Advanced LIGO

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for the LIGO Scientific Collaboration
Hanford,
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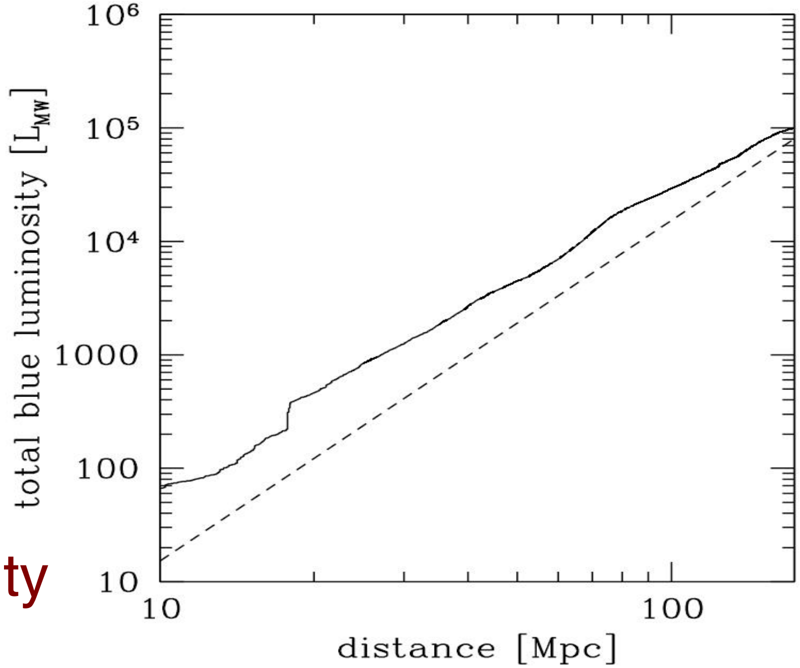
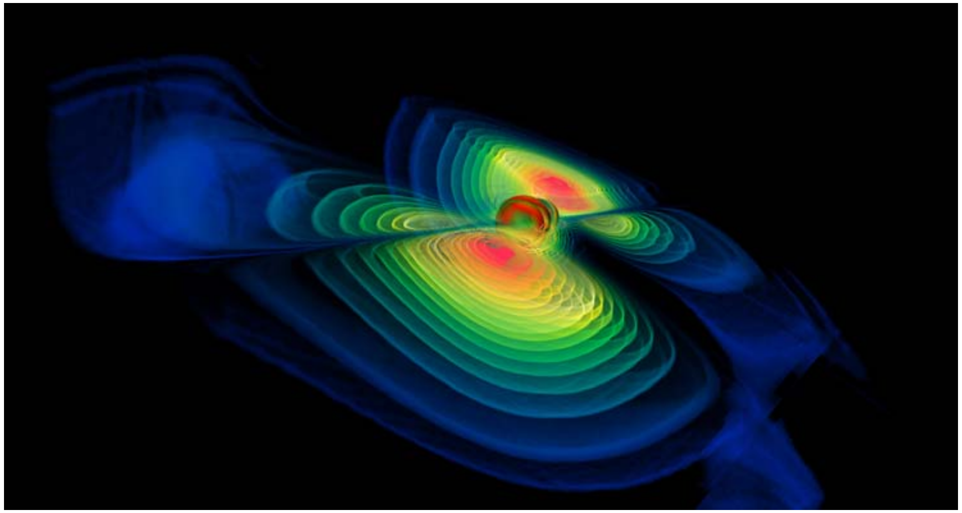
Motivation



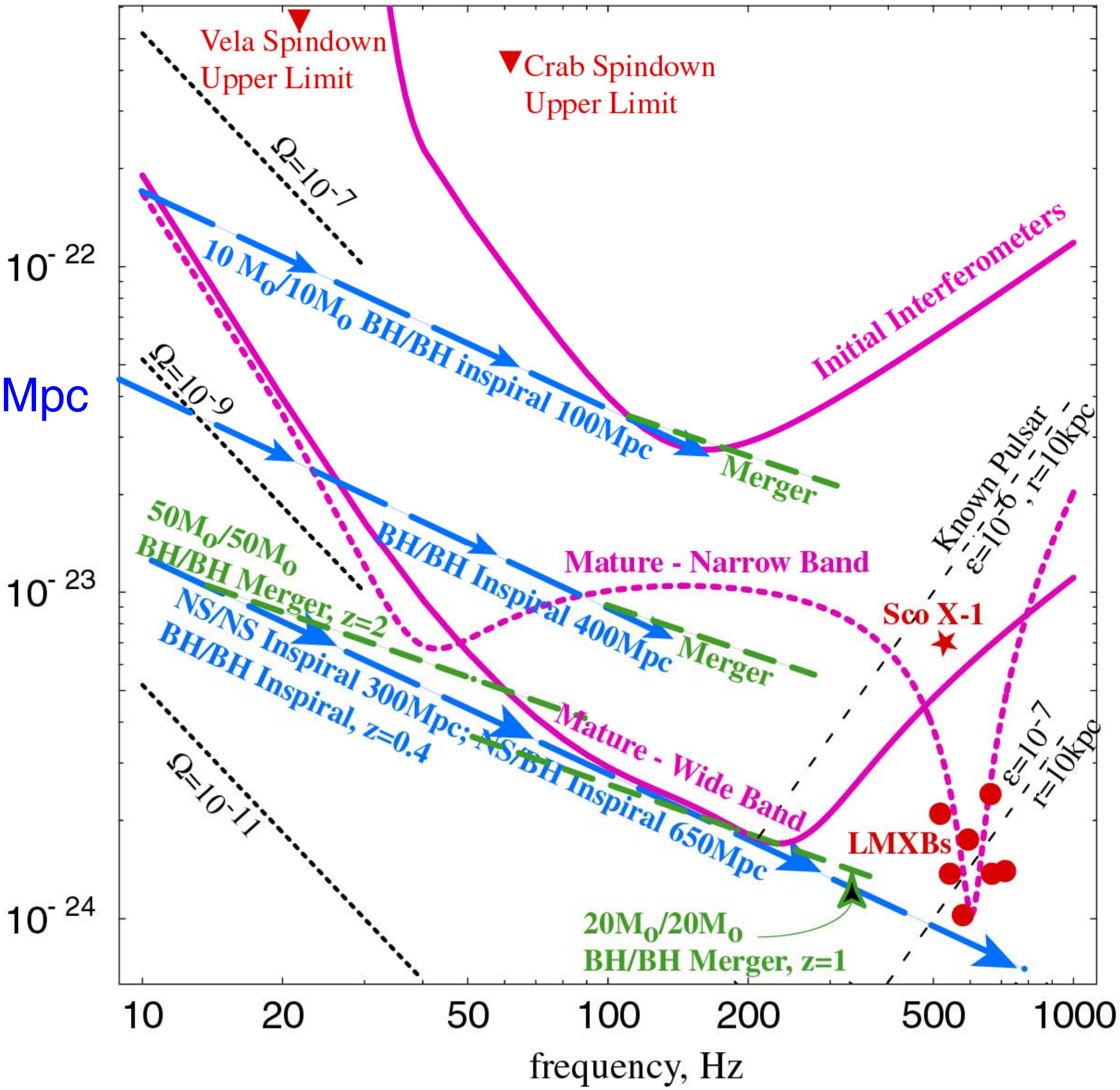
- Build a detector with assured detectability of known sources
  - Interesting astrophysics
  - Reach matters
- LIGO is nearing its design sensitivity



- New ideas and new technologies are available
  - Reasonable extrapolations of detector physics and technologies
  - Realizable, practical and reliable instrument

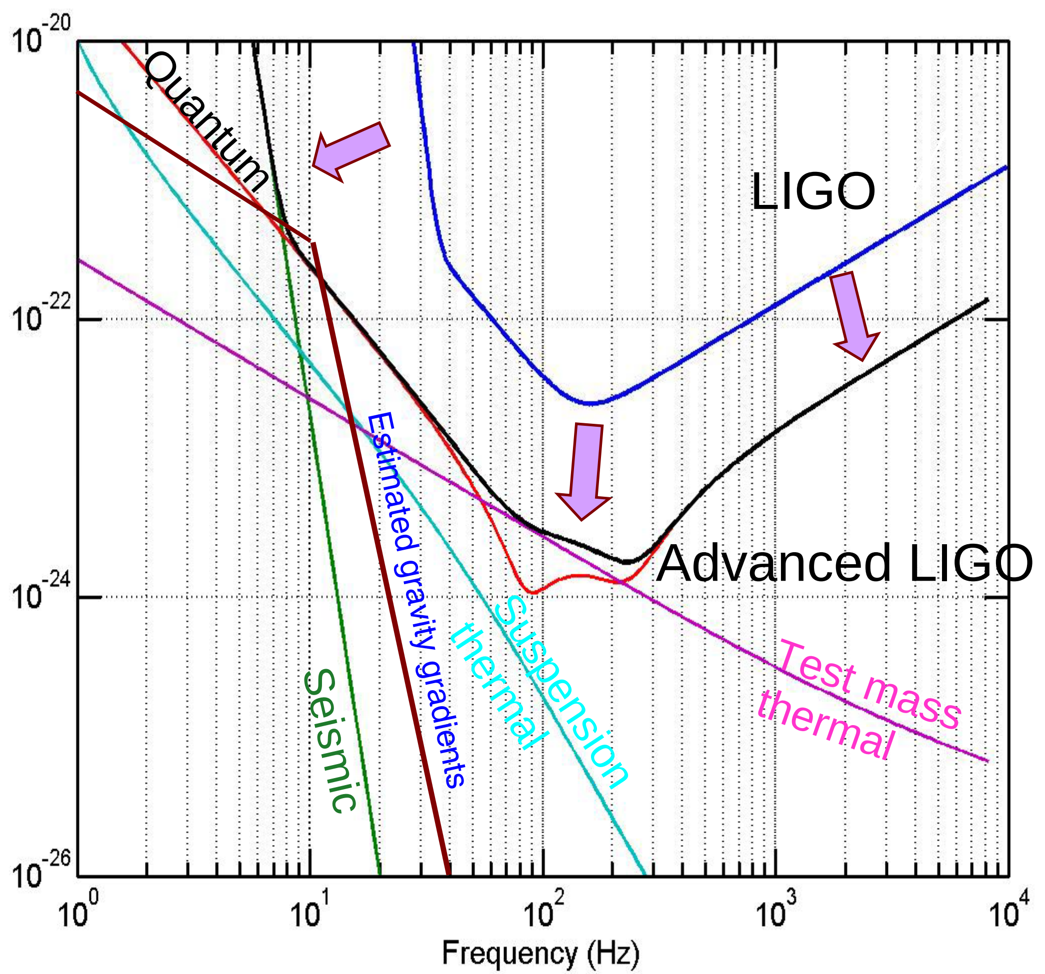
Sensitivity and Reach

- NS Binaries:
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~300 Mpc
- BH Binaries:
  - Initial LIGO: 10 $M_{\odot}$, 100 Mpc
  - Adv LIGO: 50 $M_{\odot}$, z=2
- Known Pulsars:
  - Initial LIGO: $\varepsilon = 3\times10^{-6}$
  - Adv LIGO: $\varepsilon = 2\times10^{-8}$
- Stochastic:
  - Initial LIGO: $\Omega \sim 3\times10^{-6}$
  - Adv LIGO: $\Omega \sim 3\times10^{-9}$



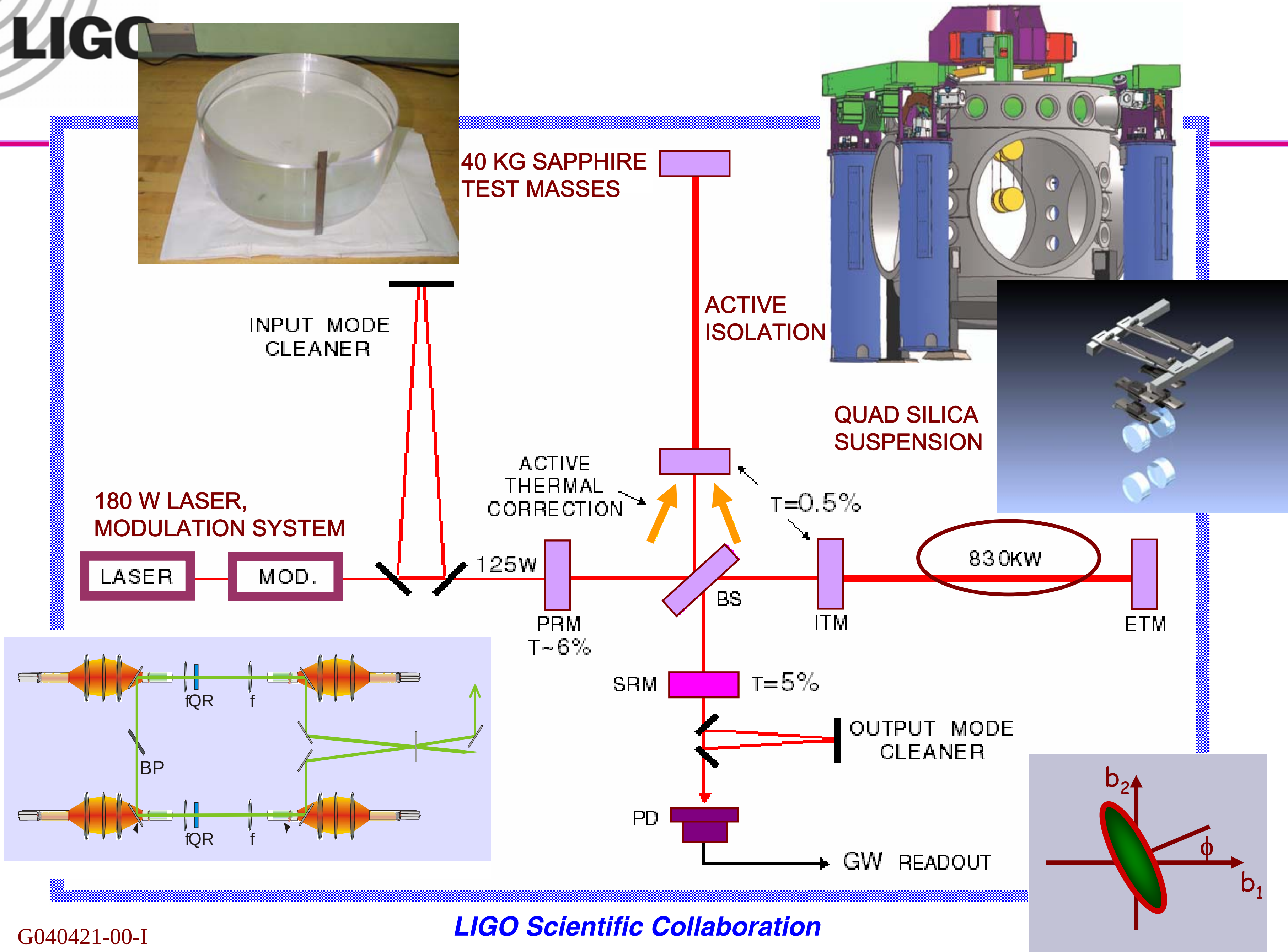
Fundamental Noise Sources

- The Target
  - Build a detector limited by fundamental noise sources
    - Gravity gradients at low f
    - Quantum noise at high f
- The Strategies
  - Seismic noise reduced 40x at 10 Hz
  - Thermal noise reduced 15x
  - Optical noise reduced 10x
- The Challenges... and overcoming them
  - Rest of this talk...



How will it get there

- Seismic noise
  - Active isolation system
  - Mirrors suspended as fourth (!!) stage of quadruple pendulums
- Thermal noise
  - Suspension → fused quartz; ribbons
  - Test mass → higher mechanical Q material, e.g. sapphire; more massive (40 kg)
- Optical noise
  - Input laser power → increase to ~200 W
  - Optimize interferometer response → signal recycling
- Platform for all currently envisaged enhancements
  - Mesa beams
  - Squeezed light interferometers
  - Newtonian background suppression


40 KG SAPPHIRE
TEST MASSES
ACTIVE
ISOLATION
QUAD SILICA
SUSPENSION
INPUT MODE
CLEANER
ACTIVE
THERMAL
CORRECTION
T=0.5%
180 W LASER,
MODULATION SYSTEM
LASER
MOD.
125W
830KW
PRM
T~6%
BS
ITM
ETM
SRM
T=5%
OUTPUT MODE
CLEANER
PD
GW READOUT
fQR
f
BP
fQR
f
b_2
ϕ
b_1

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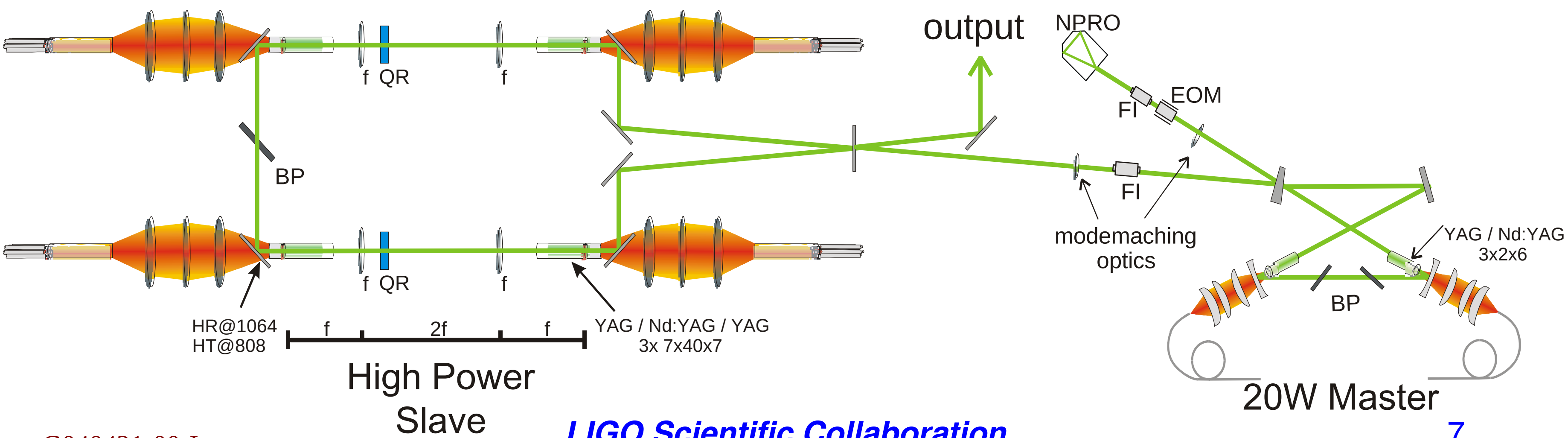
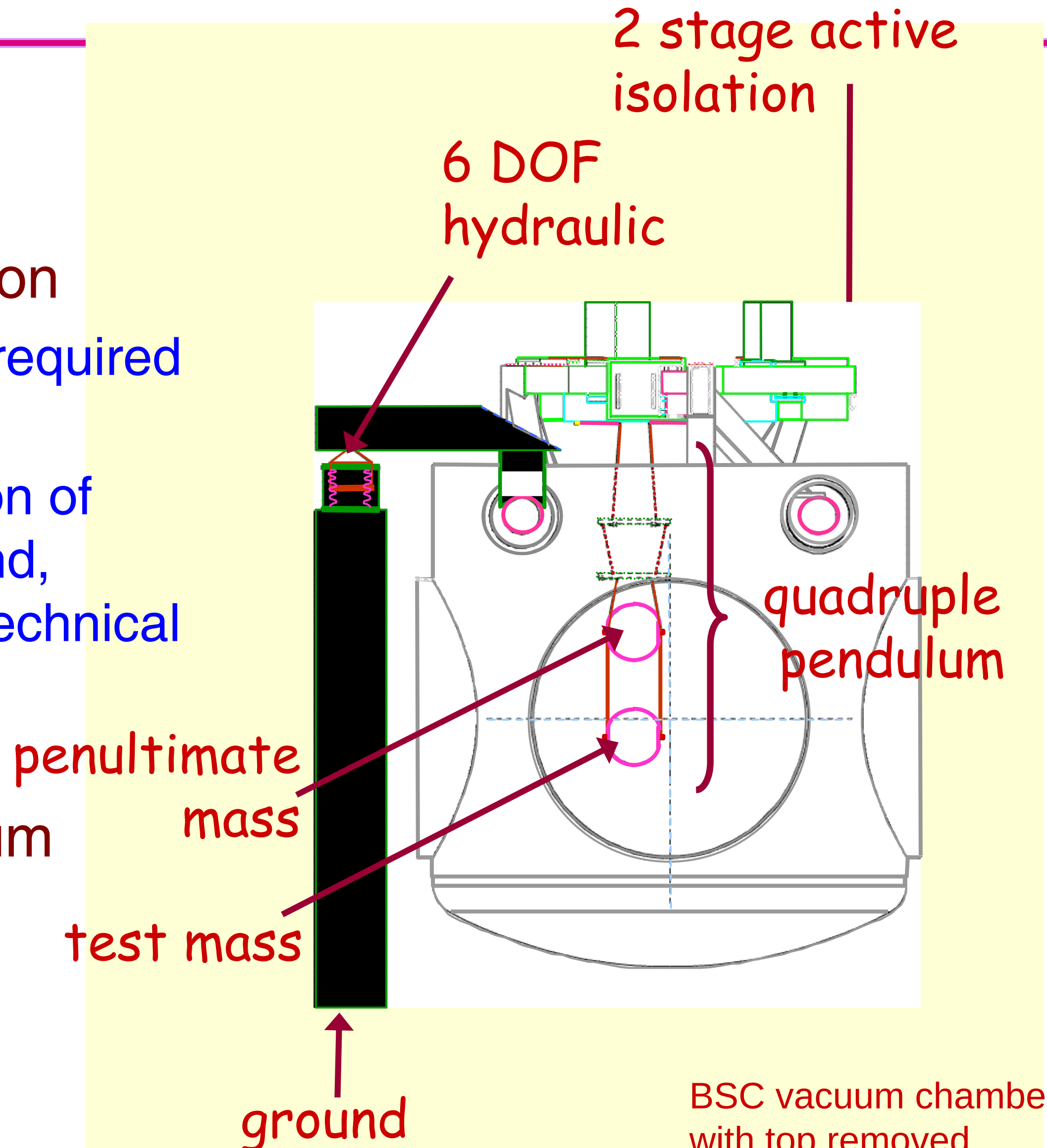
Pre-stabilized Laser

- Require the maximum power compatible with optical materials
  - 180W 1064nm Nd:YAG
  - Baseline design with end-pumped rod oscillator, injection locked to an NPRO
  - 2004: Prototyping well advanced – slave at 170 W



Seismic Isolation Strategy

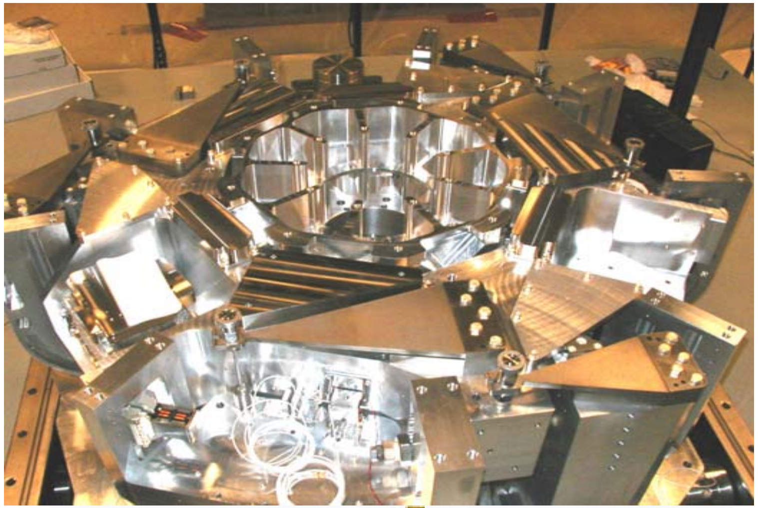
- External pre-isolation
- In-vacuum active isolation
  - Provides ~third of the required attenuation
  - Provides ~10^3 reduction of rms in the 1-10 Hz band, crucial for controlling technical noise sources
- Mirrors suspended from quadruple pendulum
  - Provides ~10^7 attenuation at 10 Hz

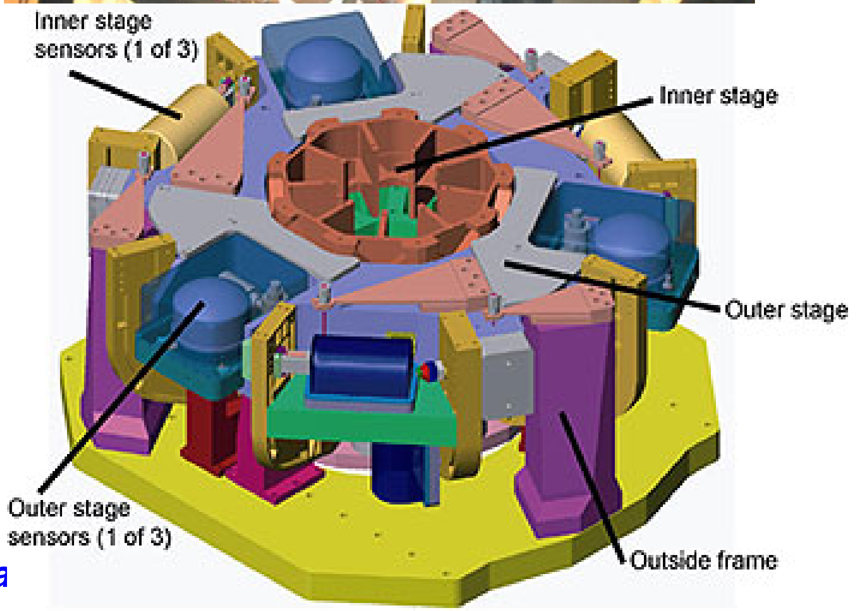


BSC vacuum chamber with top removed

Seismic Isolation

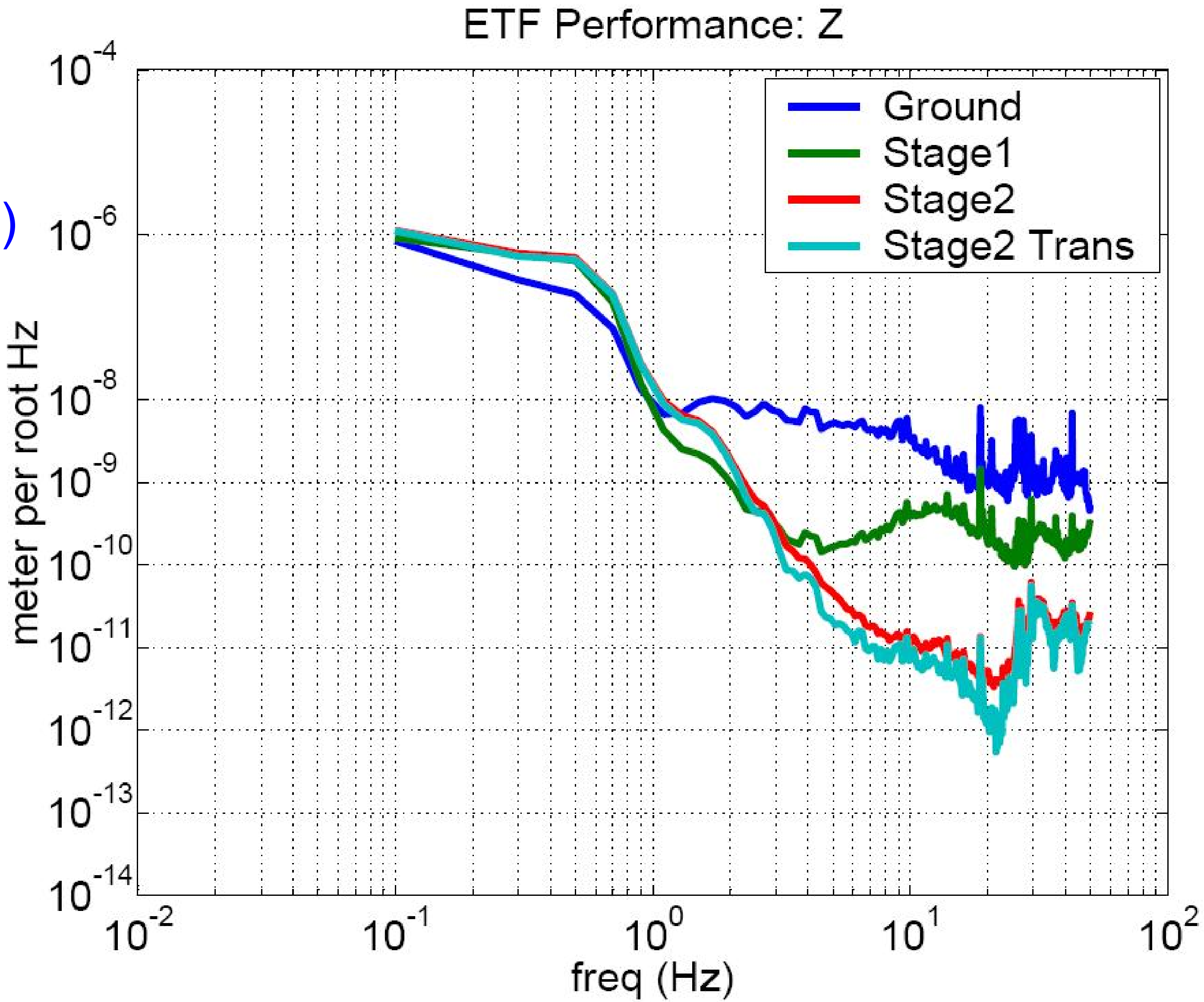
- External hydraulic actuators
  - Large dynamic range (+/-1mm)
  - Low frequency bandwidth (below GW detection band)
  - Reduce rms motion to allow sensing system at higher frequencies to remain linear
- Two in-vacuum stages of active controlled platforms
  - Active suppression of noise in 0.1 to 30 Hz band
  - Provide a quiet platform (2×10^{-13} m/$\sqrt{\text{Hz}}$ @ 10Hz) from which to suspend core optics



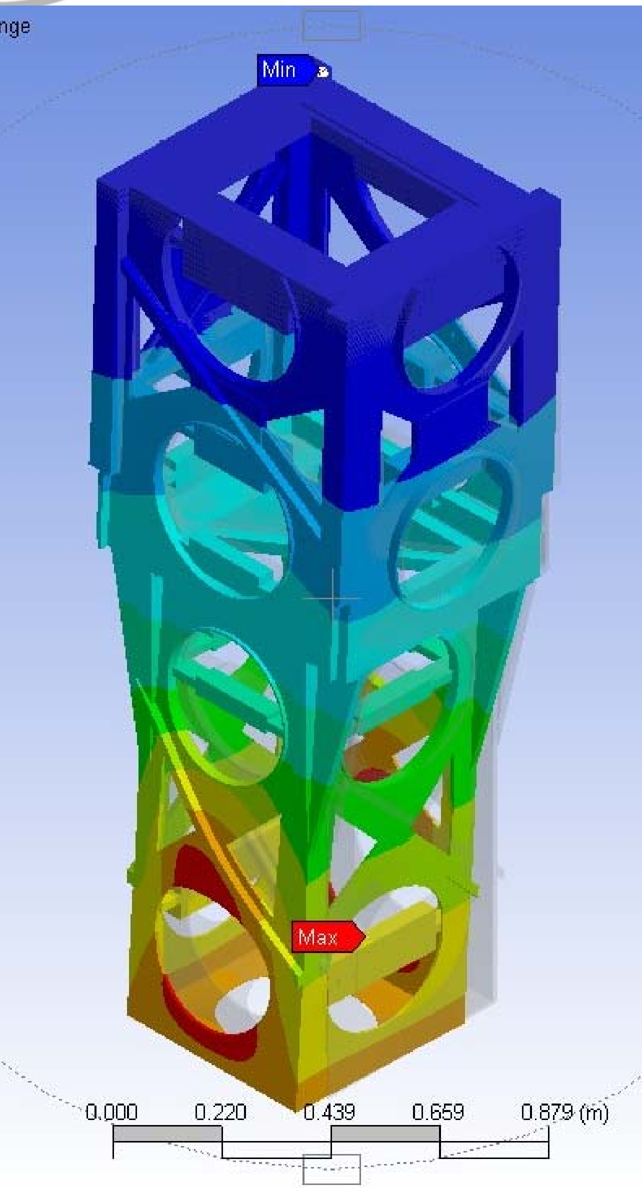


In Vacuum Active Isolation: First Performance

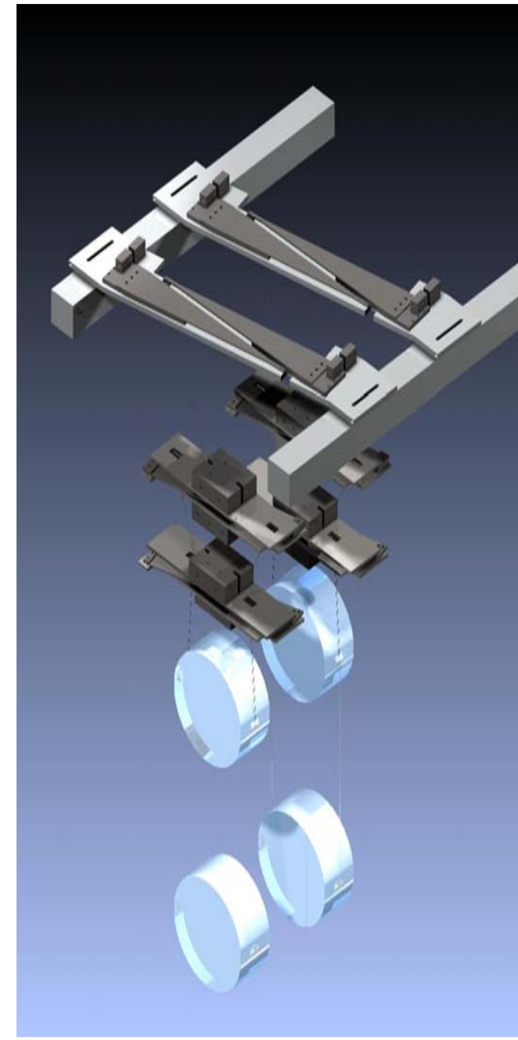
- Required: x1000 (10^{-11} m rms) 1Hz–10Hz
- Next: add sensor correction within platform



Suspensions



- Control noise is filtered by placing sensors and actuators higher up in the chain
- Controls hierarchy: Global control signals are applied at all stages of the multiple pendulum
- Forces are applied from a reaction pendulum to avoid re-introduction of noise
- Double suspension are used in GEO600



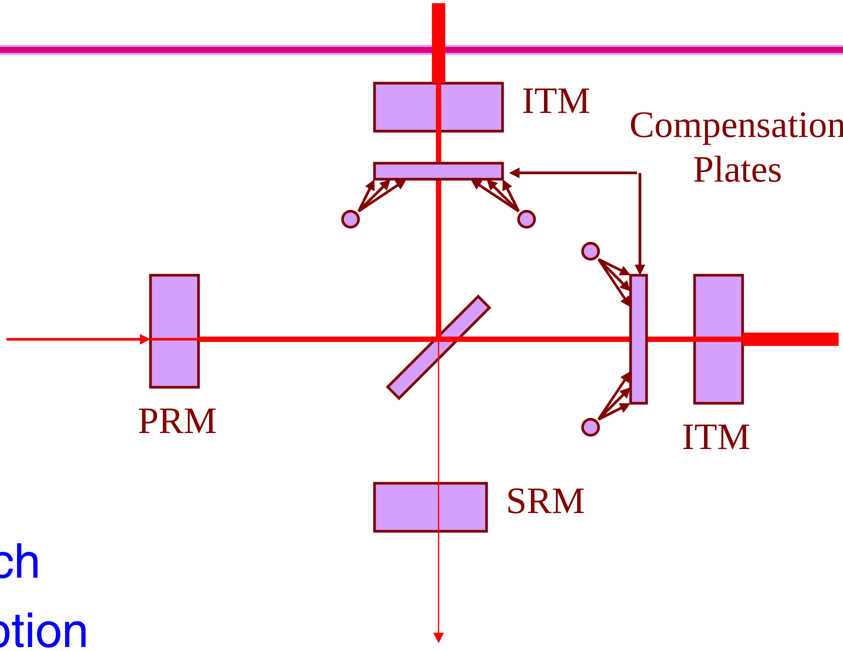
Test Masses / Core Optics

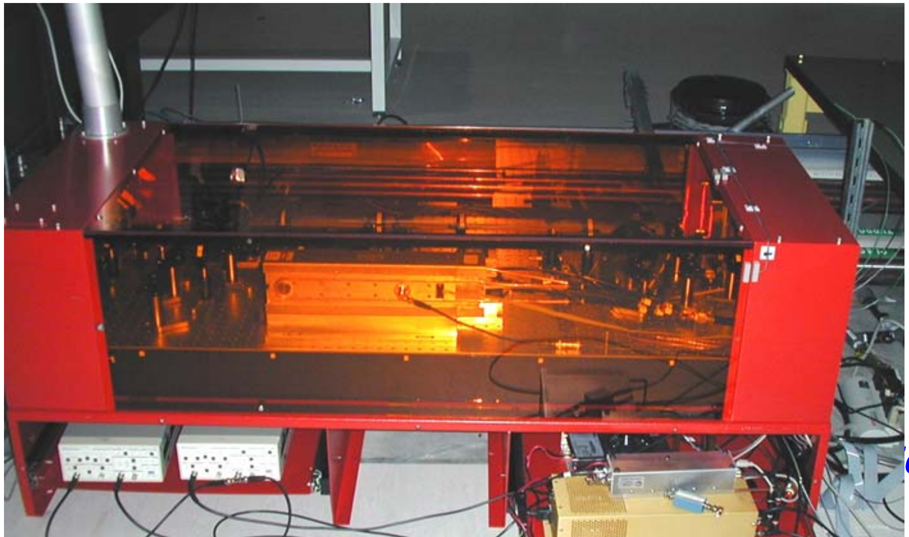
- Central mechanical *and* optical element in the detector
  - 830 kW; <1ppm loss; <20ppm scatter
  - 2×10^8 Q; 40 kg; 32 cm Ø
- Sapphire is the baseline test mass/core optic material
  - Low mechanical loss, high density, high thermal conductivity
- Fused silica fibers
  - ~10^4x lower loss than steel wire
  - Ribbon geometry ➔ more compliant along optical axis
- Fused silica remains a viable fallback option
- Coating thermal noise is significant

Full-size Advanced LIGO sapphire substrate

Active Thermal Compensation

- Removes excess 'focus'
  - Absorption in coating and substrate
  - Allows optics to be used at all input powers
- Corrections
  - Quasi-static ring-shaped additional heating to remove curvature mismatch
  - Scan to complement irregular absorption





- Added to initial LIGO
  - CO_2 laser on ITM surfaces
  - Central and annulus heating

Comparison

Parameter	LIGO I	Adv LIGO
Equivalent strain noise, minimum	$3x10^{-23}$/rtHz	$2x10^{-24}$/rtHz
Neutron star binary inspiral range	20 Mpc	300 Mpc
Stochastic background sens.	$3x10^{-6}$	$1.5\text{-}5x10^{-9}$
Interferometer configuration	Power-recycled MI w/ FP arm cavities	LIGO I, plus signal recycling
Laser power at interferometer input	6 W	125 W
Test masses	Fused silica, 11 kg	Sapphire, 40 kg
Seismic wall frequency	40 Hz	10 Hz
Beam size	3.6/4.4 cm	6.0 cm
Test mass Q	Few million	200 million
Suspension fiber Q	Few thousand	~30 million

Upgrade of all three interferometers

- In discovery phase, tune all three to broadband curve
  - 3 interferometers nearly doubles the event rate over 2 interferometers
  - Improves non-Gaussian statistics
  - Commissioning on other LHO IFO while observing with LHO-LLO pair
- In observation phase, the same IFO configuration can be tuned to increase low or high frequency sensitivity
  - sub-micron shift in the operating point of one mirror suffices
  - third IFO could e.g.,
    - observe with a narrow-band VIRGO
    - focus alone on a known-frequency periodic source
    - focus on a narrow frequency band associated with a coalescence, or BH ringing of an inspiral detected by other two IFOs

Baseline plan

- Initial LIGO observation at design sensitivity 2004–2008
  - Significant observation within LIGO Observatory
  - Significant networked observation with GEO, VIRGO, TAMA
- Structured R&D program to develop technologies
  - Conceptual design developed by LSC in 1998
  - Cooperative Agreement carries R&D to Final Design
- Planning on first funding in October 2006
  - Test mass material, seismic isolation fabrication
  - Prepare a 'stock' of equipment for minimum downtime, rapid installation
- Start installation in 2009
  - Baseline is a staggered installation, Livingston and then Hanford
- First instrument starting to observe in 2011
- Optimism for networked observation with other '2nd generation' instruments

LIGO

Advanced LIGO

- Initial instruments, data helping to establish the field of interferometric GW detection
- Advanced LIGO promises exciting astrophysics
- Substantial progress in R&D, design
- Still a few good problems to solve
- A broad community effort, international support
- Advanced LIGO will play an important role in leading the field to maturity