Downselect: Silica.
What Were We Thinking?

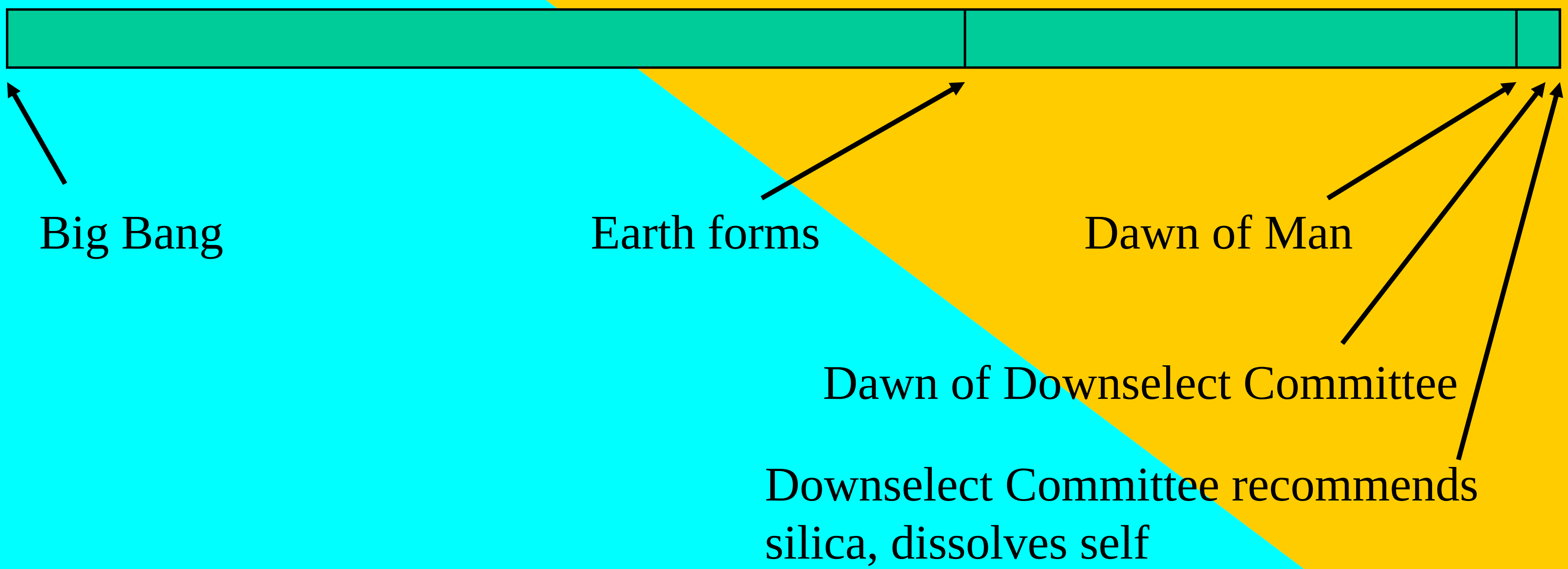
Phil Willems, Caltech
-representing-
the Downselect Committee:
David Shoemaker, Jordan Camp, Marty Fejer, Sam Finn, Peter Fritschel, Jim Hough, Peter Saulson, & yours truly

April 12, 2005

Some History

- 1996?: Sapphire proposed for Advanced LIGO test mass material.
- 2001: Downselect committee organized to recommend between sapphire and fused silica. Decision to be made by December 2002.
- December 2002: Committee defers recommendation to 2003.
- 2003: Committee defers recommendation to 2004.
- 11:59PM, Dec. 31, 2004: Committee recommends silica.

Did We Study This Long Enough?



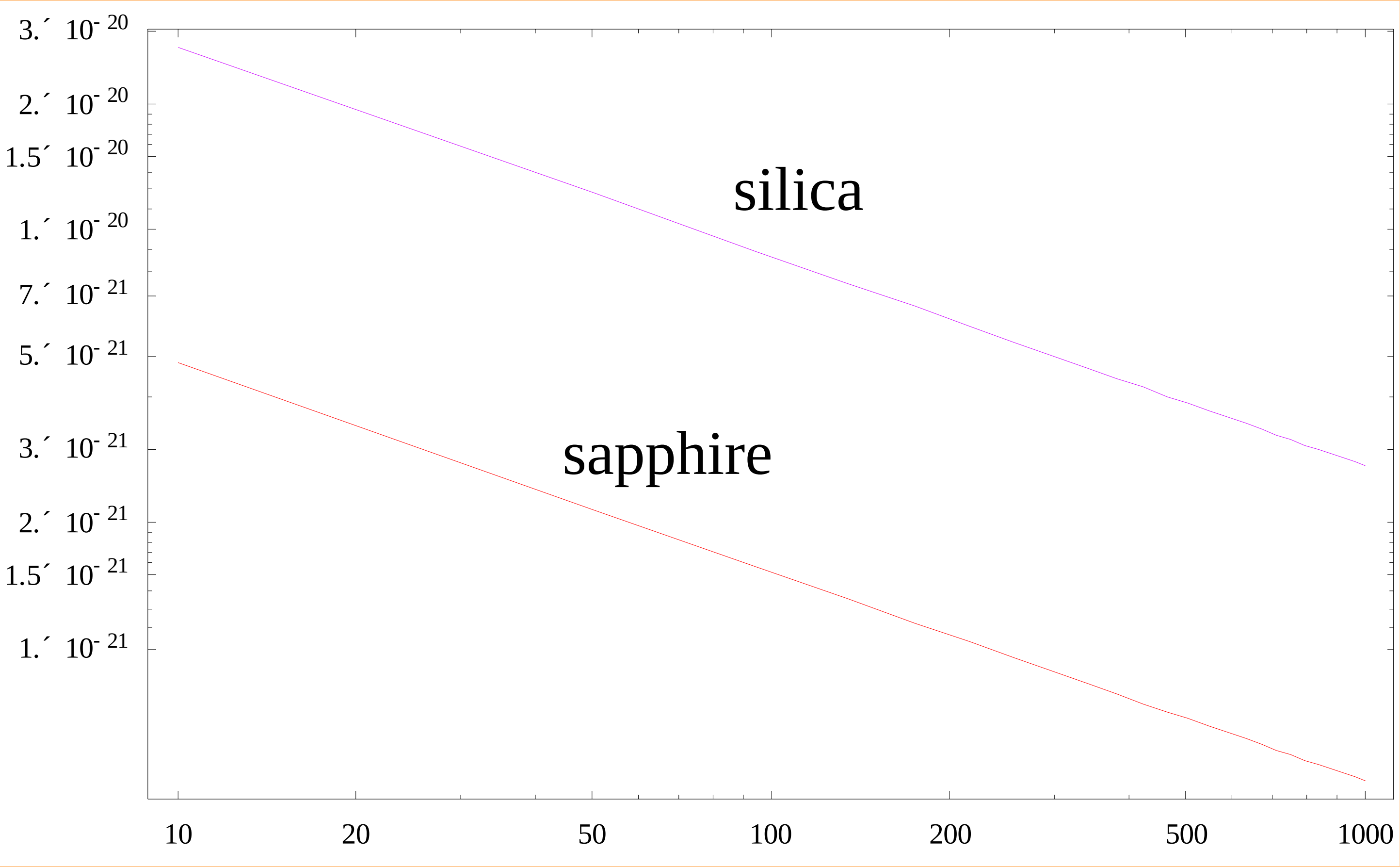
We Were Very Thorough…

- Cost
- Schedule
- Multiple Sourcing
- Coating
- Polishing
- Bonding
- Thermal Noise
- Scattering
- Absorption
- Size
- Thermal Compensation
- Astrophysical Reach
- Excess Noise
- Suspension Issues
- Radiation Pressure Instabilities
- Control Issues
- Polarization Effects
- Index Inhomogeneities

The Seduction of Sapphire

- Ten years ago, sapphire promised…
  - » Lower thermal noise
    - – At that time, the best Q of fused silica was 3x10^{7}
    - – The best Q of sapphire was 4x10^{8}
  - » Less thermal lensing
    - – Sapphire's thermal conductivity is 37W/mK
    - – Fused silica's thermal conductivity is only 1.38W/mK

How We Saw Thermal Noise Then

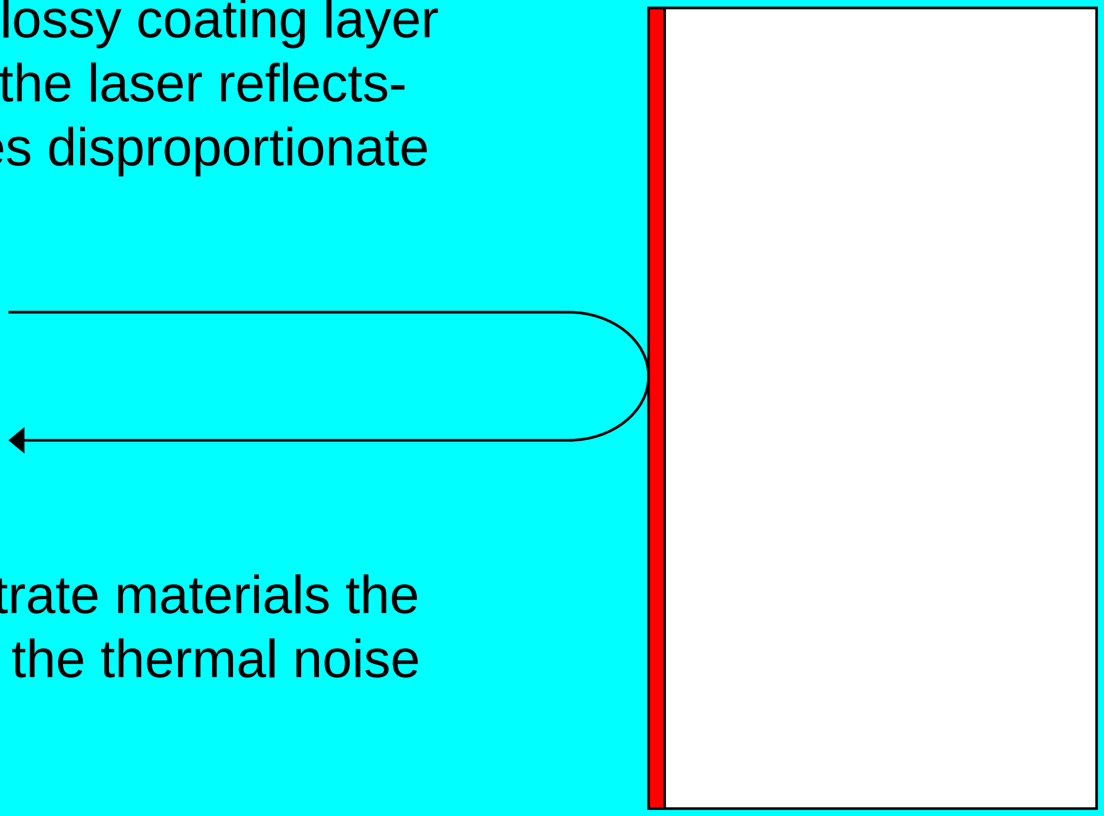


But What We Know Now…

- Coatings play a very significant role
- Thermoelastic noise in sapphire is larger than we thought
- Fused silica Q is larger than we thought (new data and a new model)

Coating Thermal Noise

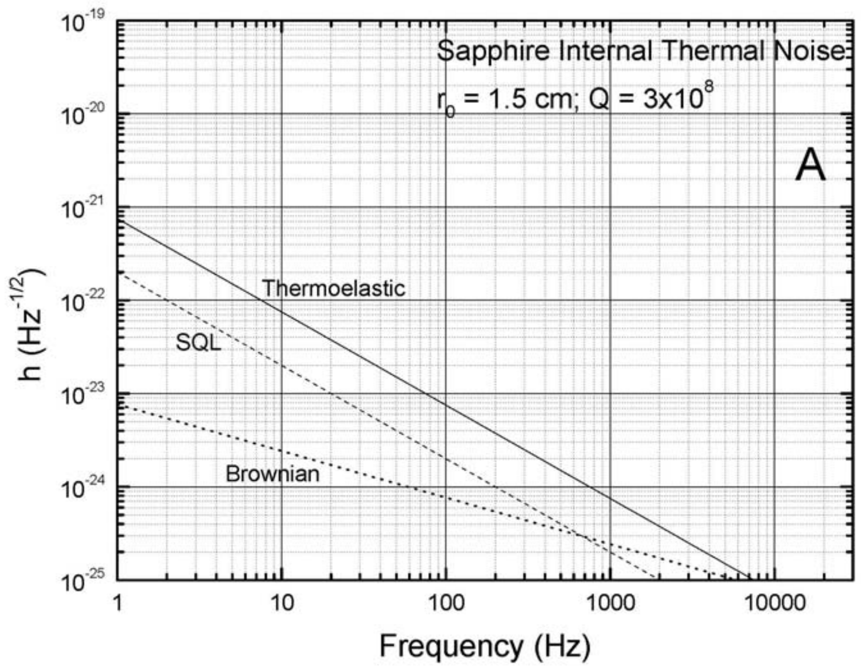
The relatively lossy coating layer is right where the laser reflects- and contributes disproportionate thermal noise.



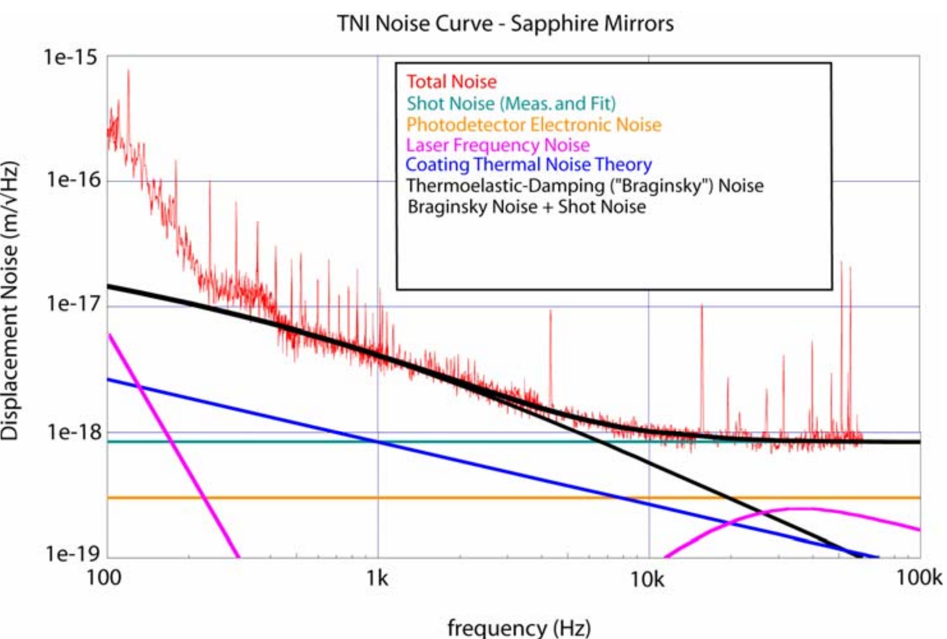
For both substrate materials the coating raises the thermal noise floor.

Thermoelastic Noise

Braginsky, a notorious hater of sapphire, detailed this effect, which dominates for sapphire and is negligible for silica…



Braginsky



…and it's been measured at the TNI!

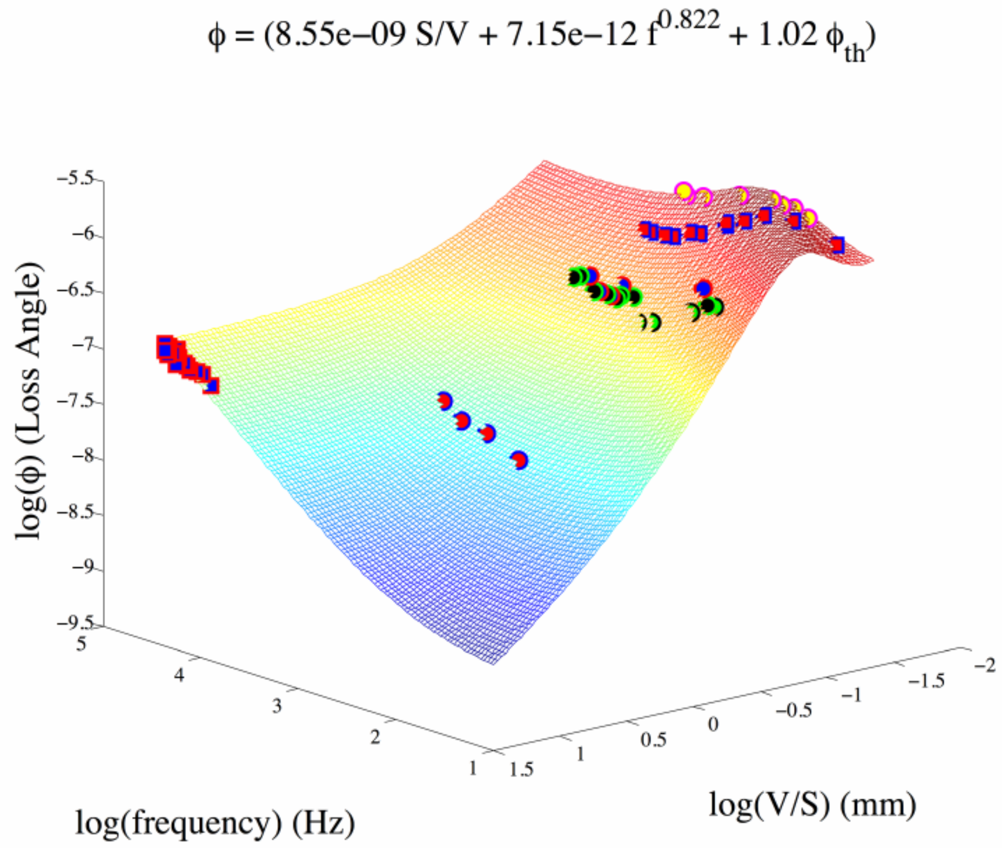
Eric Black

A Quantitative Loss Model for Silica

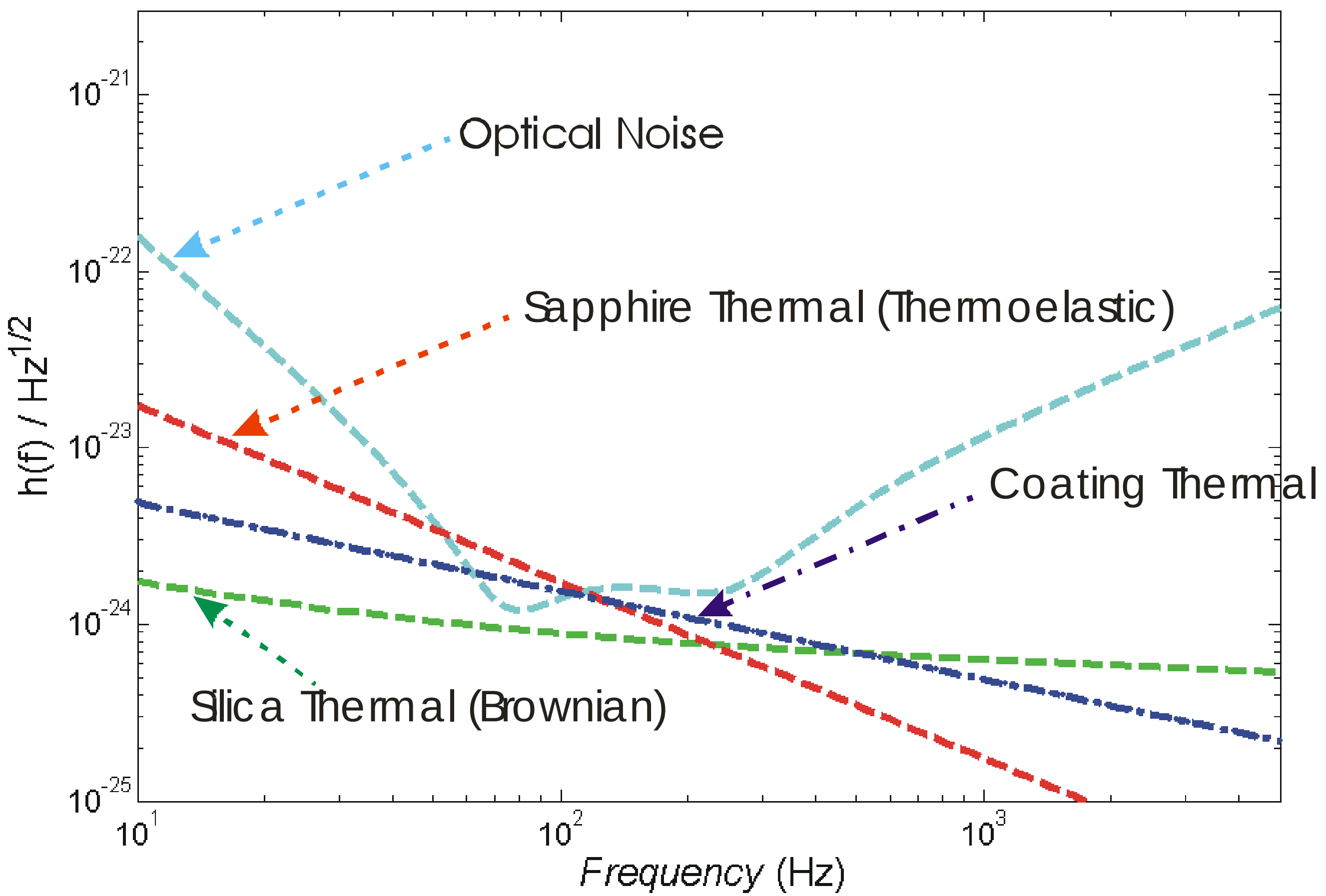
Experiments at Tokyo, Syracuse, and HSW show higher Q in annealed silica- up to 2.5×10^8 at low f.

Caltech test of unannealed initial LIGO ITM found Q of 1.2×10^8, also at low f.

All well fit to a model that distinguishes structural surface loss from Si-O-Si bond angle flexure bulk loss (and thermoelastic for fibers)



Put It All Together



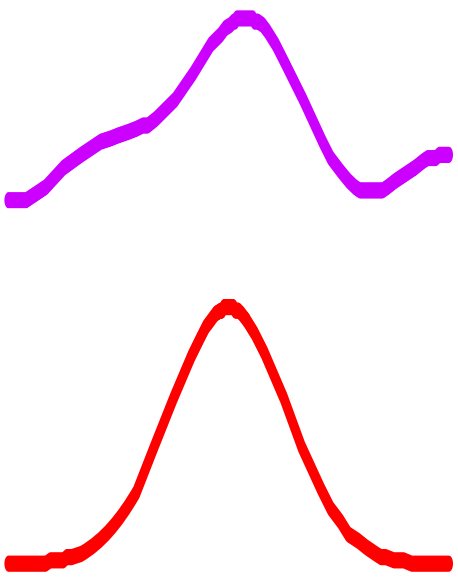
Astrophysics!

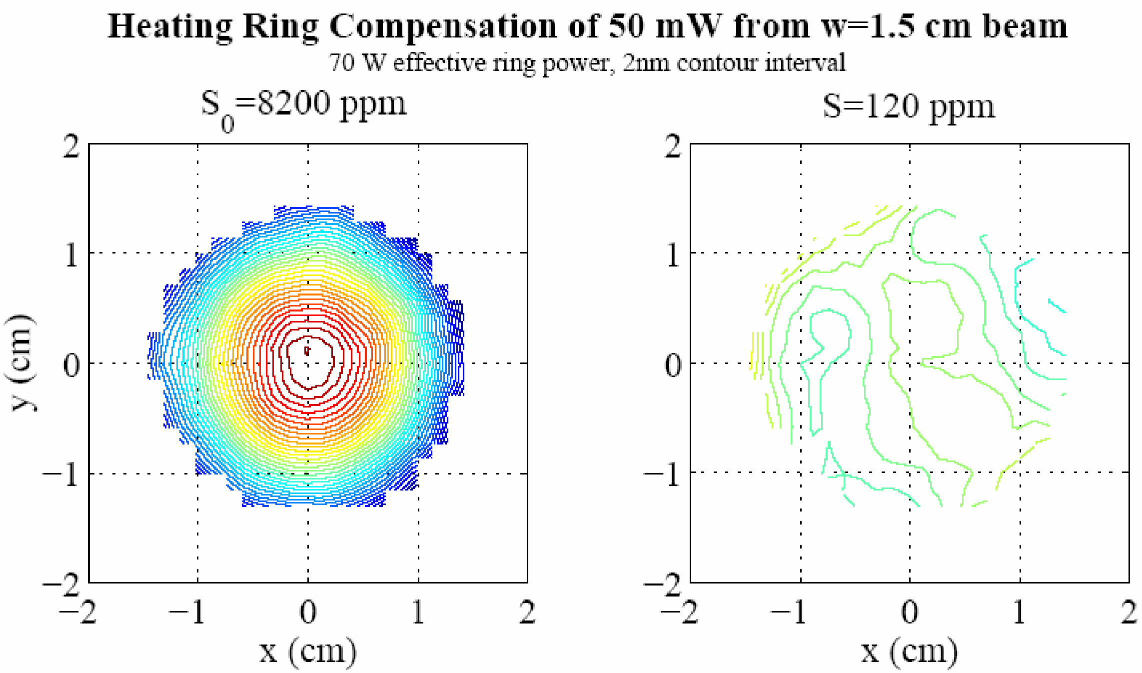
- Sapphire better at high frequency
- Silica better at low frequency
- *Which do you really want?*

	Silica	Sapphire
Binary NS Inspiral	191 Mpc	191 Mpc
Binary BH Inspiral	1050 Mpc	920 Mpc
Stochastic	2.6 X 10-9	4.8 X 10-9
Low Mass Xray Binary (750 Hz)	6.8 X 10-25	12 X 10-25

Thermal Lensing

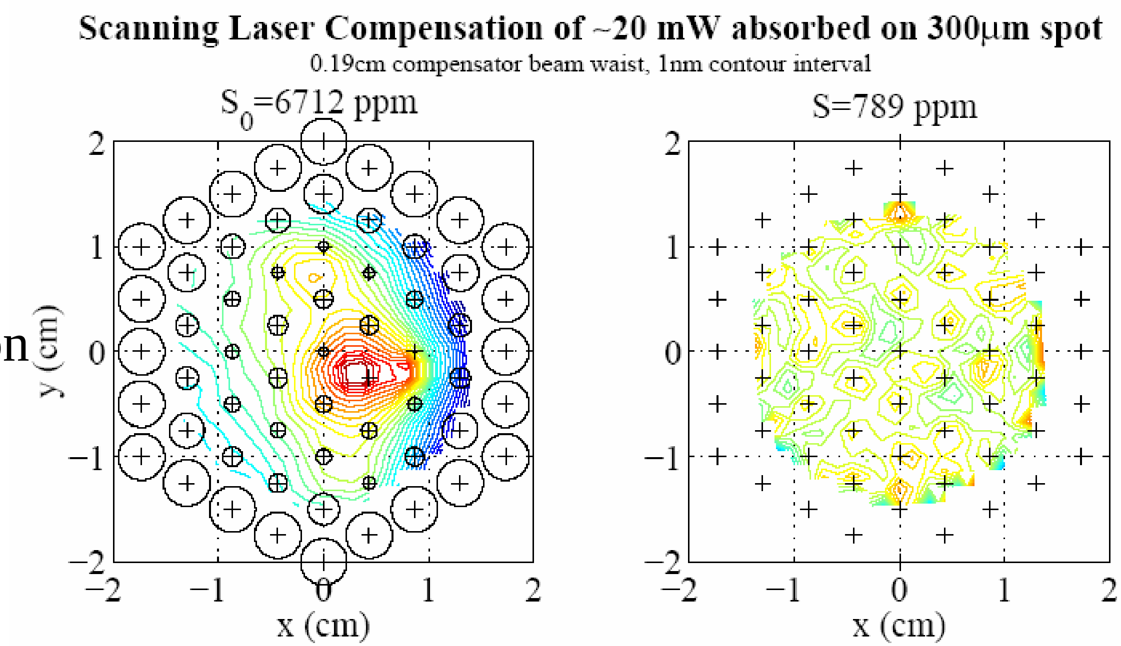
- Sapphire has higher thermal conductivity than silica- thus less thermal lensing.
- However, sapphire has higher absorption than fused silica. Still, there is less thermal lensing.
- However, sapphire absorption is highly inhomogeneous. Even though the thermal lensing is less it is harder to compensate.





best ring heater compensation

Ryan Lawrence's results



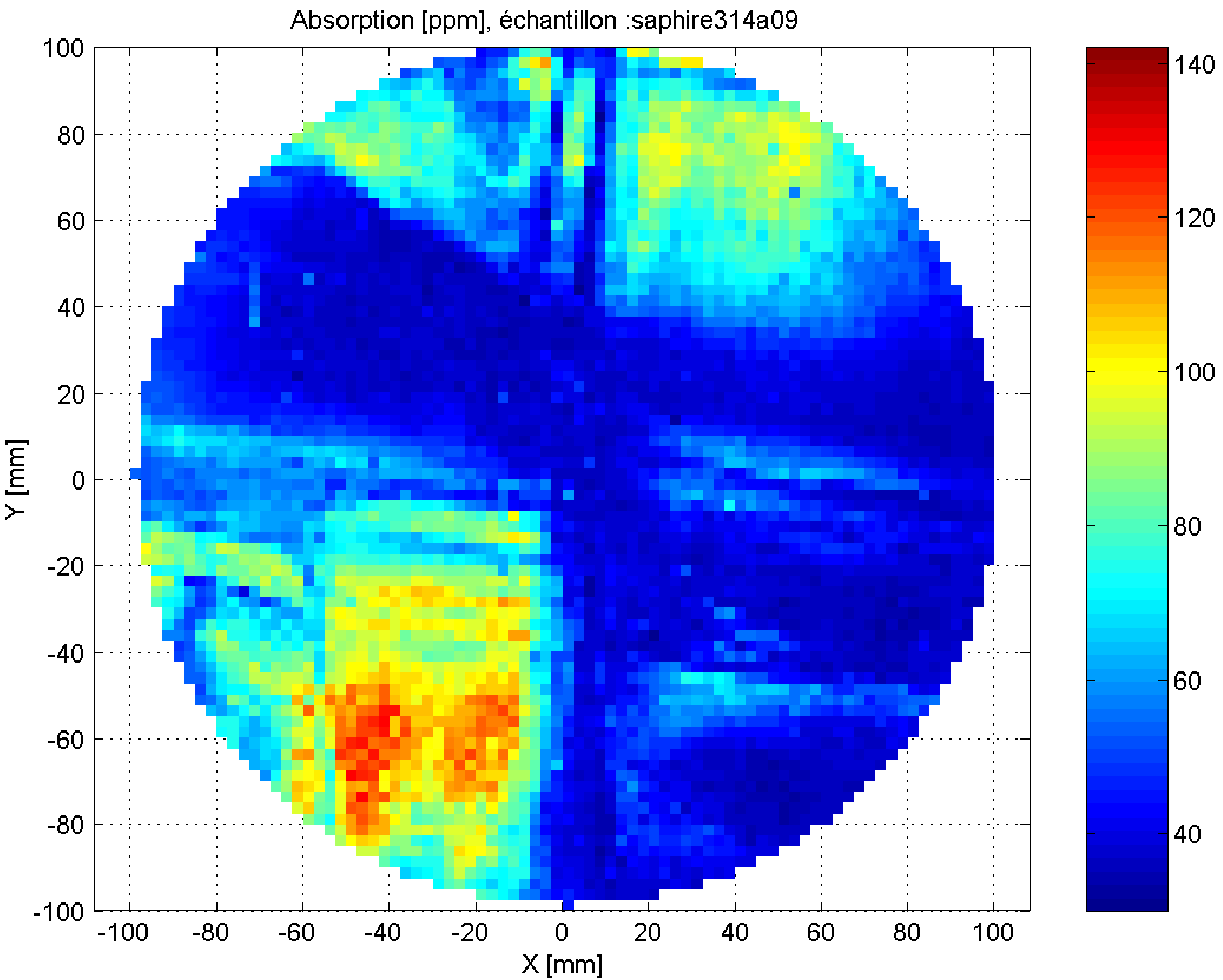
best scanning laser compensation

More about Coatings

- Coating sapphire is not as developed as coating silica
- Adhesion, scattering, absorption likely not as good
- SMA-Lyon is pessimistic about sapphire coatings

The Pathfinders

- Silica pathfinders of AdLIGO size were not manufactured, though technology seems straightforward (silica boules are huge)
  - » LIGO-size ITMs show very high Q, very low absorption, low scatter, good inhomogeneity, easy polish, etc.
- Several sapphire pathfinders were made, with mixed results
  - » Mechanical Q was high
  - » Barrel polish was rough
  - » Edges were chipped
  - » One sample had bubble inclusions and a pink cast
  - » Yield appears to be an issue

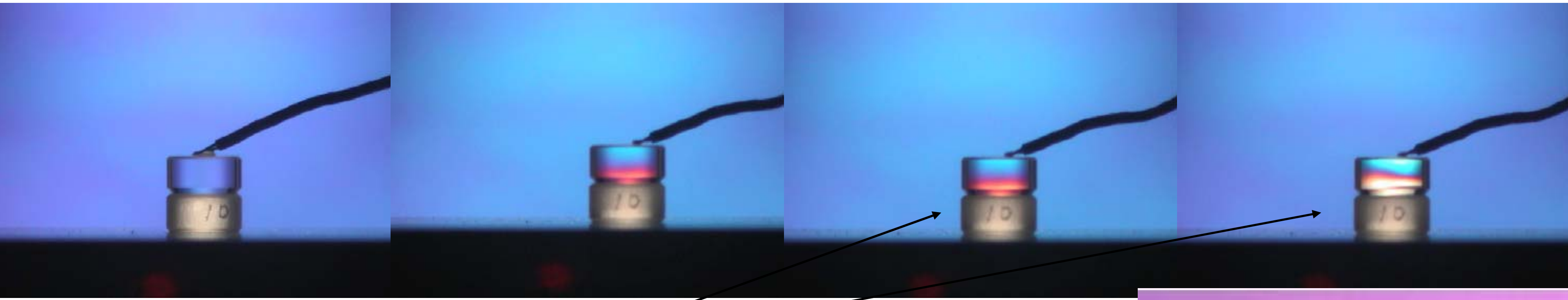

Absorption [ppm], échantillon :saphire314a09
Y [mm]
X [mm]
100
80
60
40
20
0
-20
-40
-60
-80
-100
-100
-80
-60
-40
-20
0
20
40
60
80
100
140
120
100
80
60
40

Other Factors

- Cost
  - » About the same either way
- Sources
  - » We have a backup for silica, not sapphire
- Delivery
  - » Silica clearly better- sapphire yield not great
- Polishing
  - » Fused silica demonstrably better- sapphire pathfinders have poor barrel polish and need more compensating polish of index inhomogeneities
- Scatter
  - » Okay either way
- Size, Suspension Issues, Control Issues
  - » Okay either way
- Birefringence
  - » Okay either way

Big Scary for Sapphire Silicate Bond Noise

- Bonding of sapphire to silica ears introduces differential thermal expansion, observed creep
- At what level are creak events observable?

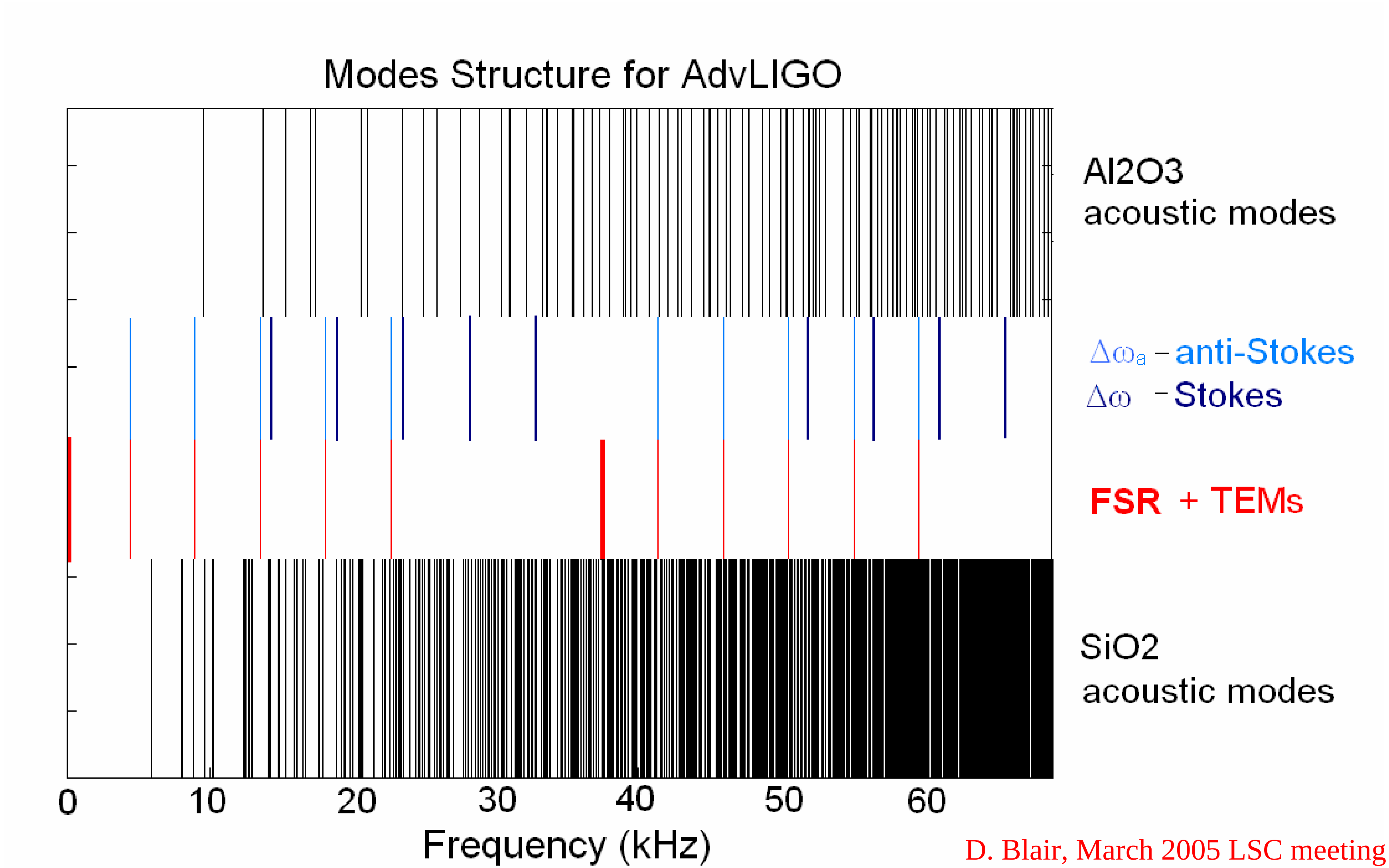


before heating

heating

after returning to room temperature

Big Scary for Silica
Radiation Pressure Instabilities



D. Blair, March 2005 LSC meeting

How Did We Try To Quantify All This?

		SAPPHIRE		SILICA		Weight
		value	normalized	value	normalized	
NSNS distance (MPC)						
	baseline	191	1.00	191	1.00	1.00
	optimistic	208	0.73	254	1.33	1.00
	pessimistic	165	1.12	153	0.89	1.00
10Ms BHBH distance (MPC)						
	baseline	923	0.82	1052	1.21	1.00
	optimistic	1016	0.52	1510	1.71	1.00
	pessimistic	762	0.97	775	1.03	1.00
LMXB at 730 Hz, $x10^{-25}$						
	baseline	6.8	2.64	12	0.48	1.00
	optimistic	4.5	2.20	7	0.54	1.00
	pessimistic	9.6	2.37	16	0.51	1.00
Stochastic background Ω, $x10^{-9}$						
	baseline	1.7	0.98	1.2	1.02	1.00
	optimistic	1.6	0.98	1.1	1.02	1.00
	pessimistic	1.7	1.01	1.9	0.99	1.00
Weighted astrophysical performance		1.28		0.98		

	Sapphire	Silica
fabrication of satisfactory substrates	0.85	0.98
polishing, also sides	0.77	0.93
coating, also adhesion	0.8	0.85
bonding suspension 'ears'	0.85	0.92
managing Stokes instability	TBD	TBD
electrostatic charging	0.85	0.9
PRODUCT of success measures	0.52	0.77

	Sapphire	Silica
fabrication of satisfactory substrates	0.8	0.98
polishing, also sides	0.57	0.87
coating, also adhesion	0.98	0.98
bonding suspension 'ears'	0.95	0.95
managing Stokes instability	TBD	TBD
electrostatic charging	TBD	TBD
PRODUCT of success measures	0.42	0.79

	Sapphire	Silica
second interferometer at a site	0.9	0.9
suspension design	0.85	0.9
thermal compensation	0.86	0.17
angular instability	0.85	0.9
fallback to the alternative substrate	TBD	TBD
PRODUCT of success measures	0.56	0.12

…and at this point we sort of gave up on this approach.

In the end, sapphire just didn’t seem worth the switch.