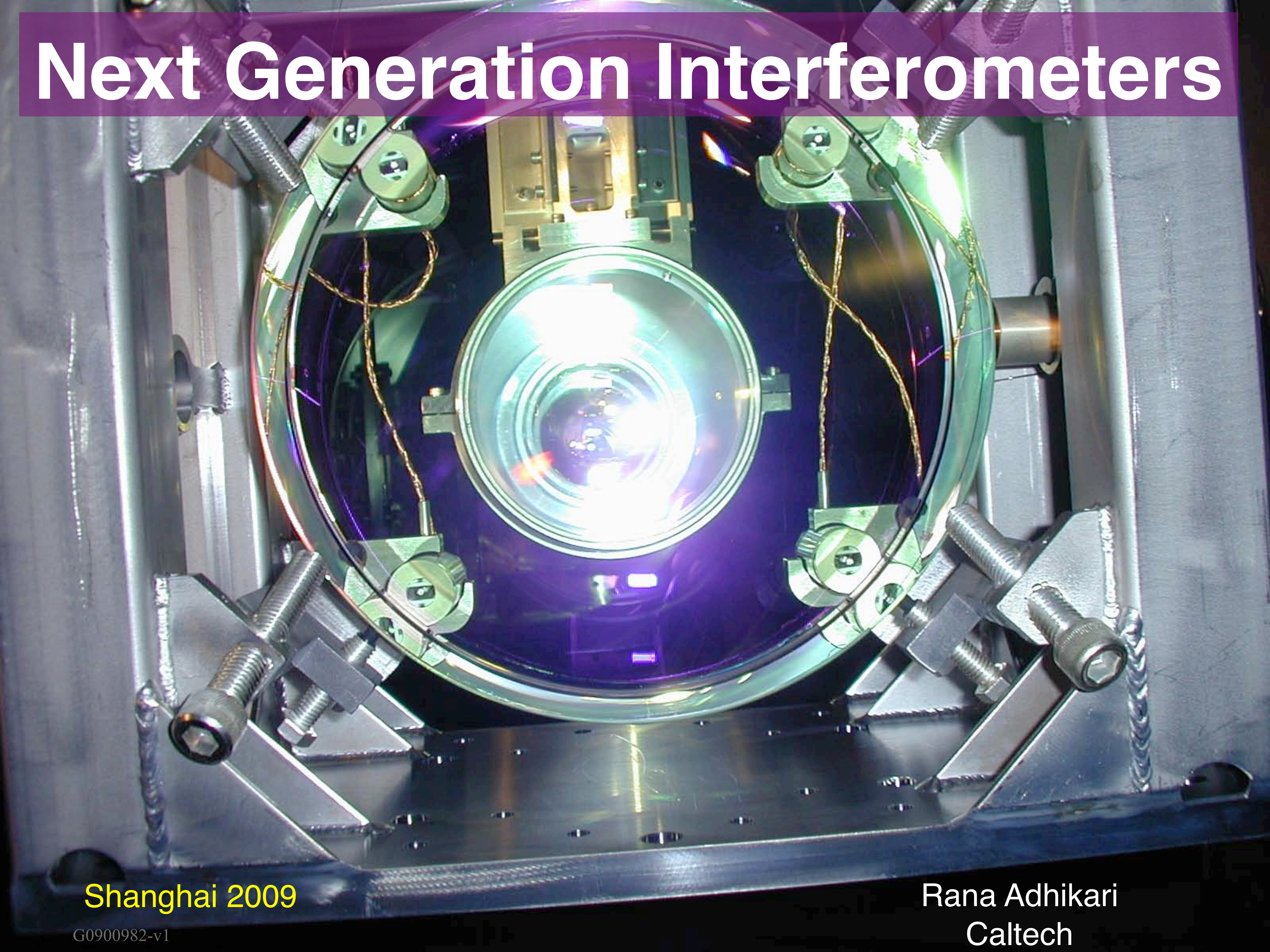
Next Generation Interferometers

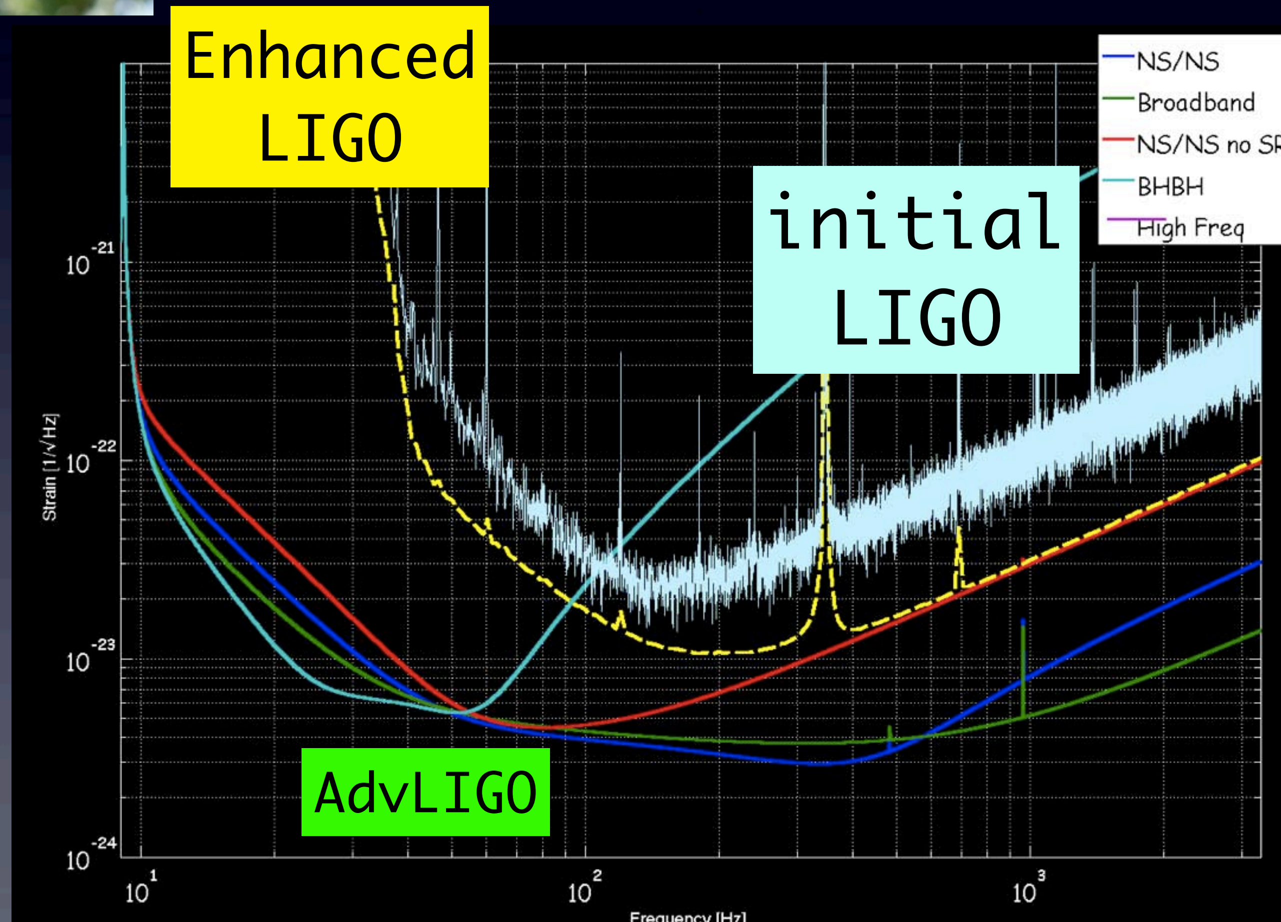


Shanghai 2009

Rana Adhikari
Caltech

G0900982-v1

- Need ~10x better SNR to make regular detections.
- Need low frequency sensitivity for massive black holes.




LIGO Hanford
MIT
[redacted]
Univ of Maryland
Caltech
LIGO Livingston
Image © 2006 MDA EarthSat
© 2005 Google

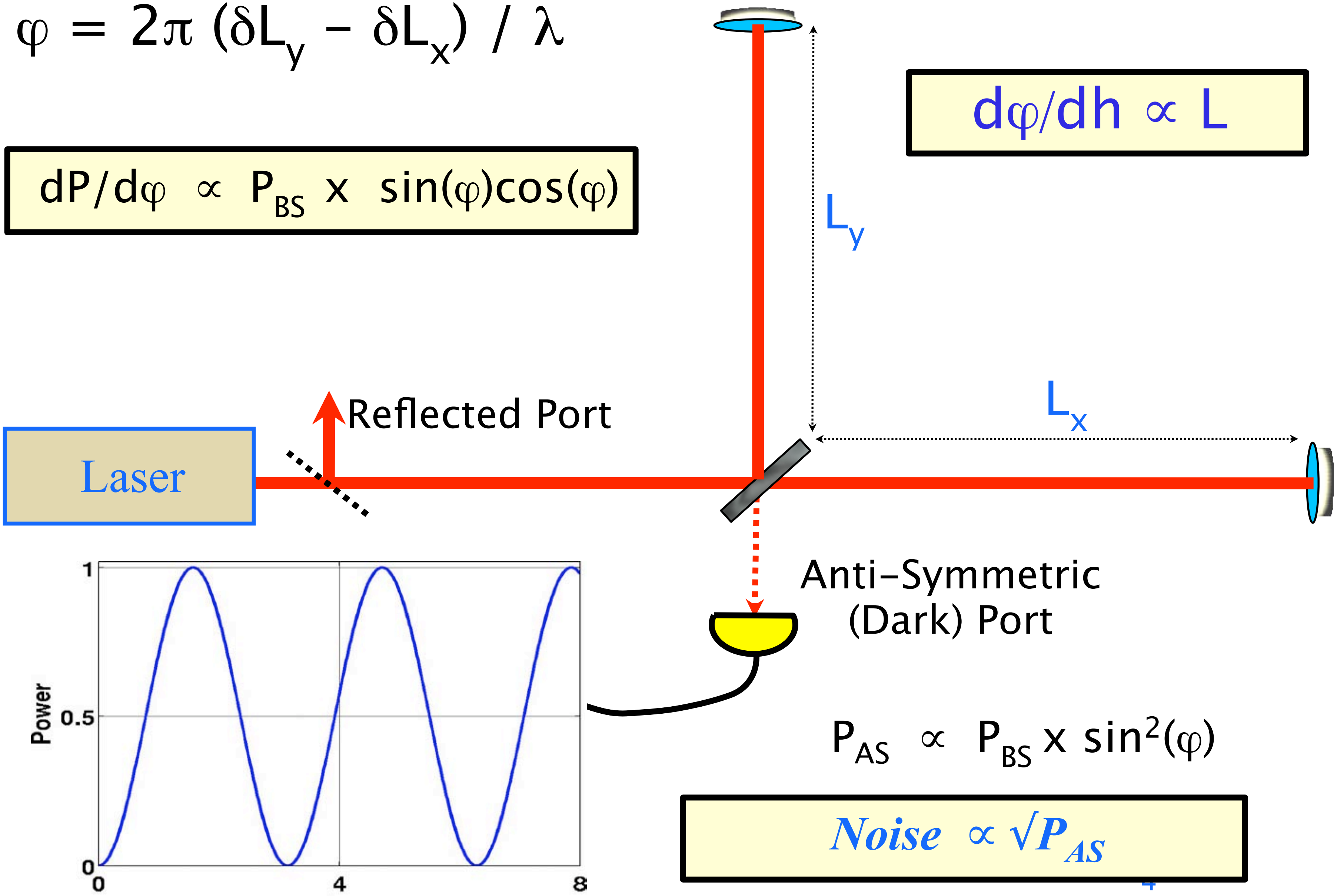

LIGO Hanford
LIGO Livingston
Image © 2006 MDA EarthSat
© 2005 Google

Michelson Interferometer

$$\varphi = 2\pi \, (\delta L_y - \delta L_x) \, / \, \lambda$$

$$dP/d\varphi \propto P_{BS} \times \sin(\varphi)\cos(\varphi)$$

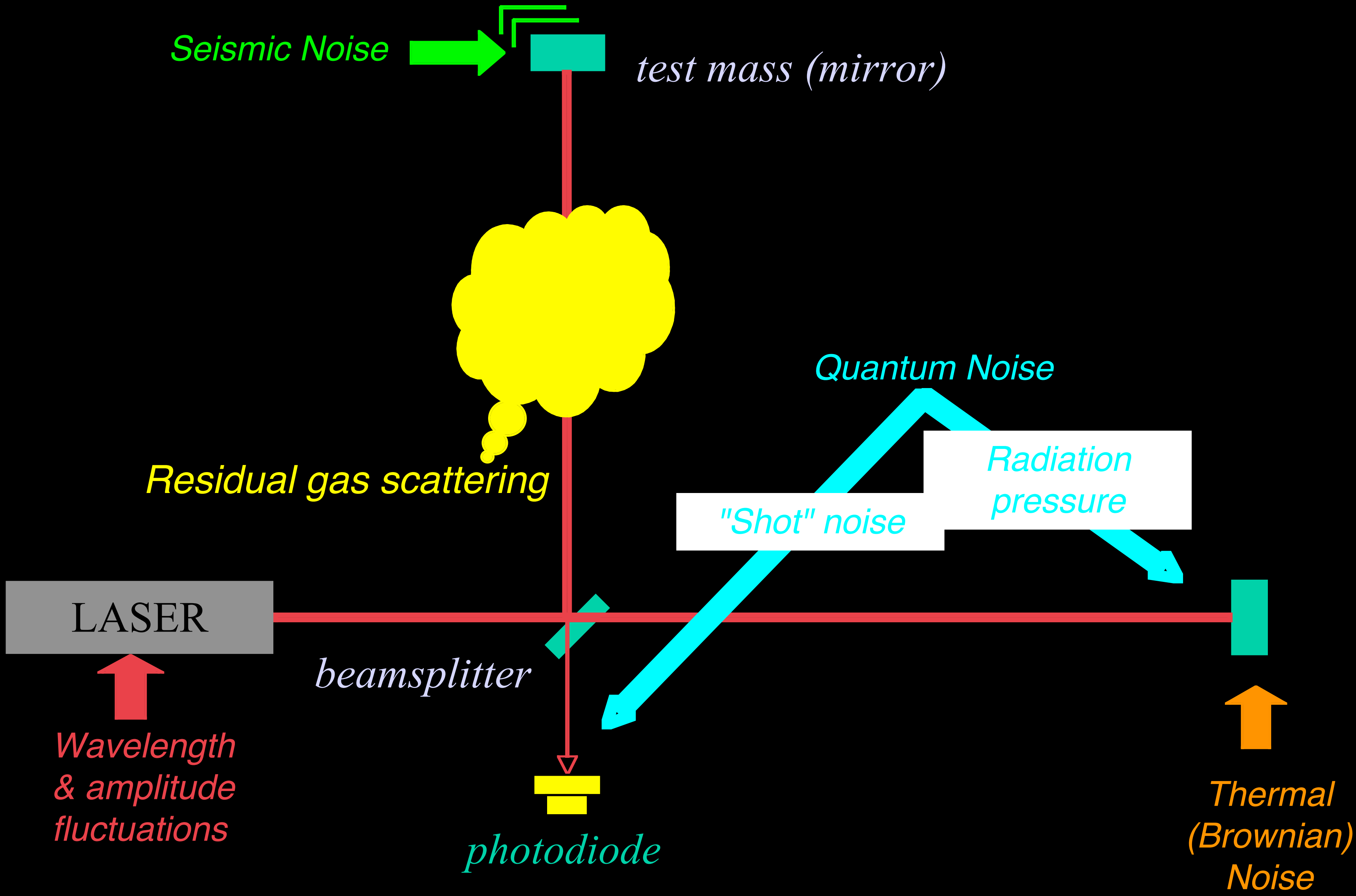
$$d\varphi/dh \propto L$$



$$P_{AS} \propto P_{BS} \times \sin^2(\varphi)$$

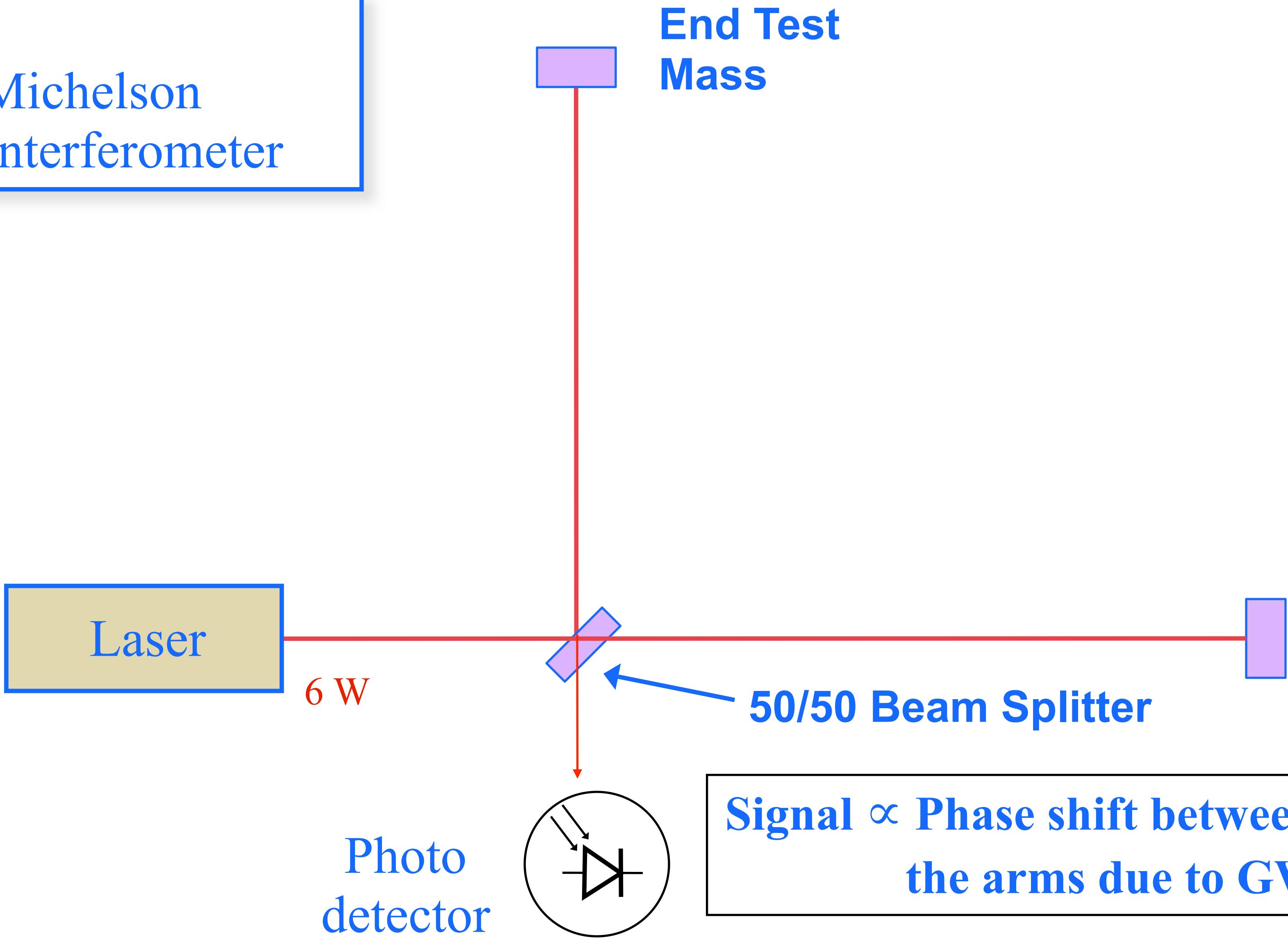
$$\textit{Noise} \propto \sqrt{P_{AS}}$$

Noise Cartoon



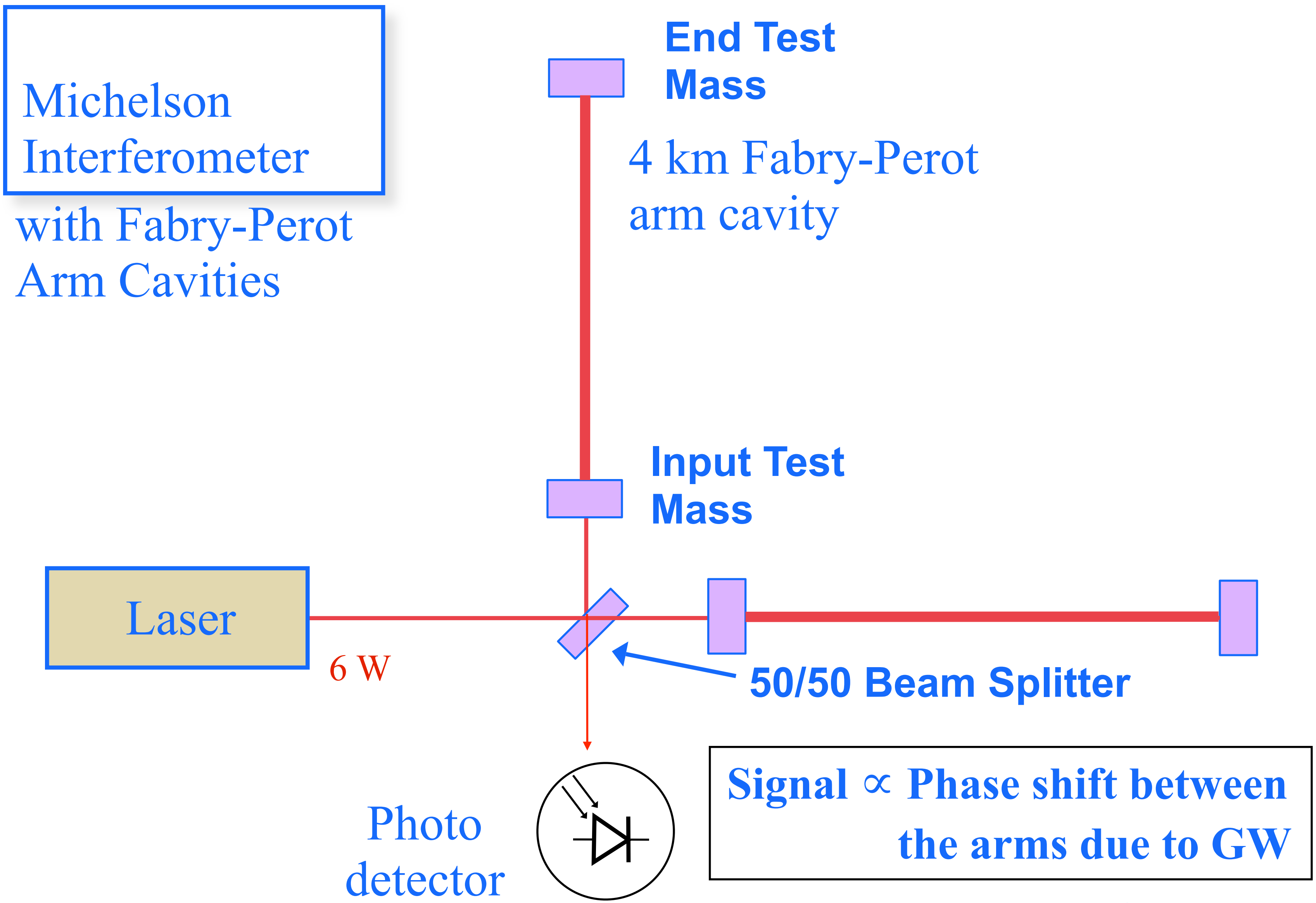
Interferometer Optical Layout

Michelson Interferometer



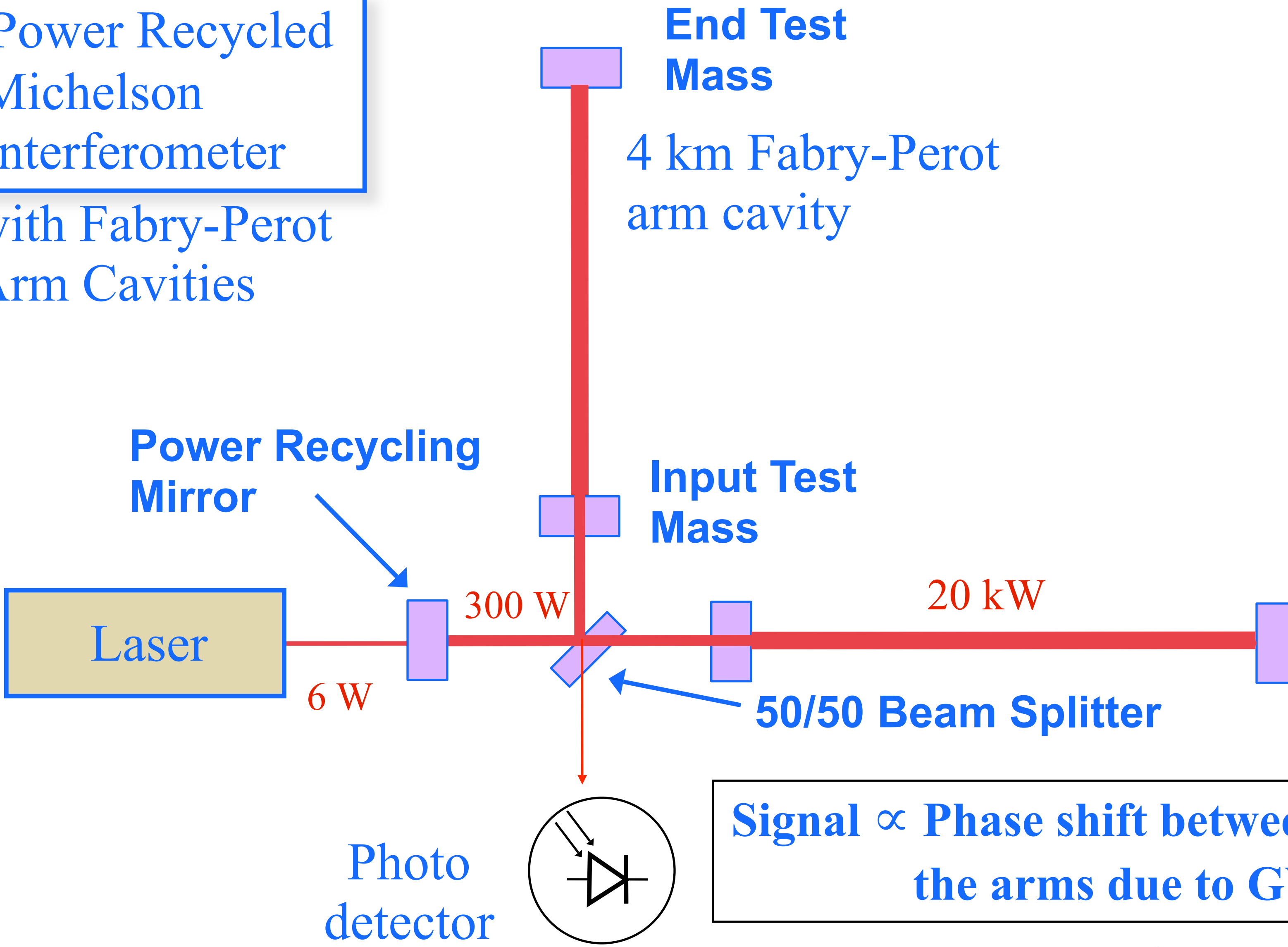
Signal $\propto$ Phase shift between the arms due to GW

Interferometer Optical Layout



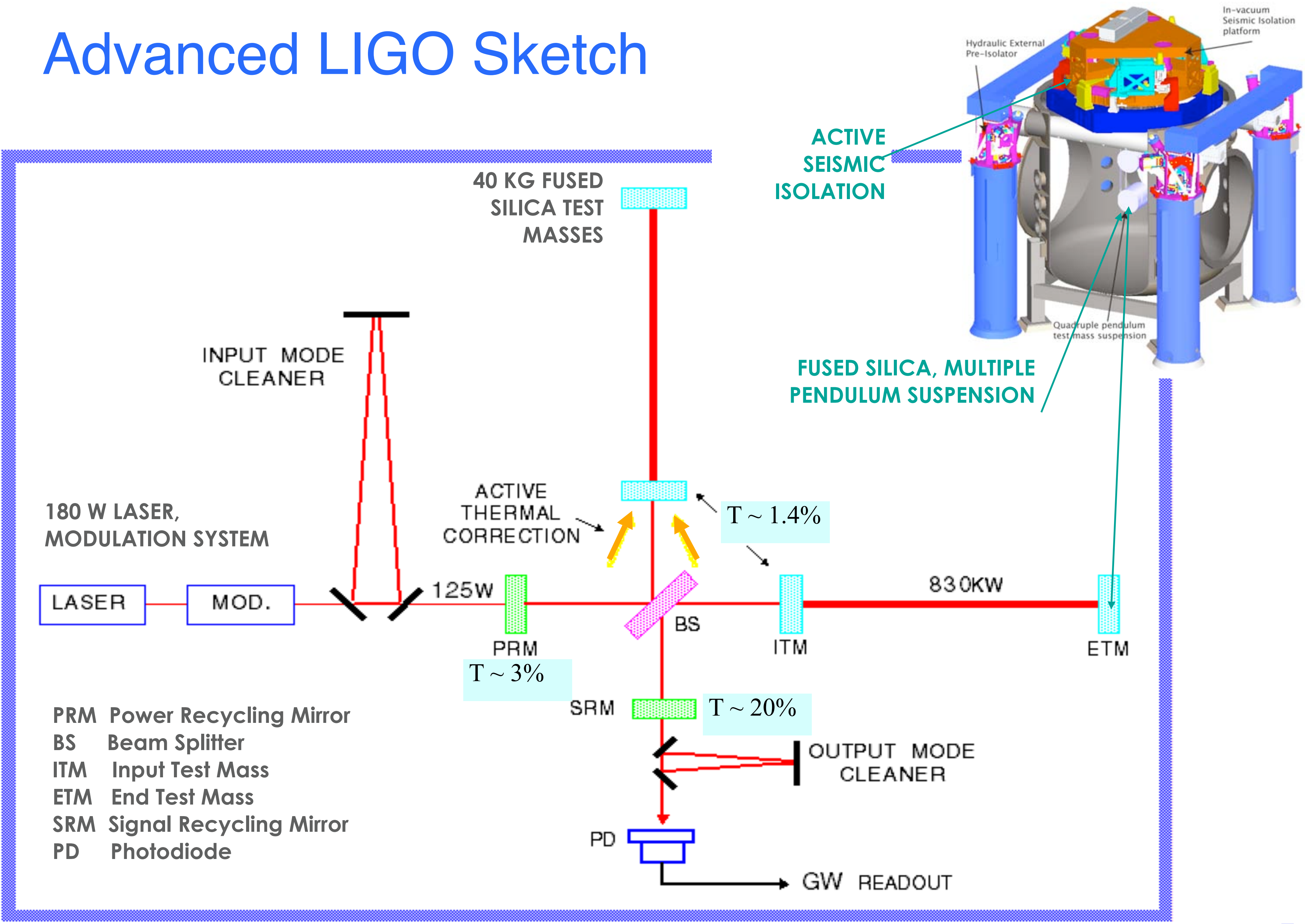
Interferometer Optical Layout

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



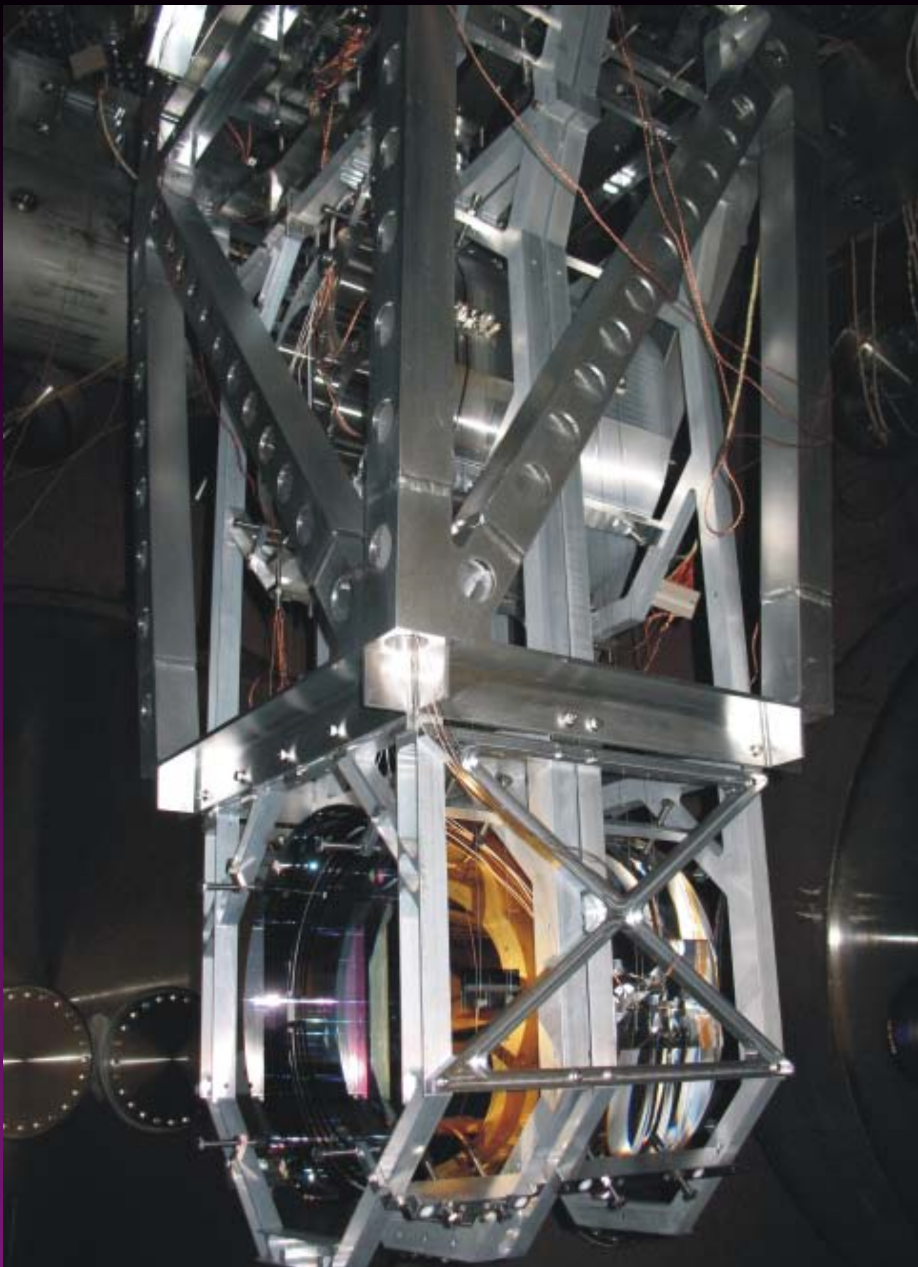
Signal ∝ Phase shift between the arms due to GW

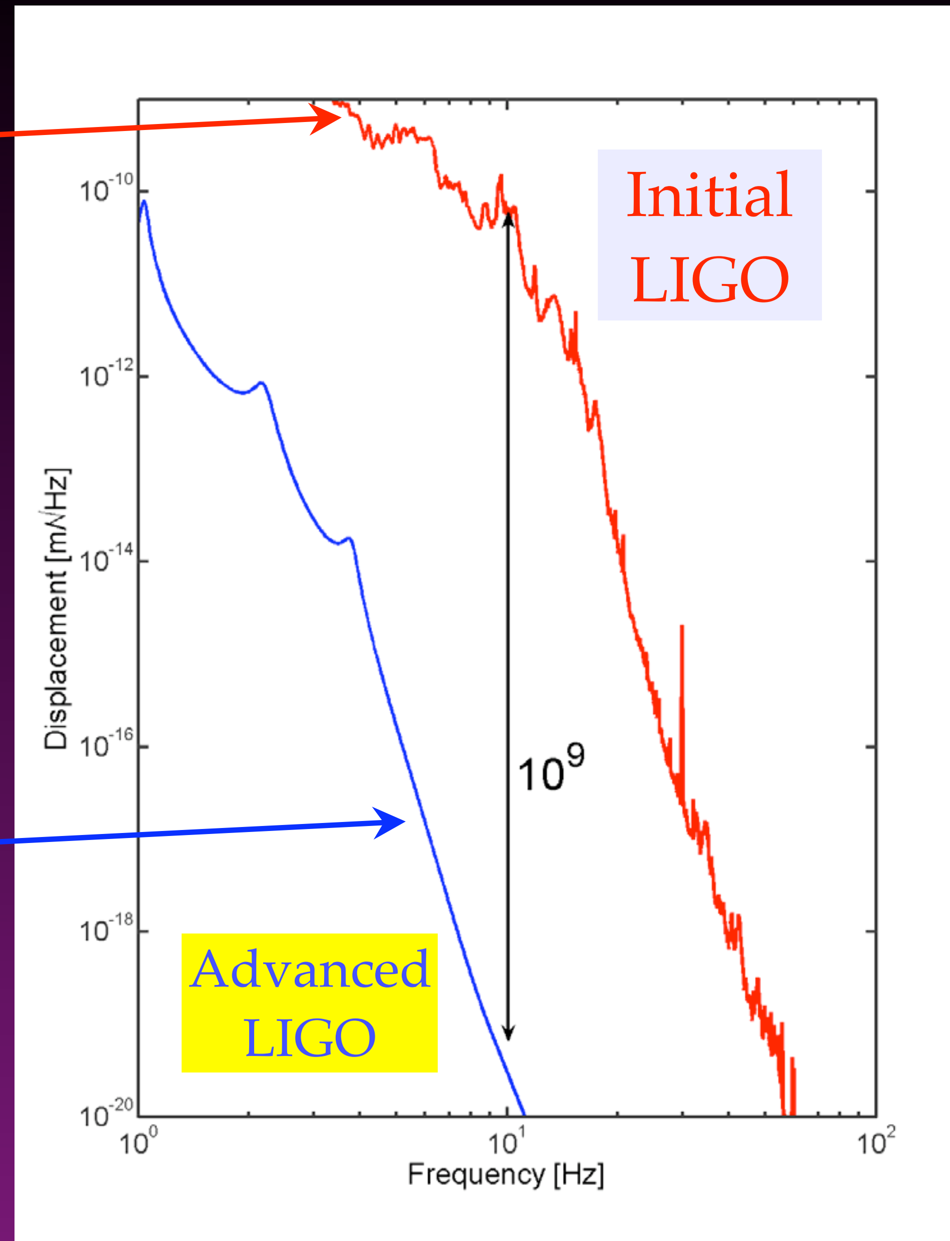
Advanced LIGO Sketch



Parameter	LIGO I	Adv LIGO
Equivalent strain noise, minimum	$3x10^{-23}$/rtHz	$2x10^{-24}$/rtHz
Neutron star binary range	45 Mpc	600 Mpc
Omega GW	$3x10^{-6}$	$1.5\text{-}5x10^{-9}$
Interferometer configuration	Power-recycled MI w/ FP arm cavities	LIGO I, plus signal recycling
Laser Power in Arm Cavities	15 kW	800 kW
Test masses	Fused silica, 10 kg	Fused Silica, 40 kg
Seismic wall frequency	40 Hz	10 Hz
Beam size	4 cm	6 cm
Test mass Q	Few million	200 million
Suspension fiber Q	Few thousand	~30 million

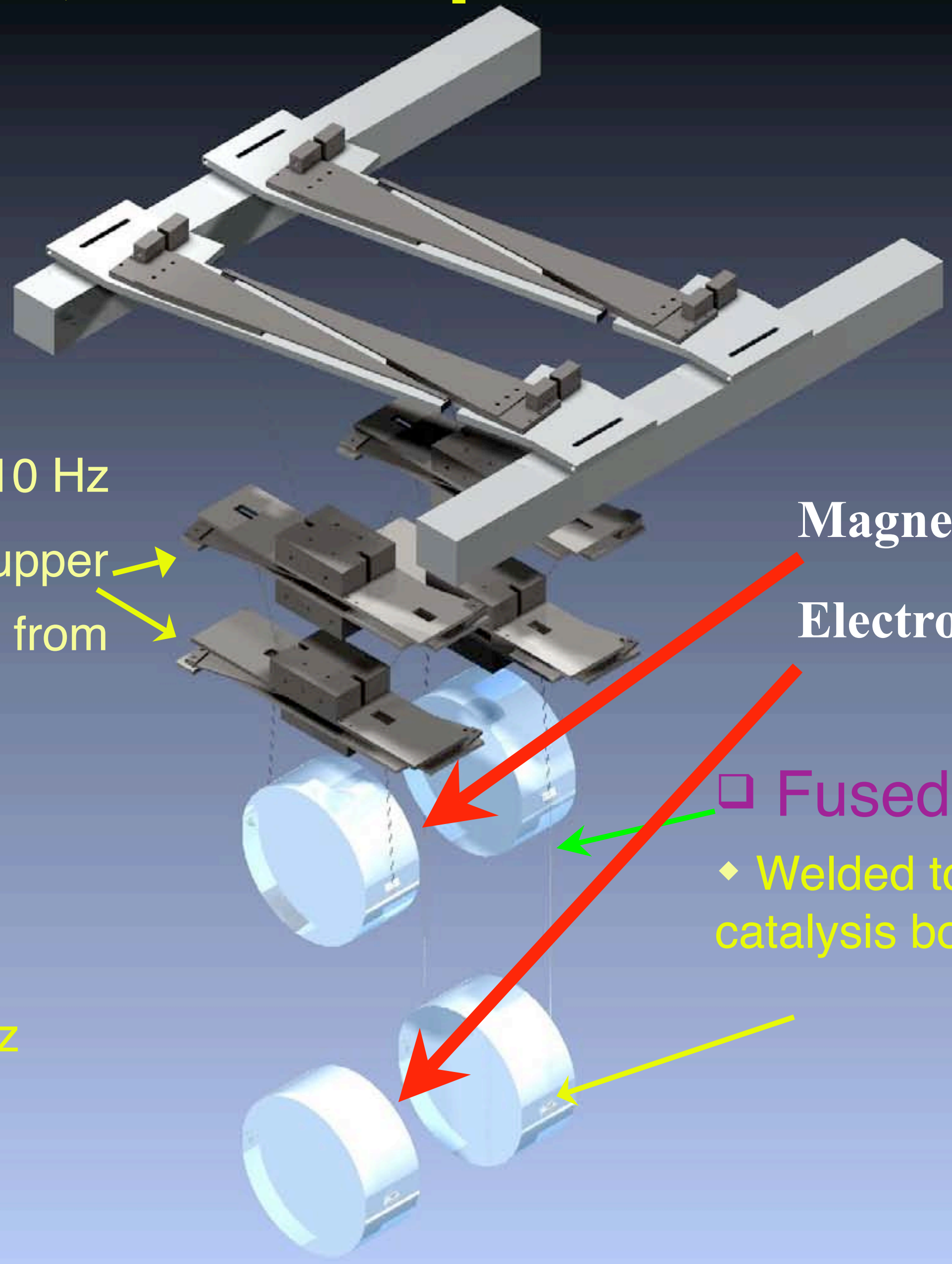
Seismic Noise





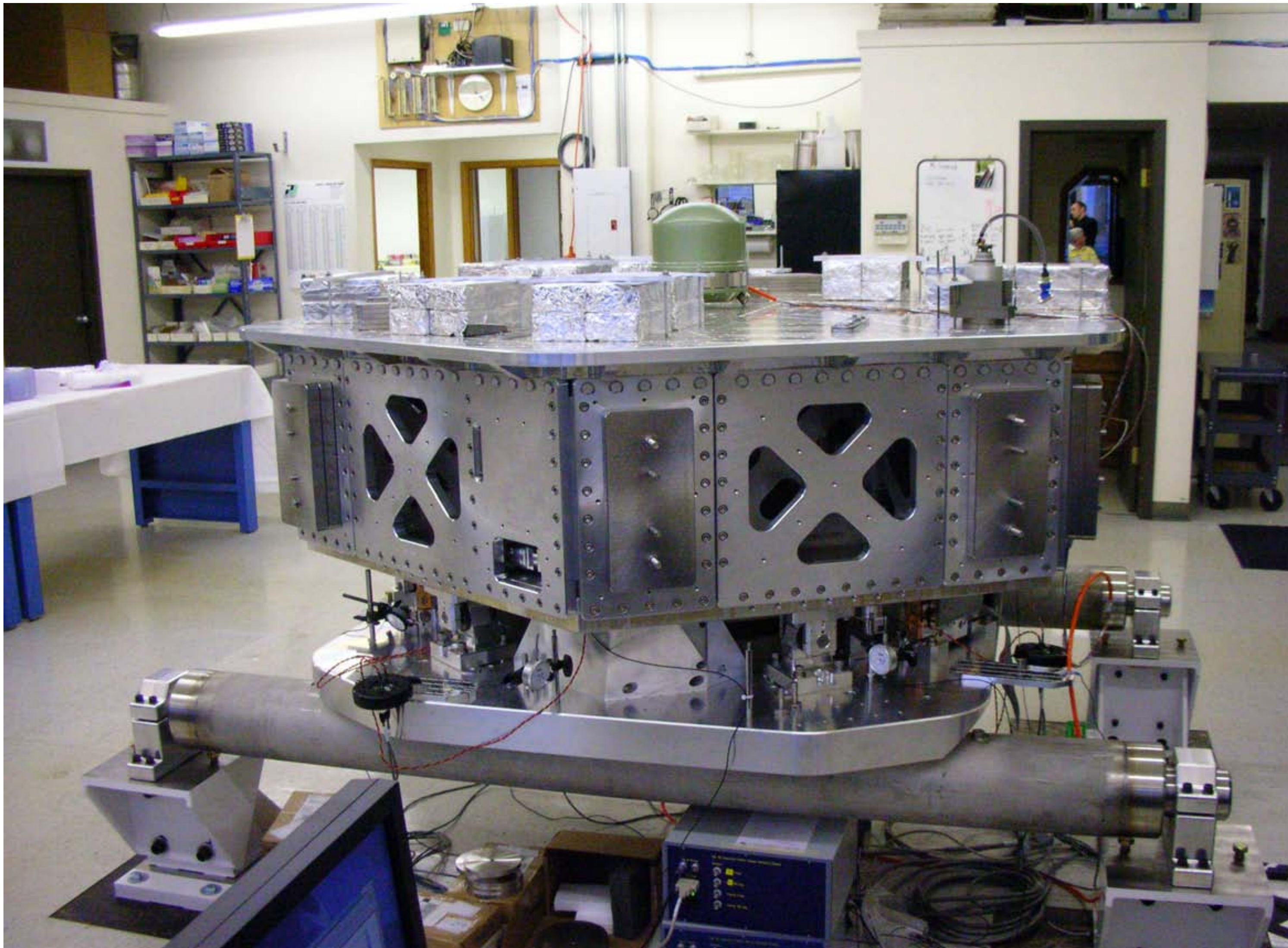
Quad Suspensions

- Quadruple pendulum:
  - » ~10^7 attenuation @10 Hz
  - » Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - » 10^{-19} m/rtHz at 10 Hz



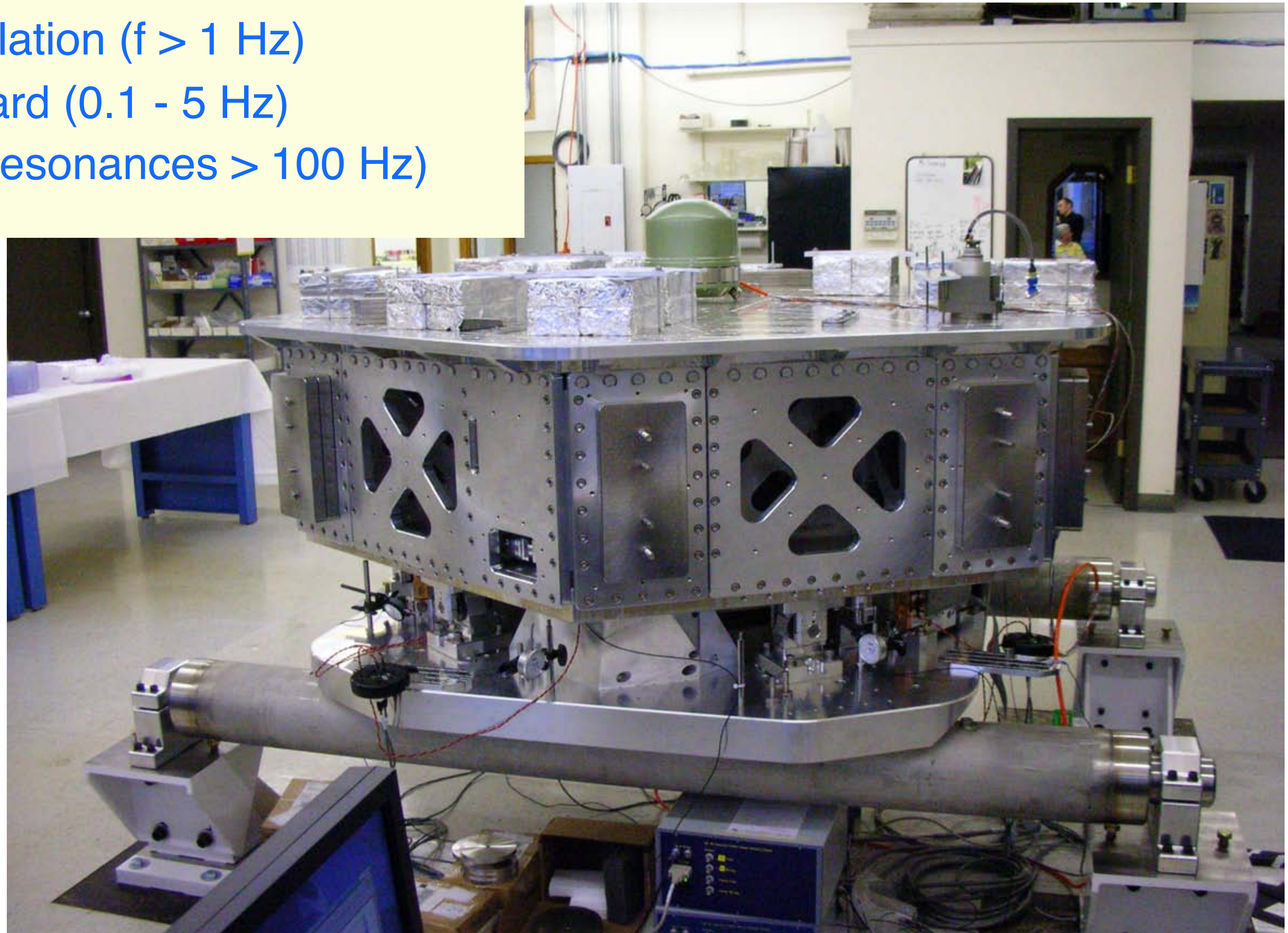
- ❑ Fused silica fiber
  - ◆ Welded to ‘ears’, hydroxy-catalysis bonded to optic

Active Isolation Table

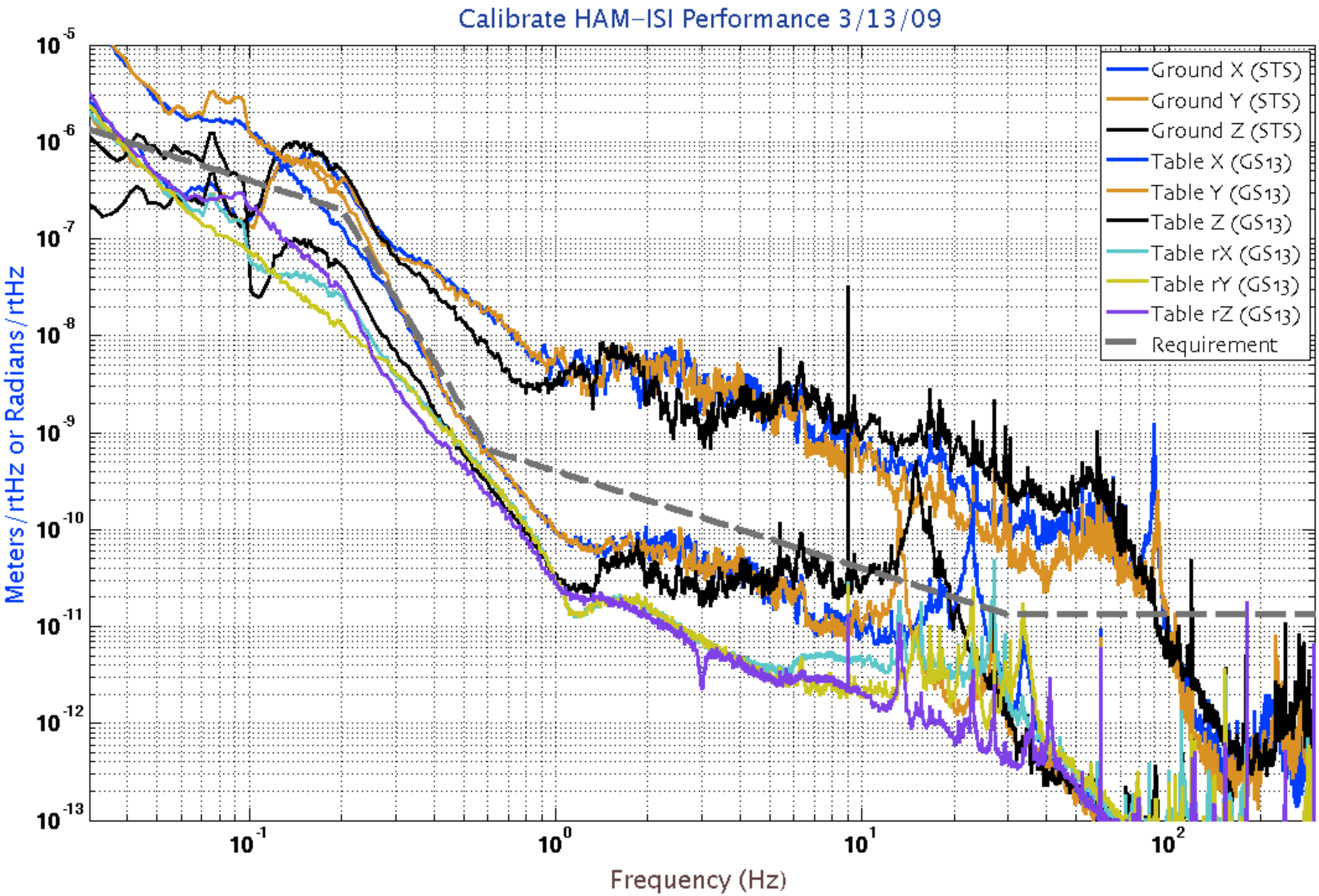


Active Isolation Table

- Inertial sensors for feedback (0.3 - 30 Hz)
- Passive isolation (f > 1 Hz)
- Feed Forward (0.1 - 5 Hz)
- Stiff table (resonances > 100 Hz)

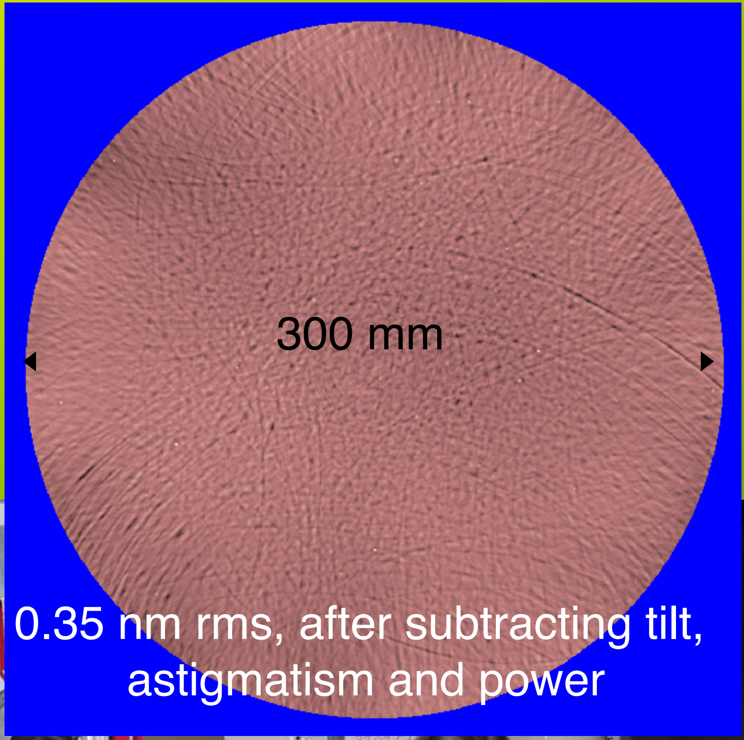


Installation of Seismic Platform

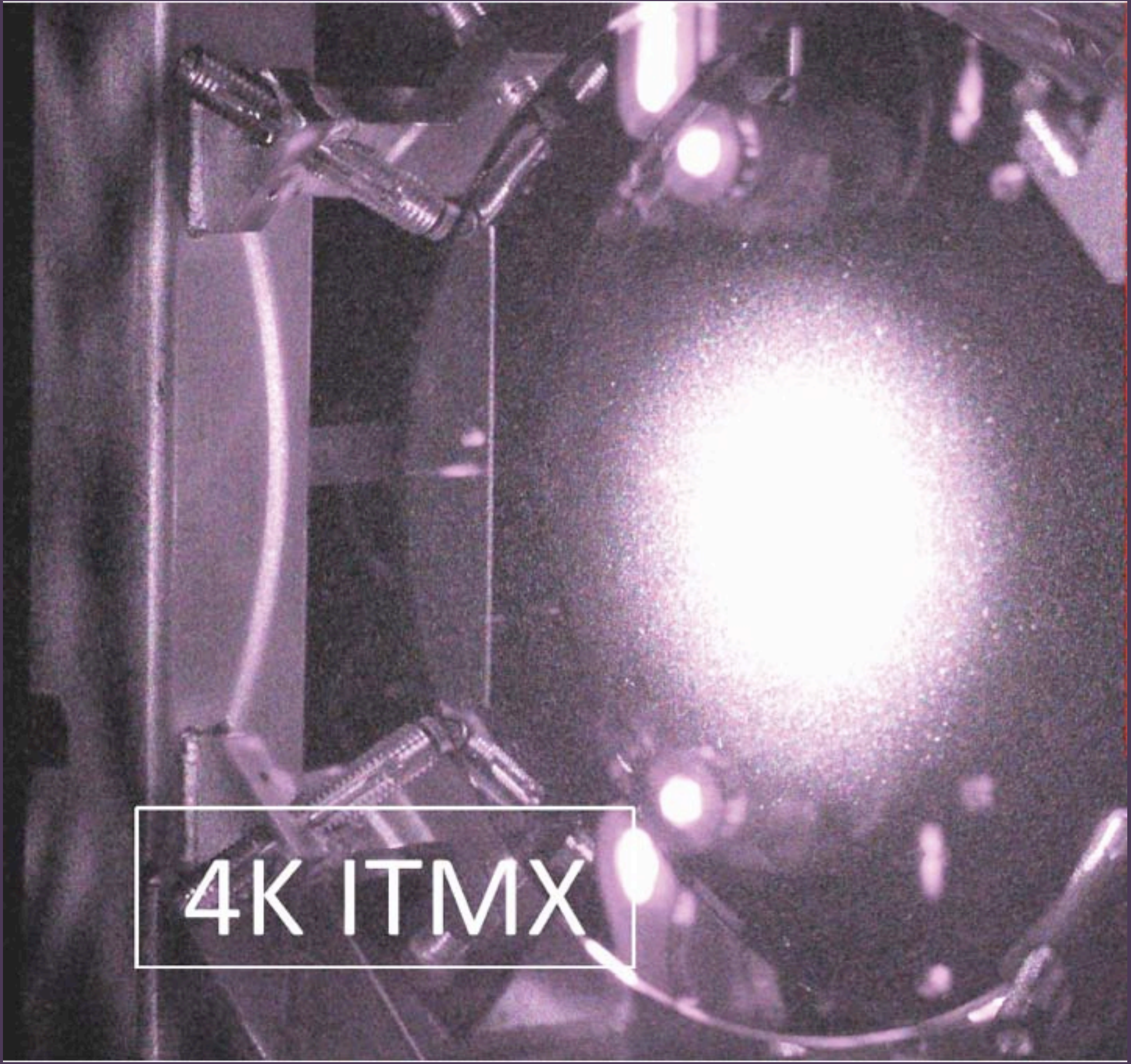

Calibrate HAM-ISI Performance 3/13/09
Meters/rtHz or Radians/rtHz
Frequency (Hz)
Ground X (STS)
Ground Y (STS)
Ground Z (STS)
Table X (GS13)
Table Y (GS13)
Table Z (GS13)
Table rX (GS13)
Table rY (GS13)
Table rZ (GS13)
Requirement

Large Optics

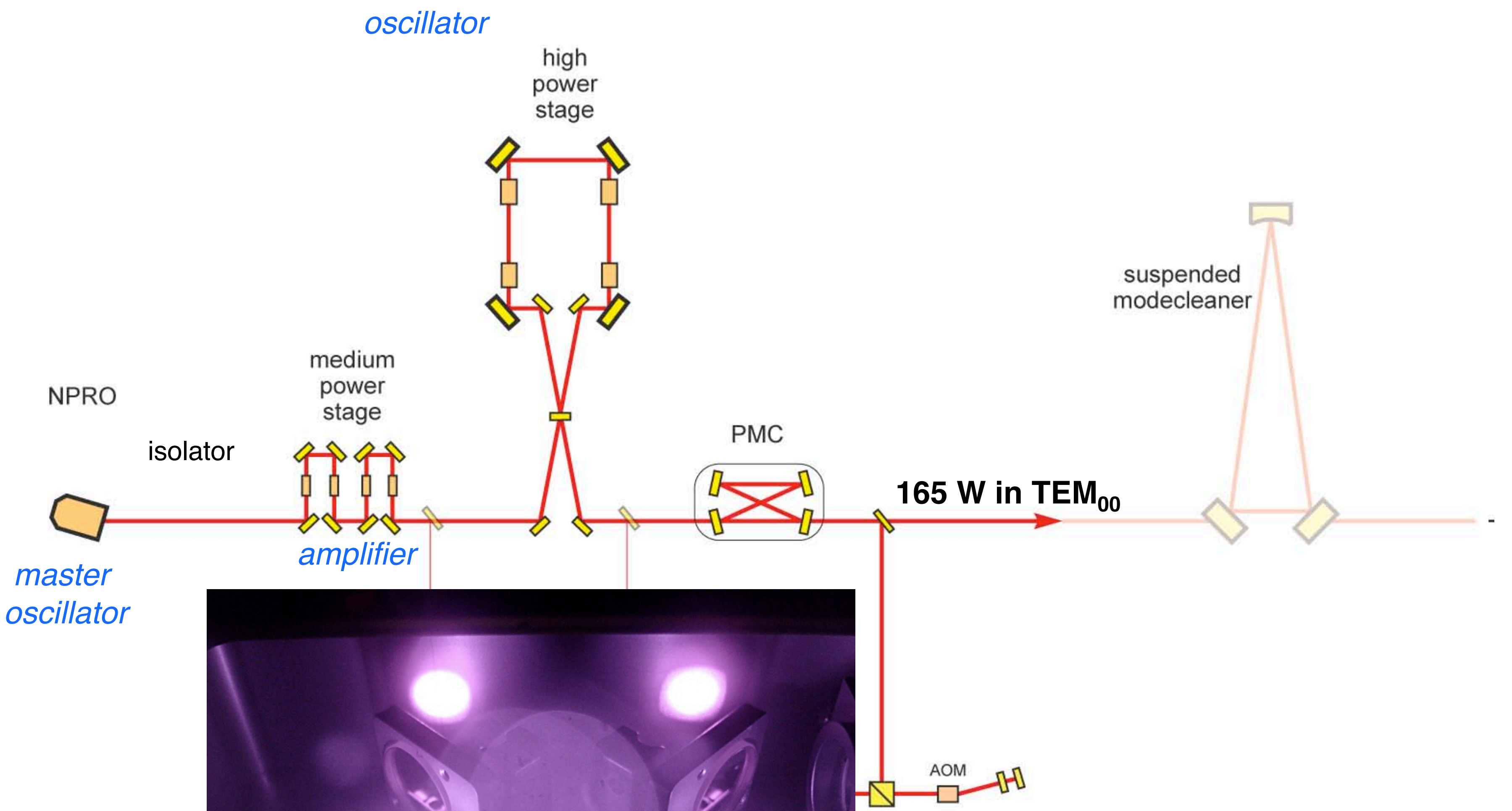
- Size: 34 cm wide, 20 cm thick => 40 kg
- Material: Heraeus Suprasil 3001 Fused Silica
- Bulk Absorption: 0.2 ppm/cm
- Coating absorption: 0.5 ppm/bounce
- High Q -> low thermal noise

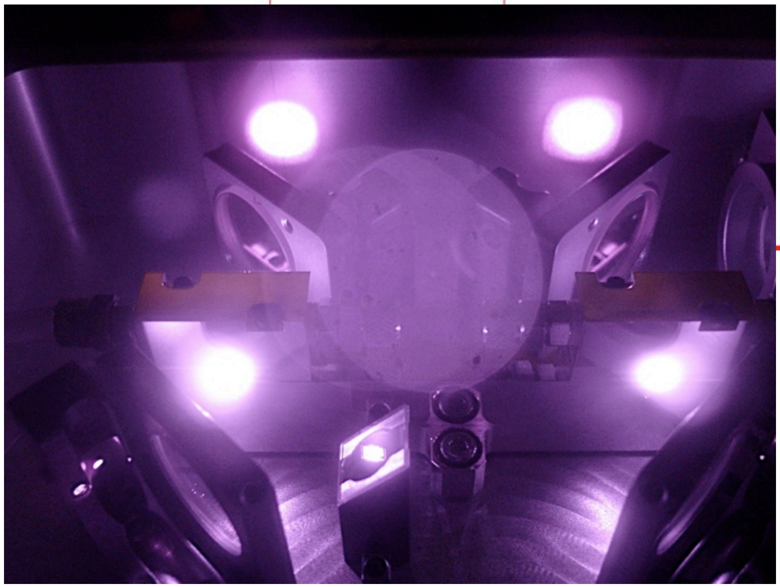


0.35 nm rms, after subtracting tilt, astigmatism and power

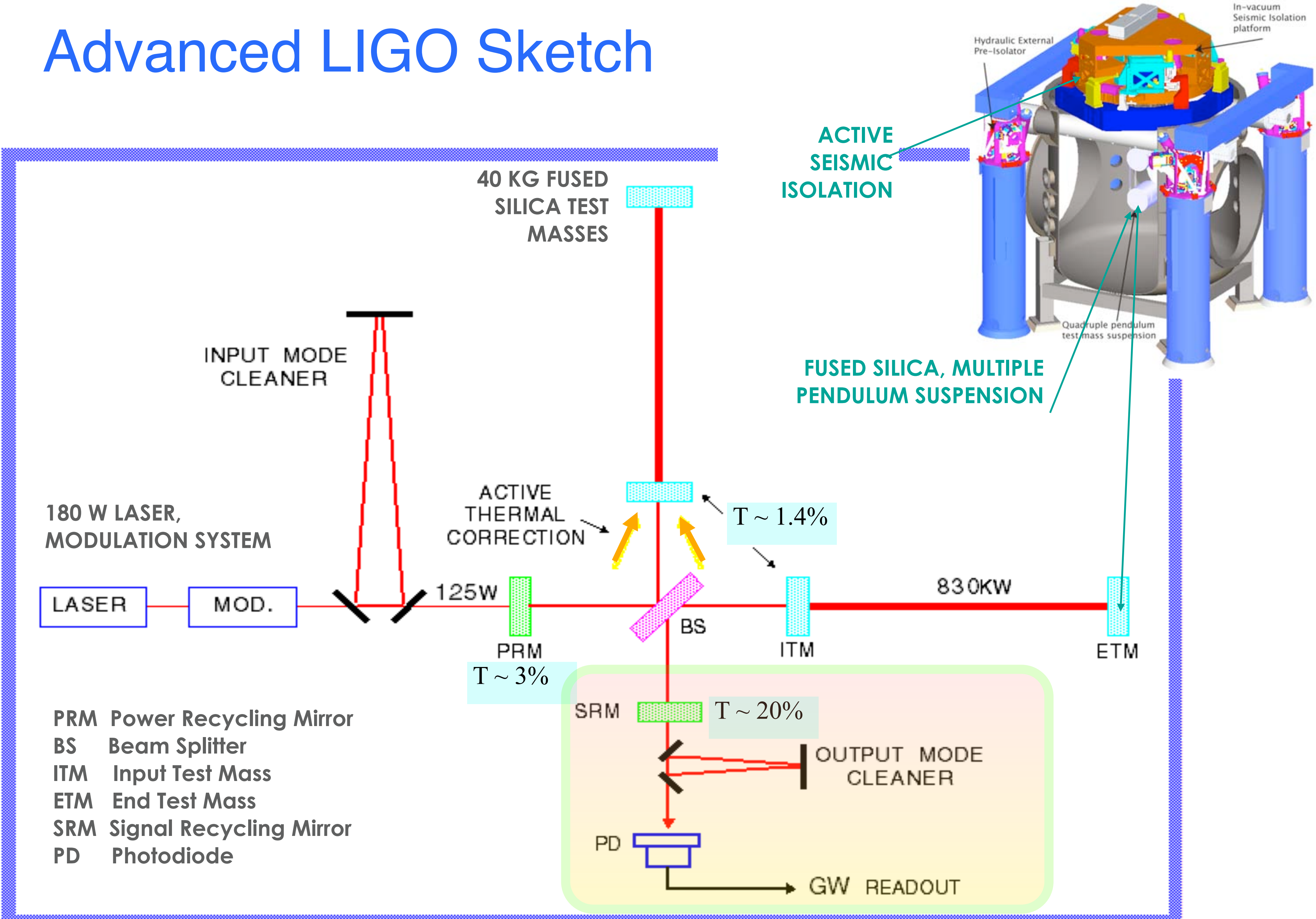

4K ITMX

Ultra Stable, High Power CW Laser



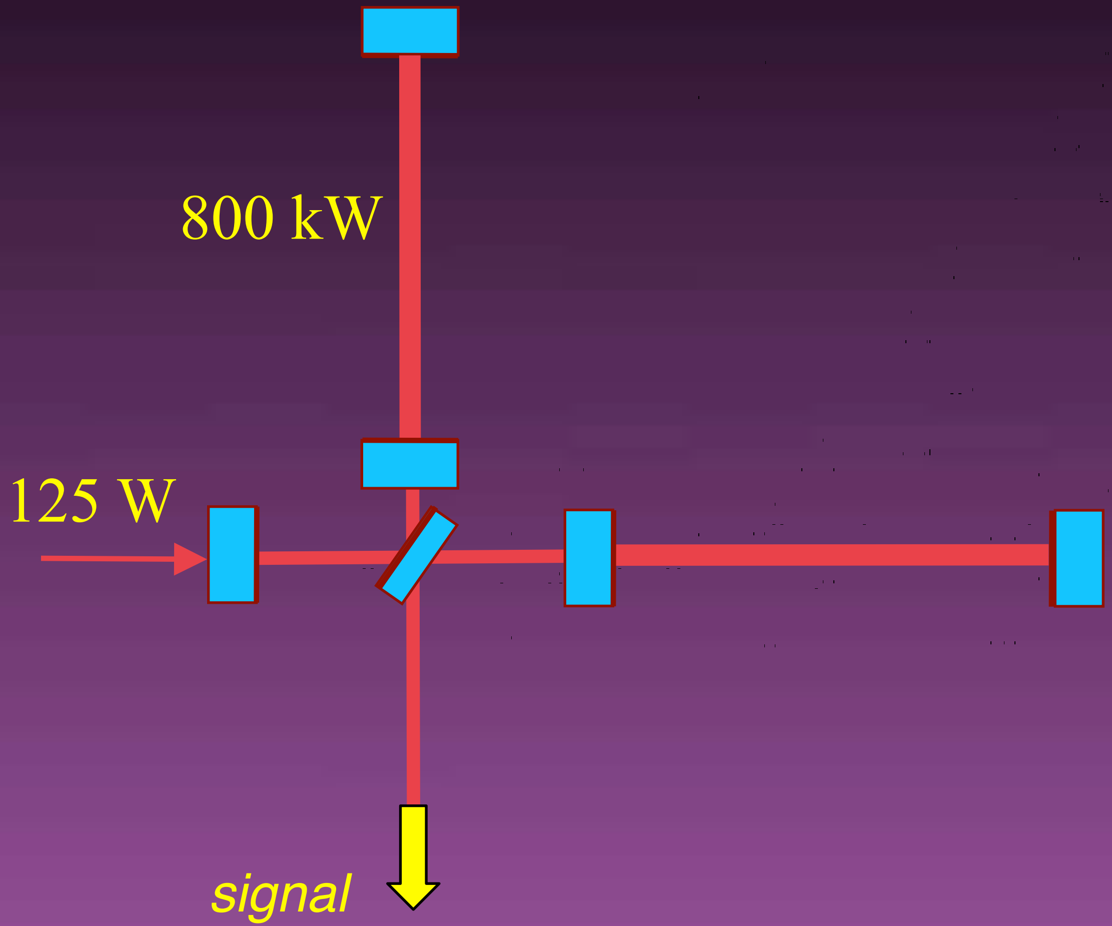


Advanced LIGO Sketch

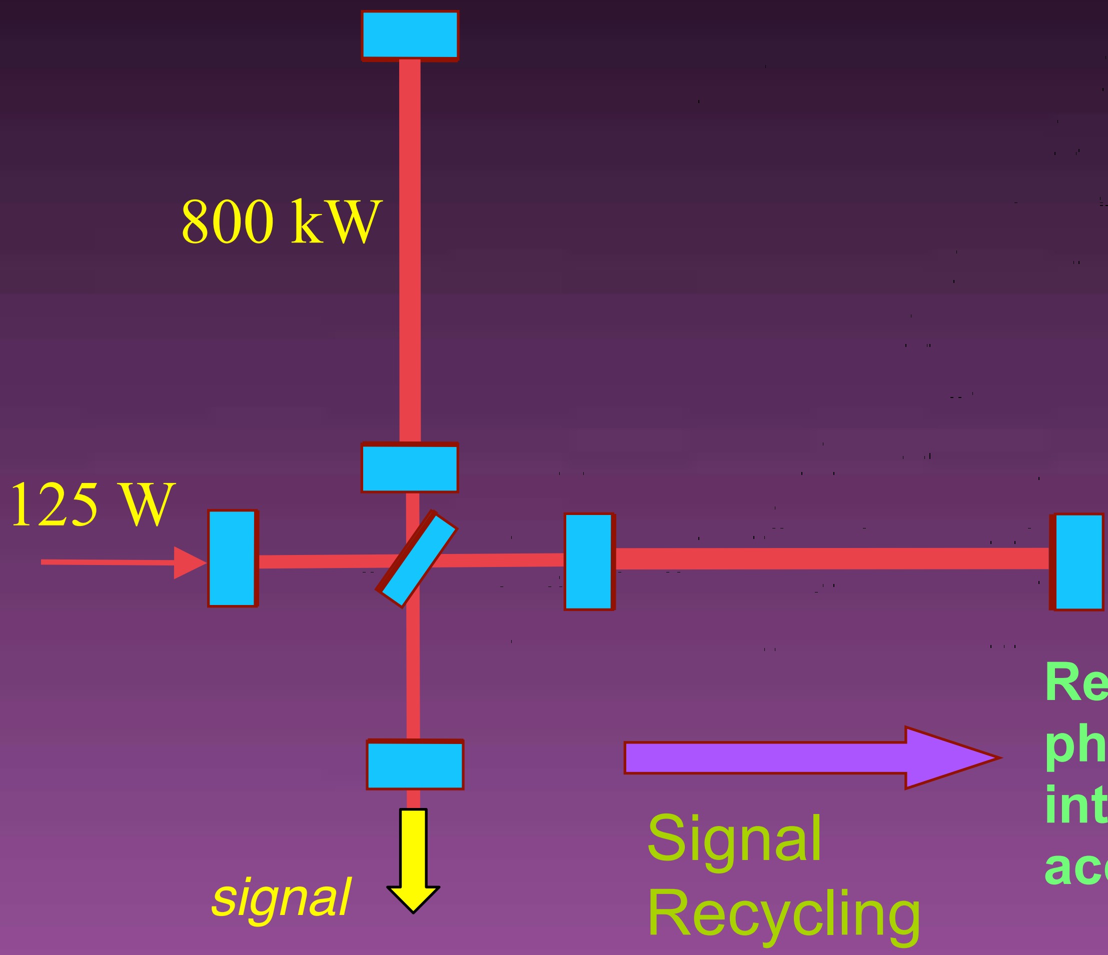


Should we consider Recycling?

Signal-recycled Interferometer

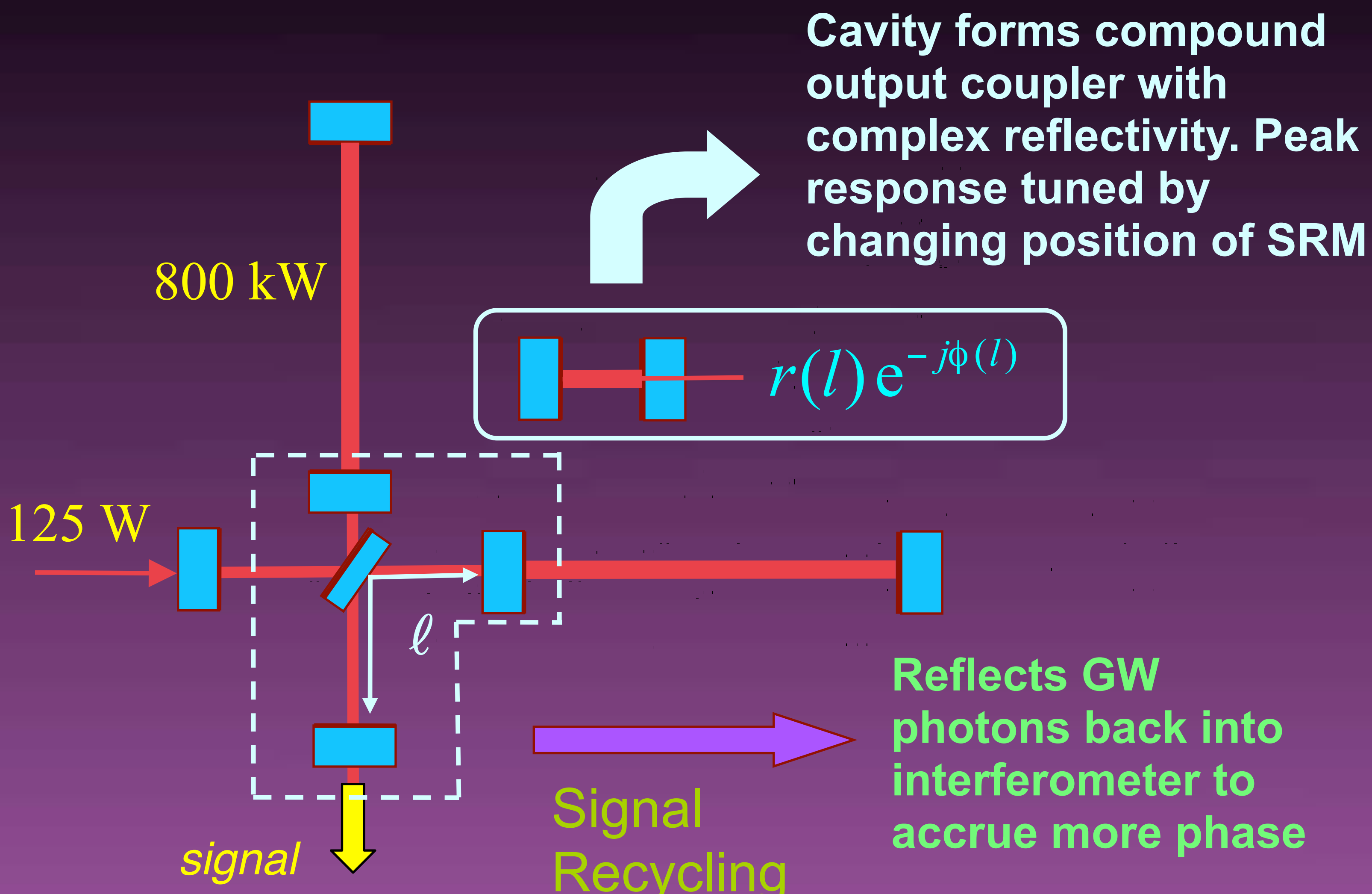


Signal-recycled Interferometer

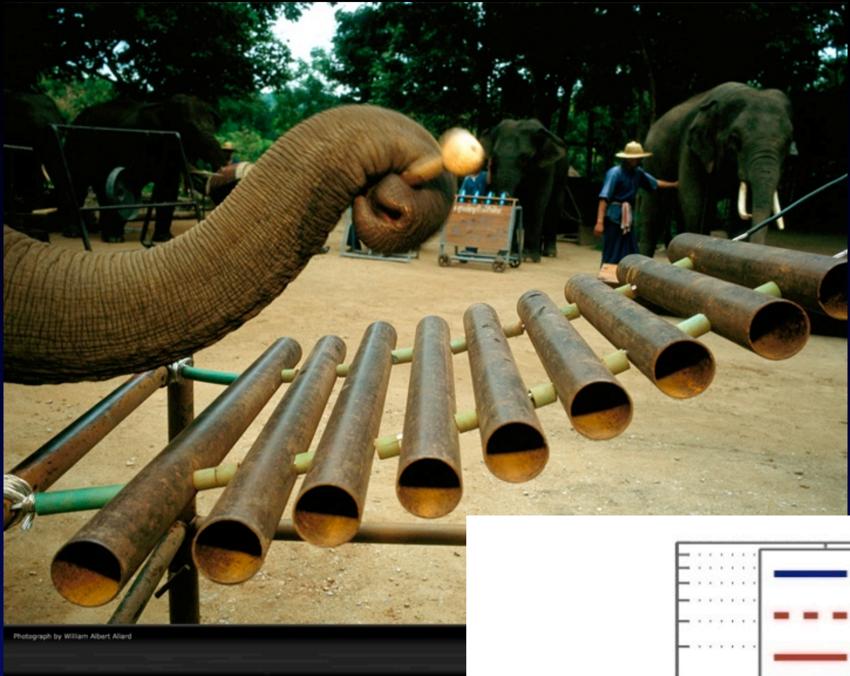


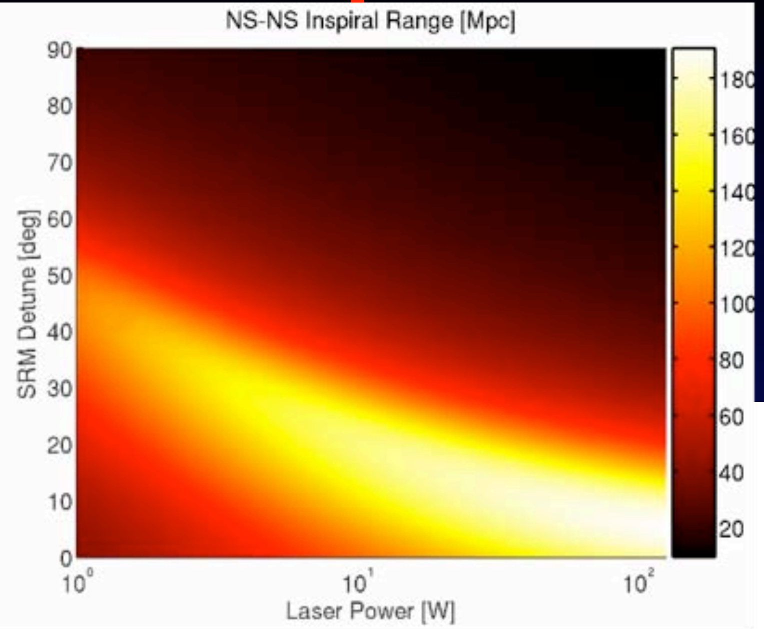
Reflects GW photons back into interferometer to accrue more phase

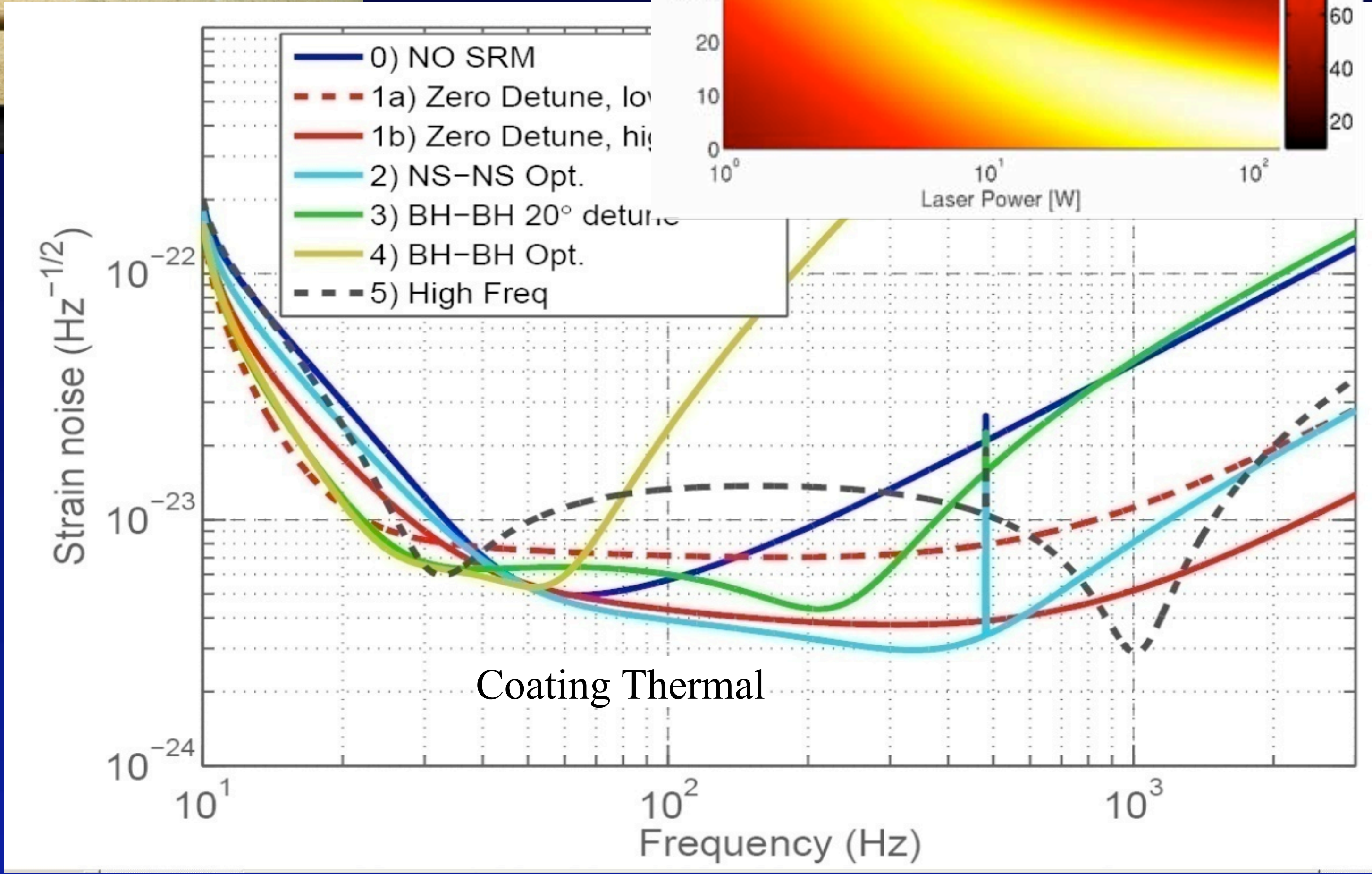
Signal-recycled Interferometer

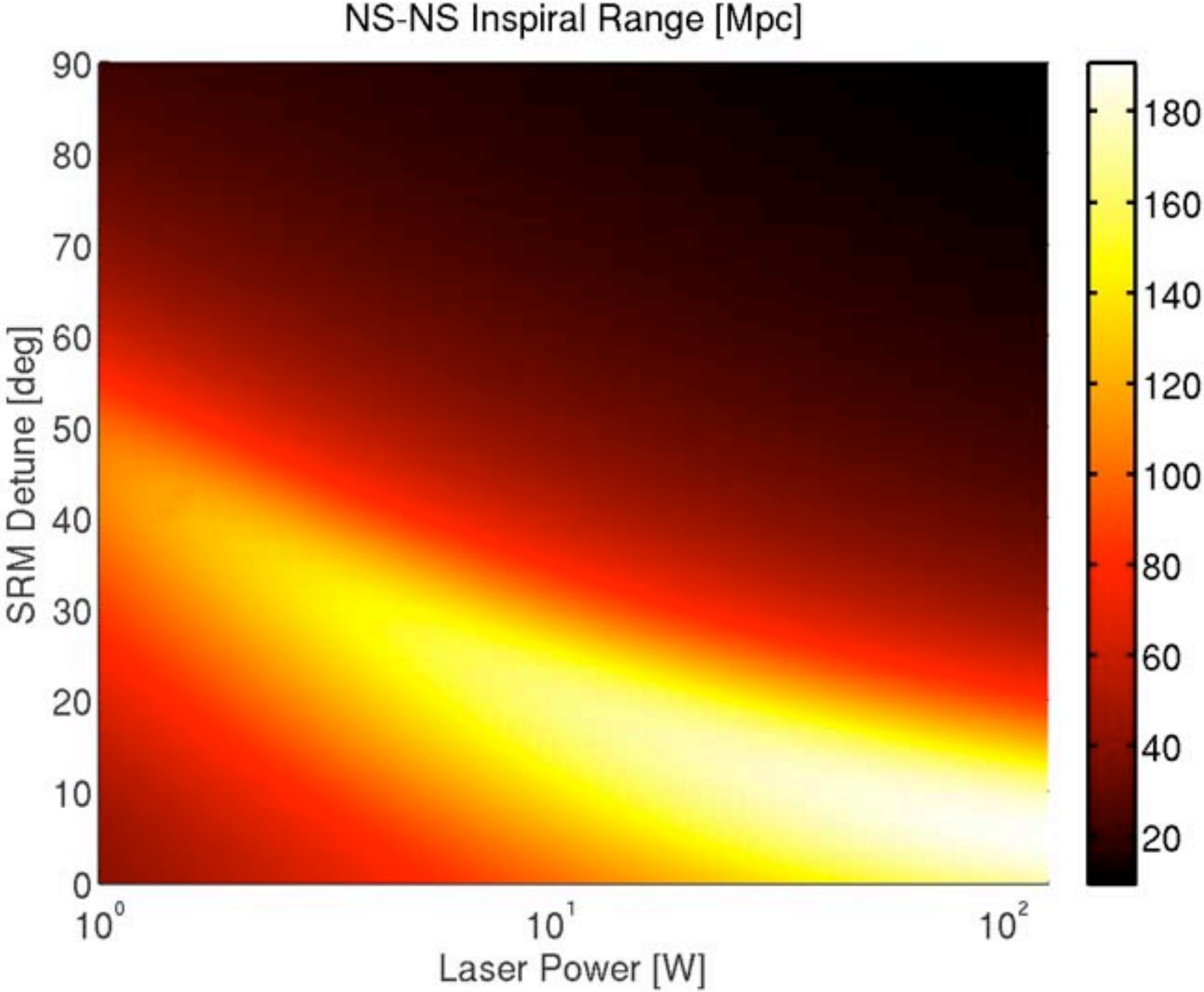


Tunable Response





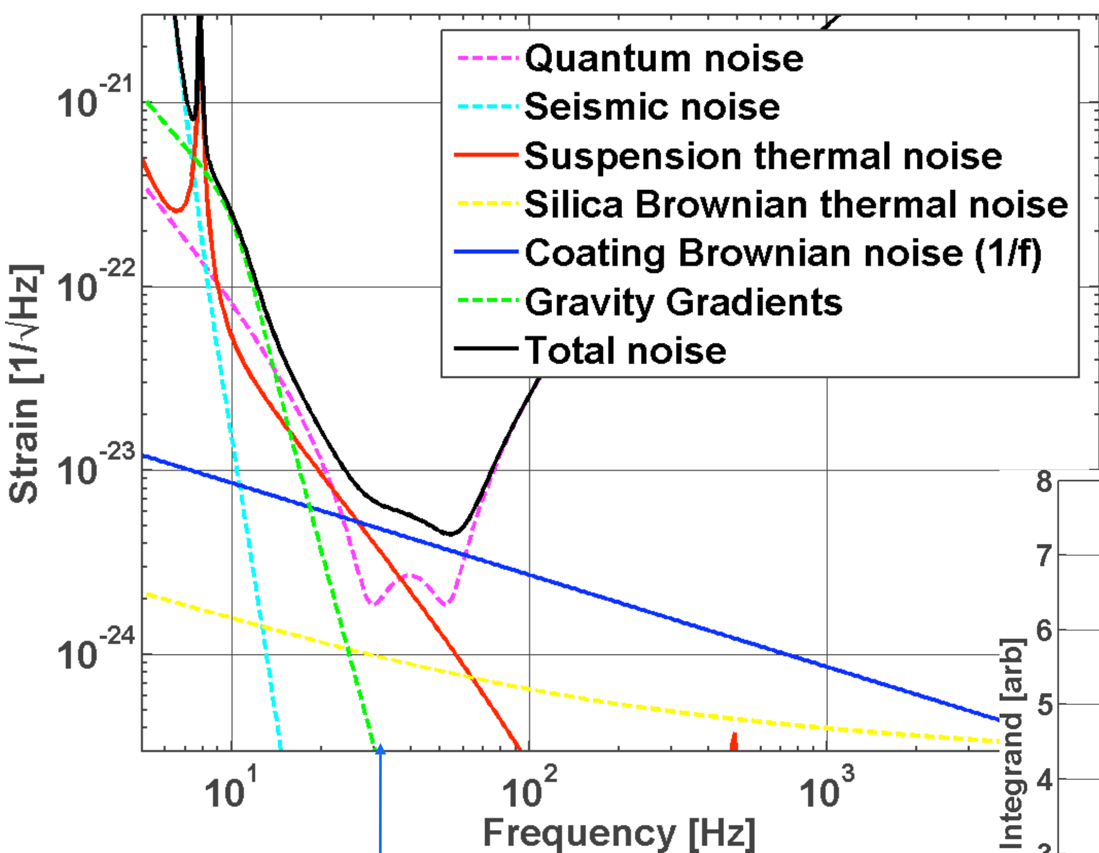


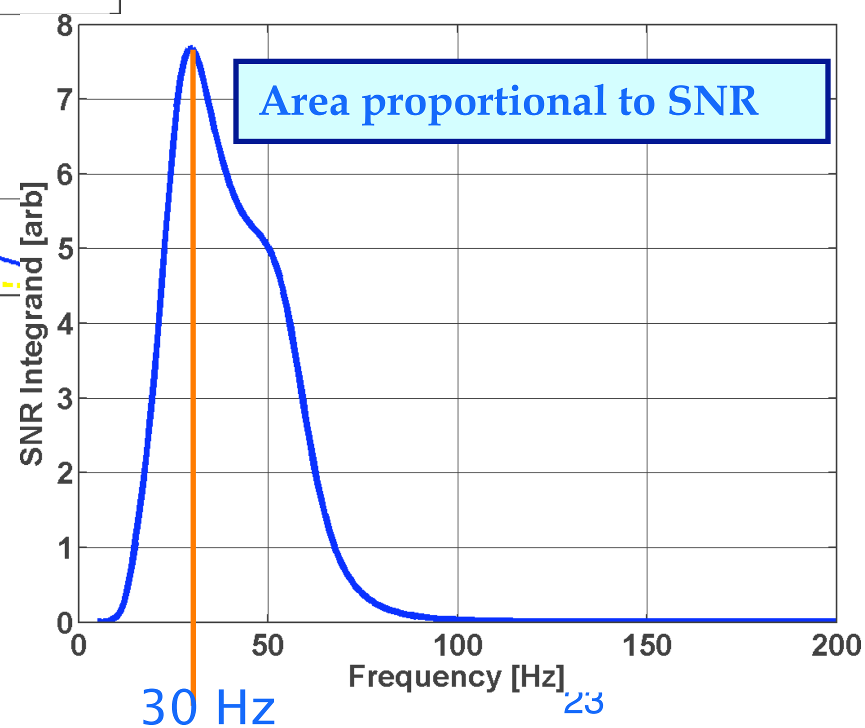


NS-NS Inspiral Range [Mpc]
SRM Detune [deg]
Laser Power [W]
0
10
20
30
40
50
60
70
80
90
10^0
10^1
10^2
20
40
60
80
100
120
140
160
180

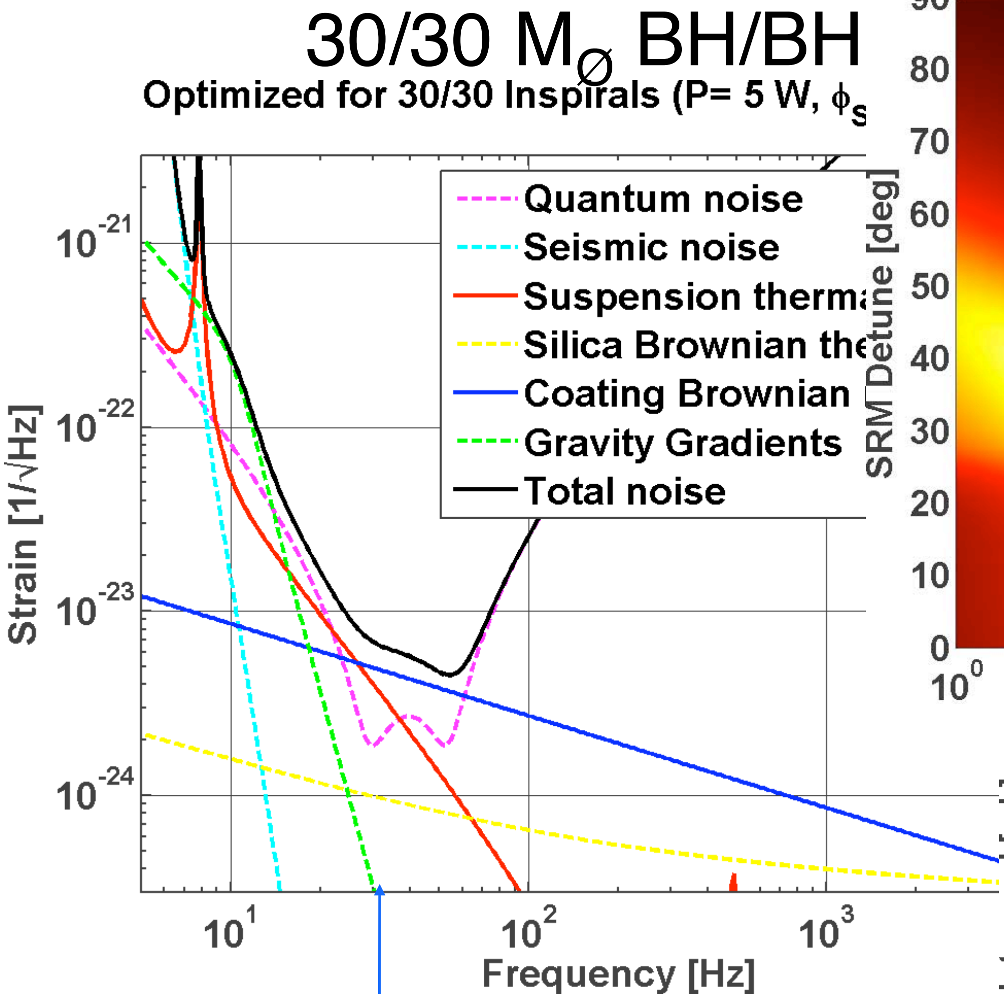
30/30 $M_{\odot}$ BH/BH

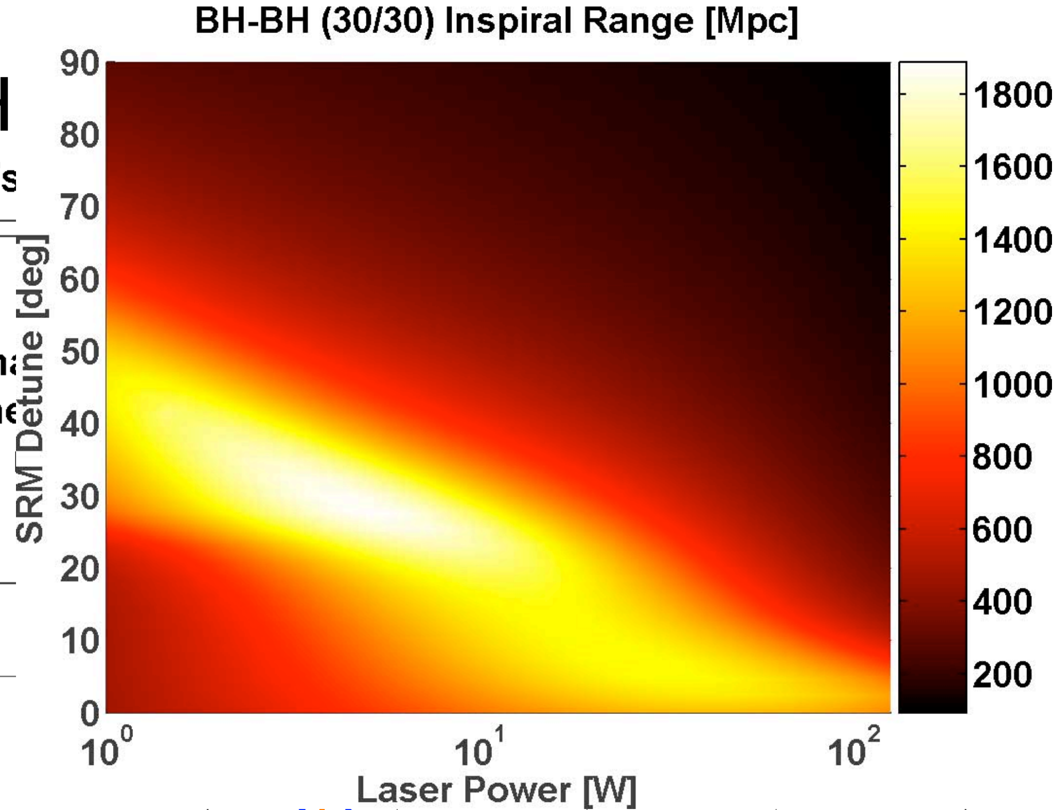
Optimized for 30/30 Inspirals (P= 5 W, ϕ_{SRM} = 28 deg)

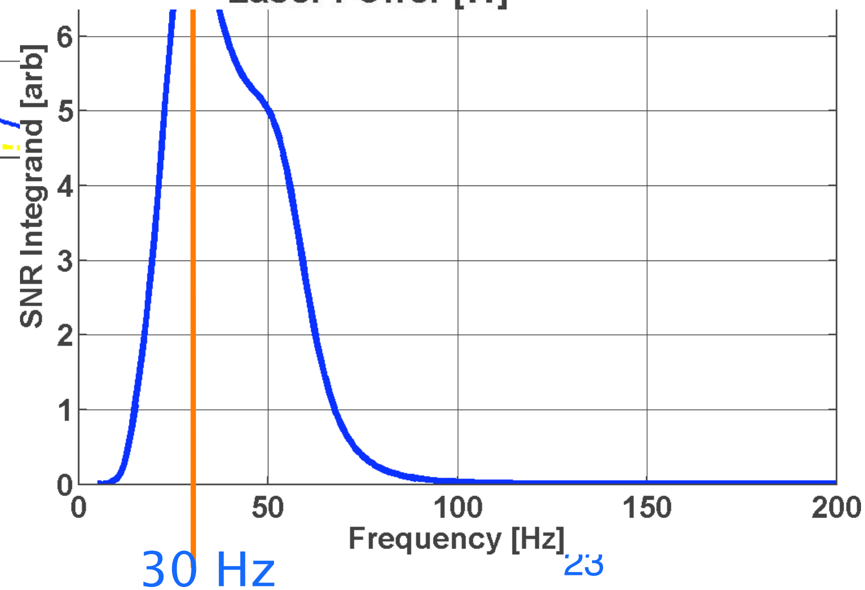




Most of the sensitivity comes from a band around 30 Hz



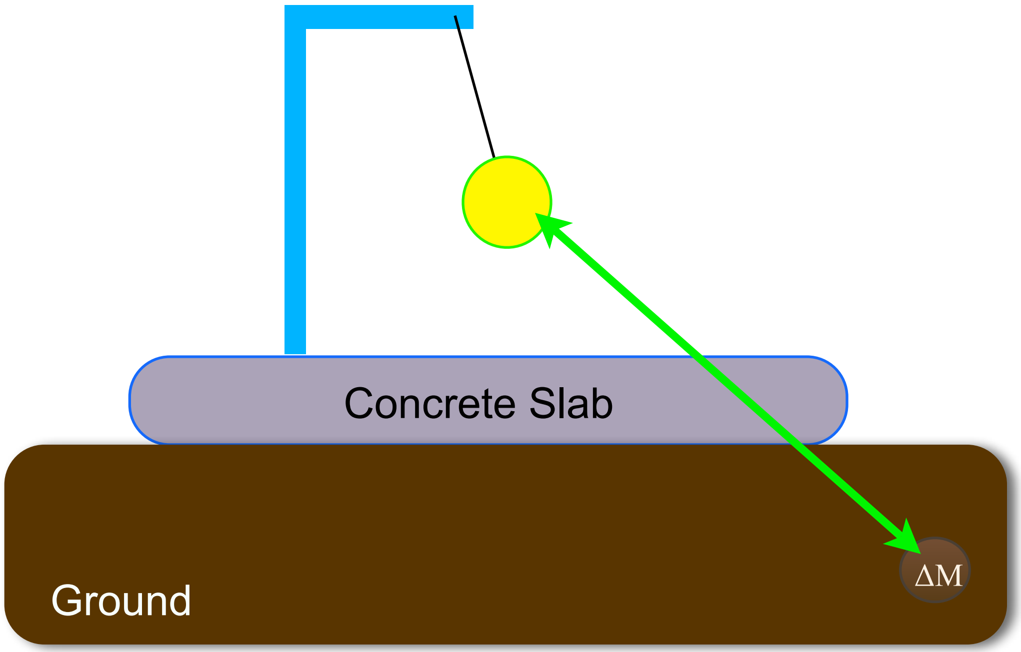




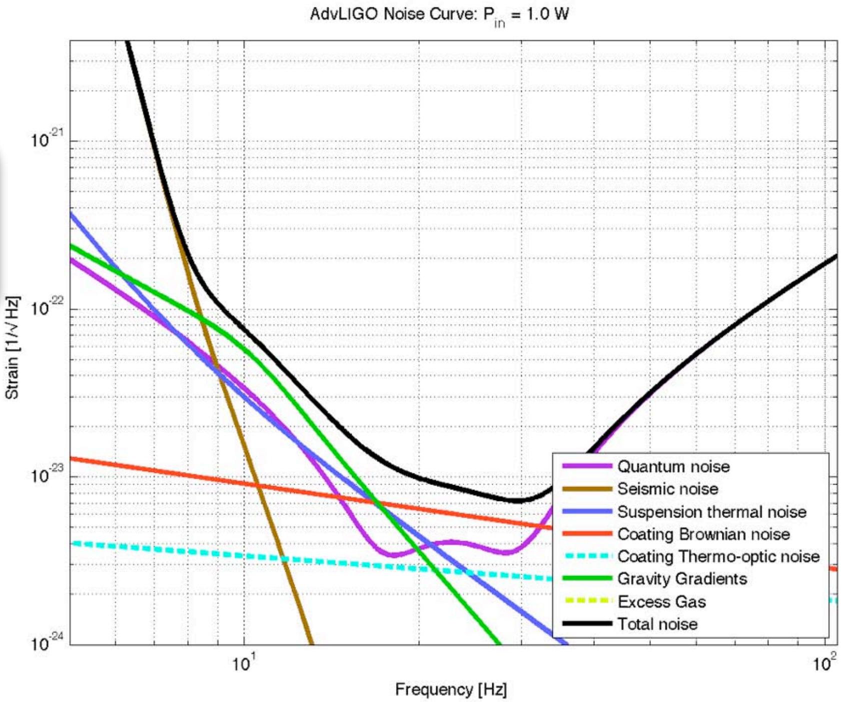
Most of the sensitivity comes from a band around 30 Hz

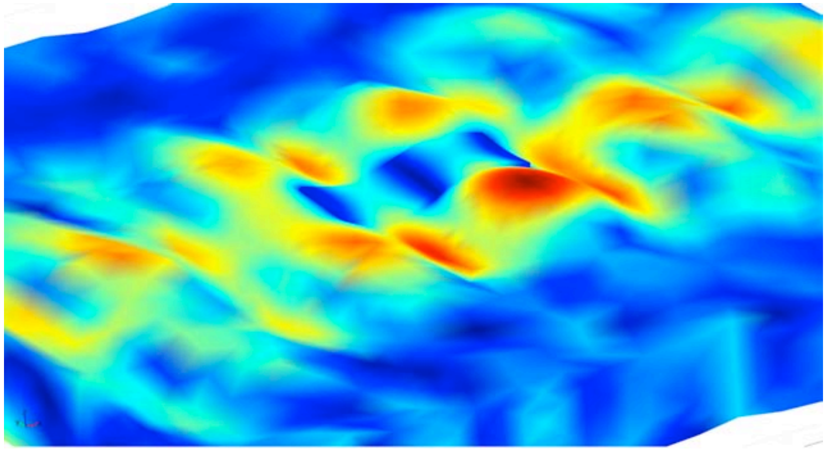
Gravity Gradient Noise

$$x(f) = G\,\Delta M(f) / (f^2\, r^2)$$

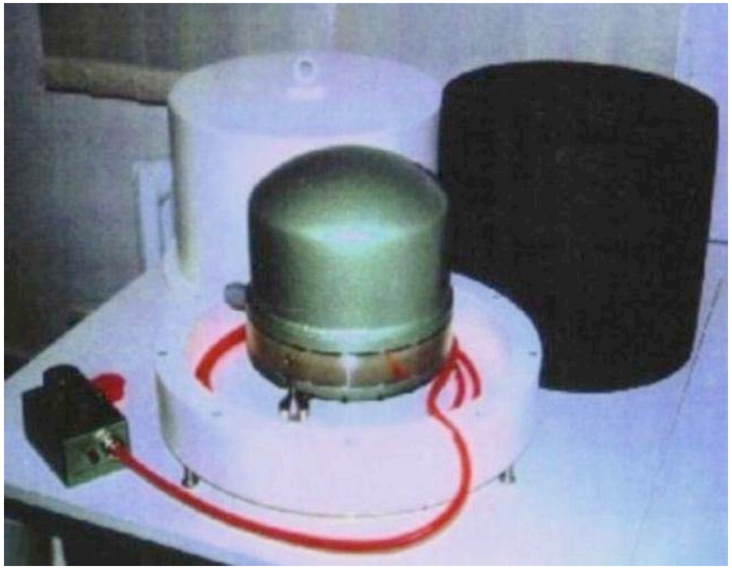


- **Noise Sources**
  - Surface Waves
  - Air Pressure Fluctuations
  - Subsurface density Fluctuation



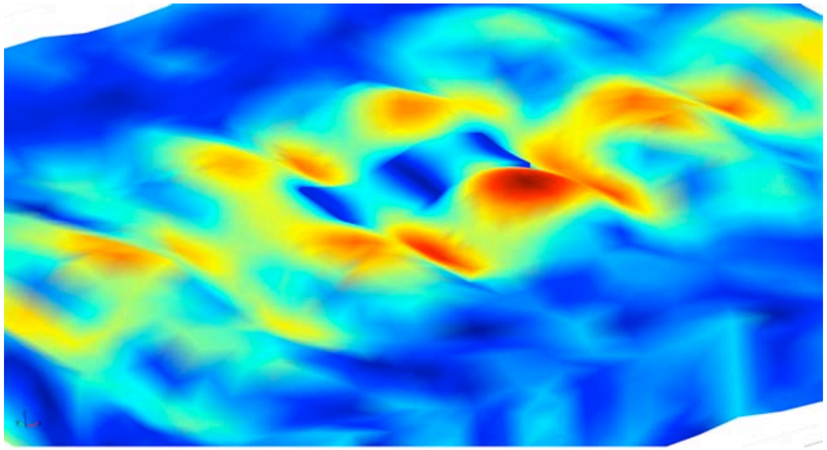


FEA of Ground

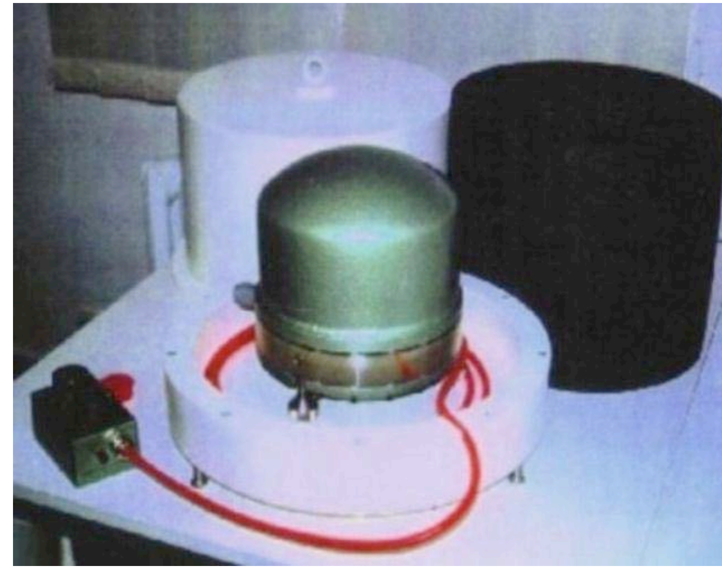


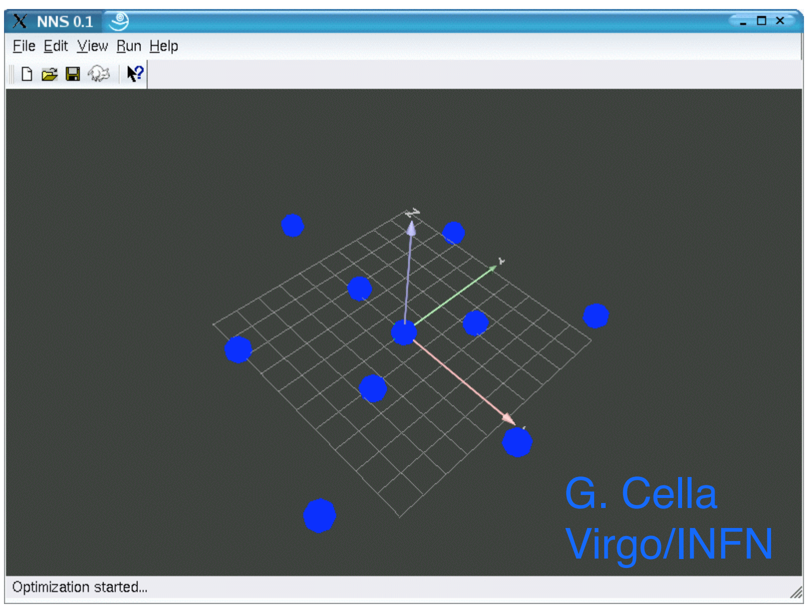
G. Cella
Virgo/INFN

- **Noise Cancellation**
  - Accelerometers measure ground motion
  - Adaptive algorithm estimates GG noise



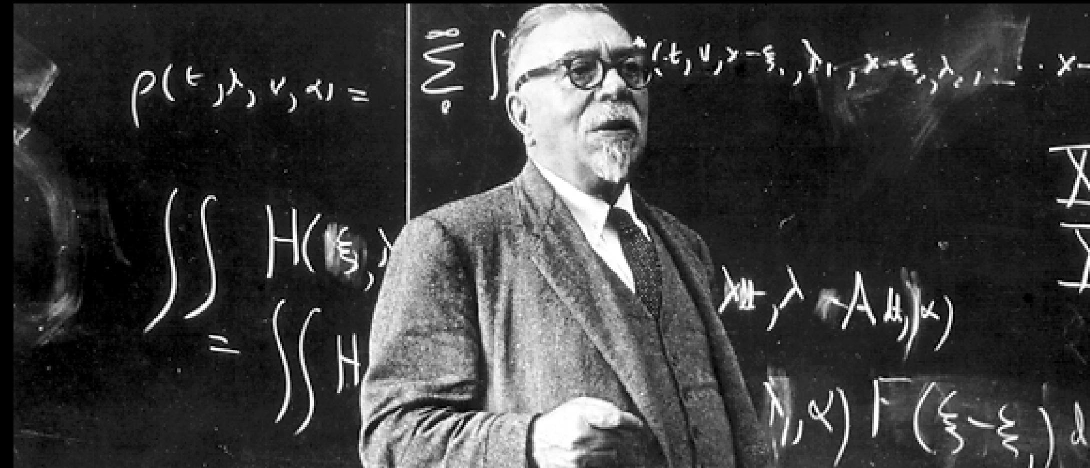
FEA of Ground





- **Noise Cancellation**
  - Accelerometers measure ground motion
  - Adaptive algorithm estimates GG noise

Wiener Filter



Norbert Wiener, MIT

$$x[n] = \sum_{i=0}^{N} a_i w[n-i]$$

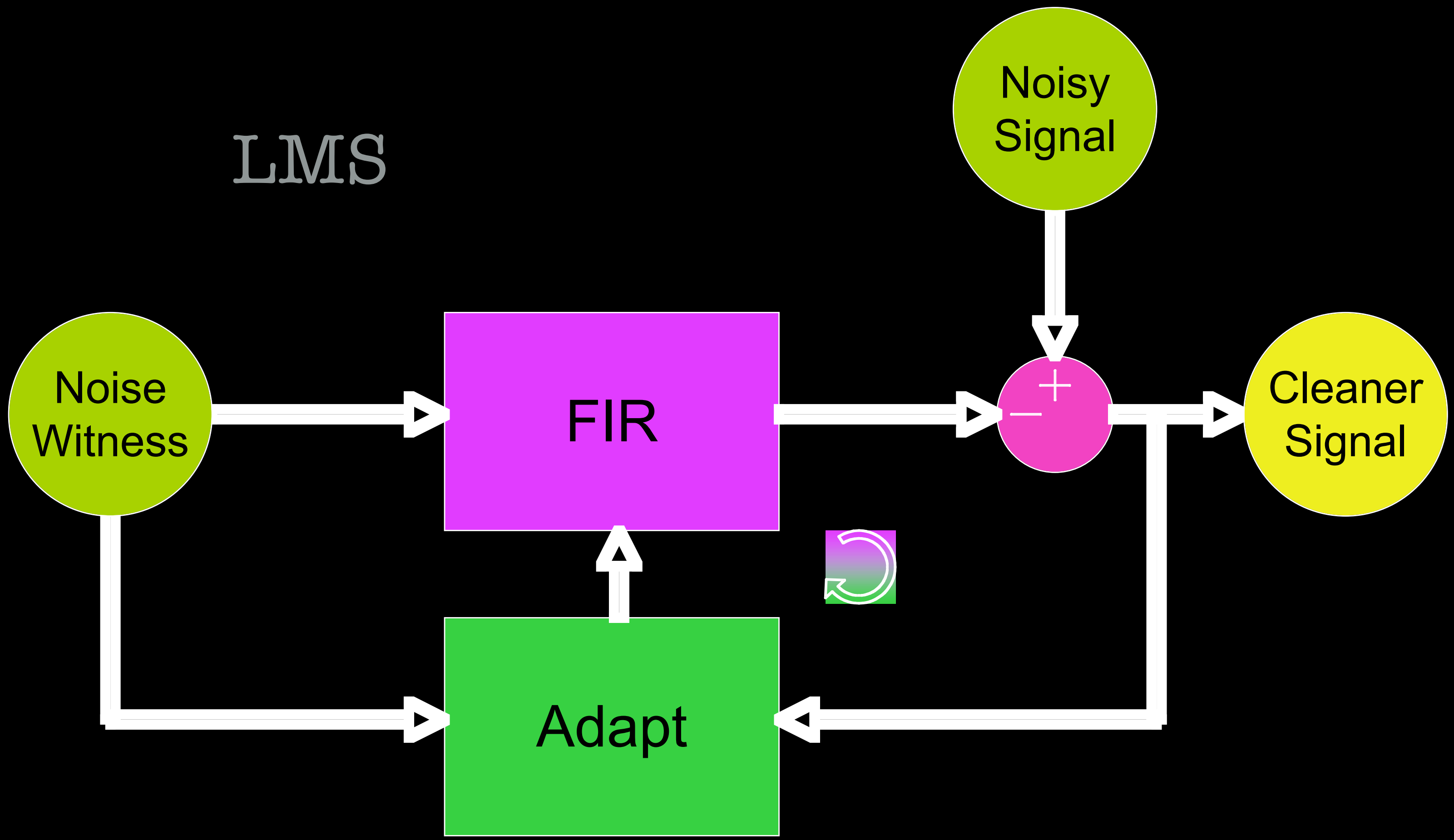
Block Toeplitz

$$\begin{bmatrix} R_w[0] & R_w[1] & \cdots & R_w[N] \\ R_w[1] & R_w[0] & \cdots & R_w[N-1] \\ \vdots & \vdots & \ddots & \vdots \\ R_w[N] & R_w[N-1] & \cdots & R_w[0] \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_N \end{bmatrix} = \begin{bmatrix} R_{sw}[0] \\ R_{sw}[1] \\ \vdots \\ R_{sw}[N] \end{bmatrix}$$

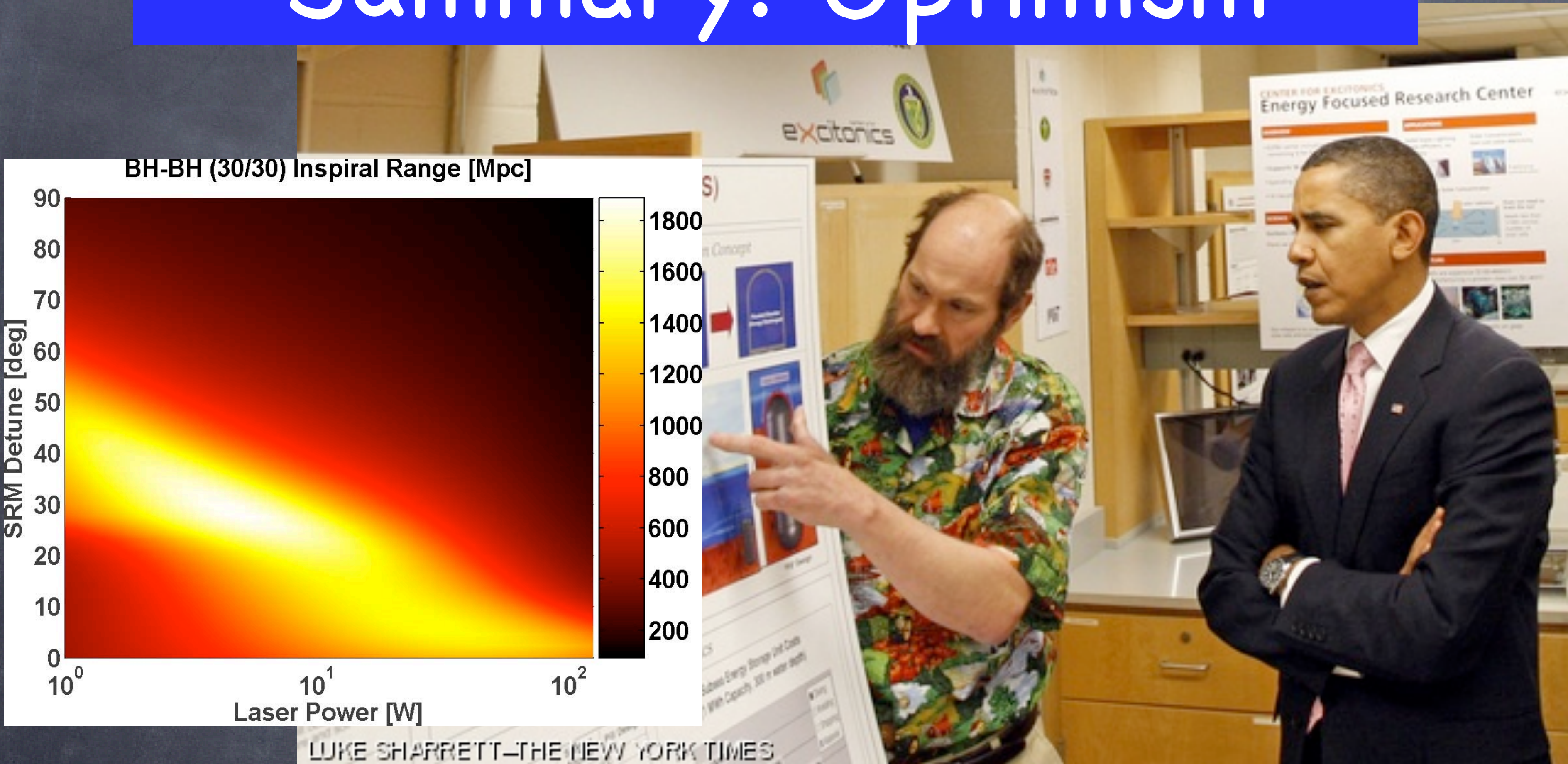
Cross Correlation Matrix

Input Signal (PEM) Covariance Matrix

From LMS to Filtered-X



Summary: Optimism



- Funding good for 2nd gen. detectors
- Ideas + designs beginning for 3rd gen.
- Preliminary data in ~2014-2015