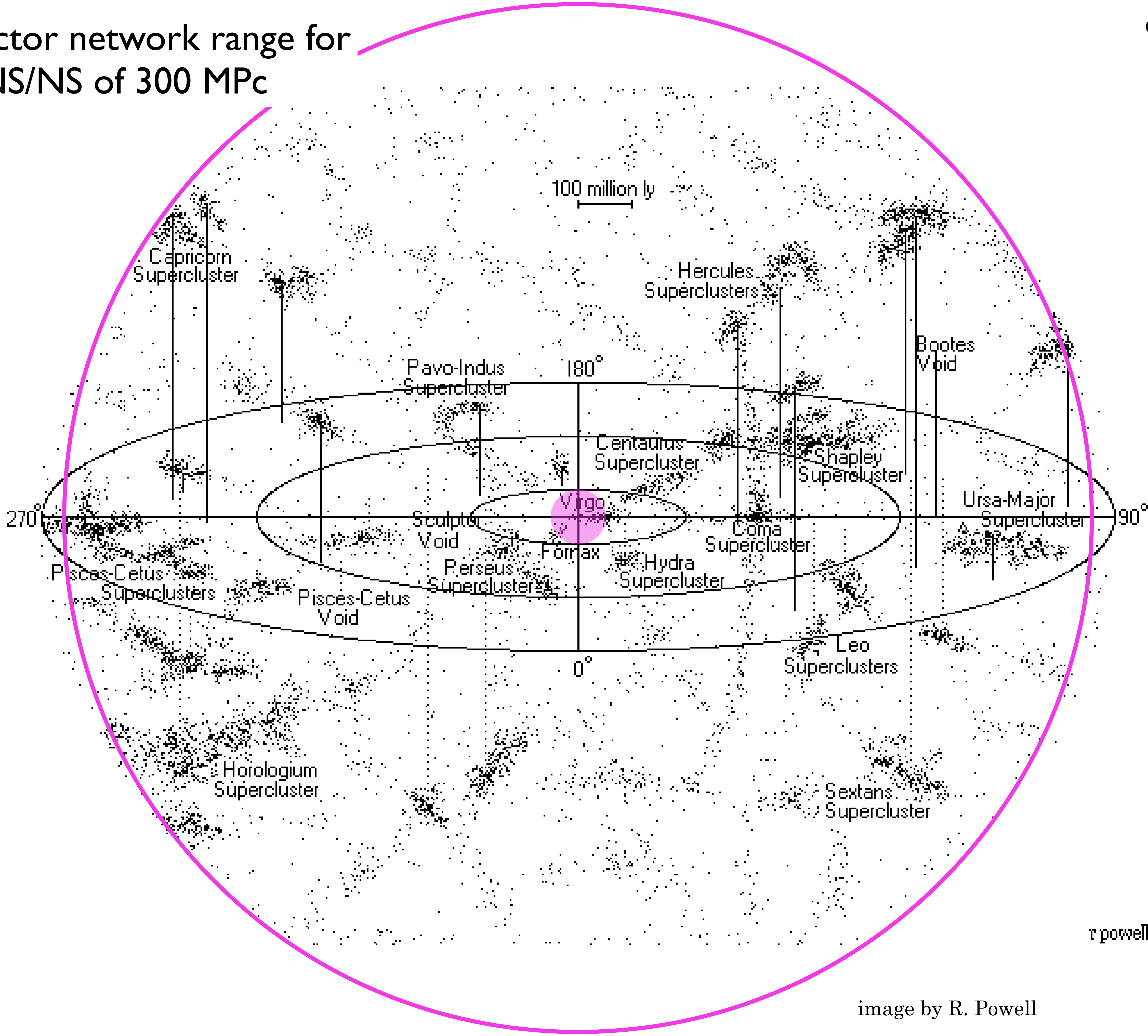


image by R. Powell

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The Advanced LIGO *proposal*

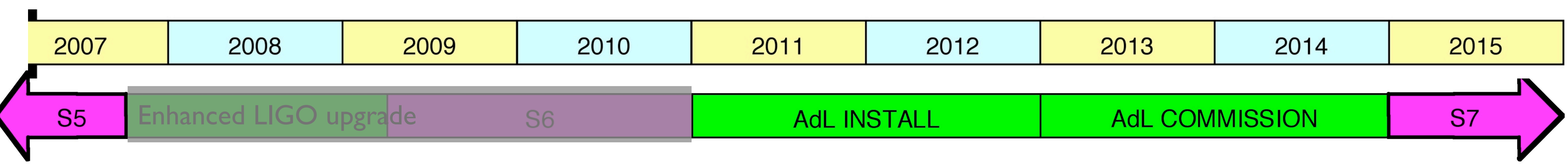
- Proposal to the NSF to improve the sensitivity of existing observatories to dramatically enhance the astrophysics.
- Part of an international network: GEO600 (Germany-UK), VIRGO (Italy-France), TAMA (Japan), ACIGA (Australia).
- Same facilities as Initial LIGO, but with new detectors.
- Development is very far along, carried out by many partners.
- 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.

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

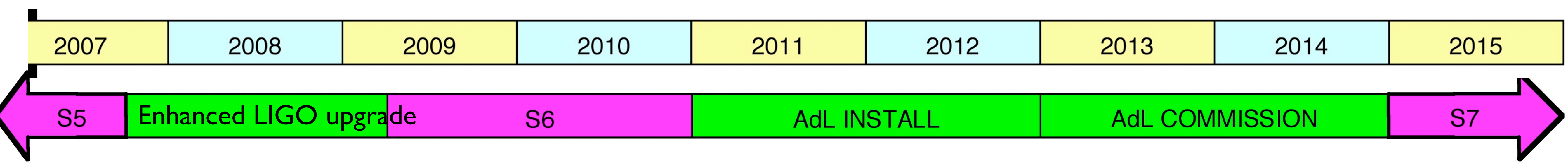
The Advanced LIGO *proposal*

- Milestones:
  - Advanced LIGO funding start in 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. Construction project completes!
  - Commissioning of instruments, Engineering runs starting in 2014, Science in 2015.



Advanced LIGO *Preparation* Enhanced LIGO

- We are currently installing a “modest” set of upgrades funded with Initial LIGO resources.
- Make the best use the time before 2011.
- Gain experience with Advanced LIGO technology
  - Take laser from 10 W to 30 W,
  - Install the new DC readout scheme,
  - Install 1 new style seismic isolation system,
  - Try the new computing/ control infrastructure.
- Make a factor of 2 improvement in the sensitivity. (about 6-7 times more galaxies in range).



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Sources

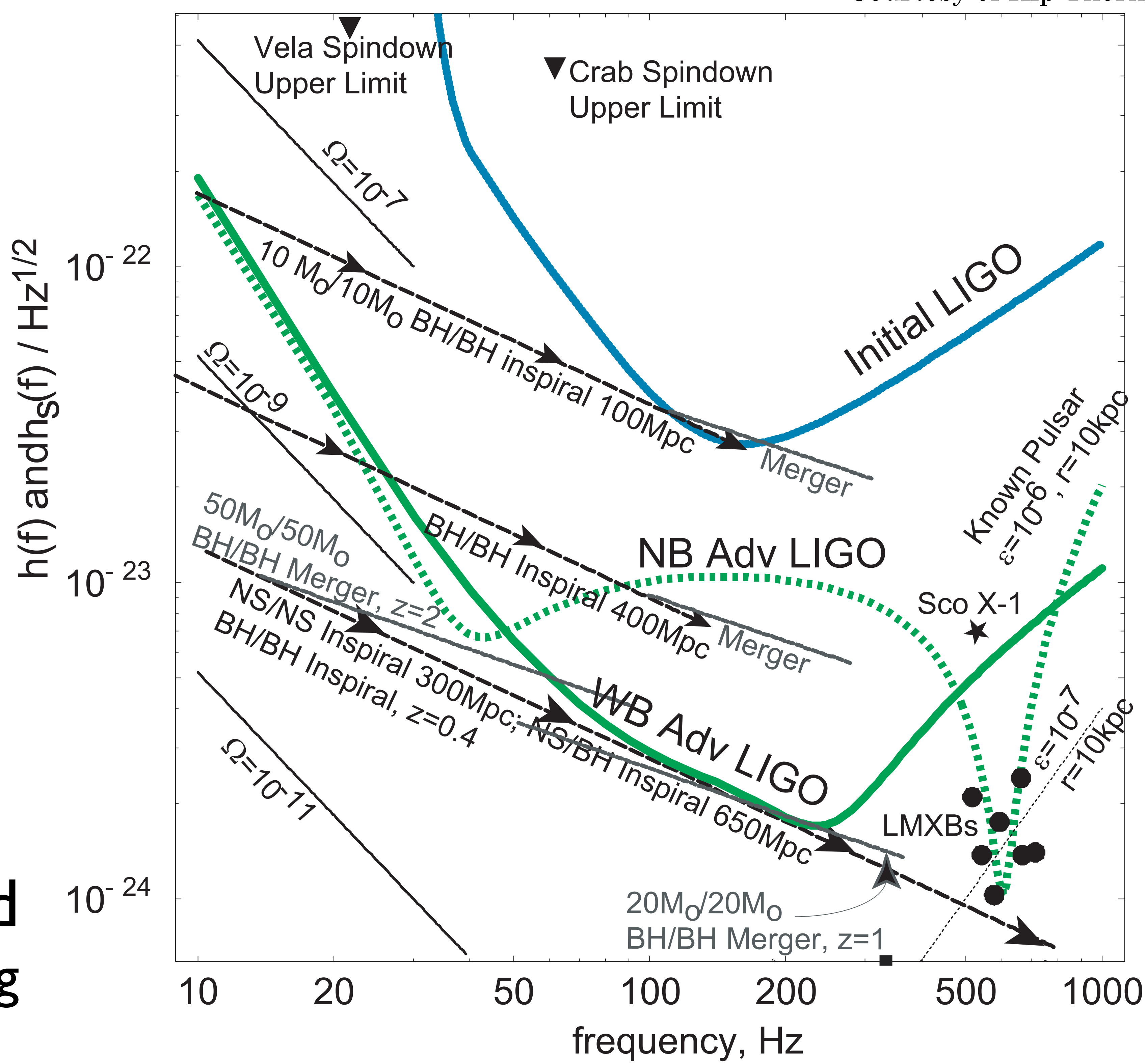
Neutron star and Black hole binaries
- inspiral
- merger

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

Birth of NS (supernovas)
- tumbling
- convection

Stochastic Background
- remnants of the big bang

Courtesy of Kip Thorne



Advanced LIGO - Technology

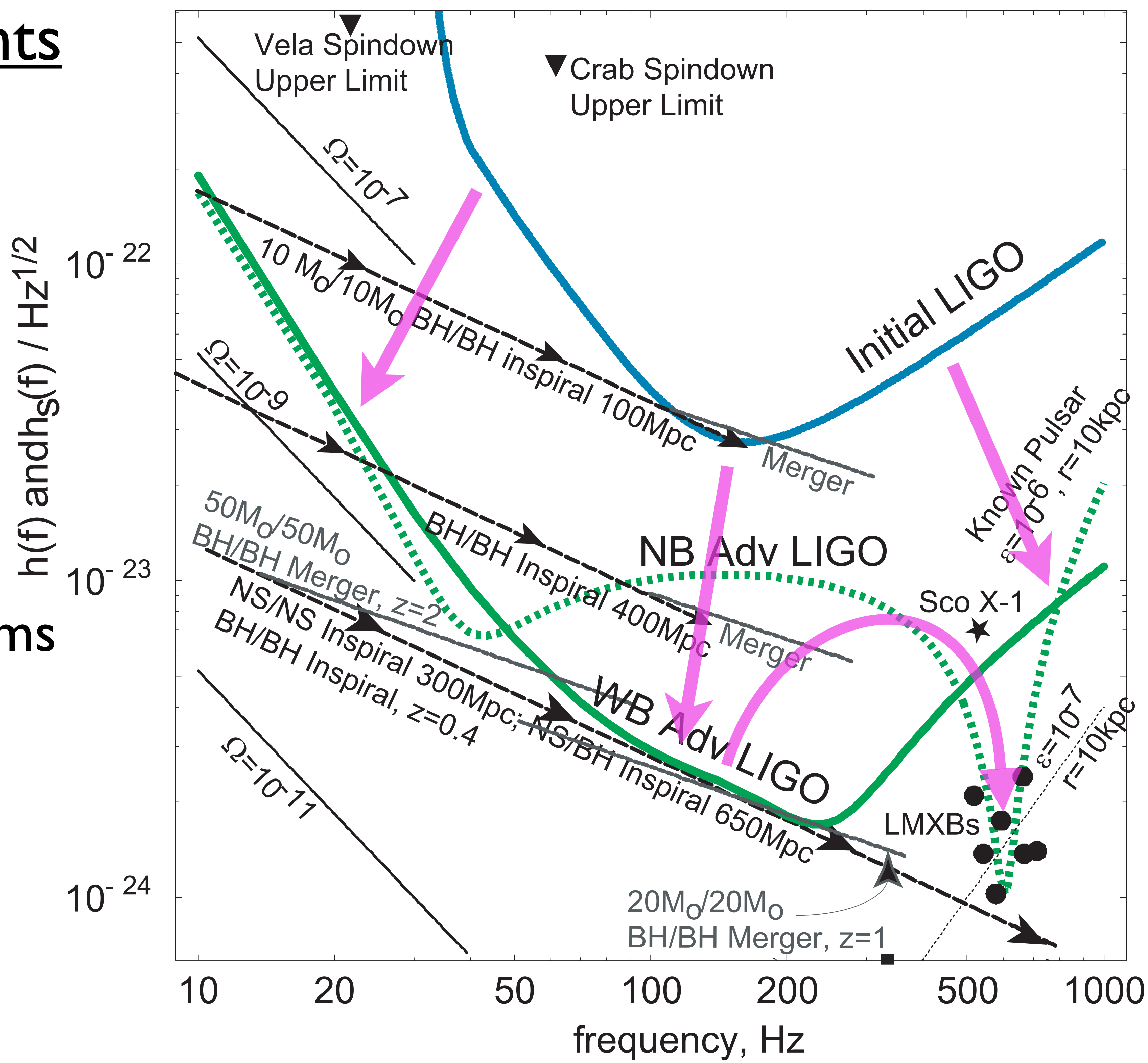
Technical Improvements

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



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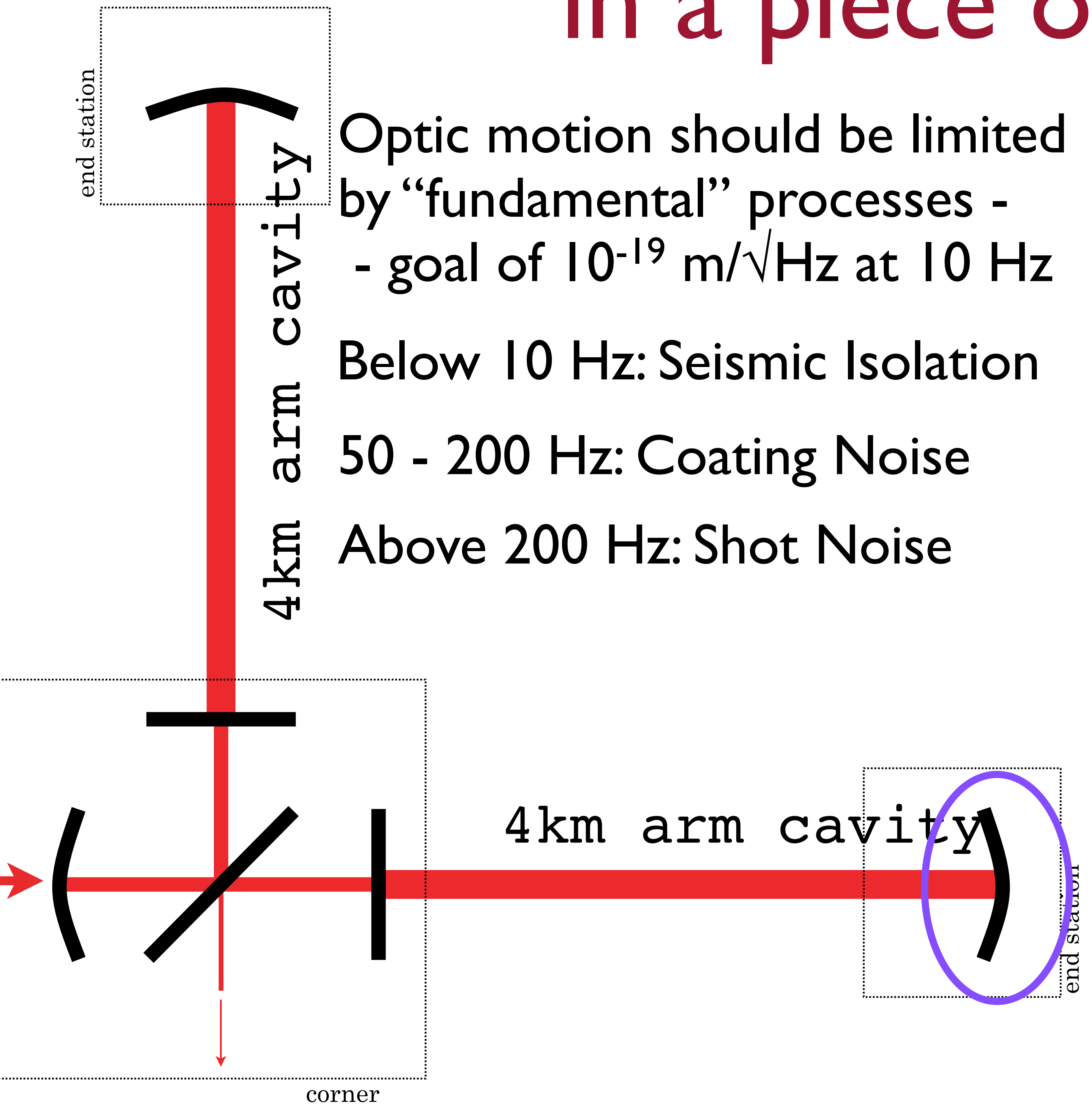
Reflections of the Technology in a piece of glass

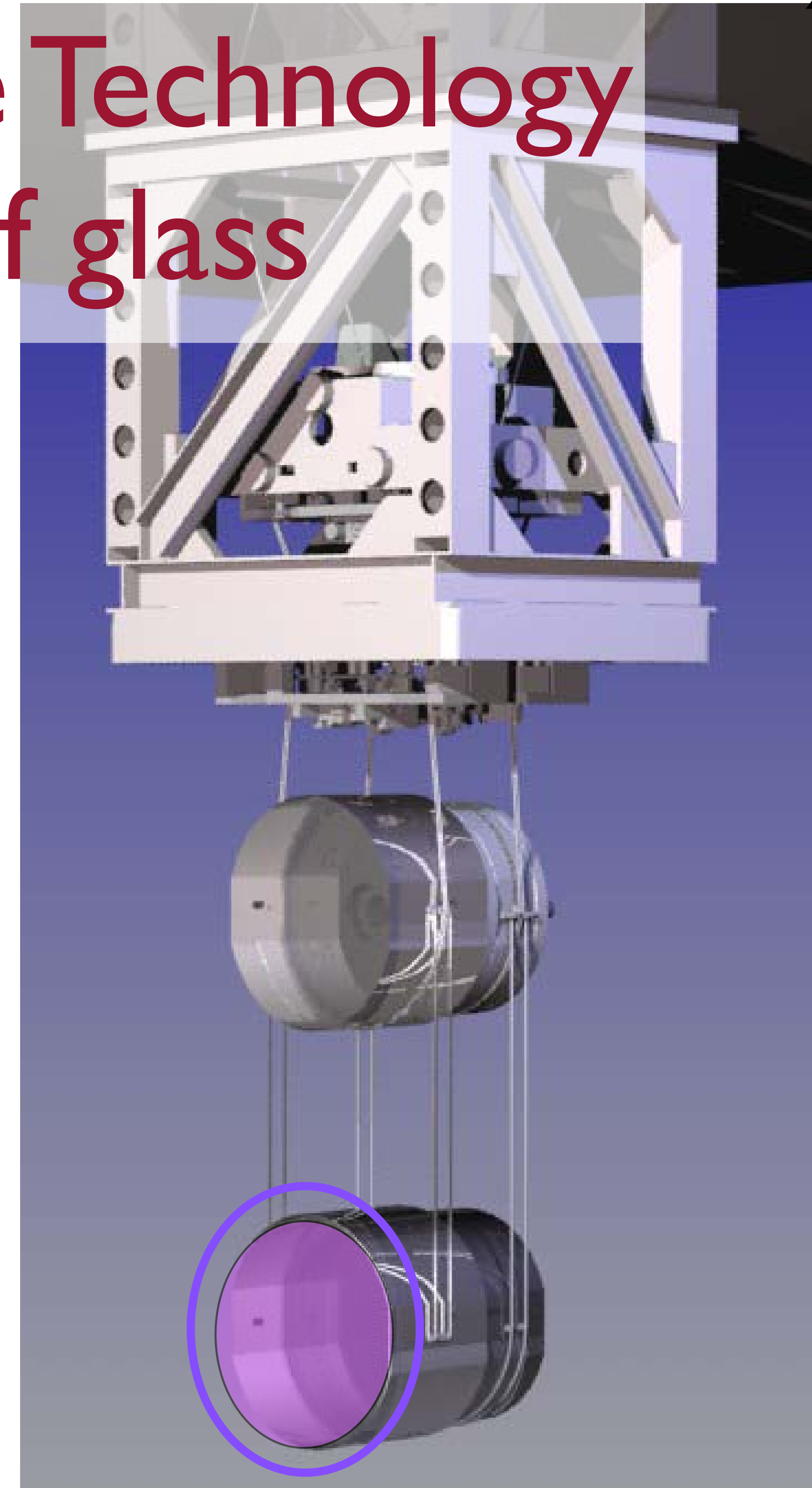


Optic motion should be limited by "fundamental" processes -
- goal of 10^{-19} m/√Hz at 10 Hz

Below 10 Hz: Seismic Isolation

50 - 200 Hz: Coating Noise

Above 200 Hz: Shot Noise



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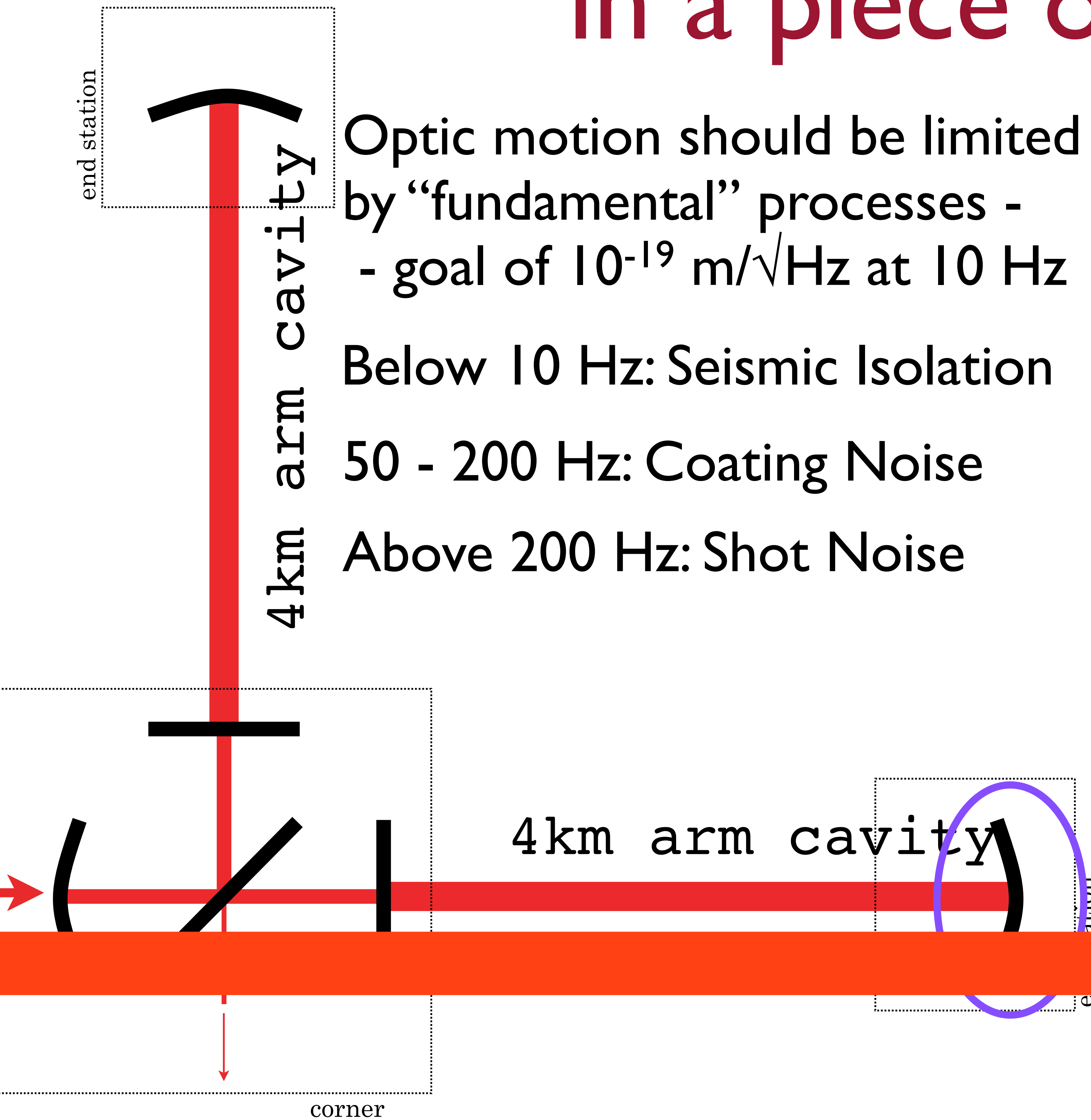

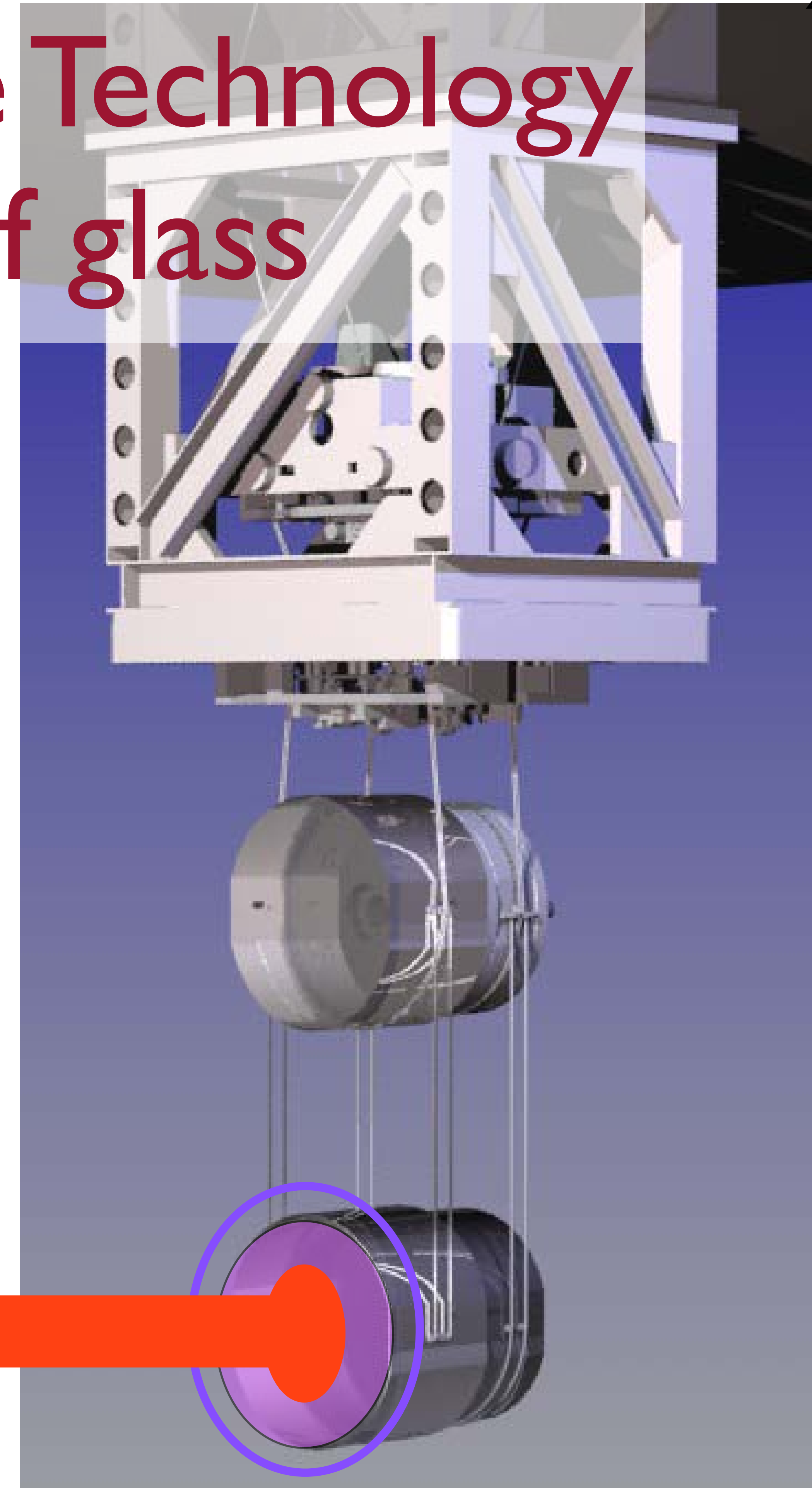

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Seismic Isolation & Alignment

Isolation of the test mass

10 Hz motion

test mass 1×10^{-19} m/√Hz

ground ~4×10^{-10} m/√Hz

rms length variation

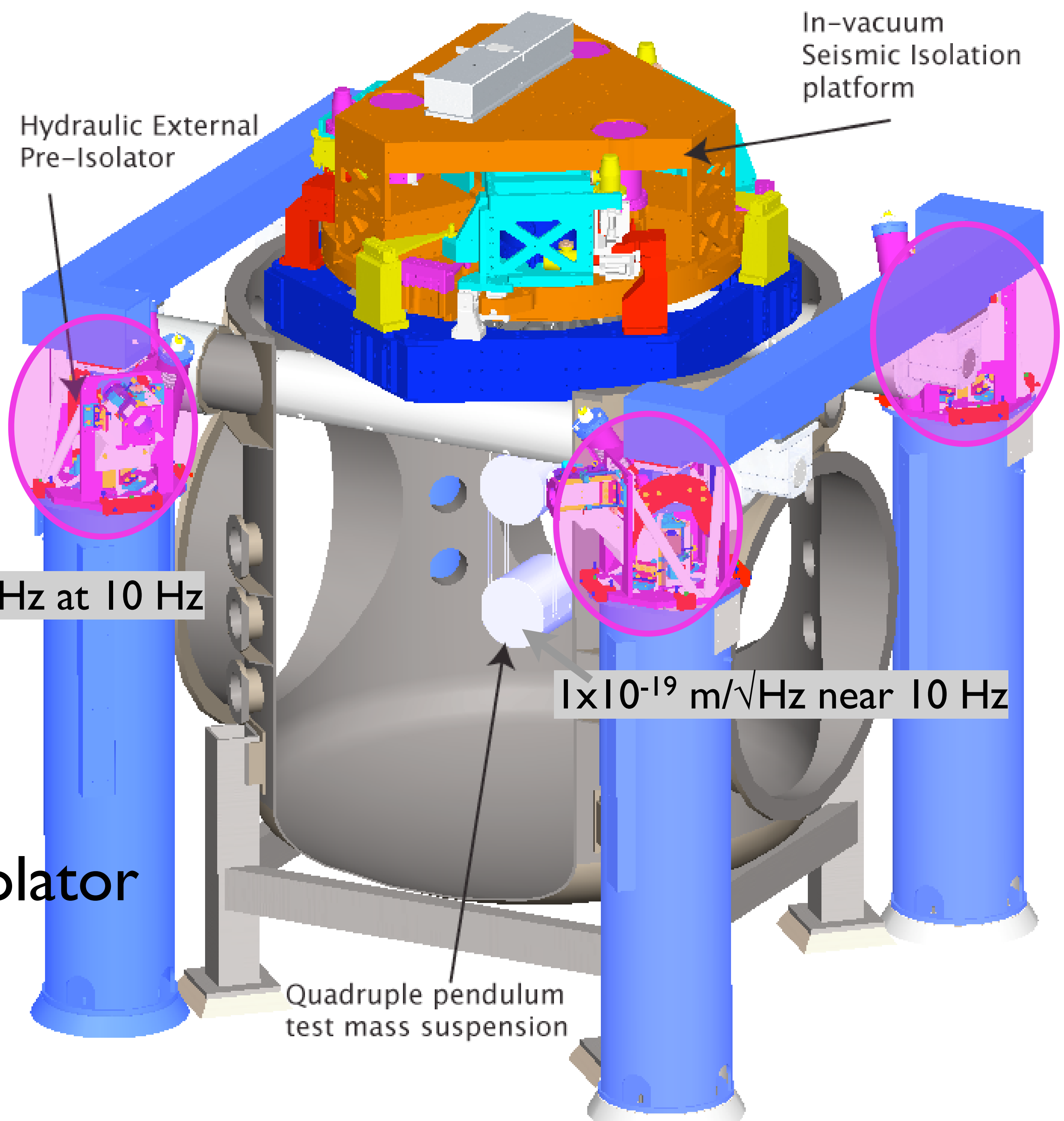
$< 1 \times 10^{-14}$ m

<u>7 layers of isolation</u>

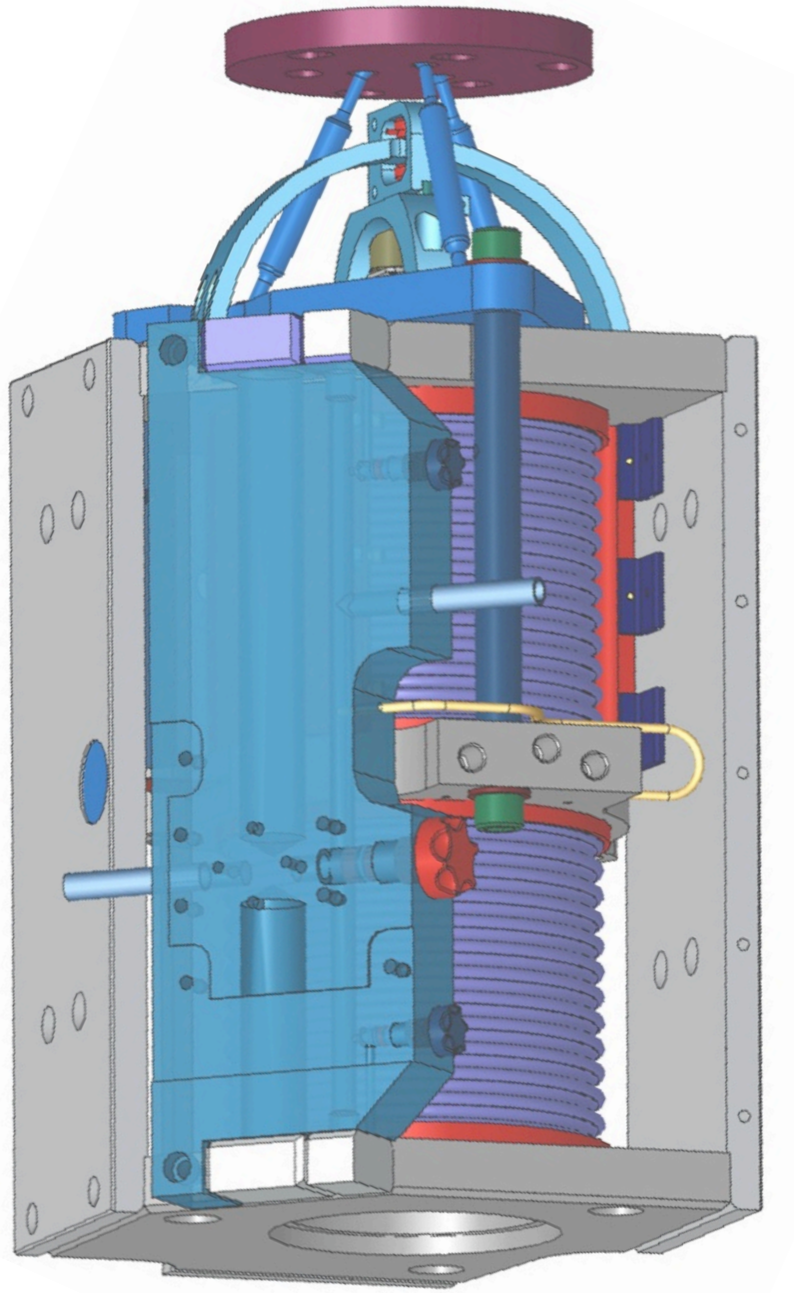
4 stage pendulum

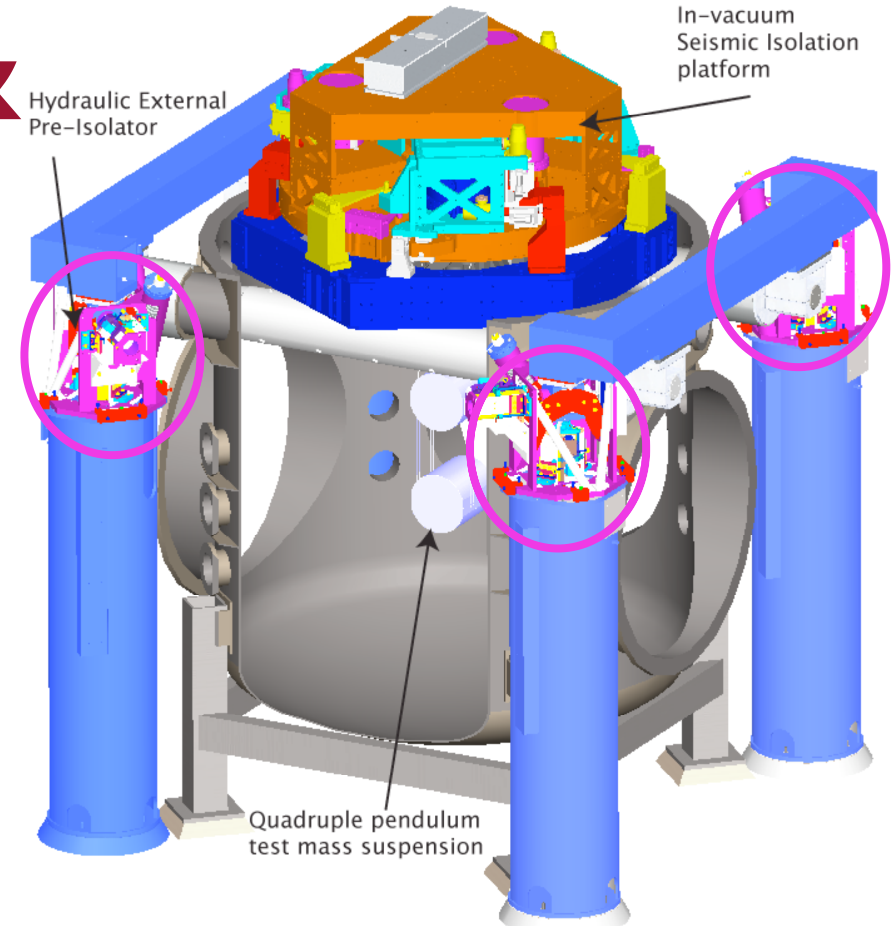
2 stage active isolation table

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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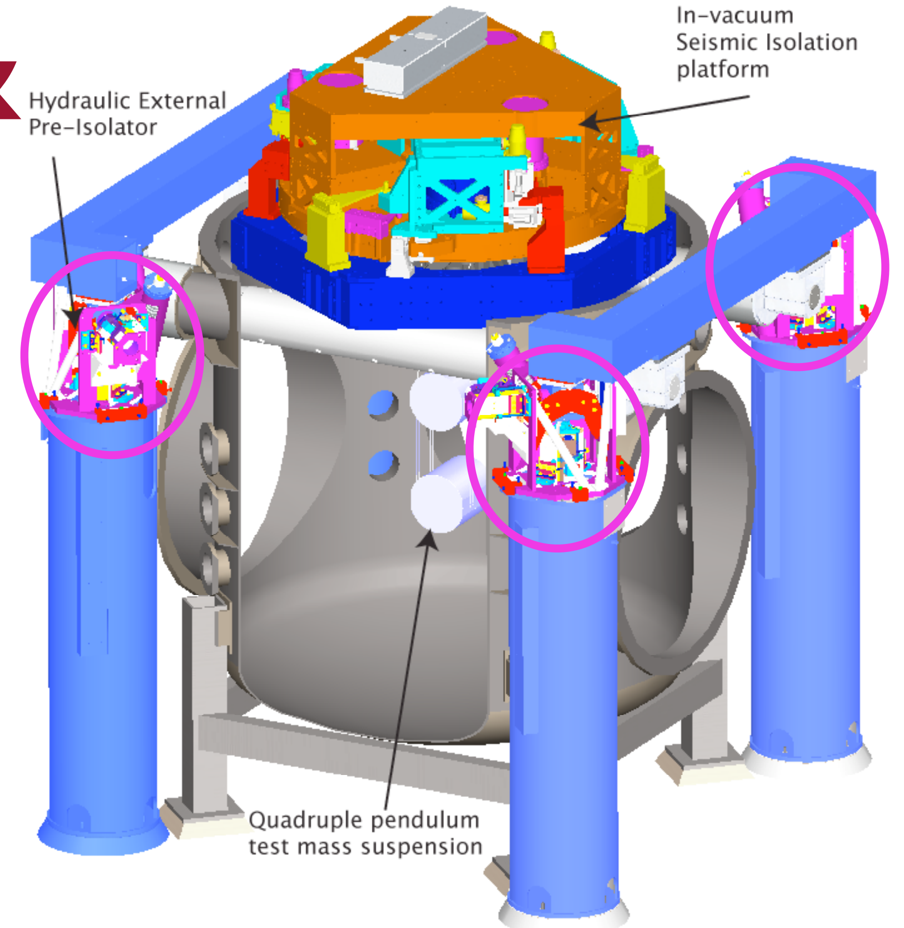
Seismic Isolation & Alignment - HEPI



- > 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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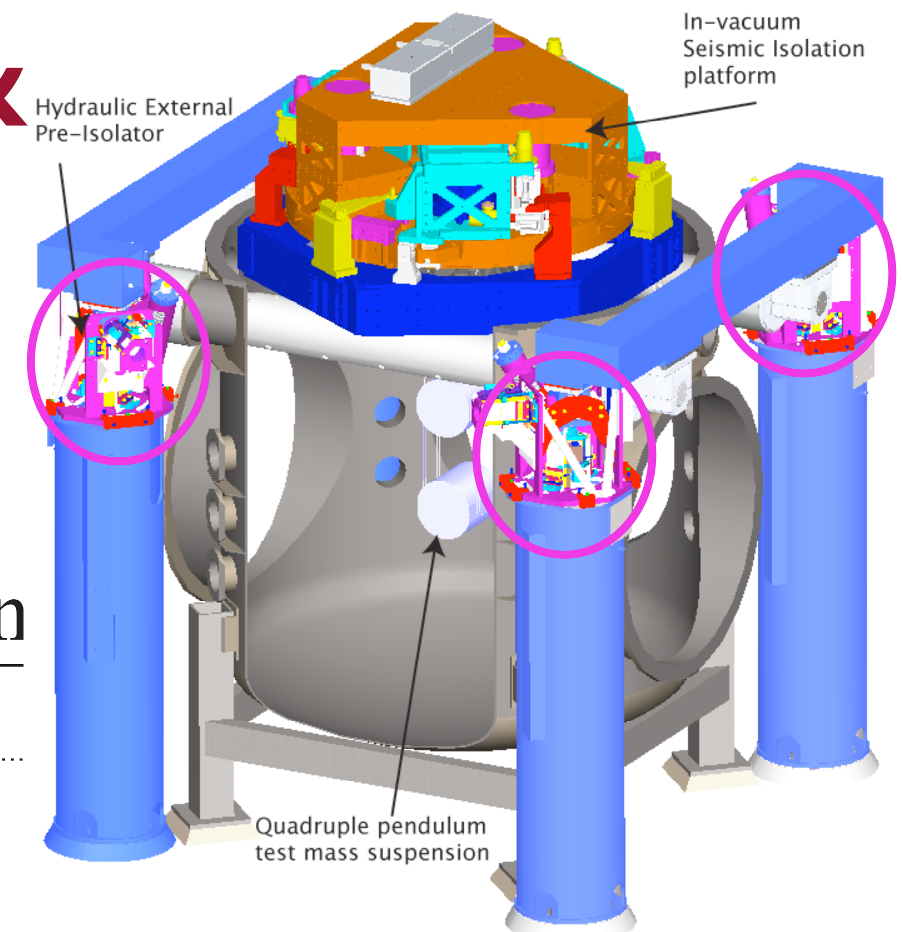
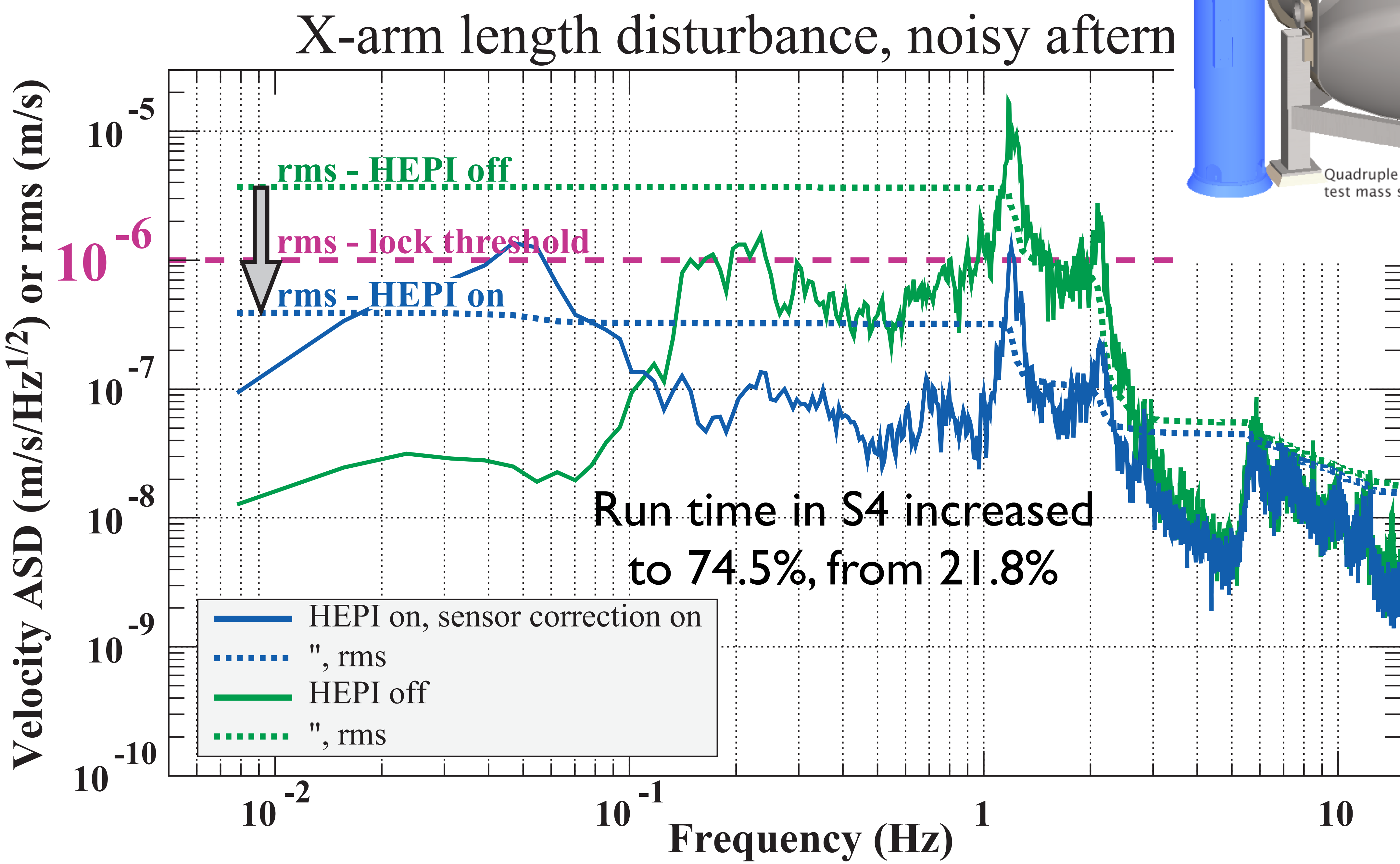
Seismic Isolation & Alignment - HEPI





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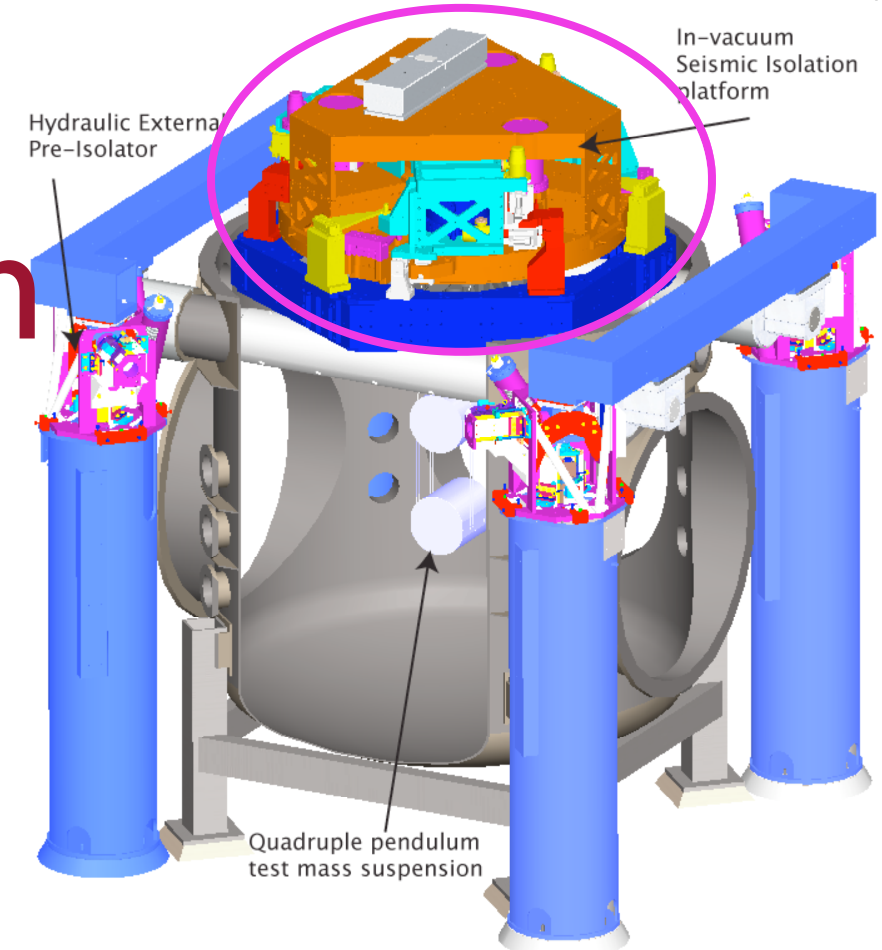
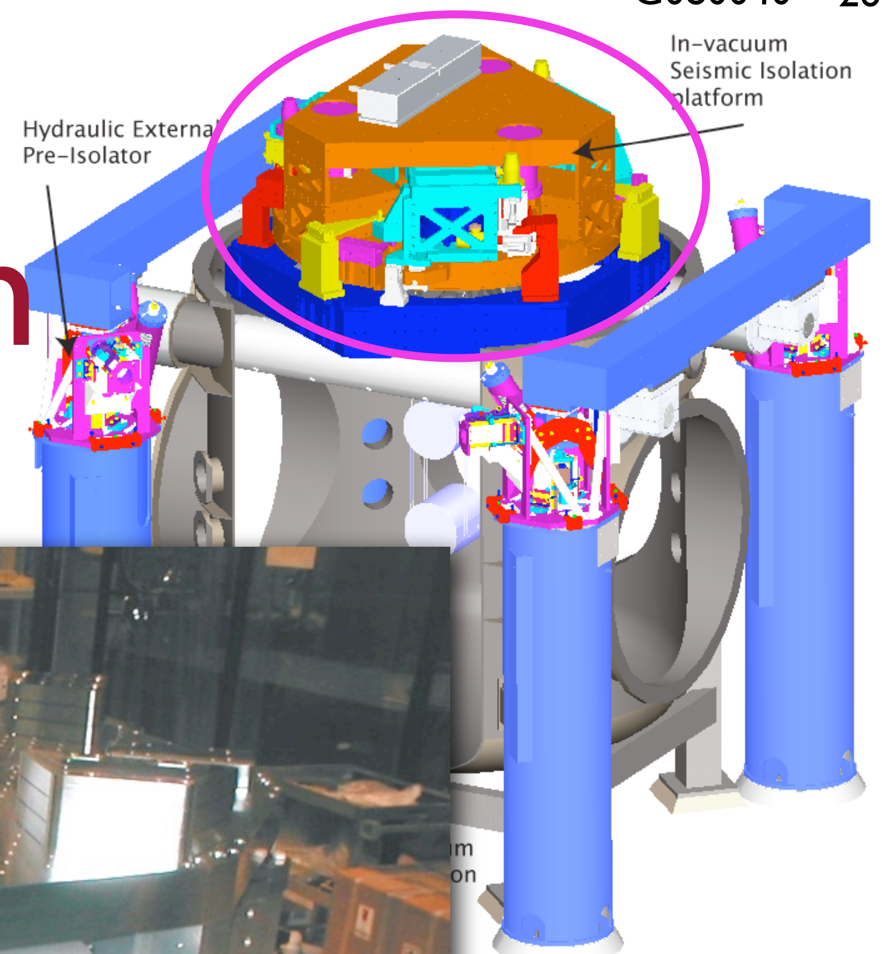
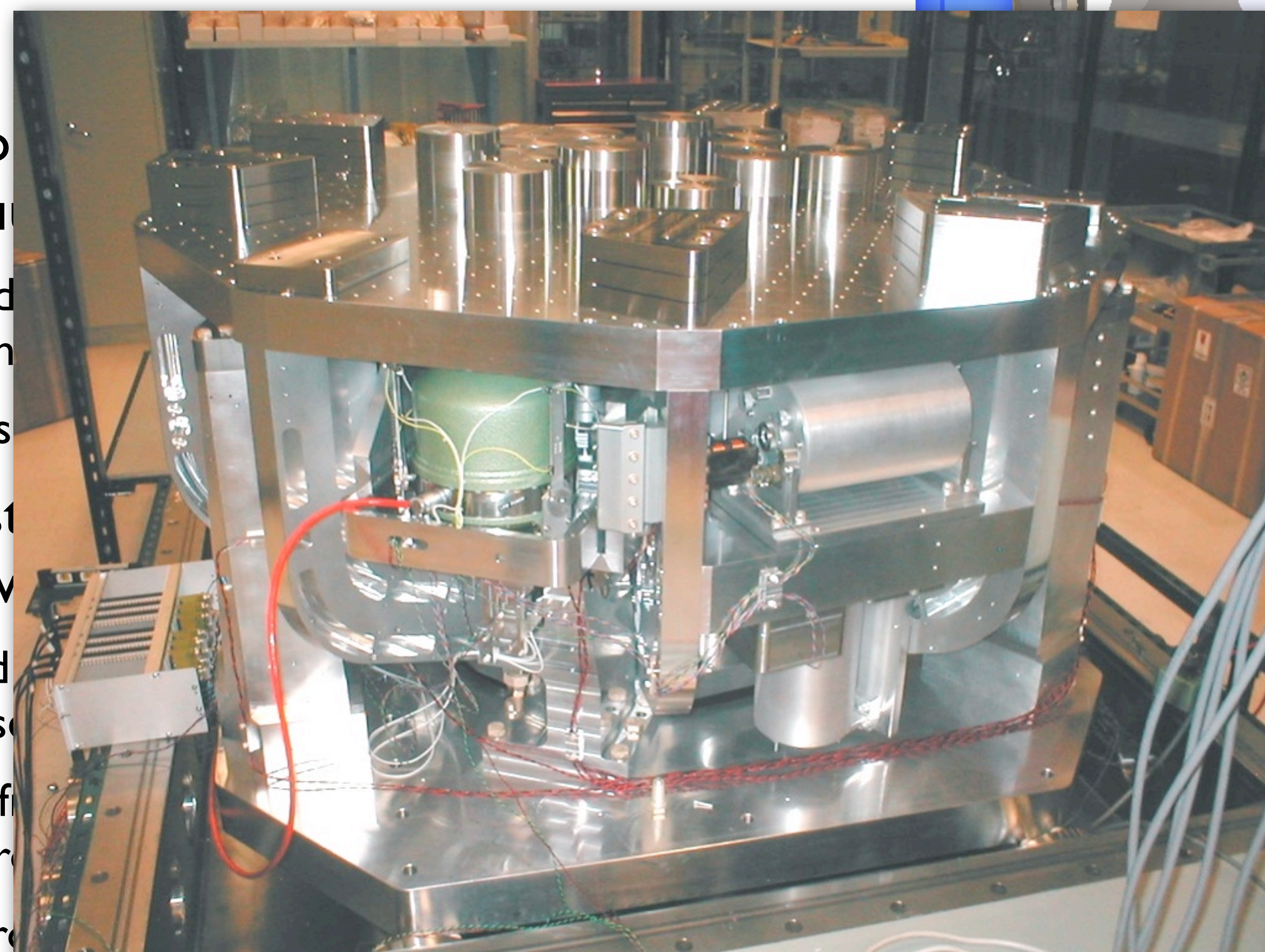
Seismic Isolation & Alignment - platform



- 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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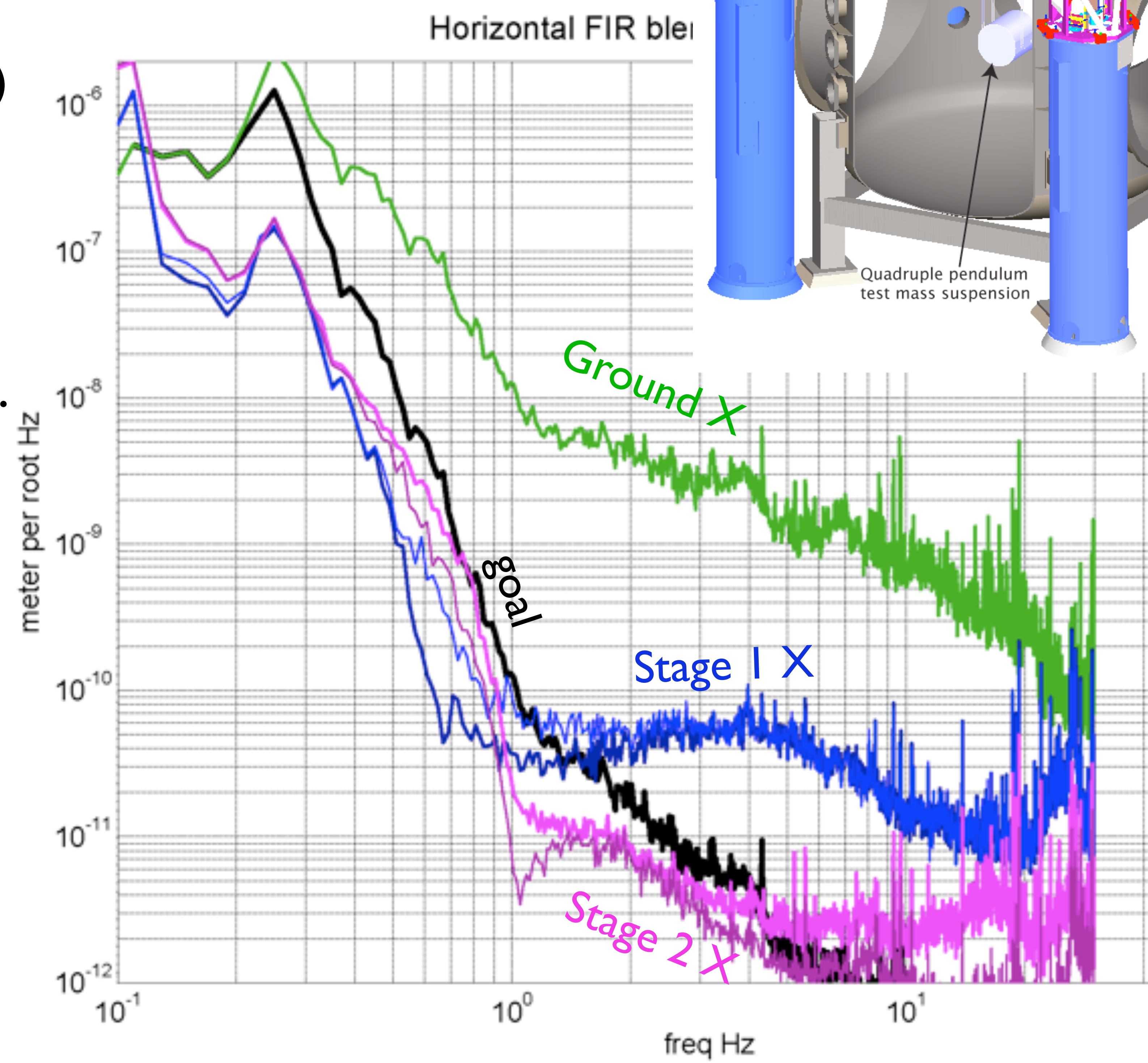
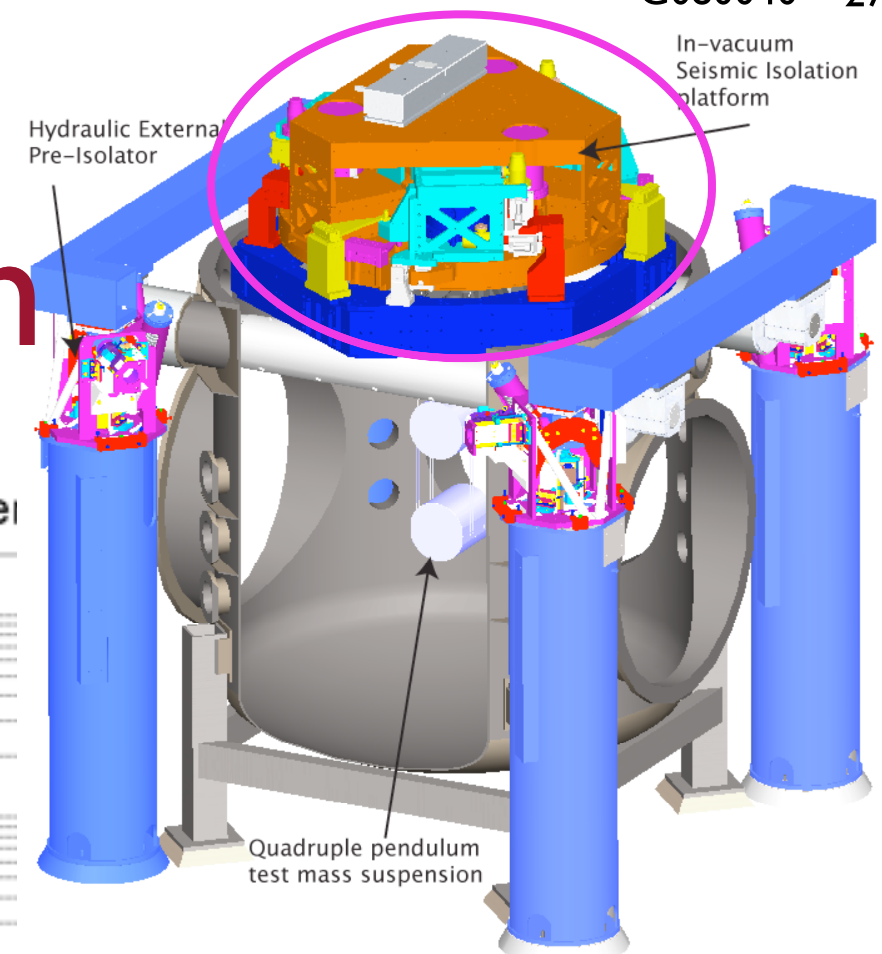
Seismic Isolation & Alignment - platform

- 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.





Seismi
Alignme

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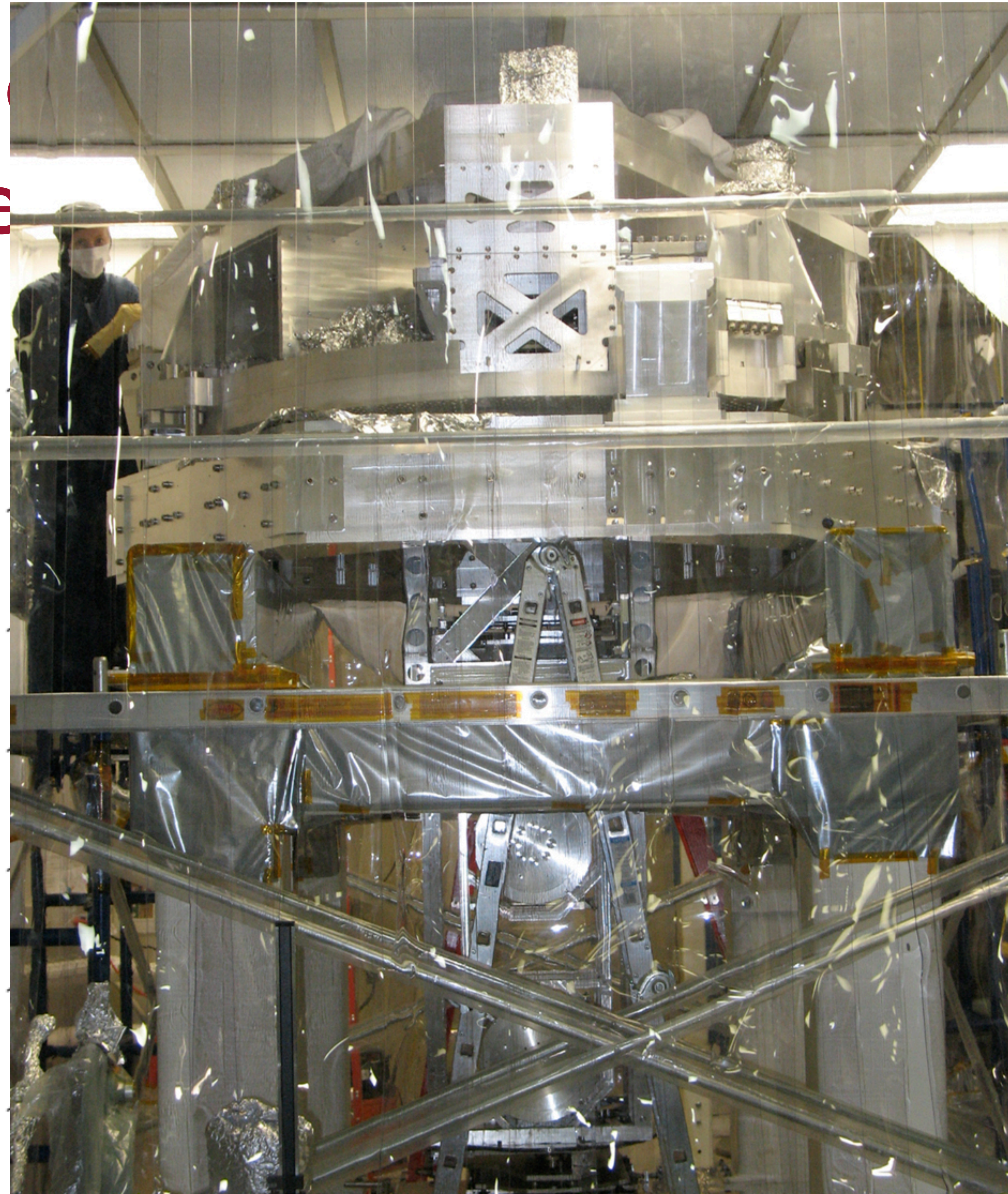
- LASTI prototype now being tested at MIT.

meter per root Hz

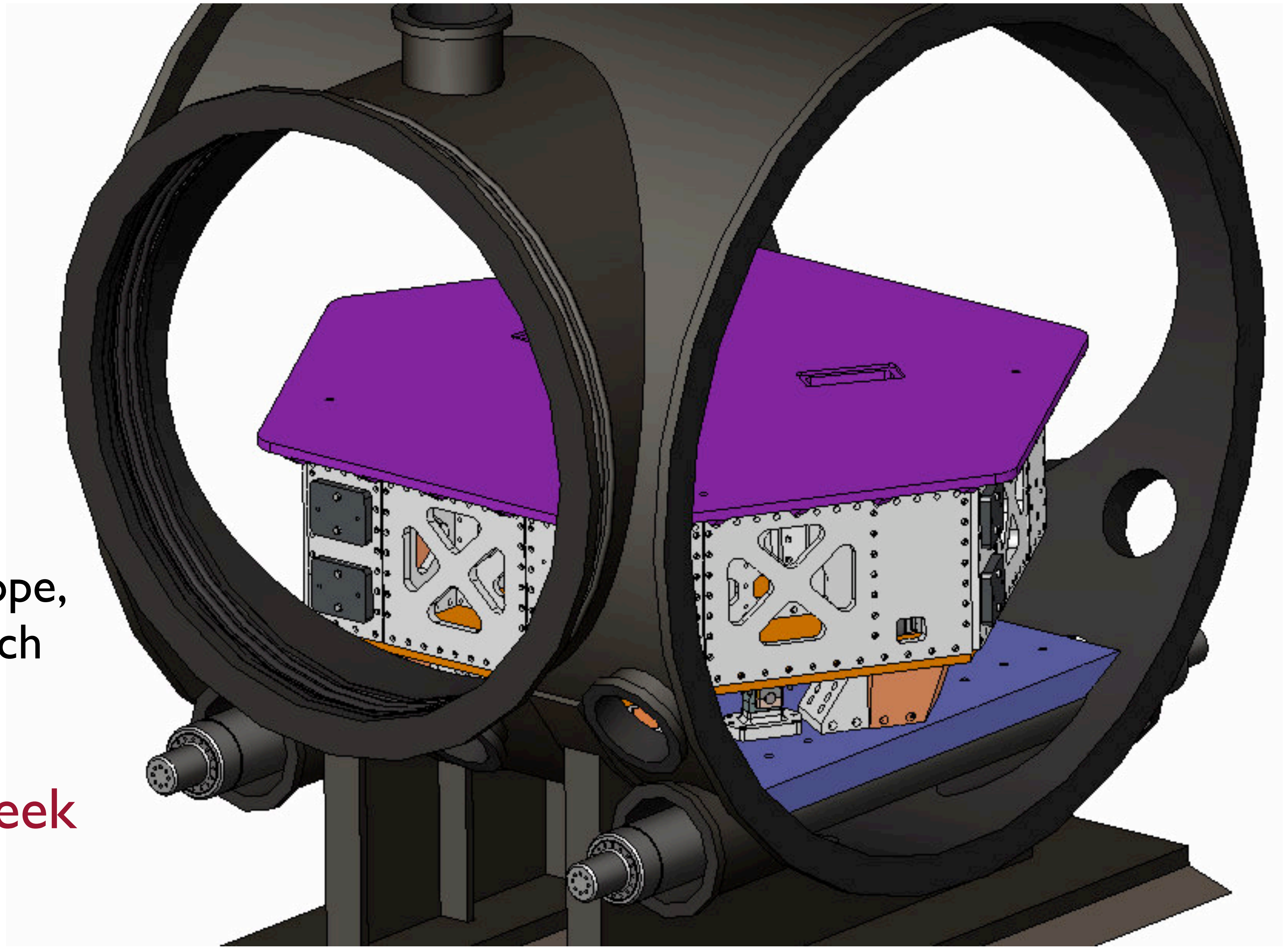


Single stage isolator for auxiliary optics

- Bolted aluminum structure Suspended by 3 blade springs & "wires"
- isolation of 50-100 above 1 Hz

- designed for "auxiliary" optics
- input and output mode cleaners,
- power and signal recycling mirrors,
- beam expanding telescope,
- GW signal readout bench

- to be installed into Enhanced LIGO next week



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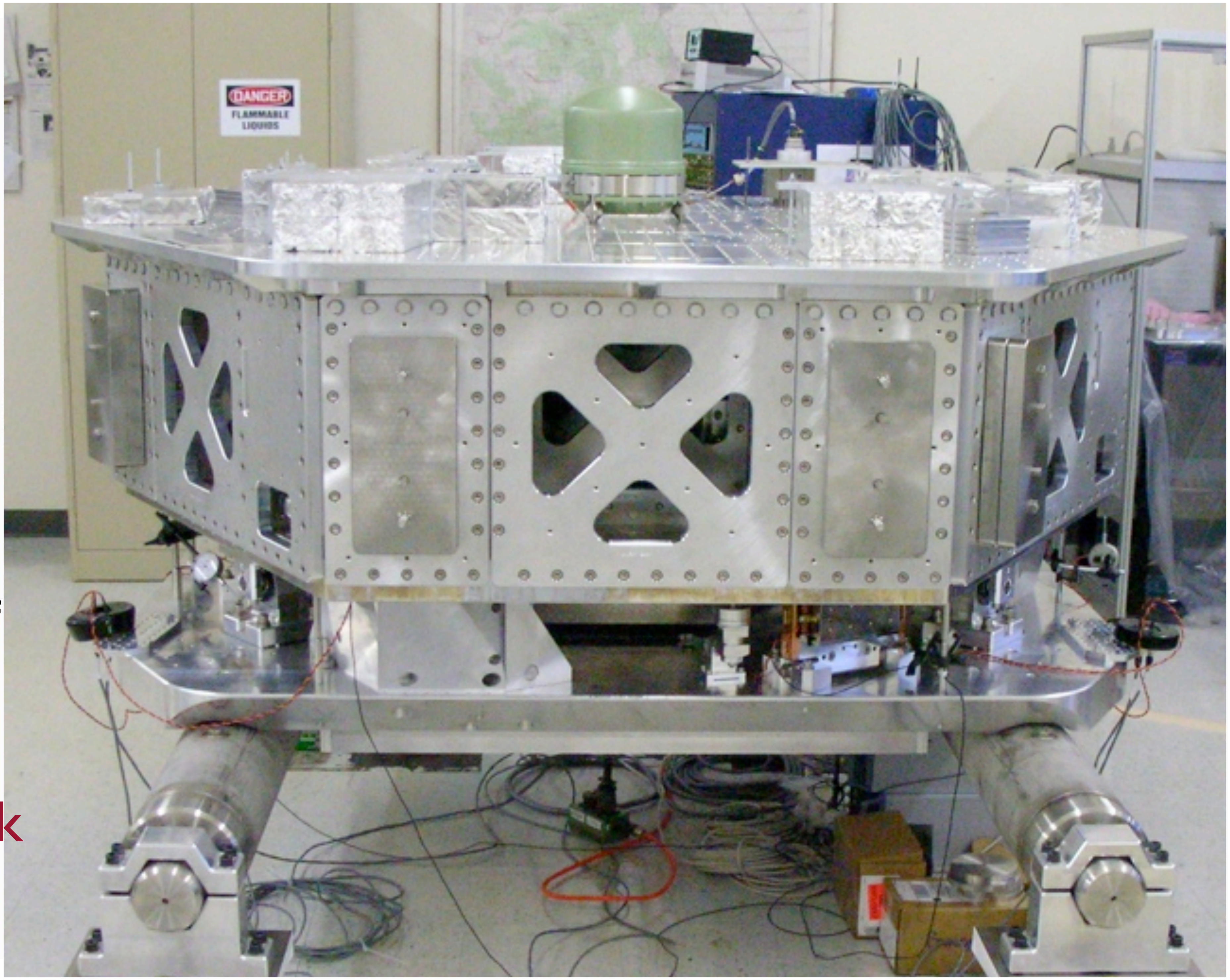

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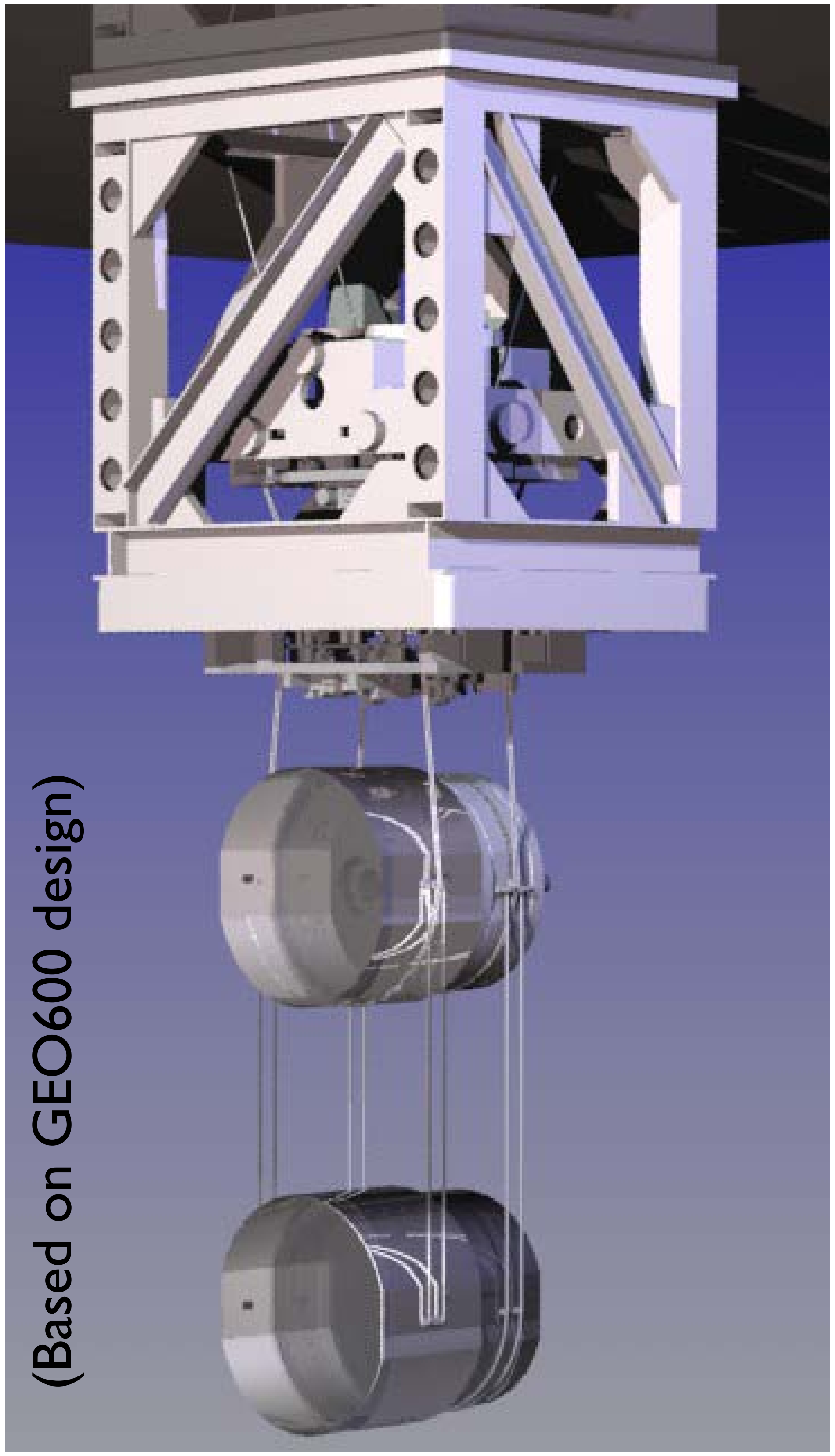
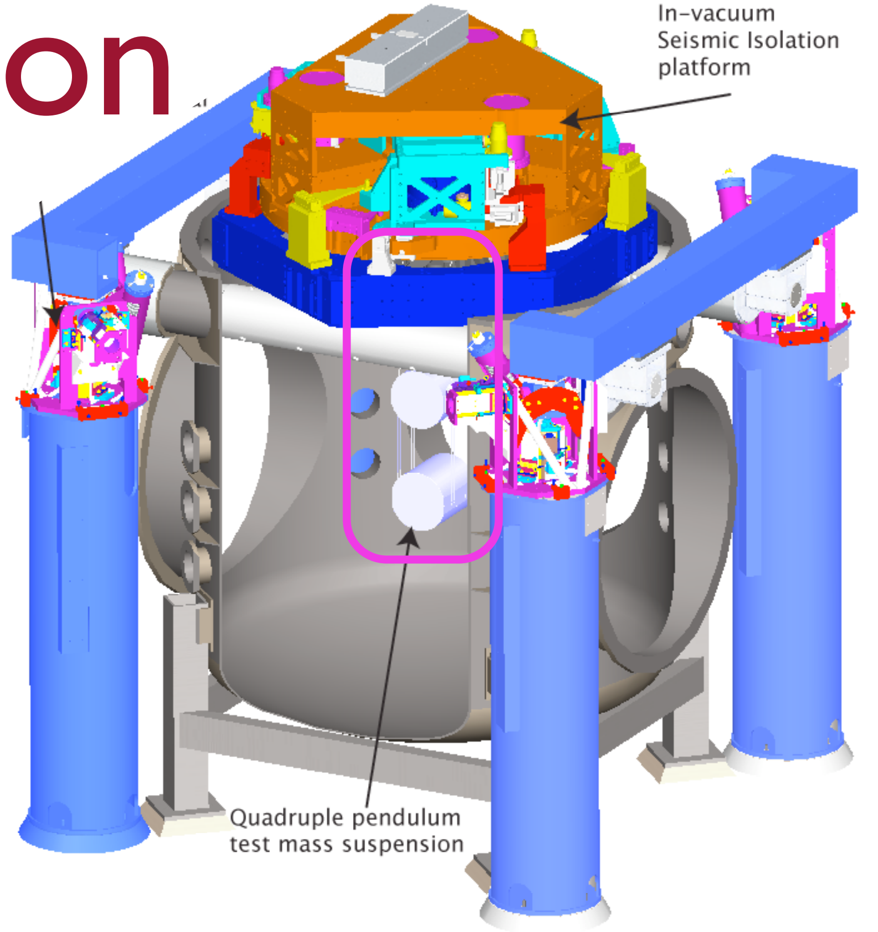
Pendulum Suspension

Suspensions material from N. Robertson, GEO600, and the SUS team



Drawings courtesy of Calum Torrie and GEO600



Multiple-pendulums
for control flexibility &
seismic attenuation

Each stage gives ~1/f2
isolation above the
natural frequency.
More that 1e6 at 10 Hz.

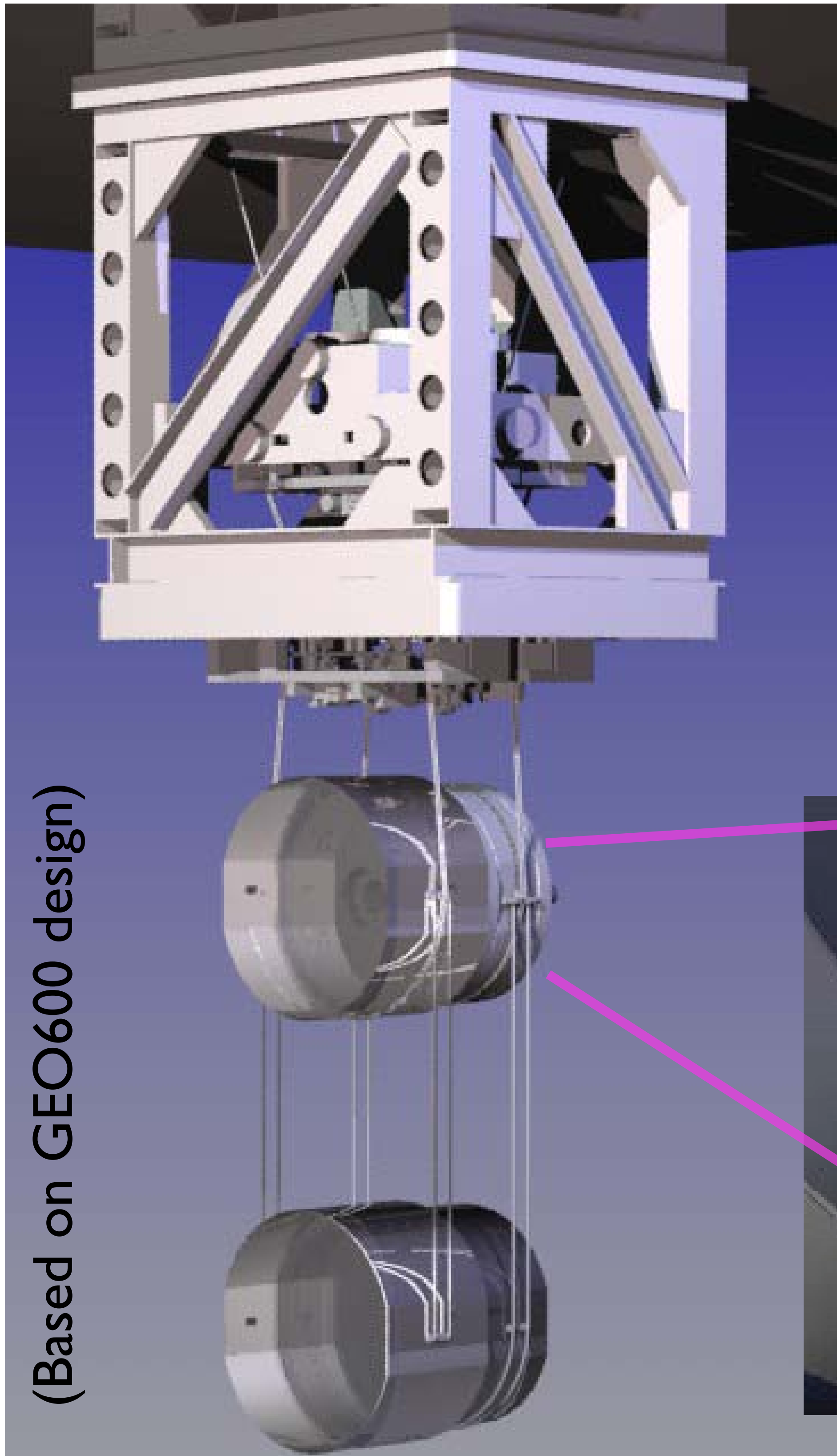
Test masses:
Synthetic fused silica,
40 kg, 34 cm dia.

- » 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.

Pendulum Suspension



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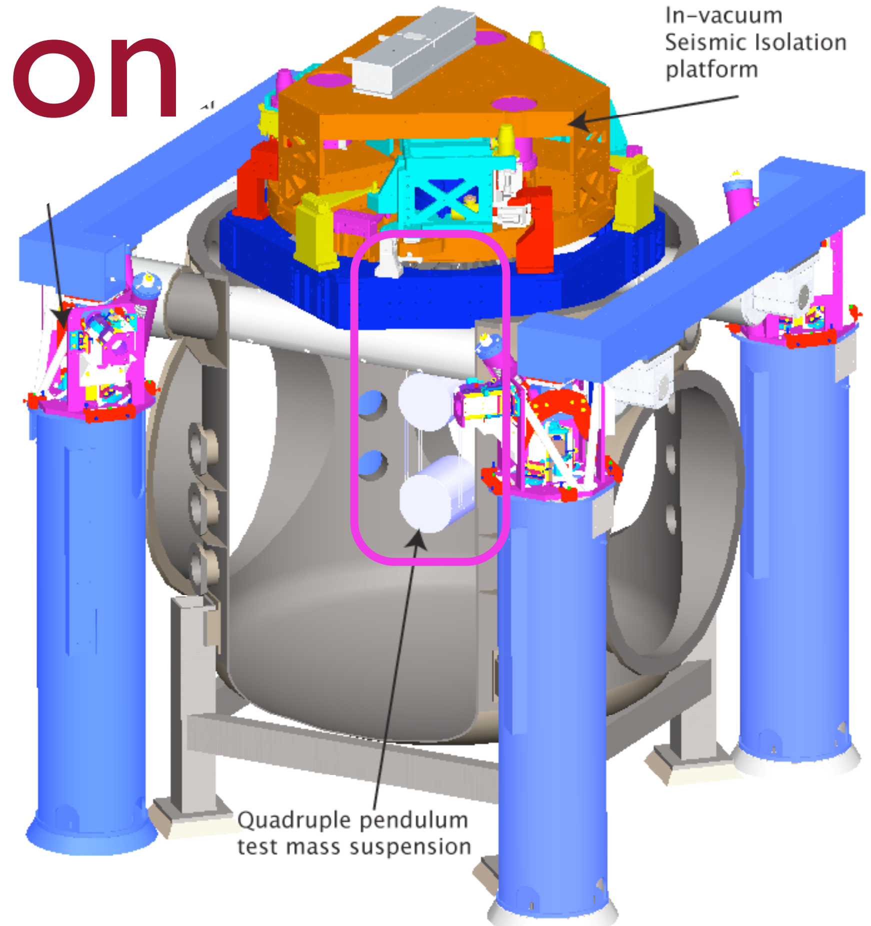

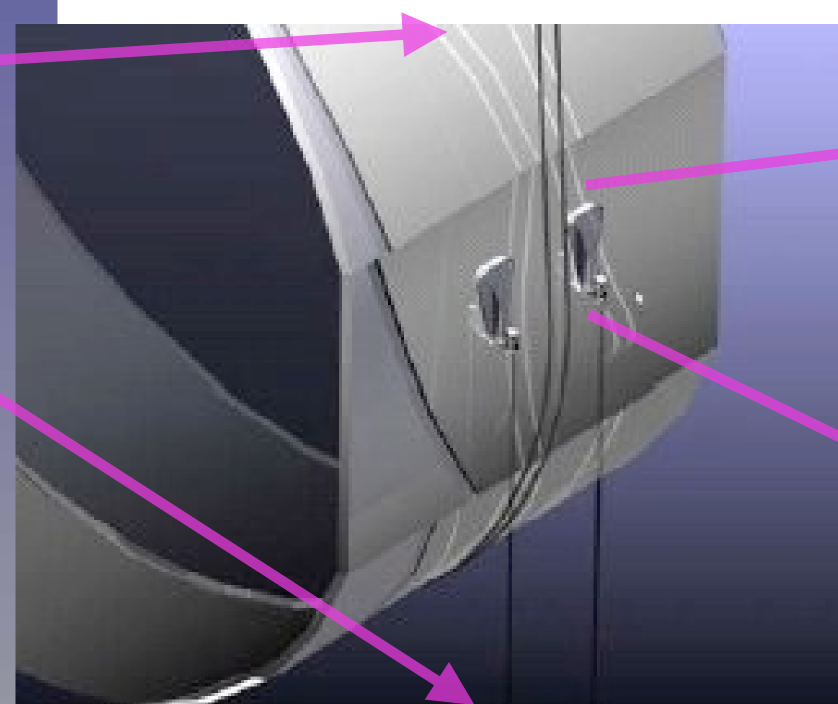

silicate bonding creates a monolithic final stage

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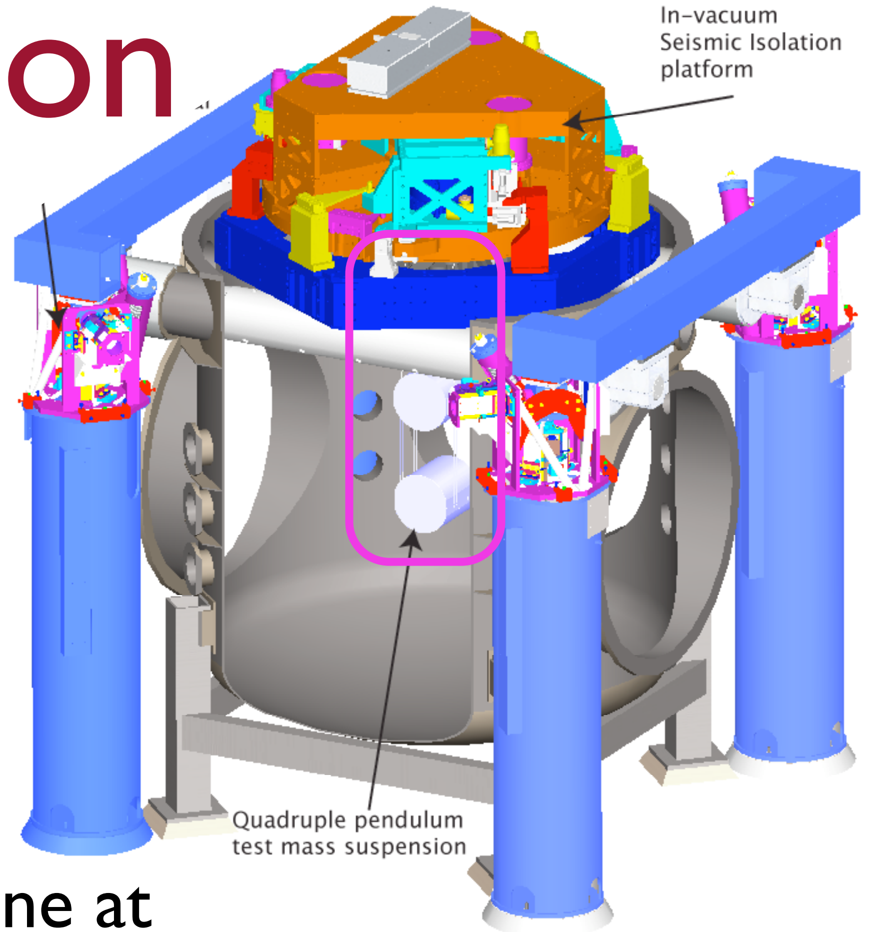
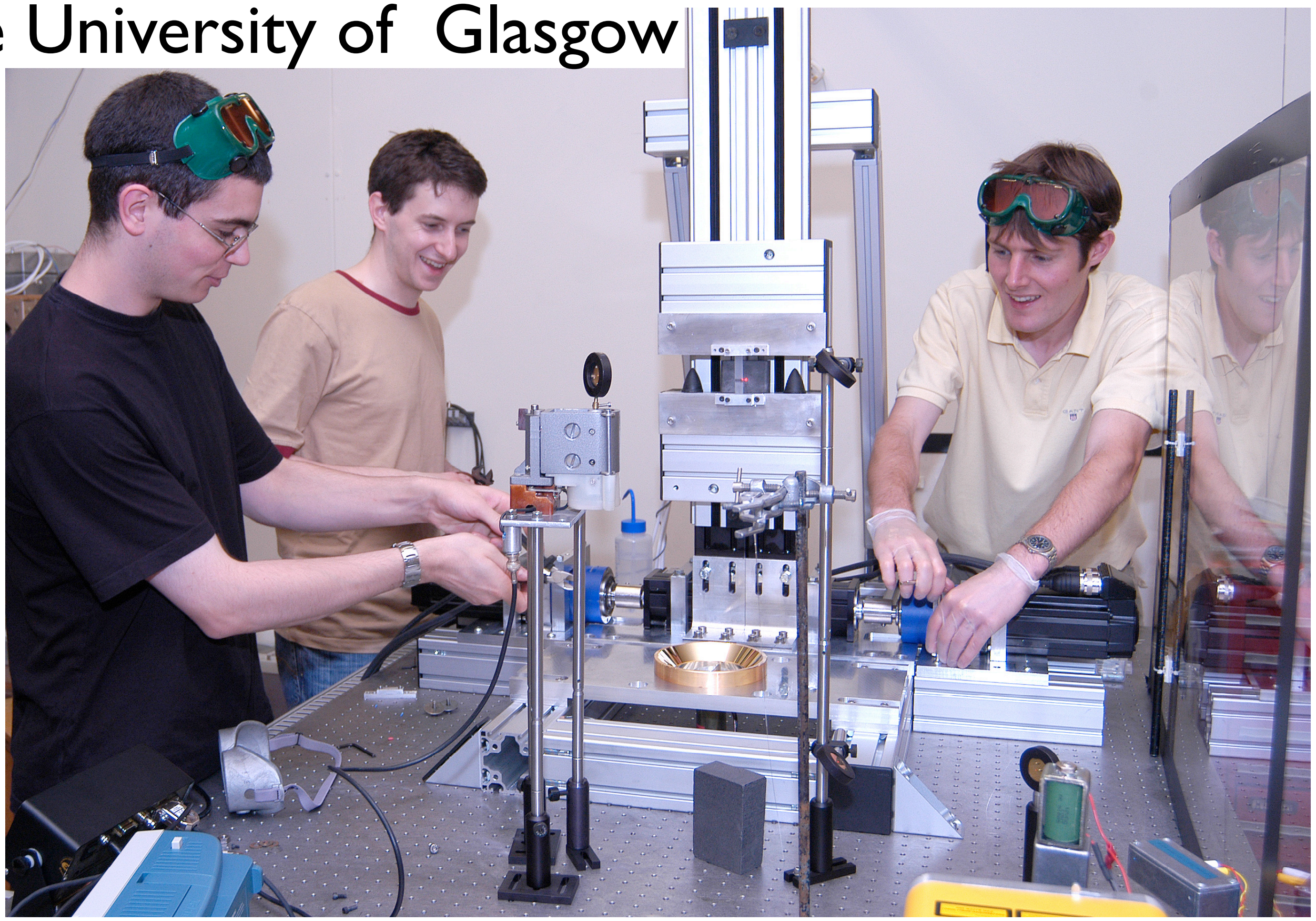
Pendulum Suspension

Quadruple pendulum now installed at MIT with "metal mirrors".



Interaction tests between pendulum and platform have begun

Ribbon pulling machine at the University of Glasgow

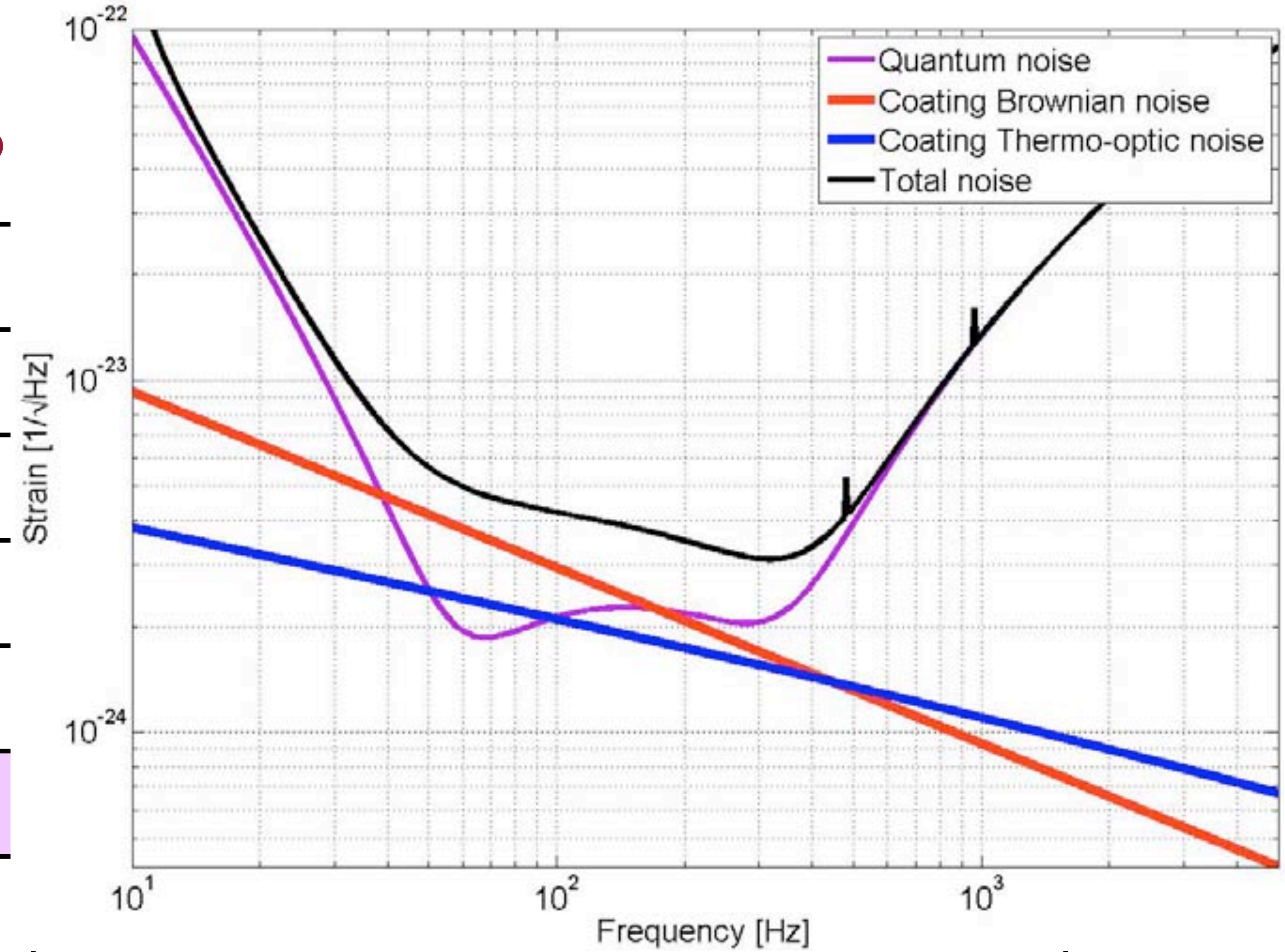


Test Mass Requirements

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 (Heraeus Suprasil 311)	< 3 ppm/cm
Bulk mechanical loss	$< 3\times10^{-9}$
Optical coating: Titania doped Tantala/ silica	
Optical coating absorption	< 0.5 ppm(required) < 0.2 ppm(goal)
Optical coating mechanical loss	$< 2\times10^{-4}$ (required) $< 3\times10^{-5}$ (goal)
Optical coating scatter	< 2 ppm(required) < 1 ppm(goal)
Arm cavity optical loss / round trip	< 75 ppm

courtesy of G. Harry, S. Rowan, and the optics working group

Test Mass

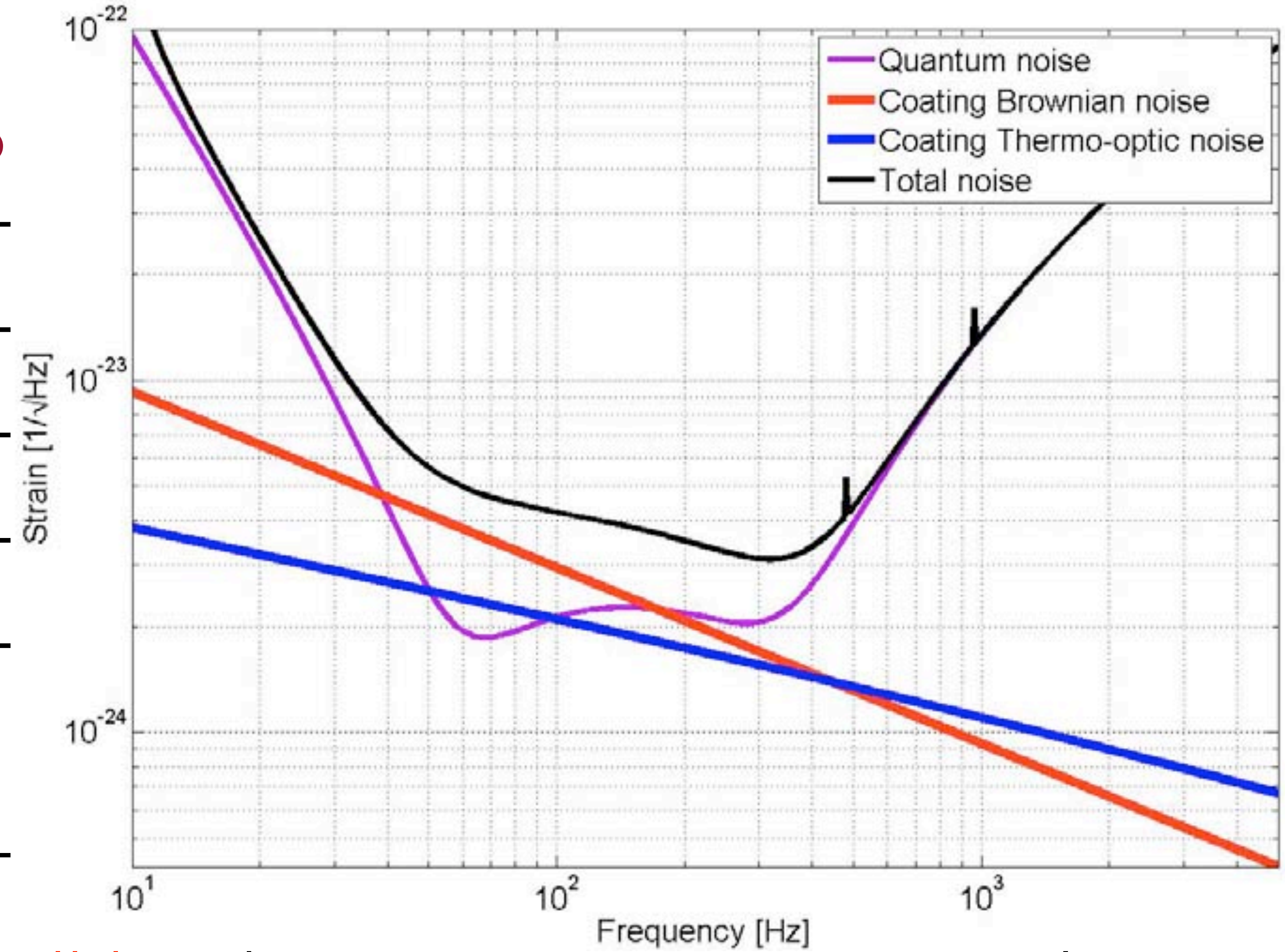


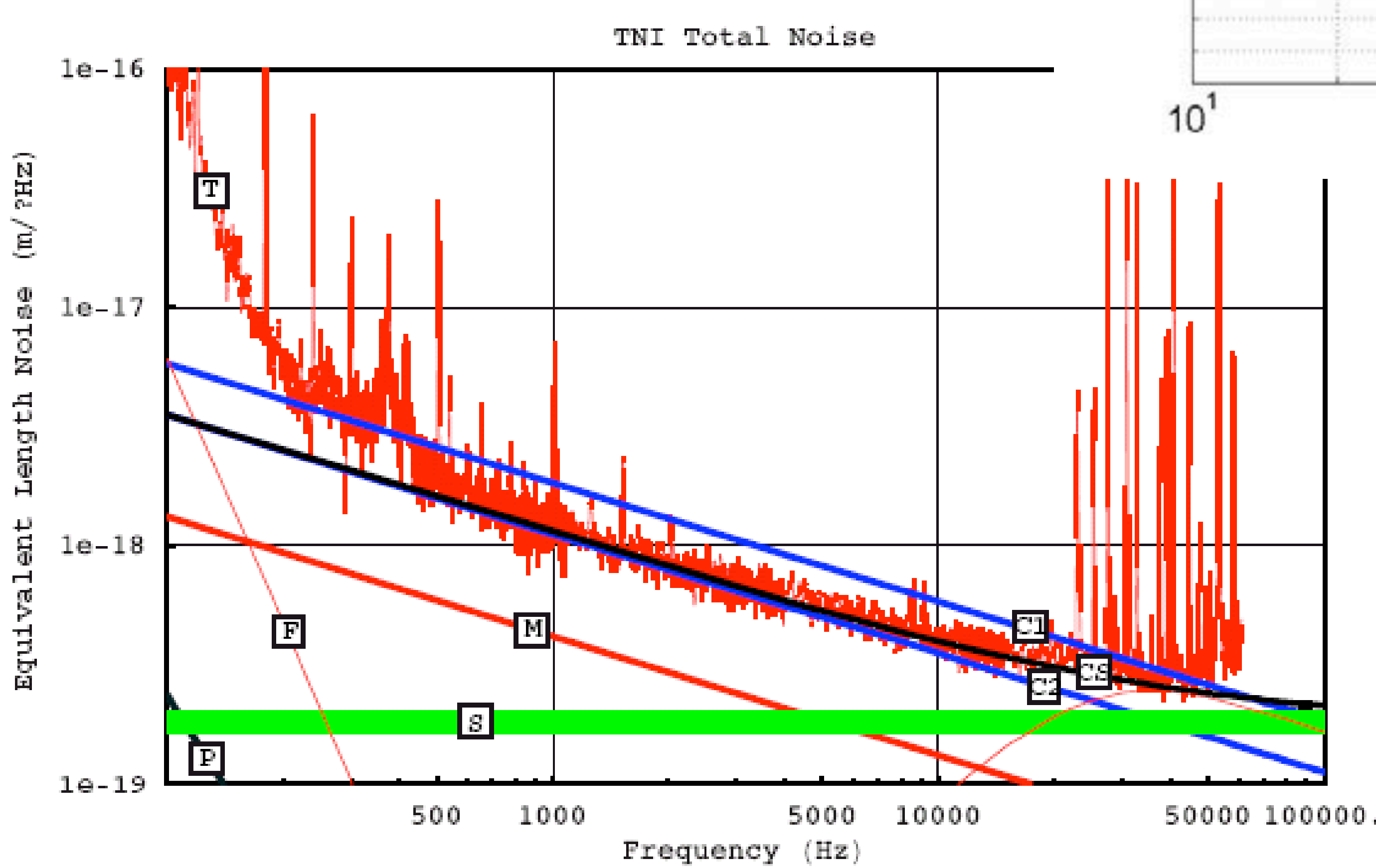
Mass	
Dimensions	
Surface figure	
Micro-roughness	
Double-pass optical homogeneity	
Bulk absorption (Heraeus Suprasil 311)	
Bulk mechanical loss	
Optical coating: Titania doped Tantala/ silica	
Optical coating absorption	< 0.5 ppm(required) < 0.2 ppm(goal)
Optical coating mechanical loss	< 2×10^{-4} (required) < 3×10^{-5} (goal)
Optical coating scatter	< 2 ppm(required) < 1 ppm(goal)
Arm cavity optical loss / round trip	< 75 ppm

courtesy of G. Harry, S. Rowan, and the optics working group

Test Mass

Mass		
Dimensions		
Surface figure		
Micro-roughness		
Double-pass optical homogeneity		
	equired) < 0.2 ppm(goal	samples at 0.4 ppm
	quired) < $3x10^{-5}$ (goal)	measured $8.5x10^{-5}$
	quired) < 1 ppm(goal)	not yet...





courtesy of G. Harry, S. Rowan, and the optics working group

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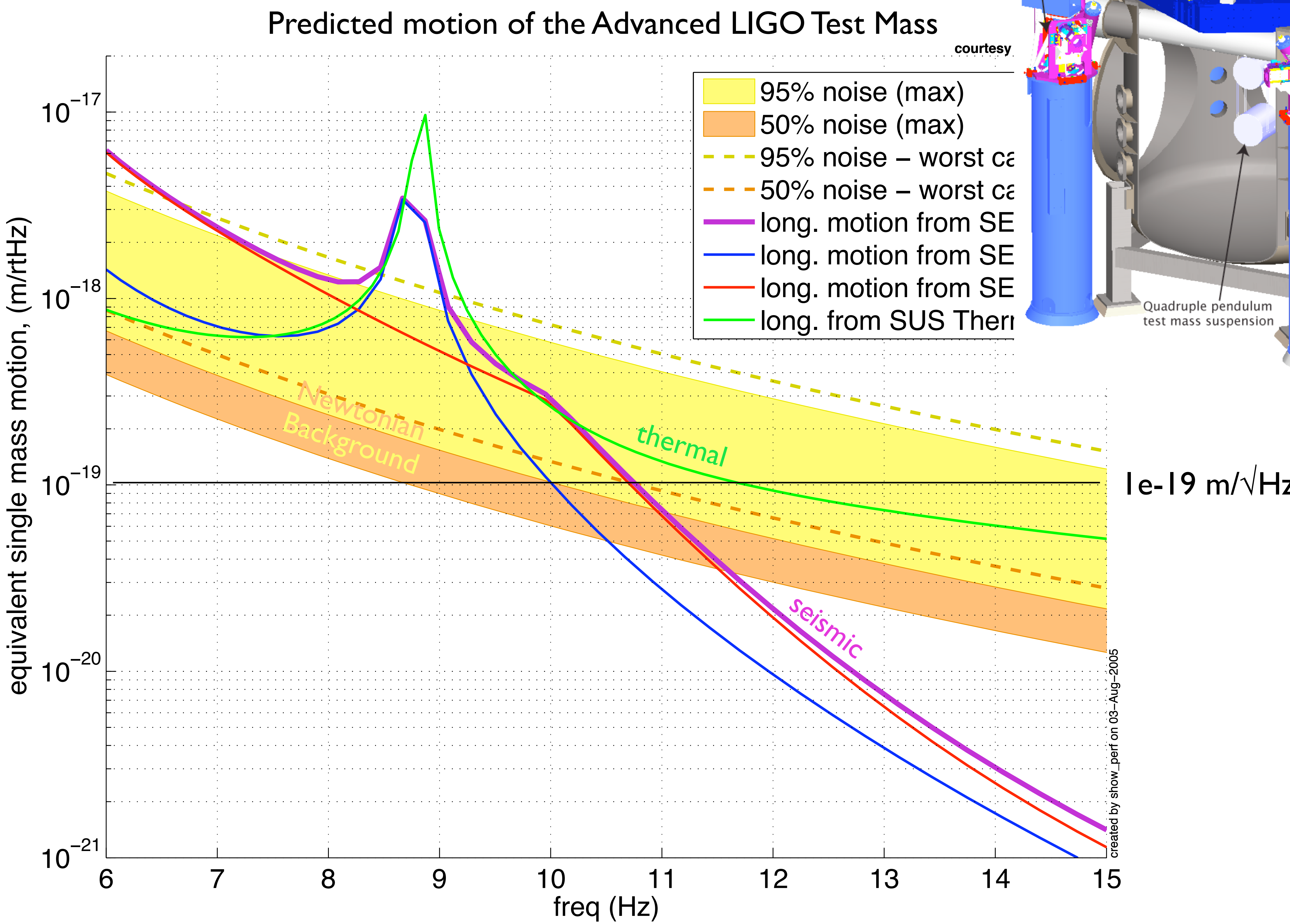
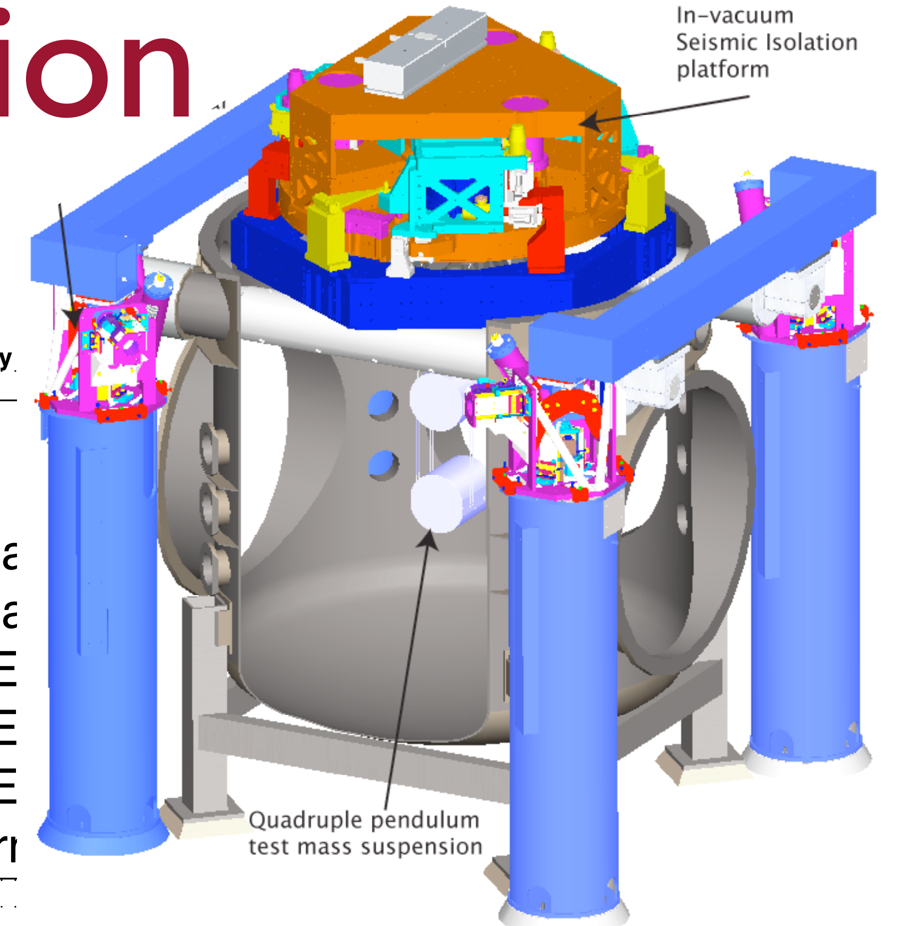
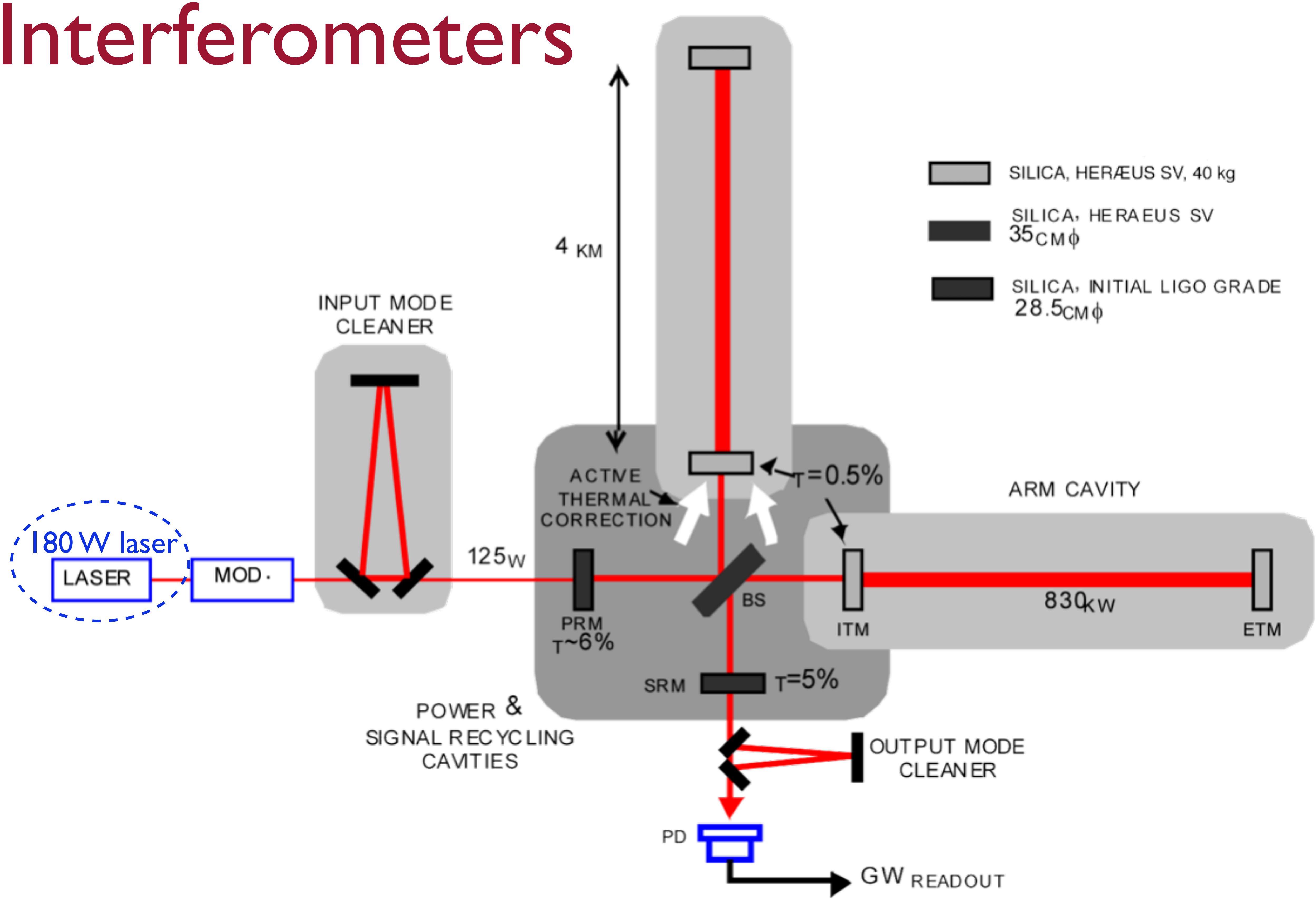
Pendulum Suspension





Power, Optics, and Interferometers



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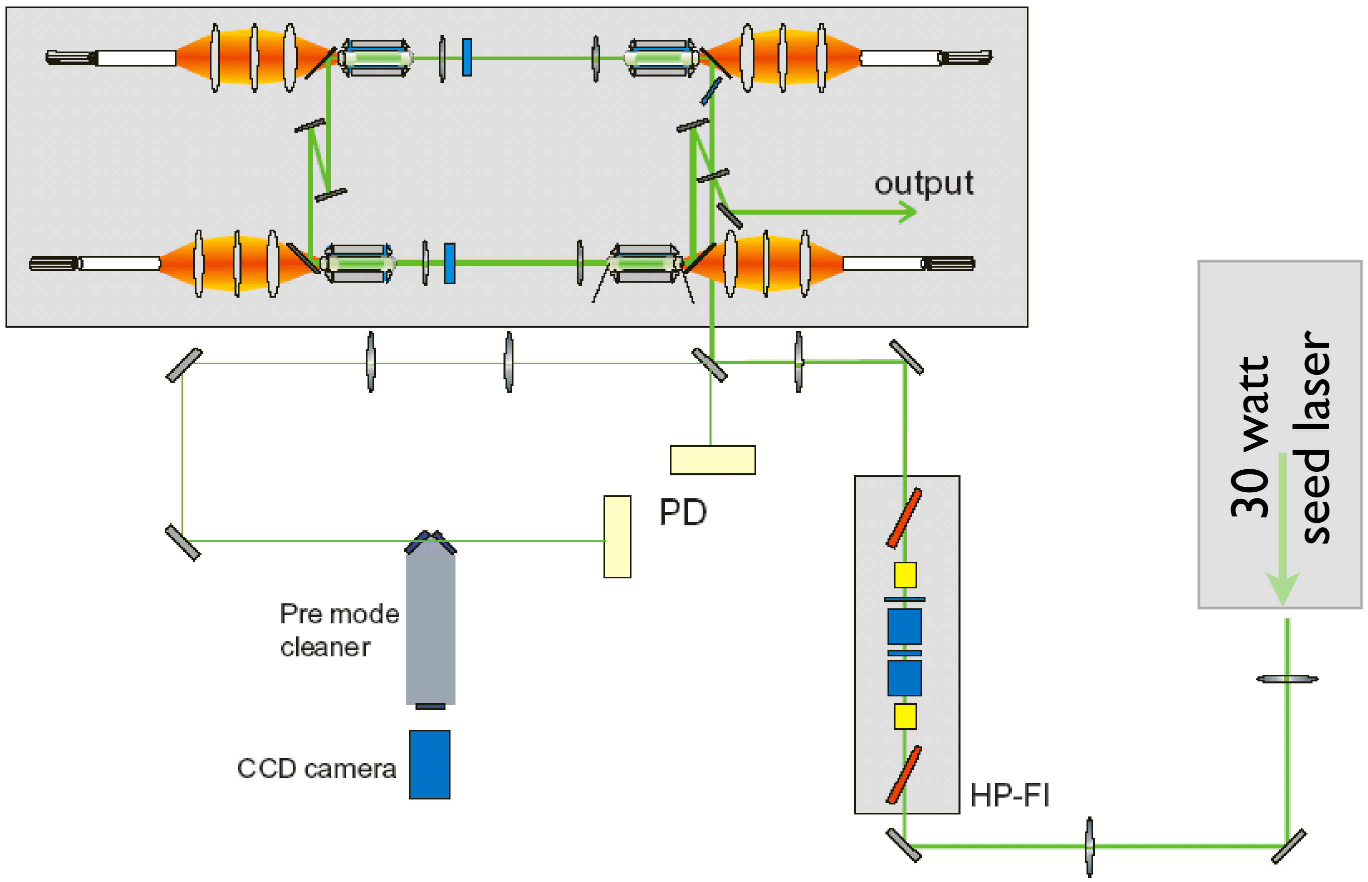
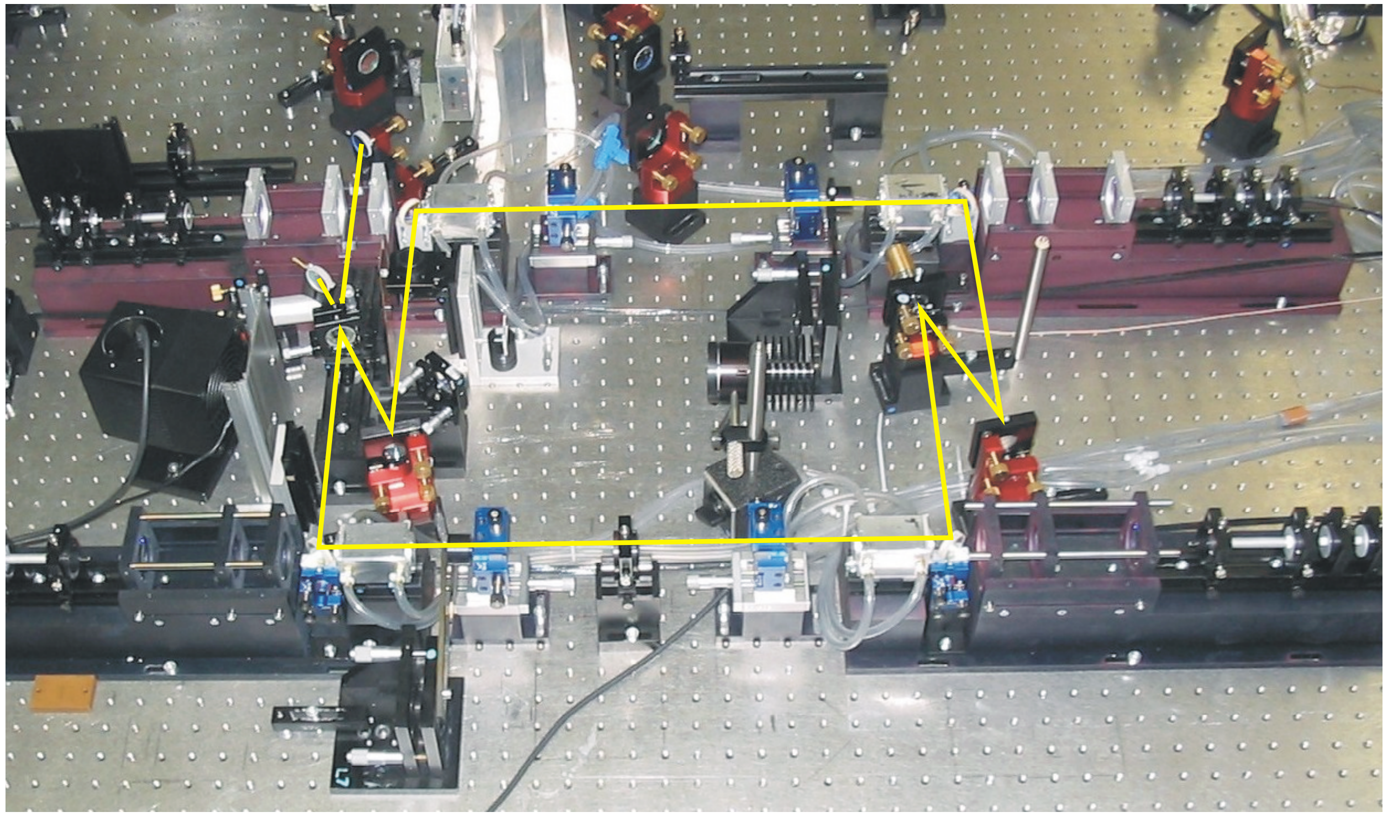
High Power Laser

- 180 W with good beam shape
- 1064 nm (YAG)
- very low intensity and frequency noise
- Developed by AEI (Max-Planck Institute, Hanover) & Laser Zentrum Hanover (LZH)
- stable front end determines laser frequency and frequency fluctuations. (NPRO & 4 rod Nd:YVO)
- high power stage, Injection seeded ring oscillator determines power, power fluctuations, and beam shape.

high-power injection-locked oscillator

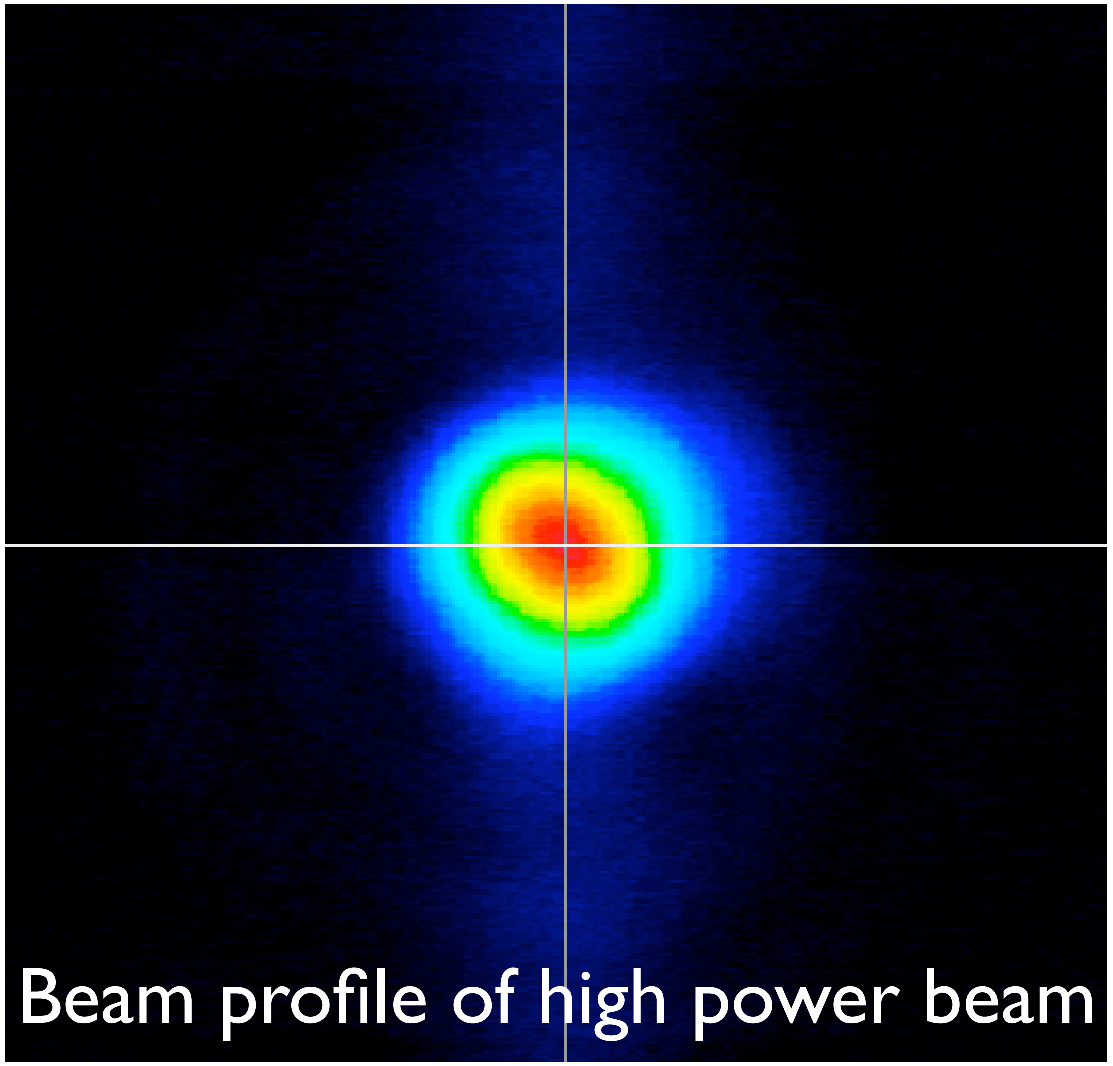


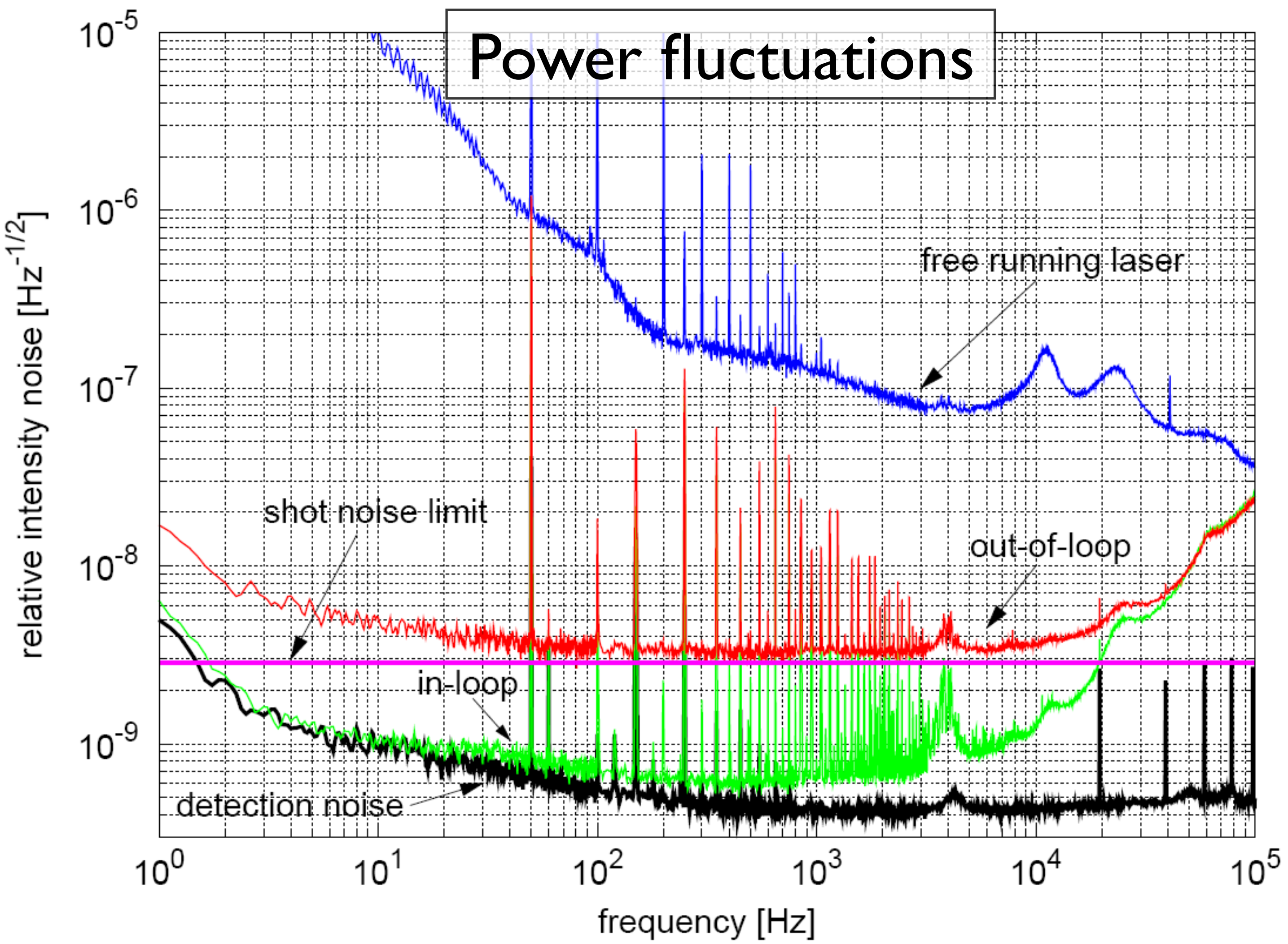


Laser material from B. Wilke, P. Wessels, GEO600, AEI, LZH

High Power Laser

- 180.5 W output power (91.5% in TEM_{00})
- good spatial profile
- power fluctuations close to requirement.
- 37 W "seed" laser installed at one and about to be installed at second site for Enhanced LIGO.

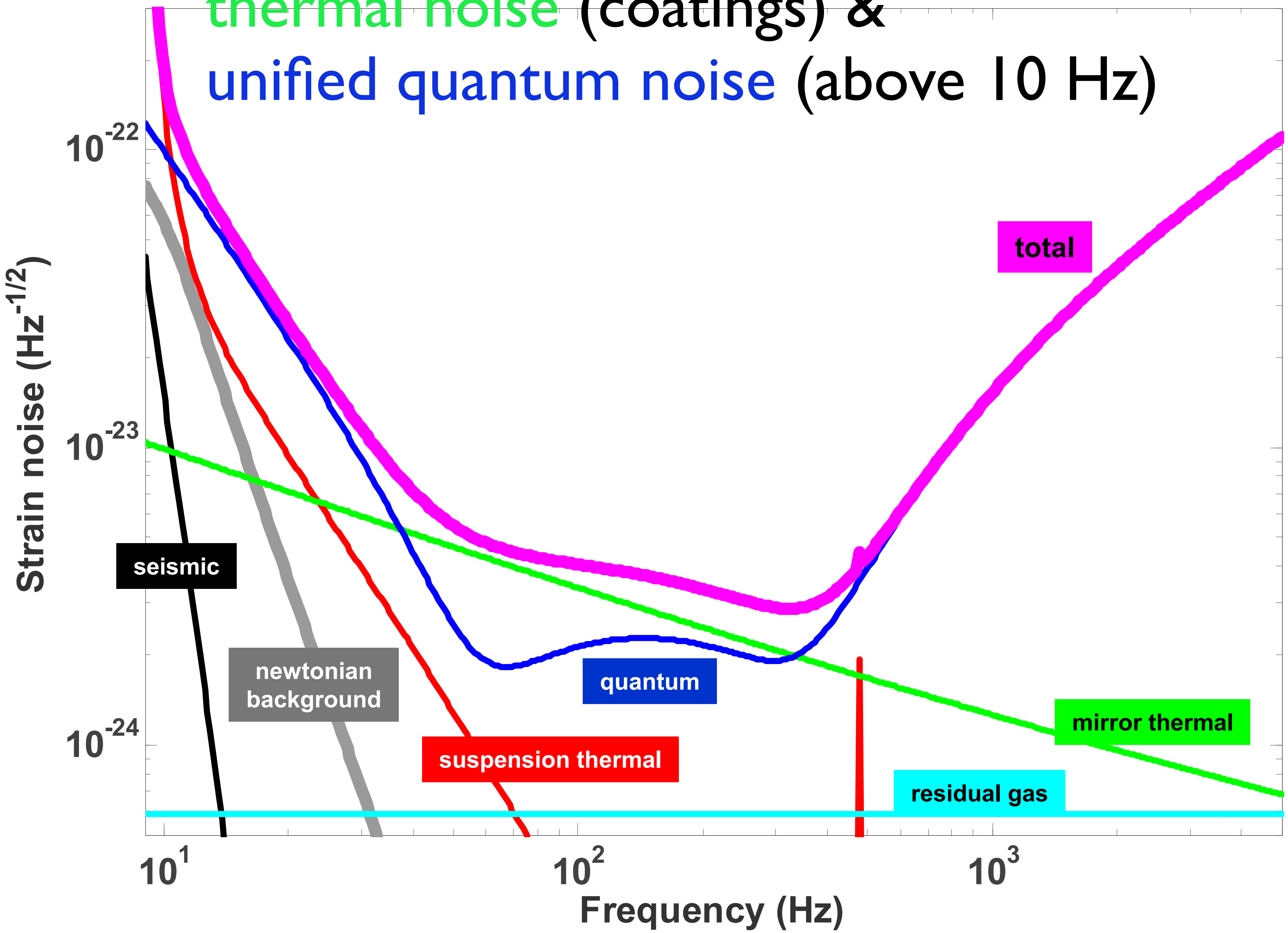




Still to Verify:
- RIN at low frequency
- preparing to build Engineering Prototype

Tuning

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



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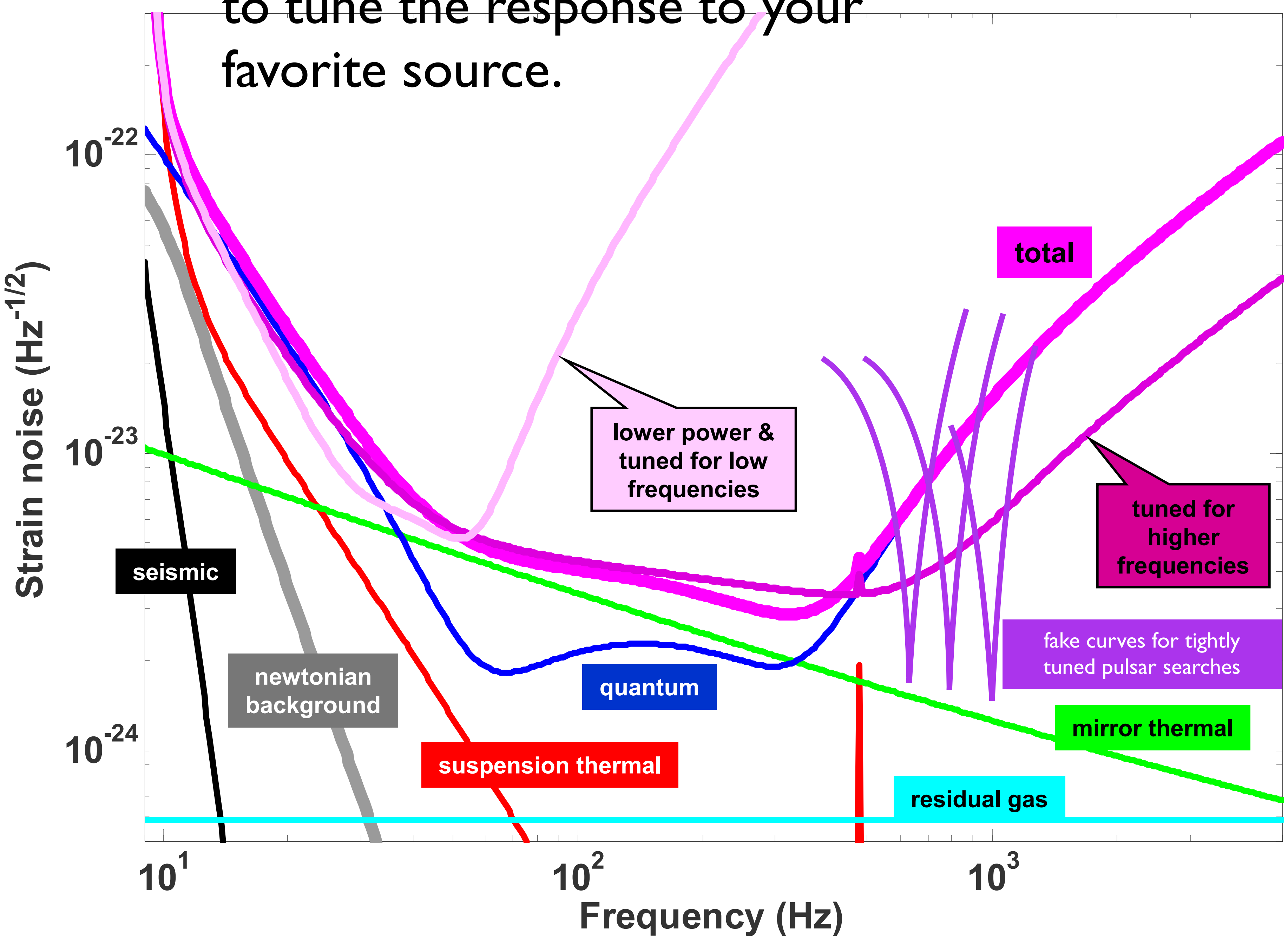
Tuning

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.

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...

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 are ready to start the construction.

The astrophysics will be great!