Thermal noise from optical coatings

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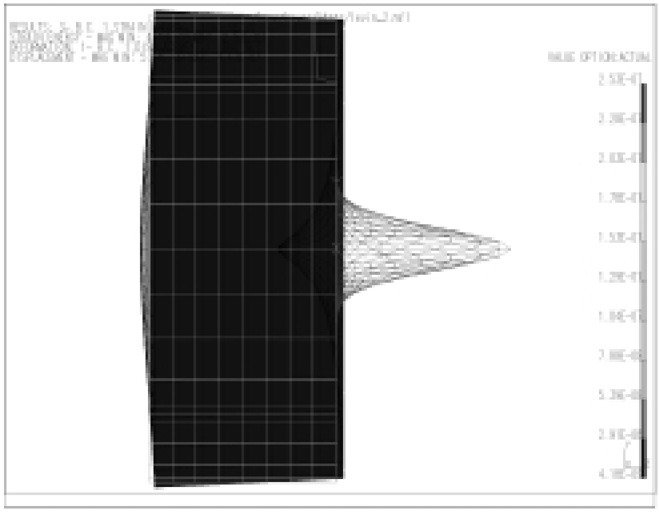
Yuri Levin's Theorem

$$S_x(f) = 2\, k_B T \,/\, (\pi^2 f^2)\, W_{diss}/F_0^{\,2}$$



- **Levin's theorem more easily handles loss inhomogeneities than modal expansion**

- **Coatings contribution to thermal noise high because of proximity to laser**

- **Other mirror losses (magnets, wire, standoffs) less important**

Theory of Brownian thermal noise from coatings

$$\phi_{\mathrm{readout}} = \phi_{\mathrm{bulk}} + \frac{1}{\sqrt{\pi}} \frac{(1-\sigma_{\mathrm{sub}})}{(1-2\sigma_{\mathrm{sub}})} \frac{d}{w} \left(\frac{Y_{\mathrm{coat}}}{Y_{\mathrm{sub}}} \phi_{\mathrm{coat}\,\parallel} + \frac{Y_{\mathrm{ub}}}{Y_{\mathrm{coat}}} \phi_{\mathrm{coat}\,+} \right)$$

- **Derived from Levin's theorem (Gretarsson et al)**
- **Derived independently (Nakagawa et al)**
- **Dependance on $\phi_{coat||}$, ϕ_{coat+}, ϕ_{sub}, Y_{coat}, and Y_{sub}**
- **Noise decreases as laser spot size increases**

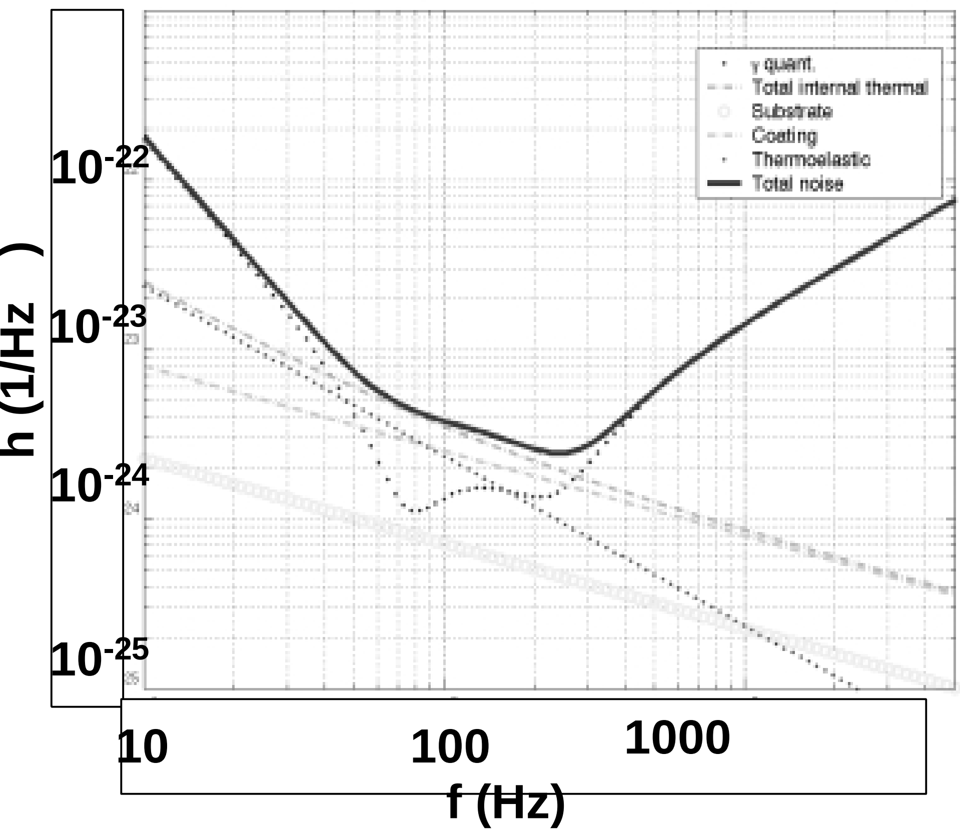
  Plan to use largest possible (6 cm) spots in Adv LIGO

- **Assumes infinite mirror substrates**

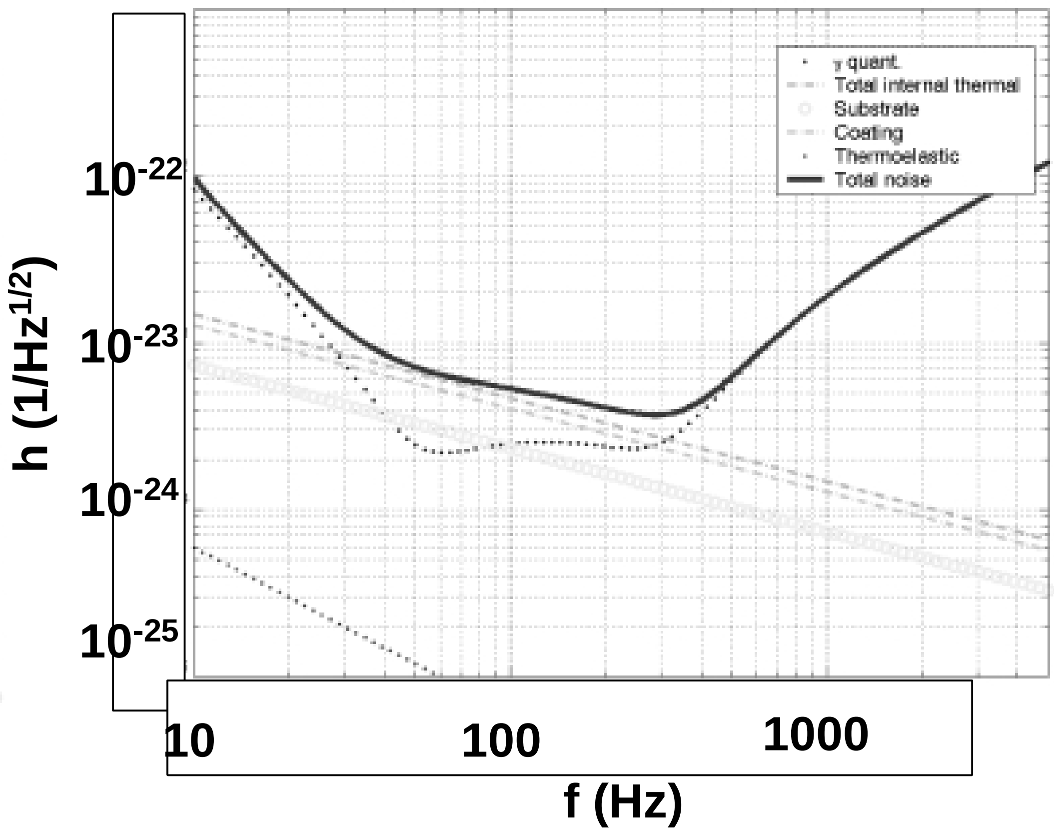
  FEA modeling by Numata et al shows noise slightly lower for finite mirrors

Advanced LIGO sensitivity

Sapphire Mirrors
160 Mpc BNS Range



Silica Mirrors
140 Mpc BNS Range



Coating used for Initial LIGO (REO tantala/silica) $\phi = 1.5 \times 10^{-4}$

Advanced LIGO target 200 Mpc BNS Range

Mechanical loss in tantala/silica coatings

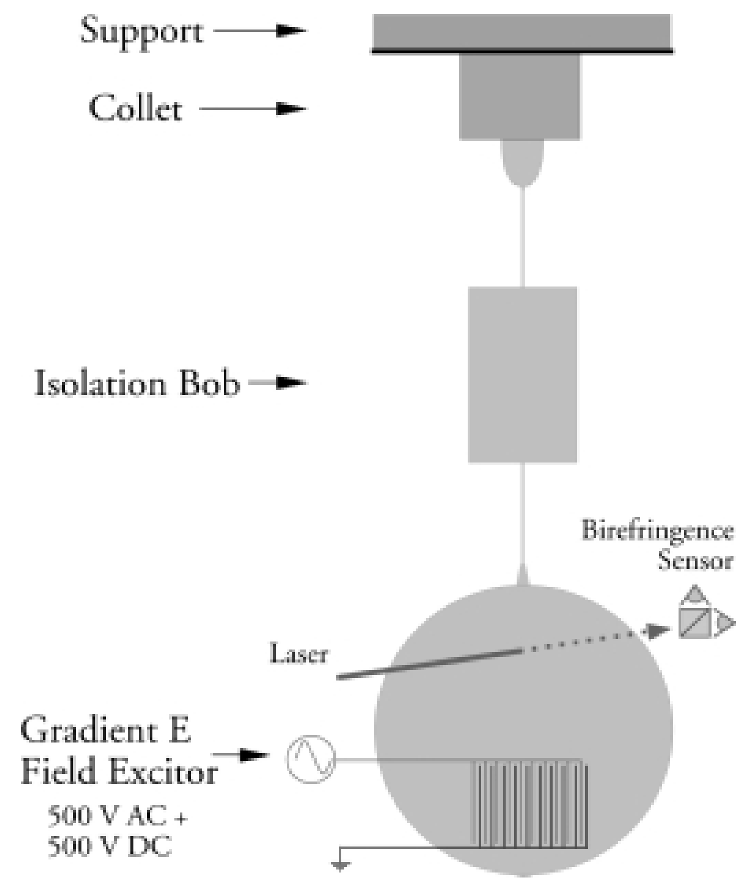
- Measured Q's of initial LIGO coating on silica disks
- Measured coatings with varying thickness and number of layers

  Loss depends on amount of materials
  Independent of number of layers

- $\phi_{coat||}$ = 2.7 +/- 0.7 10^{-4} for Q measurements
- ϕ_{silica} = 0.5 +/- 0.3 10^{-4}
- $\phi_{tantala}$ = 4.4 +/- 0.5 10^{-4}
- ϕ_{coat+} = 1.5 +/- 0.3 10^{-4} for thermal noise

- Good agreement between coatings from three vendors (REO, MLD, SMA/Virgo)

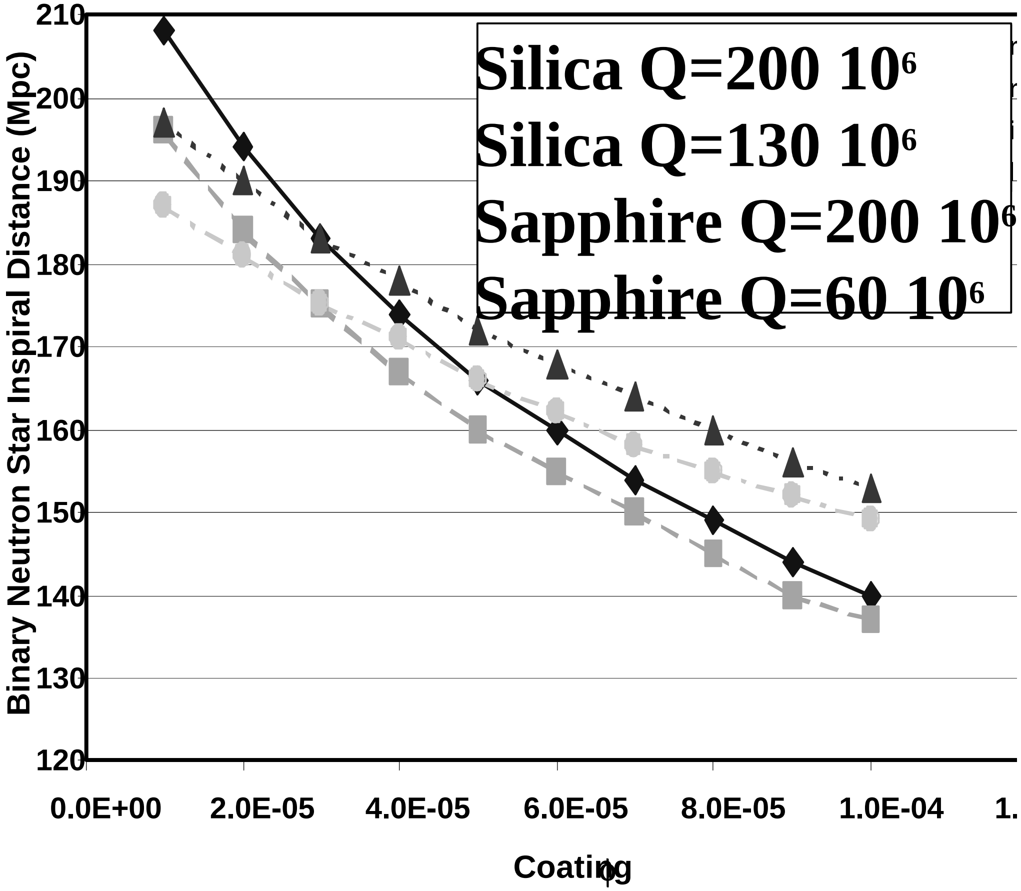
- Loss too high for Advanced LIGO sensitivity



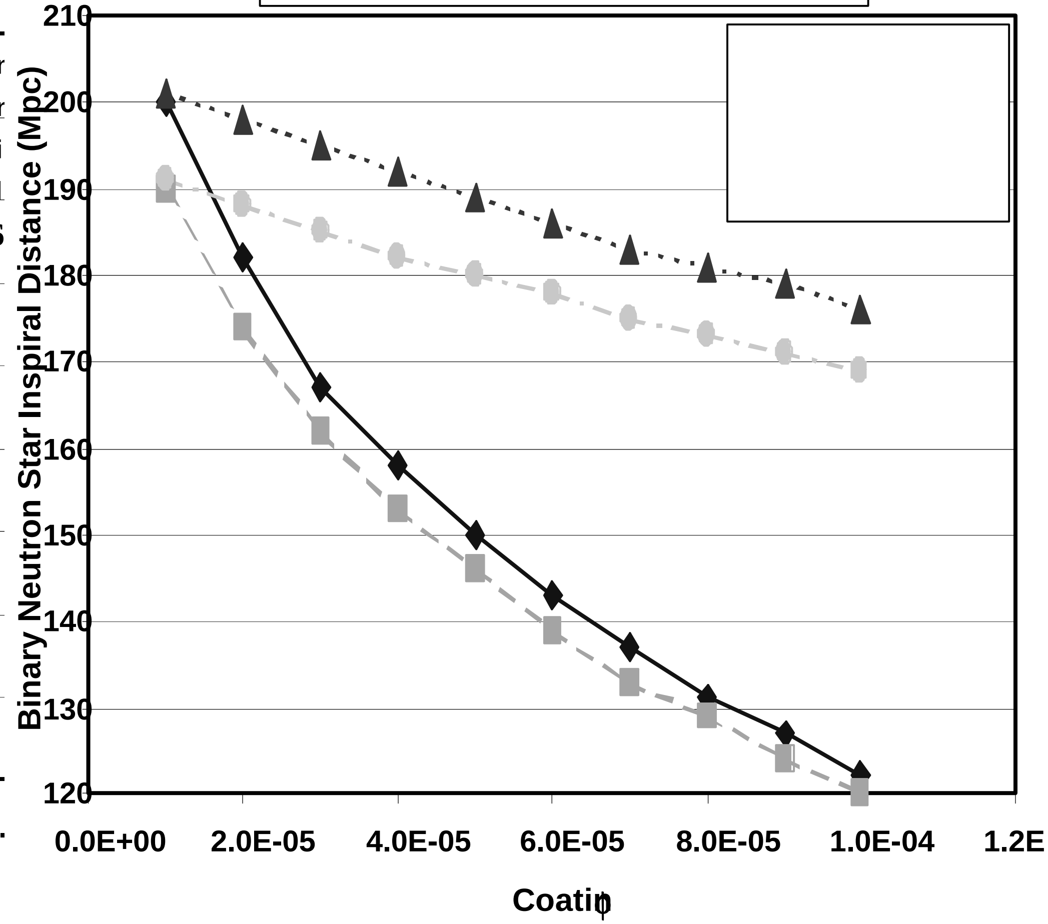
Monolithic suspension and birefringence readout for thin silica sample coating measurments

Advanced LIGO sensitivity vs coating loss angle

Y_{coat} = 70 10^9 Pa



Y_{coat} = 200 10^9 Pa



Alternate materials in optical coatings I

Materials other than silica and tantala have been examined

- **Low index material : Alumina (Al_2O_3 with Ta_2O_5)**
  Mechanical loss
  From General Optics ϕ_{al2o3} consistent with 0
  From MLD $\phi_{al2o3} = 2.4\ 10^{-4}$
  Optical loss about 2 ppm after annealing (goal <1 ppm)
  $Y_{al2o3} > Y_{sio2}$

- **High index material: Niobia (Nb_2O_5 with SiO_2)**
  Mechanical loss $\phi_{nb2o5} = 6.7\ 10^{-4}$
  Optical loss about 0.3 ppm after annealing (goal <1 ppm)
  $Y_{nb2o5} < Y_{ta2o5}$

Alternate materials in optical coatings II

Tantala/silica with dopant added to tantala

- Dopant is proprietary (SMA/Virgo)

  Young's modulus unchanged from Ta_2O_5 to 0.2 %
  Index of refaction unchanged from Ta_2O_5 to 1 %
  Mechanical loss $\phi_{ta2o5} = 2.1\ 10^{-4}$ (was $4.4\ 10^{-4}$)

- Doped tantala/silica coating in Advanced LIGO

  Mechanical loss $\phi_{coat+} = 9.0\ 10^{-5}$
  BNS Range 145 Mpc (was 140 Mpc)

- Work is continuing on dopants in coatings

  Possibly related to stress reduction ?

Theory of thermoelastic noise from coatings

- **Recent work shows that *thermoelastic damping* between the coating and the substrate can be a significant source of thermal noise (Fejer, Rowan et al, Braginsky et al)**
- **Match thermal expansion between coating and substrate**
- **Some rough loss values for coating/substrate matches**

Silica coating on sapphire	$\phi \sim 1\ 10^{-3}$
Silica coating on silica	$\phi \sim 1\ 10^{-5}$
Alumina coating on sapphire	$\phi \sim 2\ 10^{-5}$
Alumina coating on silica	$\phi \sim 2\ 10^{-4}$

- **Baseline is sapphire substrate with alumina in coating**

Future plans: Improved coatings

- Coating vendors are responding to request for proposals
  - Multiple international vendors have replied
  - Two vendors for R&D phase
  - One (possibly two) vendors for production of optics
- Three directions of research
  - New materials - hafnia, zirconia, titania, alloys
  - Dopants - aluminum, titanium, designed to reduce stress?
  - Annealing - known to improve loss in silica
- Input solicited from material scientists and others
- Correlate loss with stress in coatings

Conclusions

- Internal mode thermal noise fundamental limit to gravitational wave interferometer sensitivity
- Thermal noise from coatings represent significant part of overall thermal noise
- Noise depends on many thermal and mechanical parameters of coatings as well as spot size
- Tantala/silica coatings have been characterized, but do not meet Advanced LIGO goals
- Other materials and techniques are being explored
- Collaboration and plan in place to find a workable coating for advanced LIGO

Future plans II: Measurements

Coatings need to be characterized for all relevant parameters

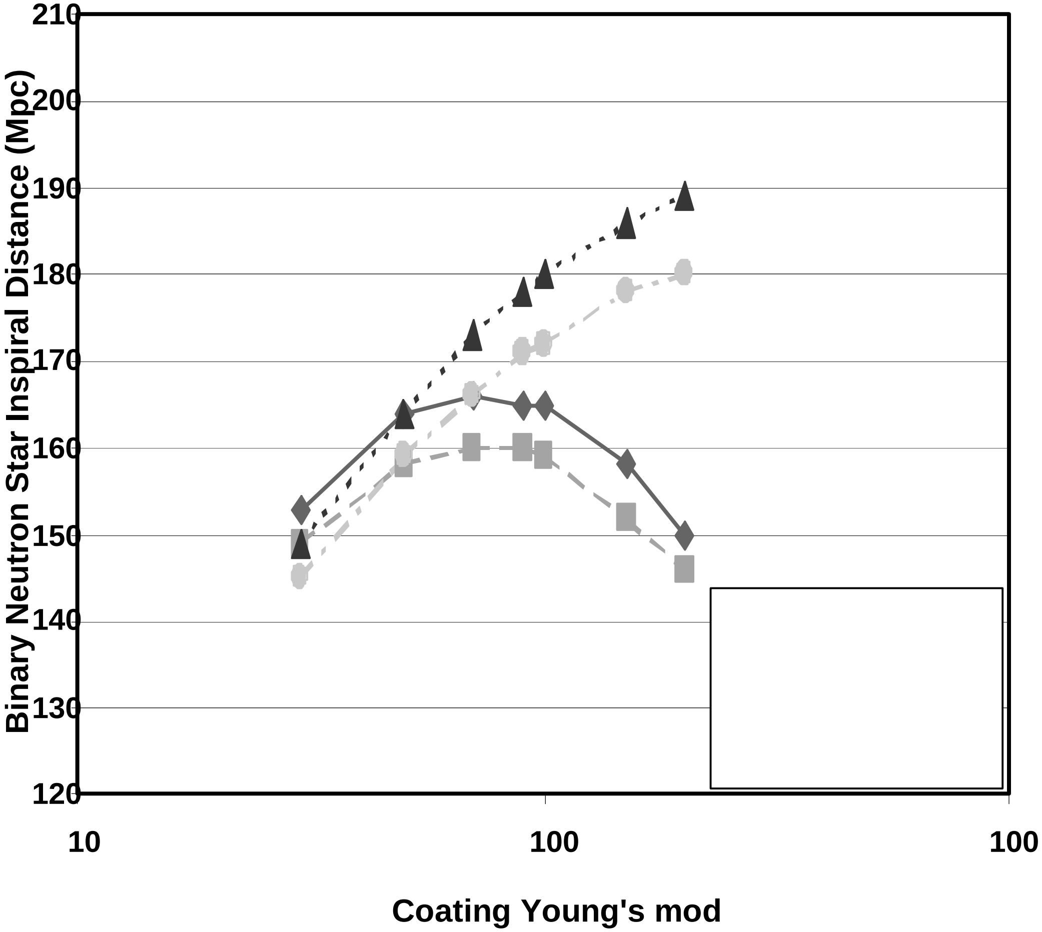
- **Mechanical loss -ringdown Q experiments (MIT, Glasgow, Stanford, and Hobart and William Smith)**
- **Optical loss- absorption measurements (Stanford)**
- **Young's modulus - acoustic reflection experiment (Stanford)**
- **Thermal expansion - optical lensing experiment (Caltech, Stanford)**
- **Direct thermal noise measurement - (Caltech, Hongo)**

  Interferometers to measure thermal noise in short cavities

  Two different spot sizes (~50μm at Hongo, 160 μm at TNI)

Advanced LIGO sensitivity vs coating Young's Modulus

$\phi_{coat} = 5\ 10^{-5}$



$\phi_{coat} = 1\ 10^{-5}$