Thermal Noise Reduction in Future Gravitational Wave Interferometers

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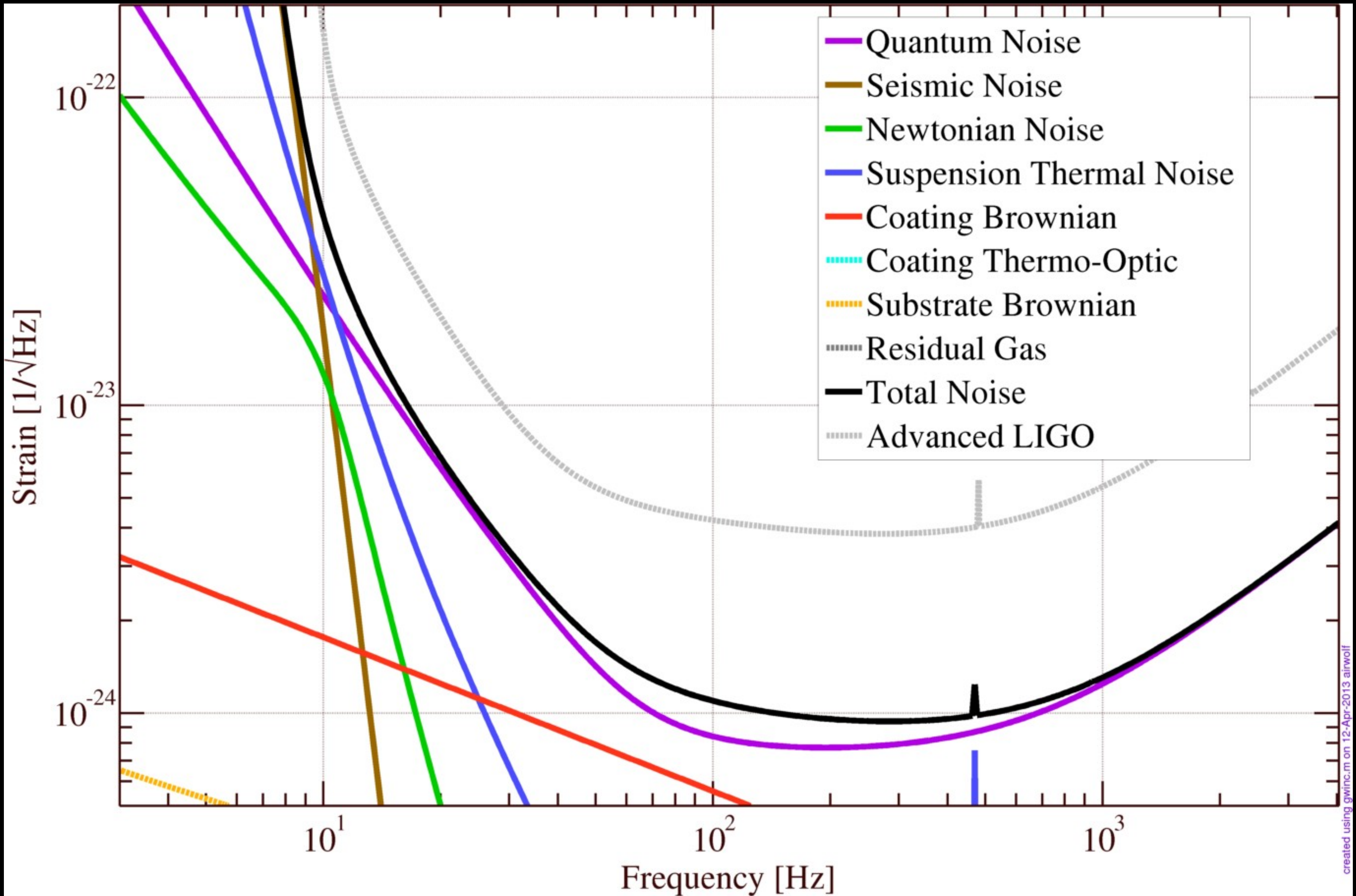
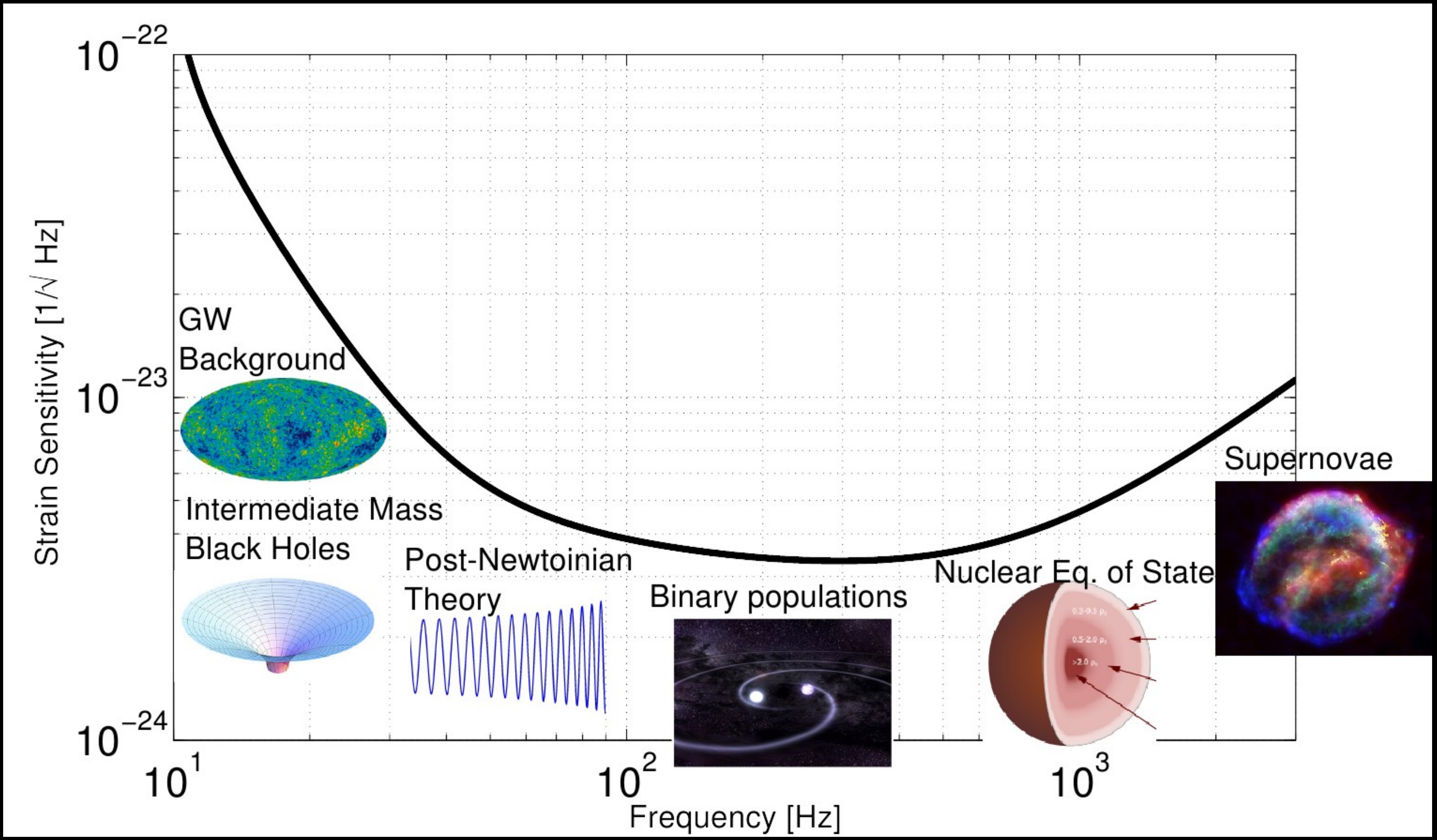
April APS 2013

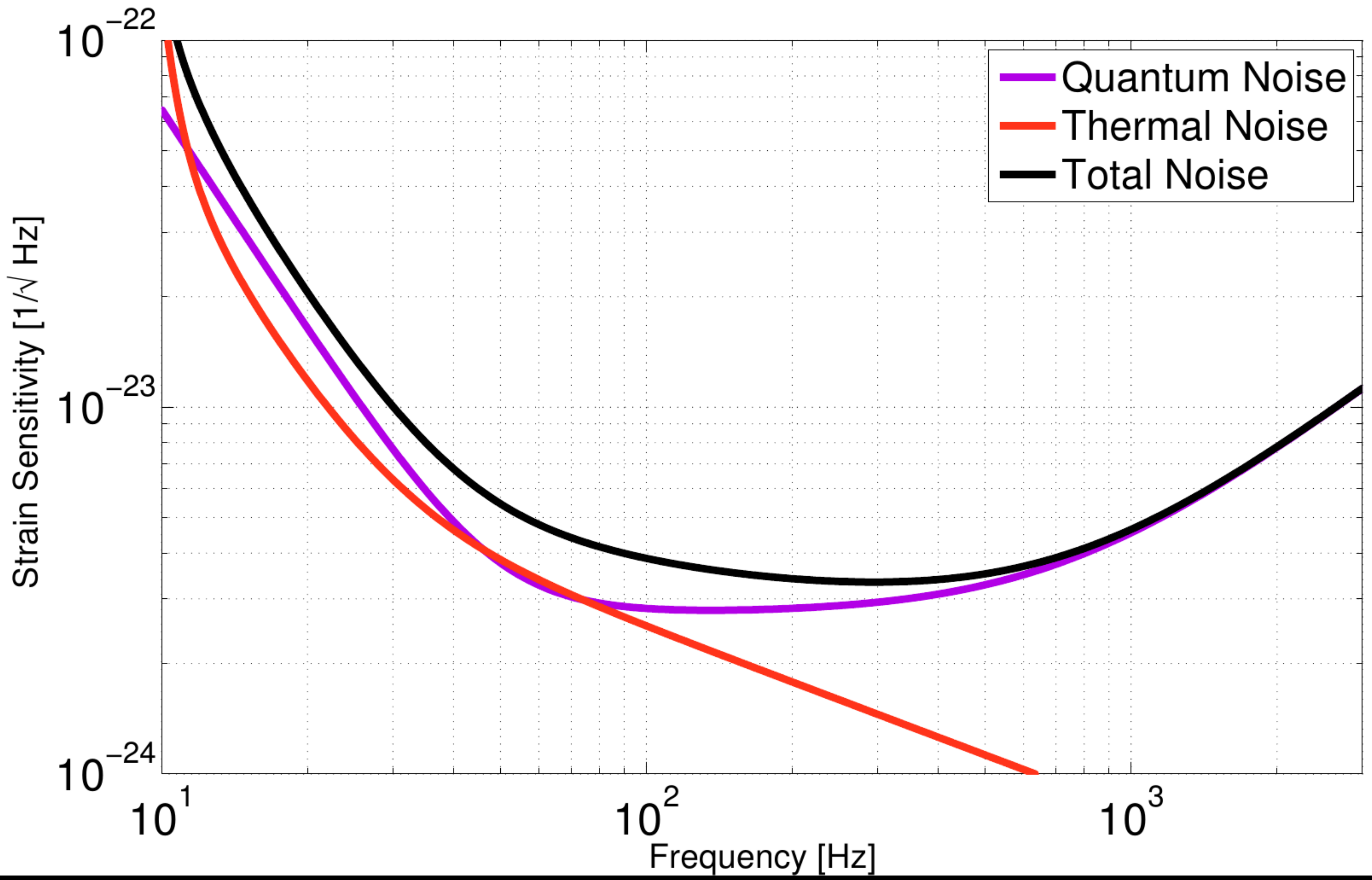
Punch line first



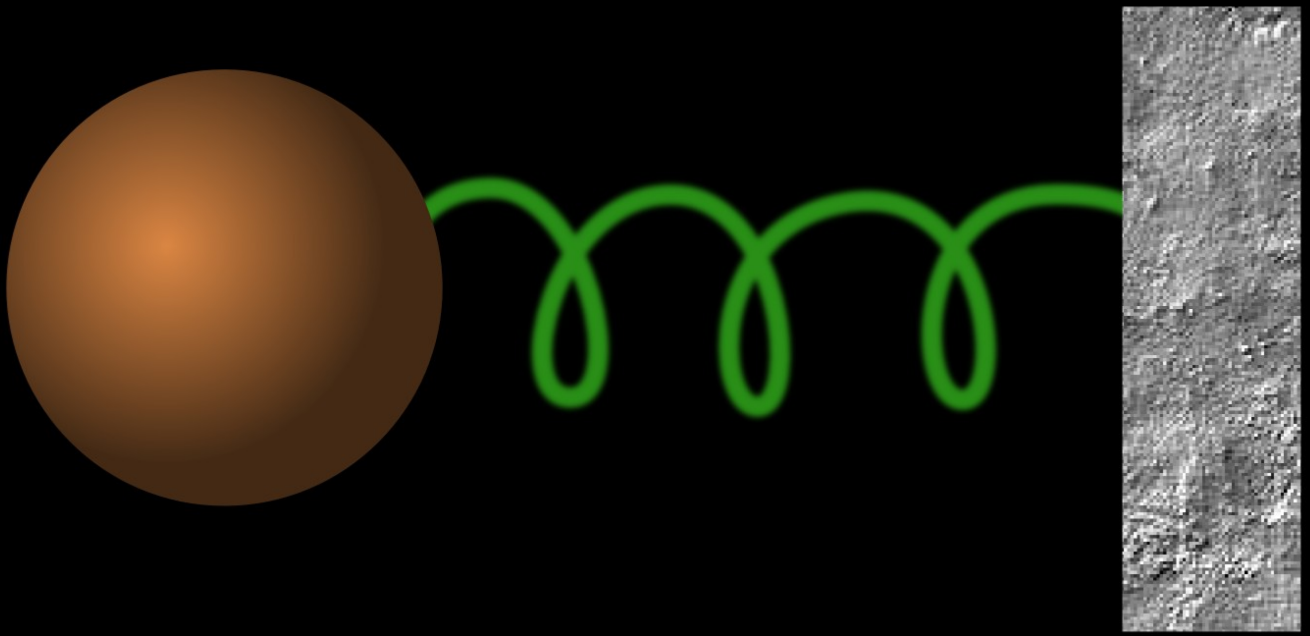
Astrophysical benefits beyond Advanced LIGO

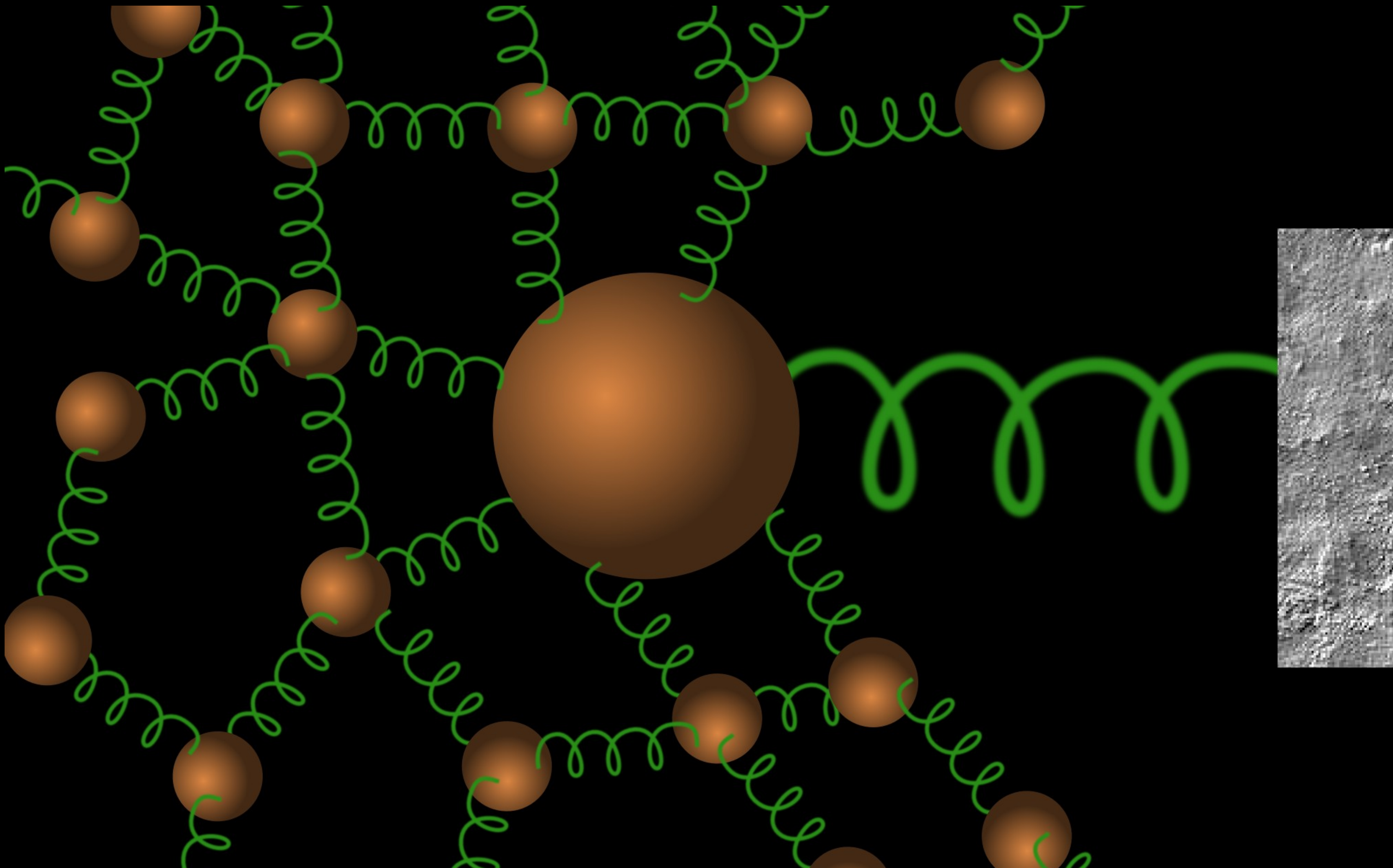


Advanced LIGO Noise



Thermal Noise, a physics lesson





Fluctuation-Dissipation Theorem

- The FDT tells us that thermal fluctuations are closely related to friction

$$\left\langle x_{\mathrm{th}}^2 \right\rangle \propto \frac{T}{Q}$$

- Q is the mechanical quality factor (inverse of fractional energy lost after one oscillation)

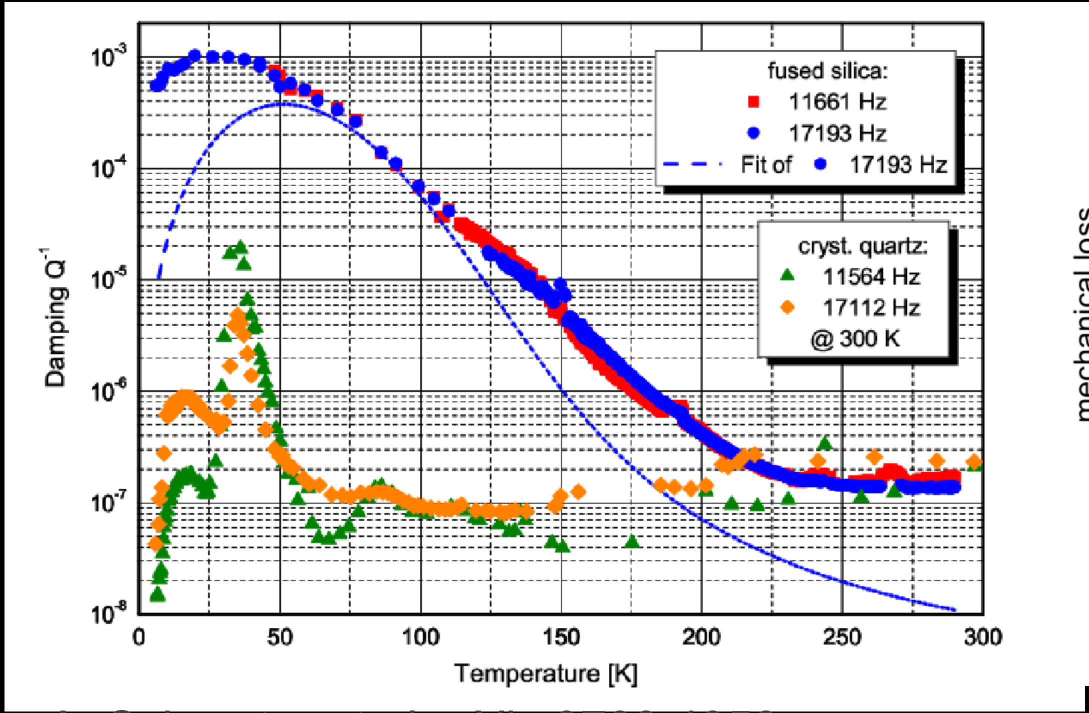
FDT explains...

- Johnson-Nyquist noise in electronic systems
- Brownian motion of particles in fluids
- Blackbody radiation
- Quantum noise...

T and Q are not independent

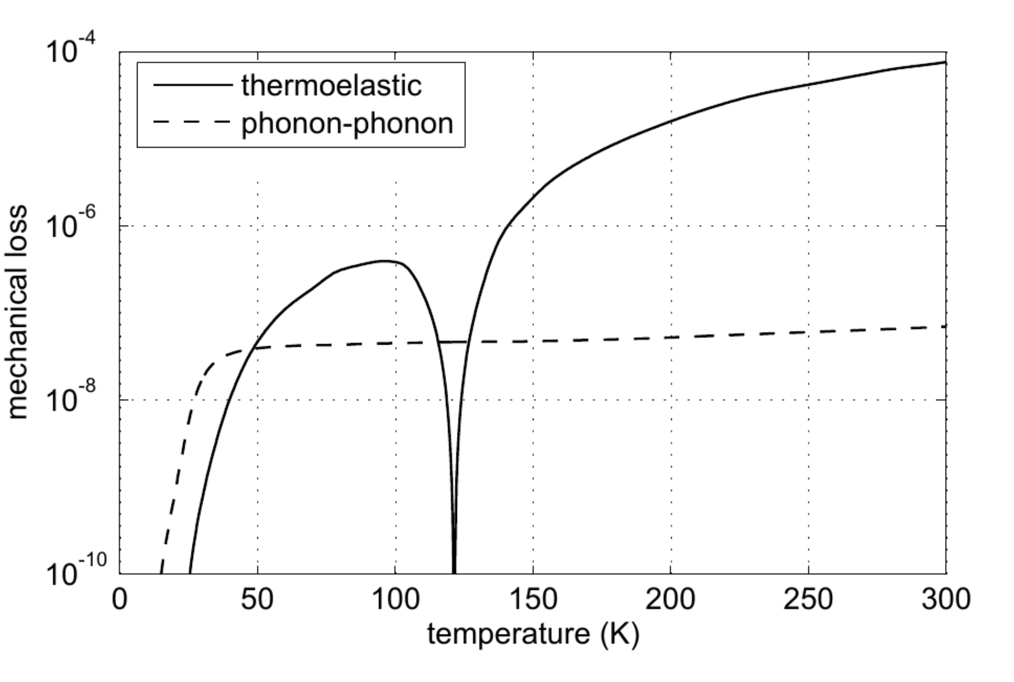
- Silica gets worse at low temperatures
- Thermoelastic (Zener) damping

- Silica loss v T



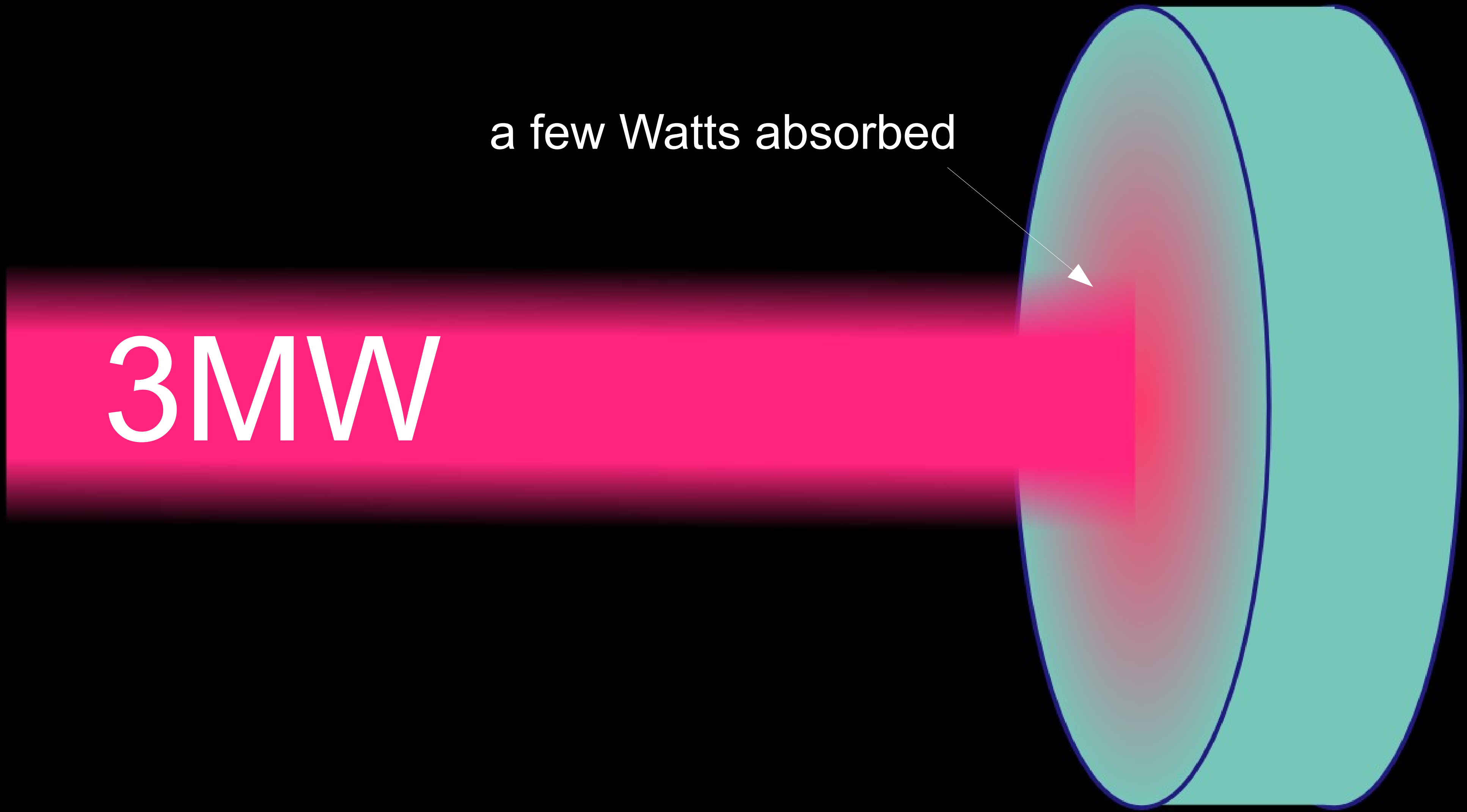
A. Schroeter et al arXiv:0709.4359

- Silicon loss v T

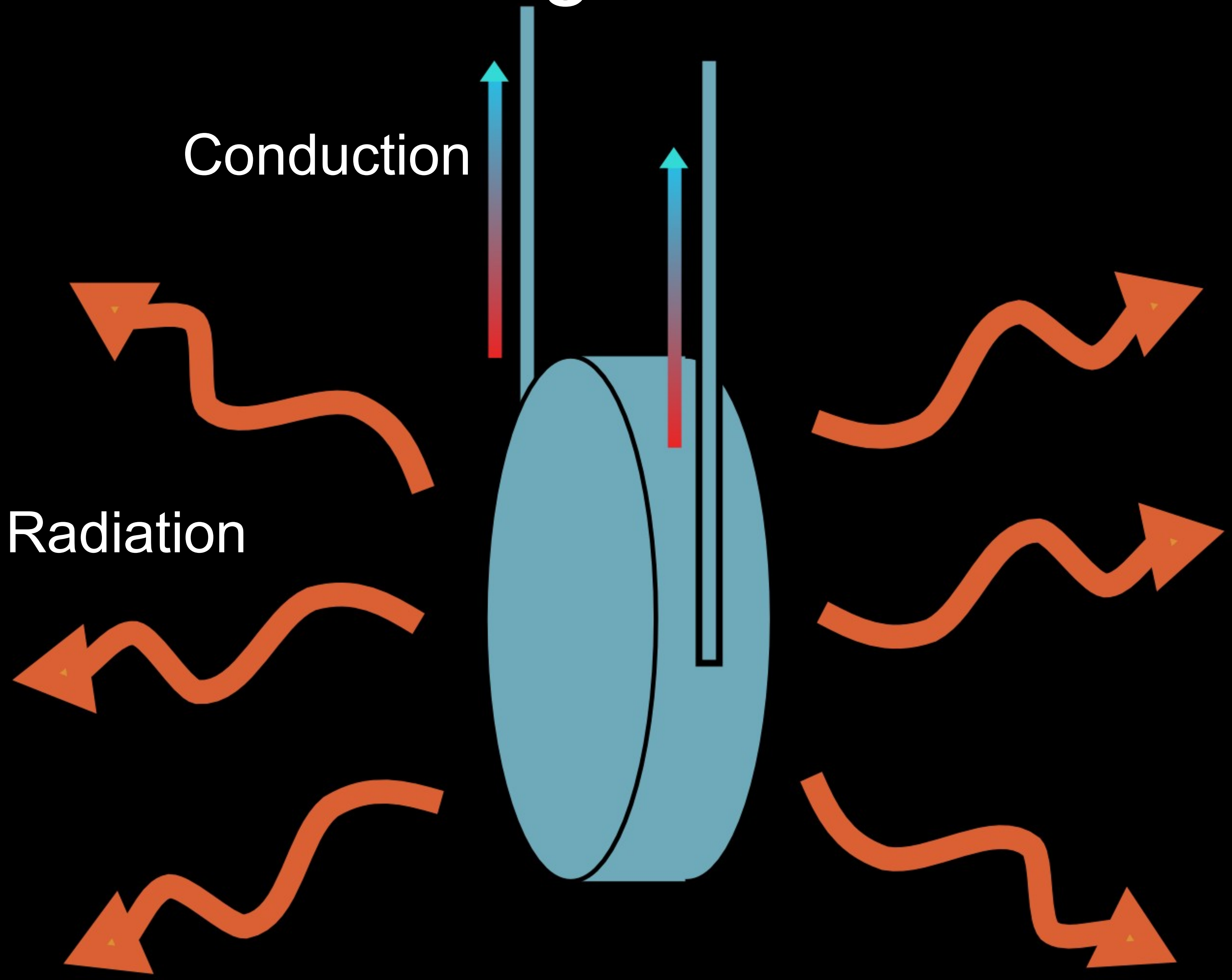


R. Nawrodt et al arXiv:1003.2893

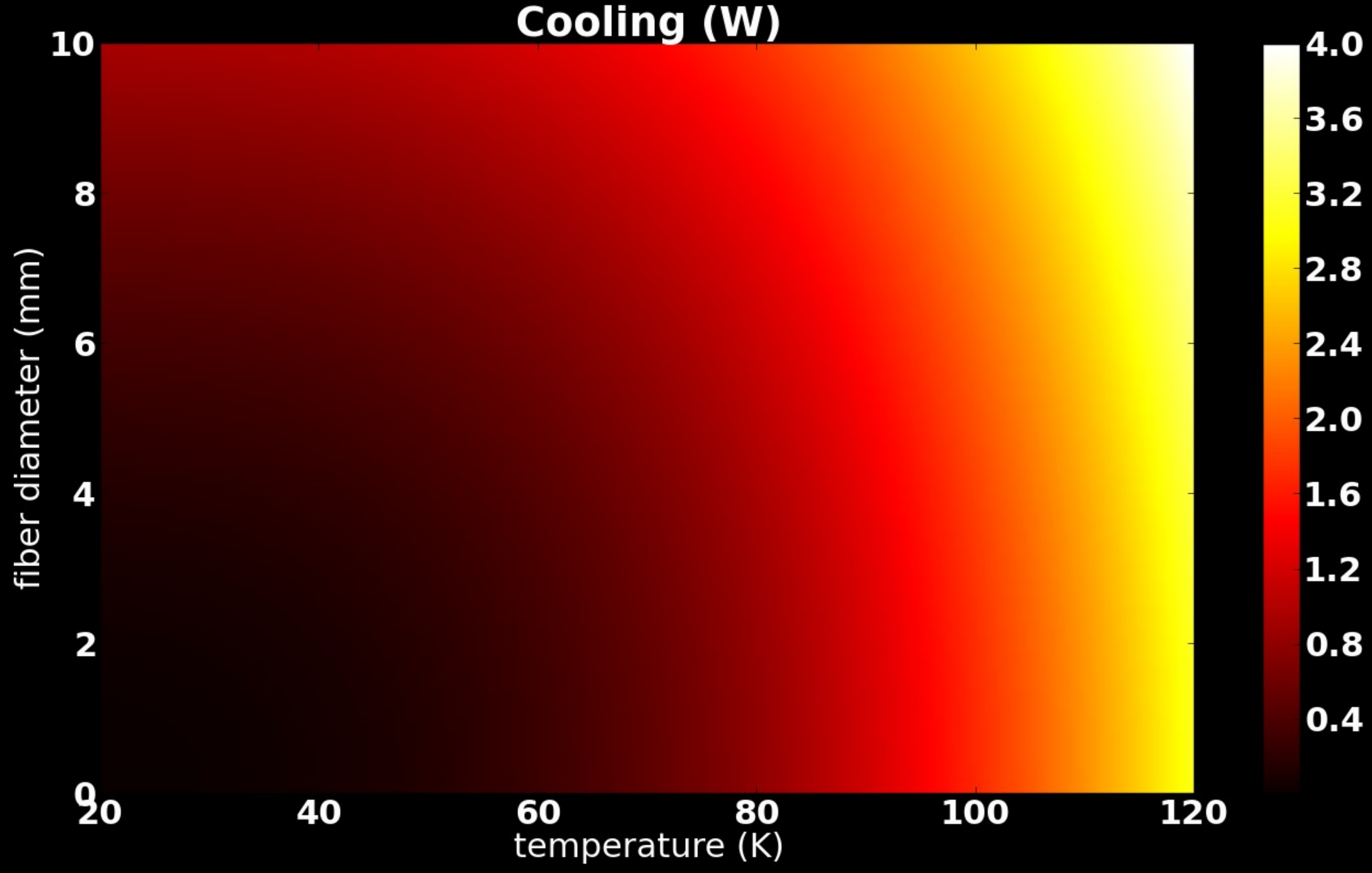
Cryogenics in Gravitational Wave Interferometers: the cooling problem



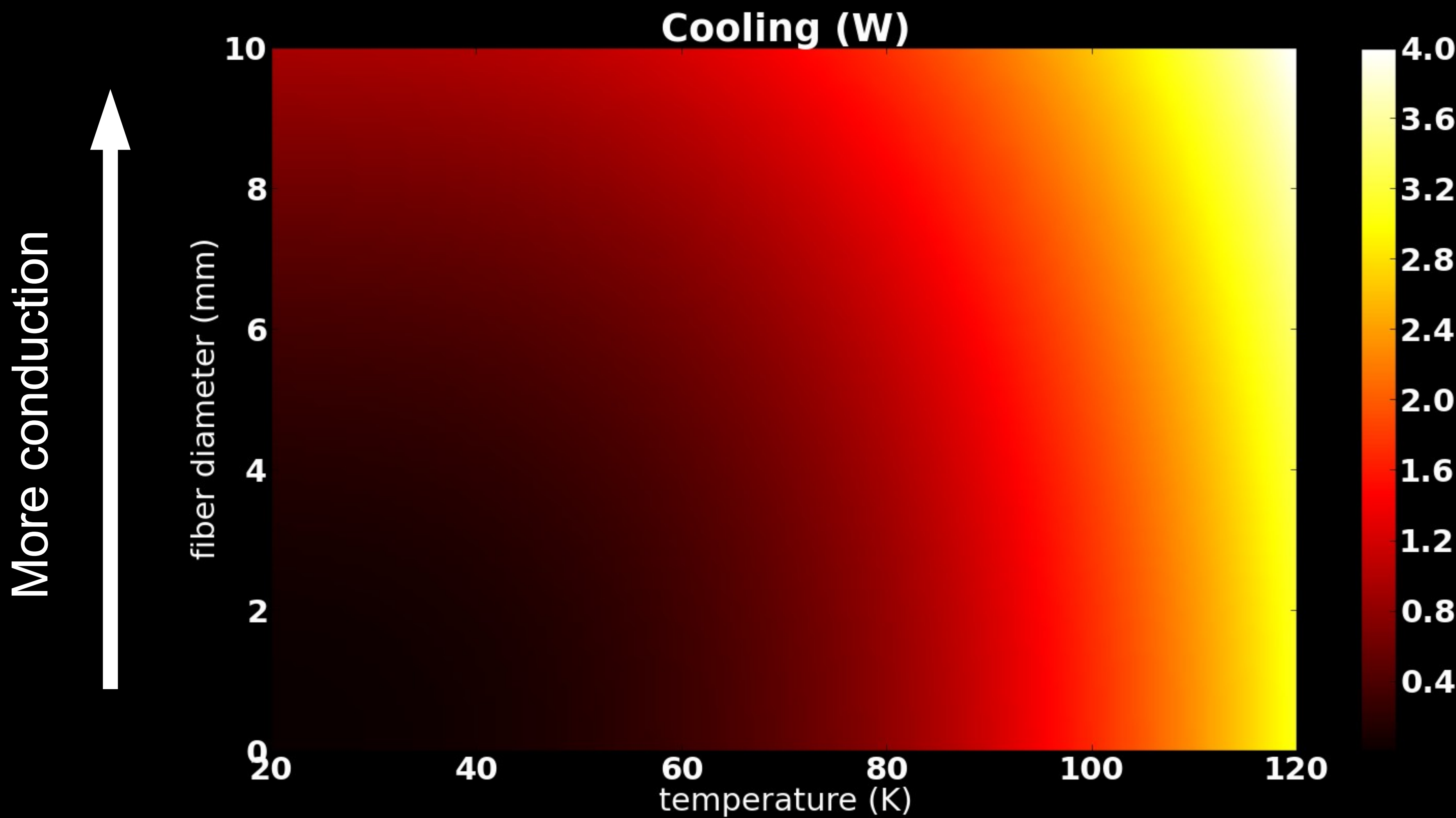
Cooling methods



Cooling power as a function of fiber diameter and temperature

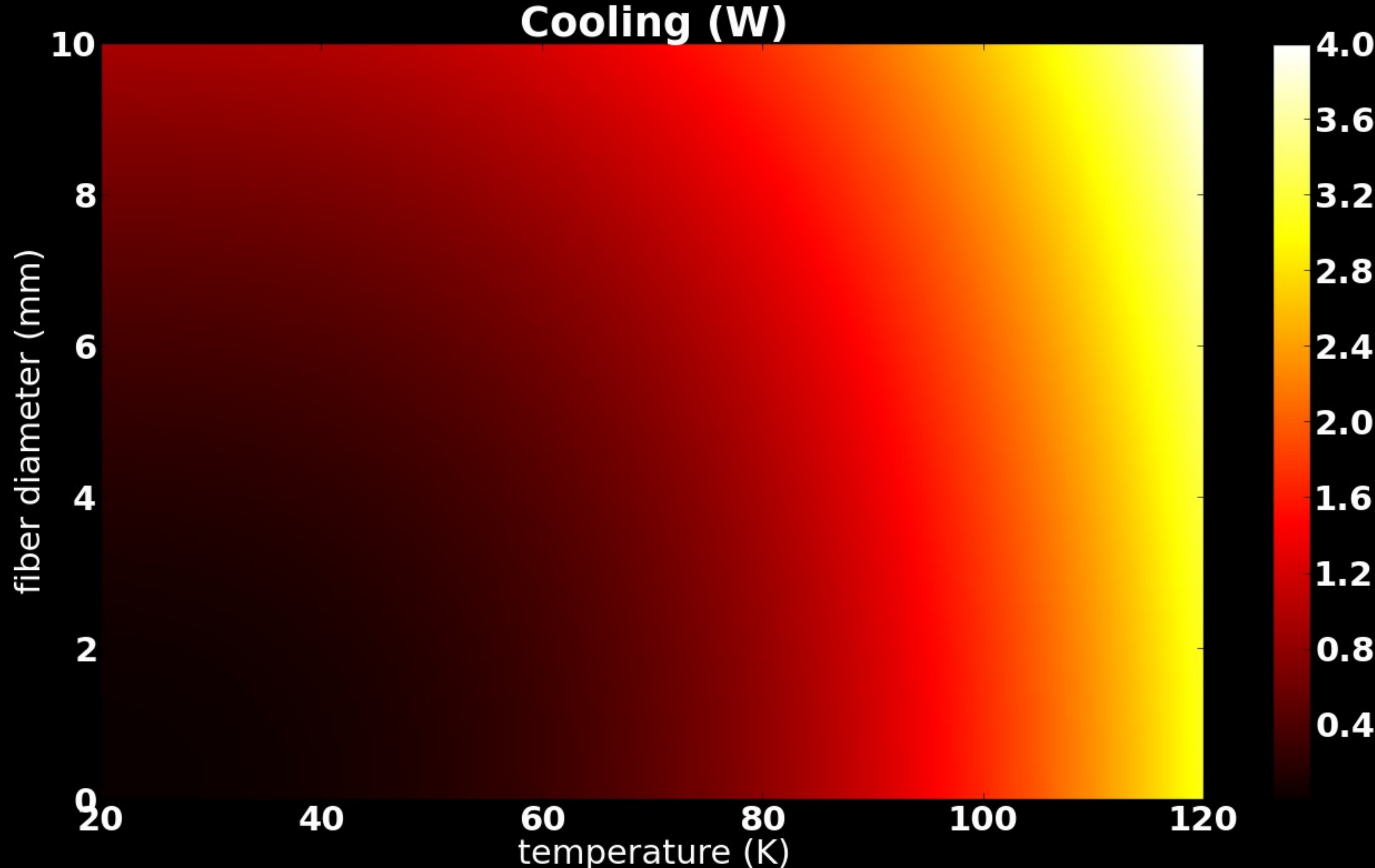


Cooling power as a function of fiber diameter and temperature



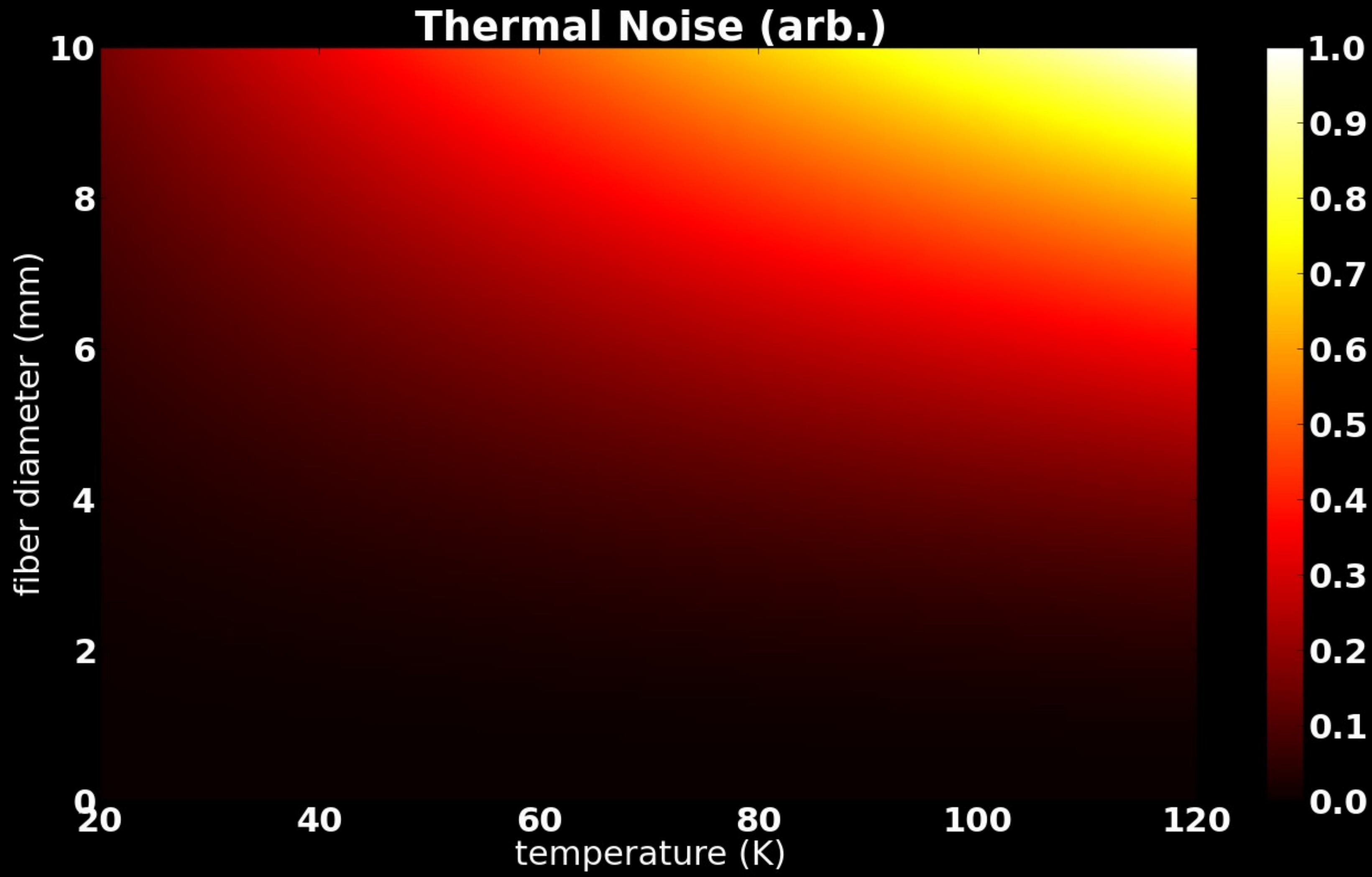
Cooling power as a function of fiber diameter and temperature

More conduction

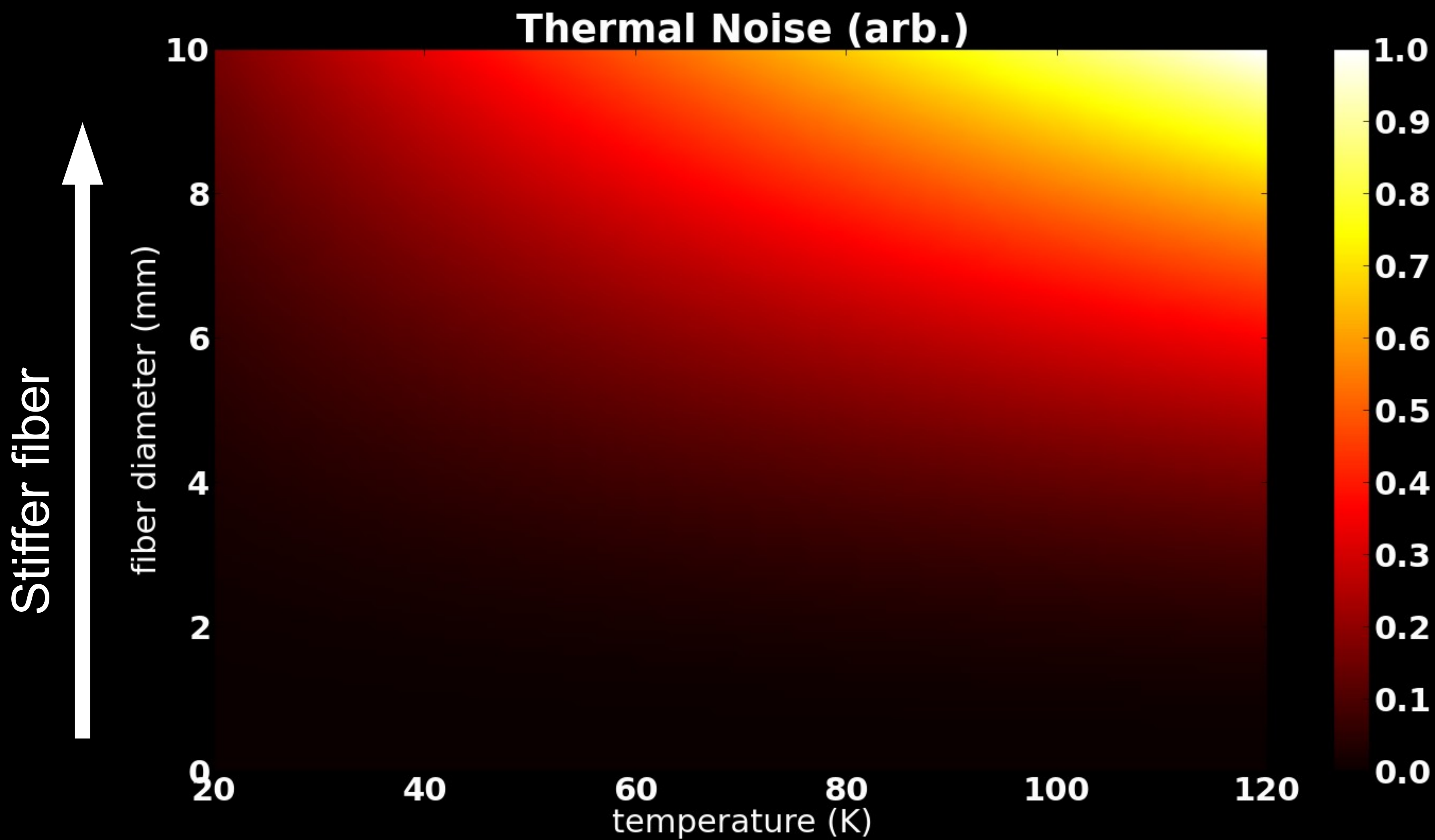


More radiation

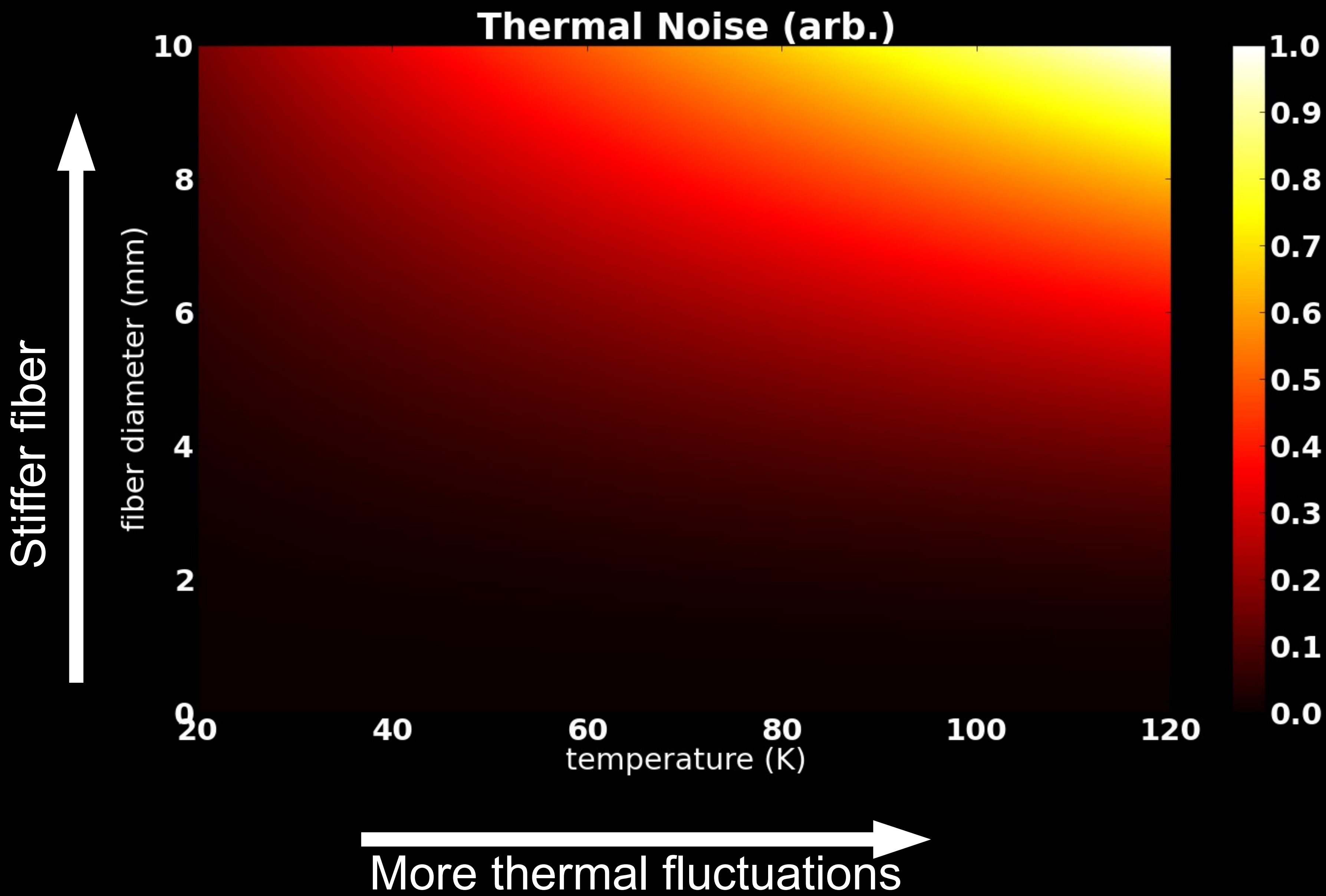
Thermal Noise as a function of fiber diameter and temperature



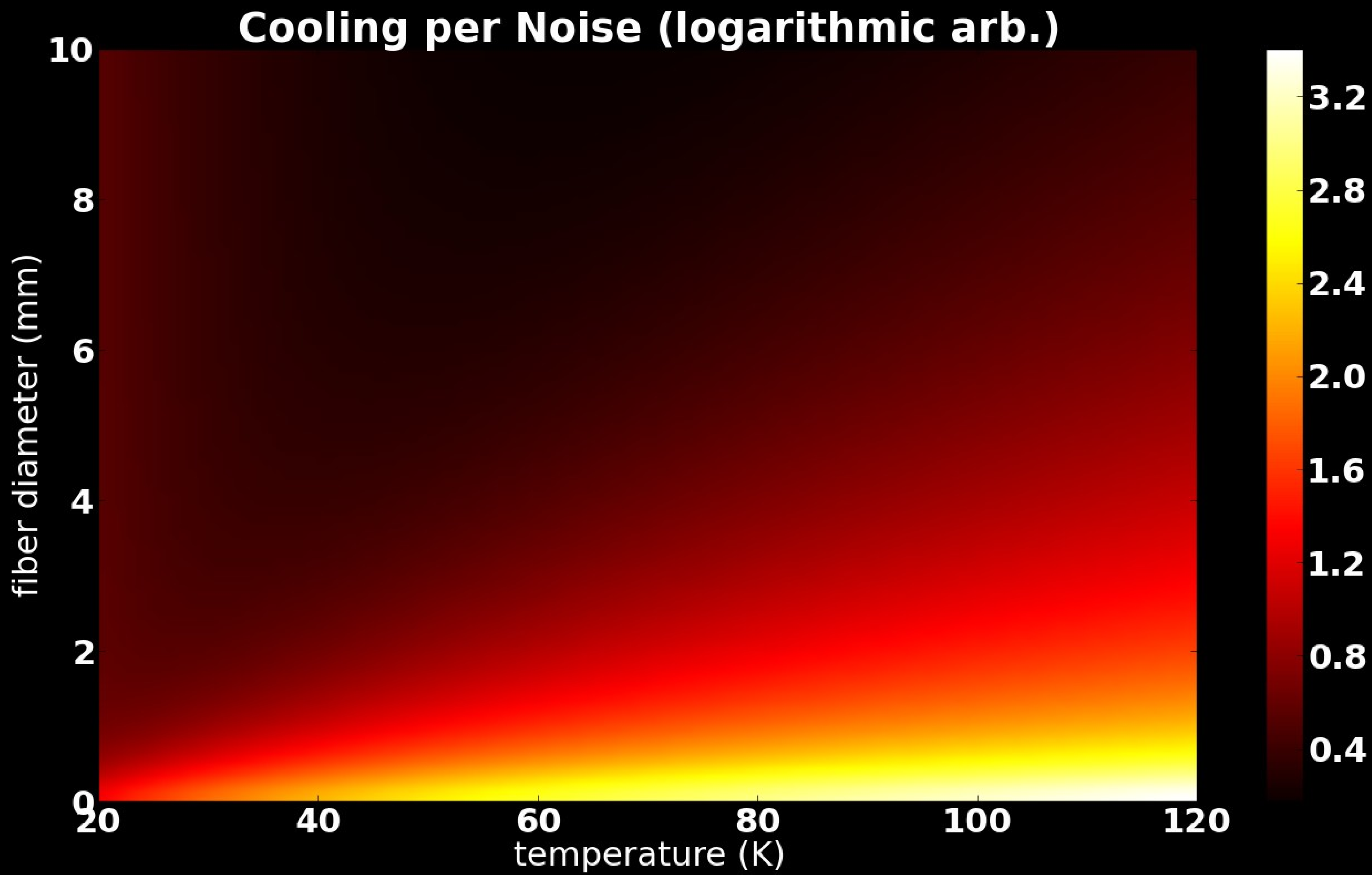
Thermal Noise as a function of fiber diameter and temperature



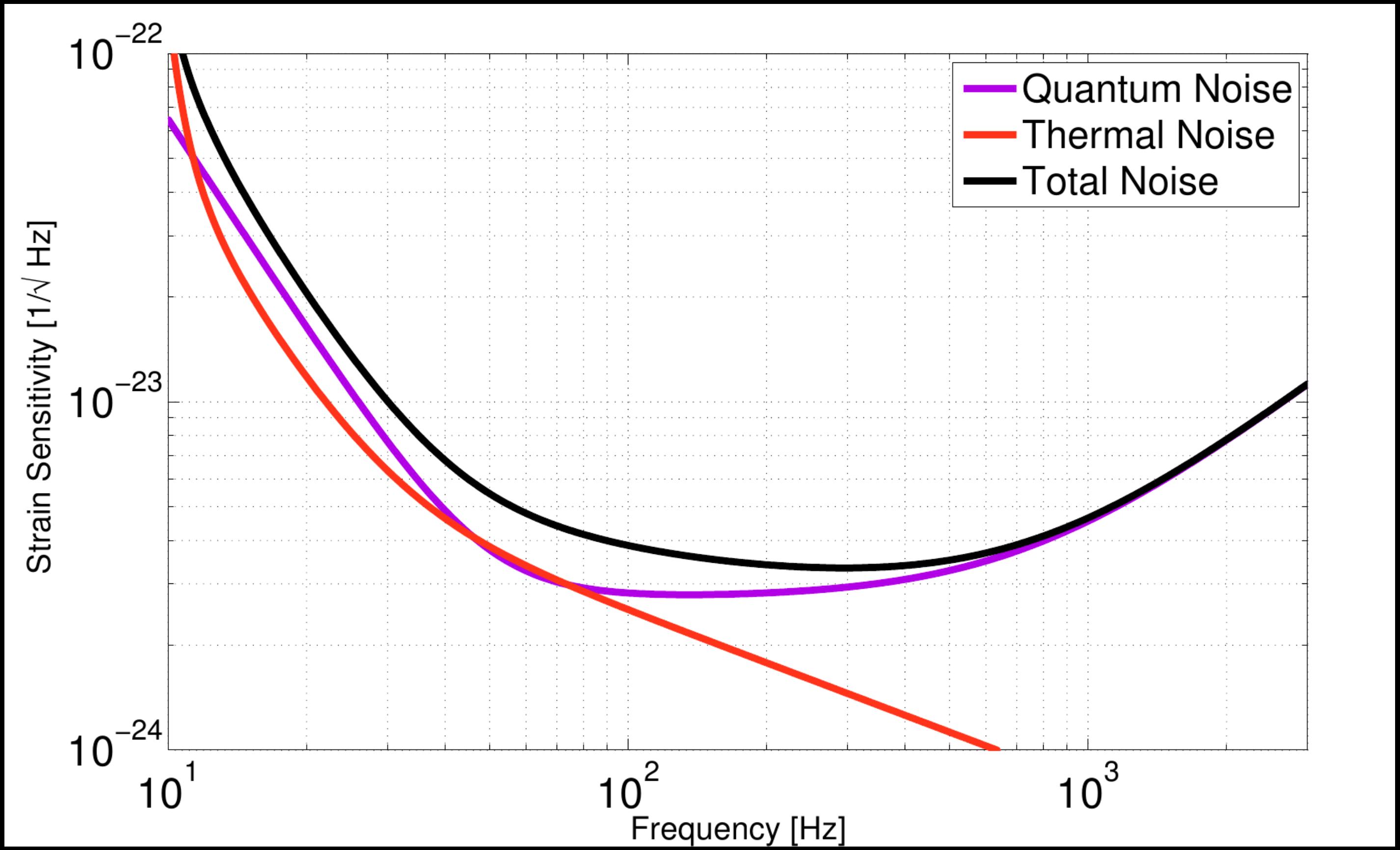
Thermal Noise as a function of fiber diameter and temperature

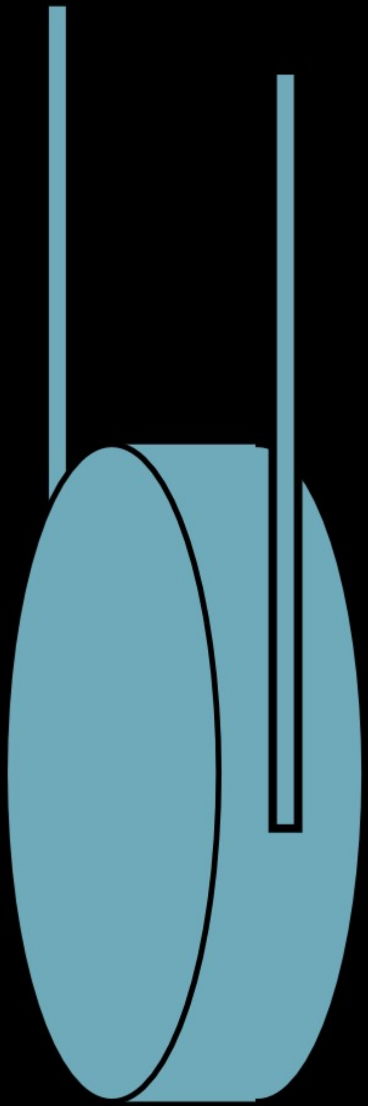


Cooling vs Noise trade-off



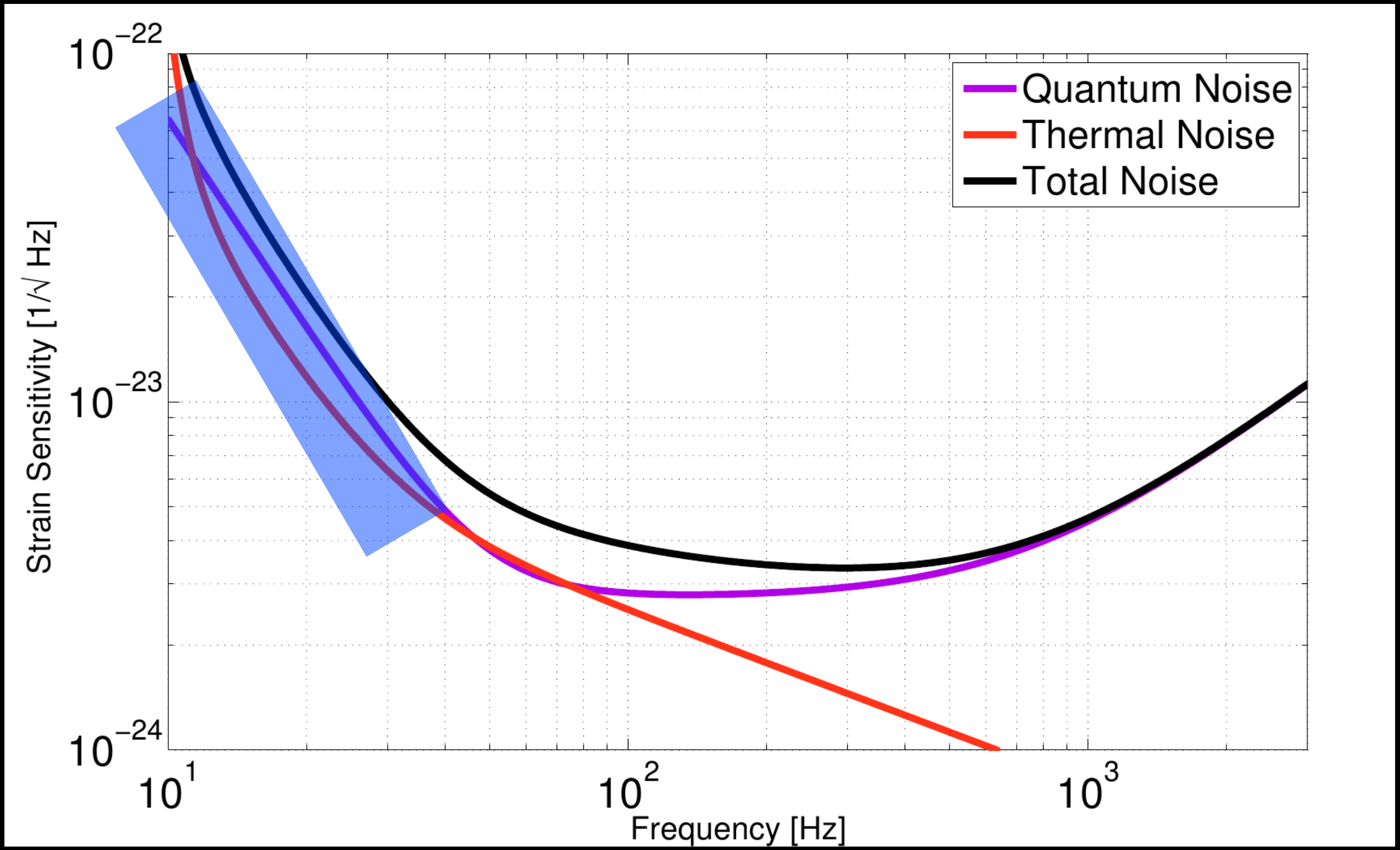
Primary sources of thermal noise

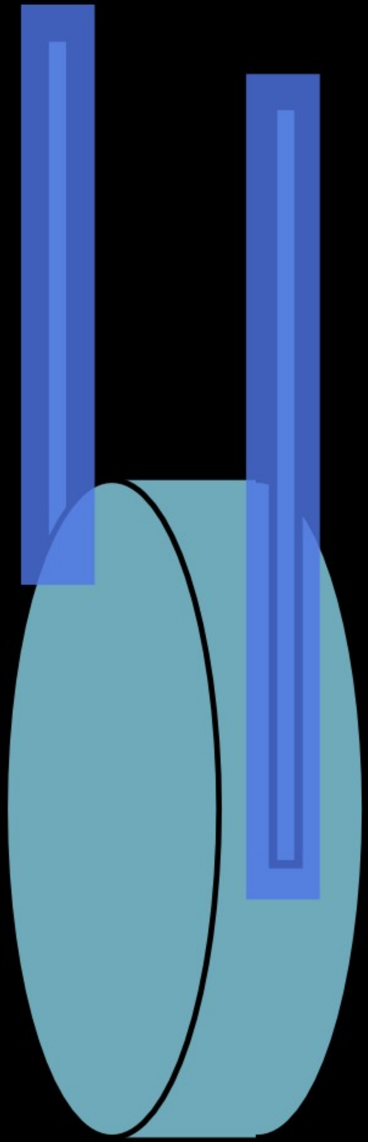




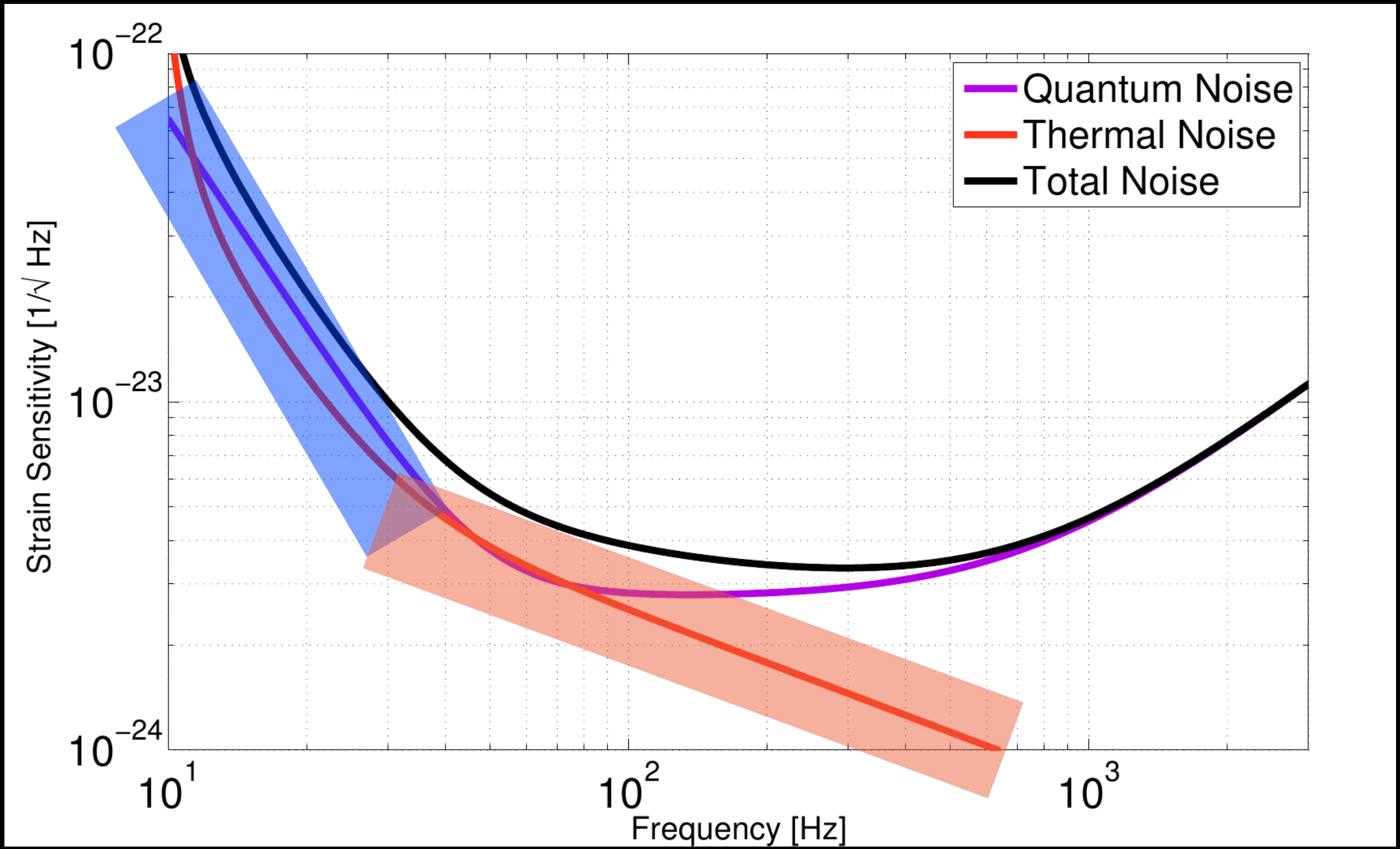
Primary sources of thermal noise

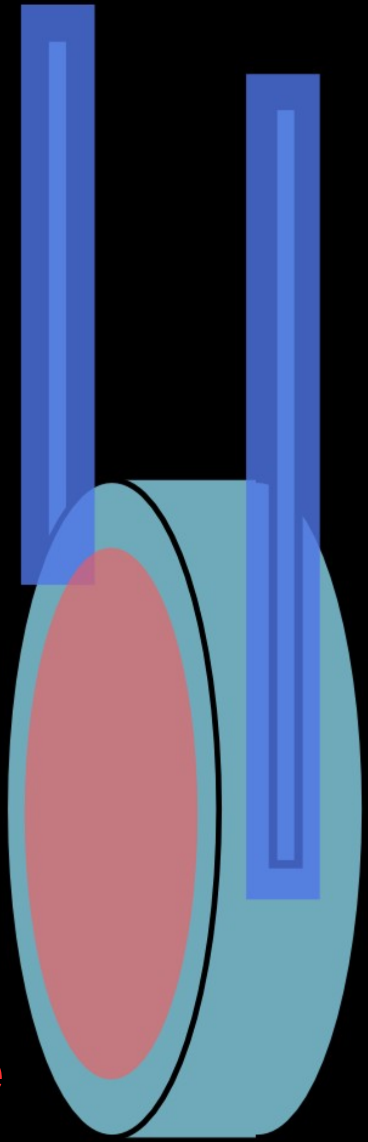
Suspension Thermal Noise





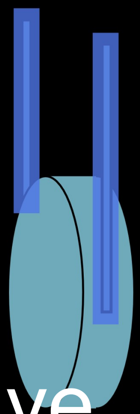
Primary sources of thermal noise





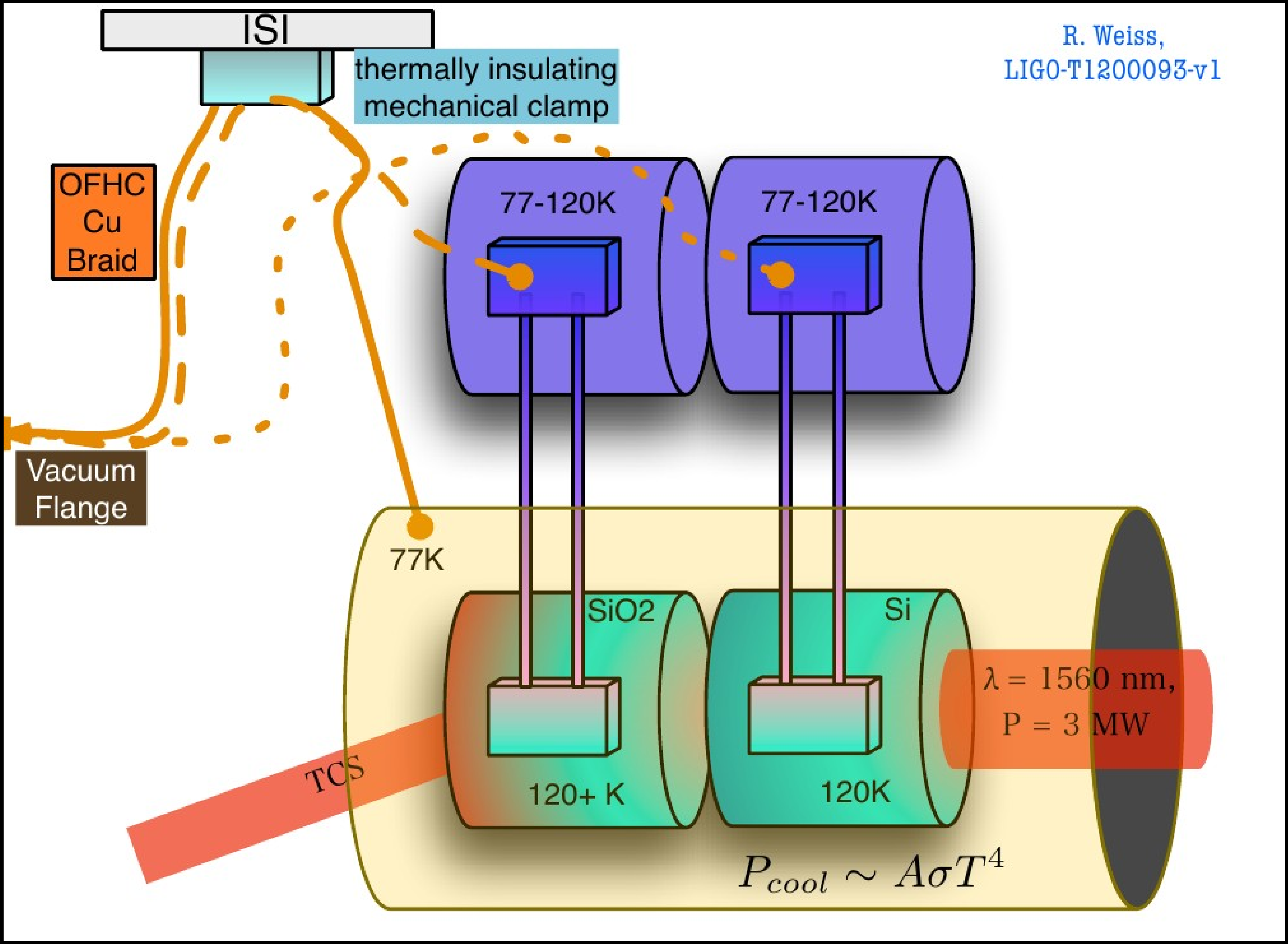
Coating Thermal Noise

The Silicon Bullet

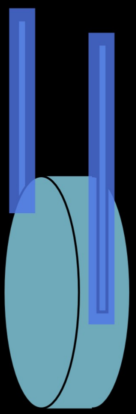


- Very low intrinsic loss at 124K, where radiative cooling is still feasible
  - Zero crossing of thermal expansion coefficient, so no Zener damping
- Large thermal conductivity (10W/cmK), low thermal distortion, lots of circulating power in the arms
  - Fused Silica is limited to <1MW, (1000 times worse conductivity)
- Requires move to 1550nm laser, squeezed light research maturing rapidly (12dB at high-f)

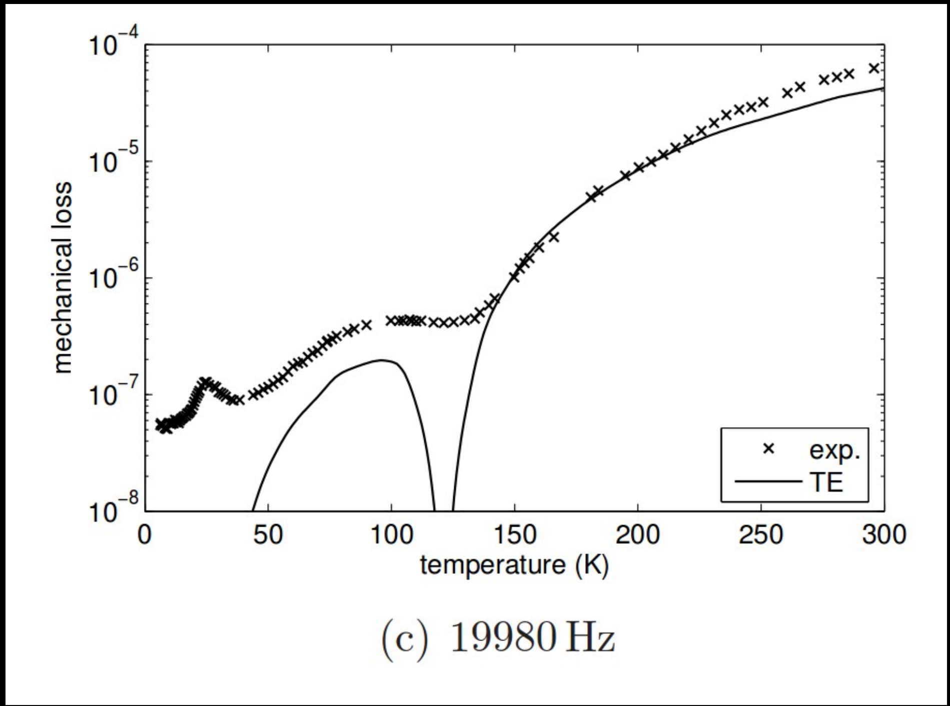
Cryogenic Silicon Suspensions



Losses in Silicon Samples @Jena/Glasgow/Moscow



- Losses in silicon samples still limited by surface quality or other dirty physics
- More tests required to hit the true loss limit



(c) 19980 Hz

Silicon Cantilever @ Jena/Glasgow
Nawrodt et al. arXiv:1003.2893

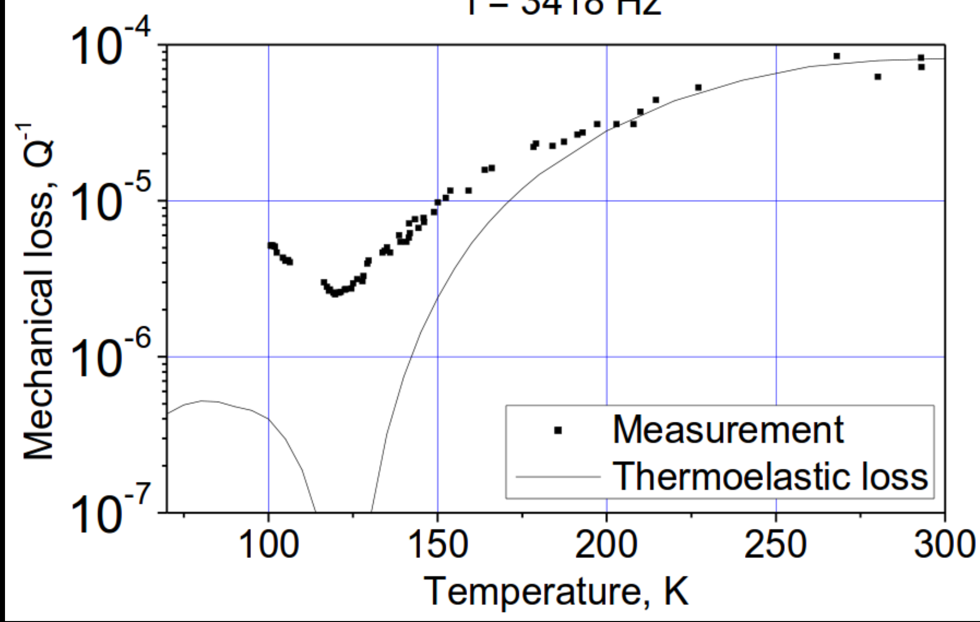
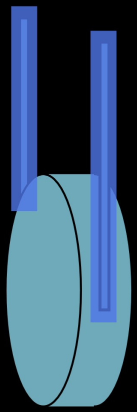


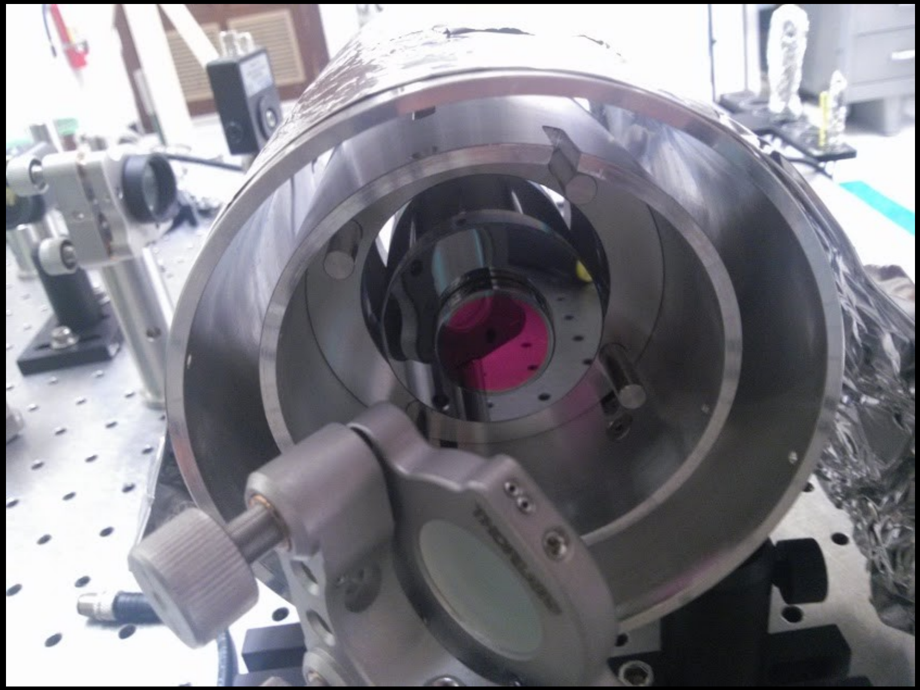
Fig 3.

Silicon Wafer @ Moscow
Prokhorov, Mitrofanov

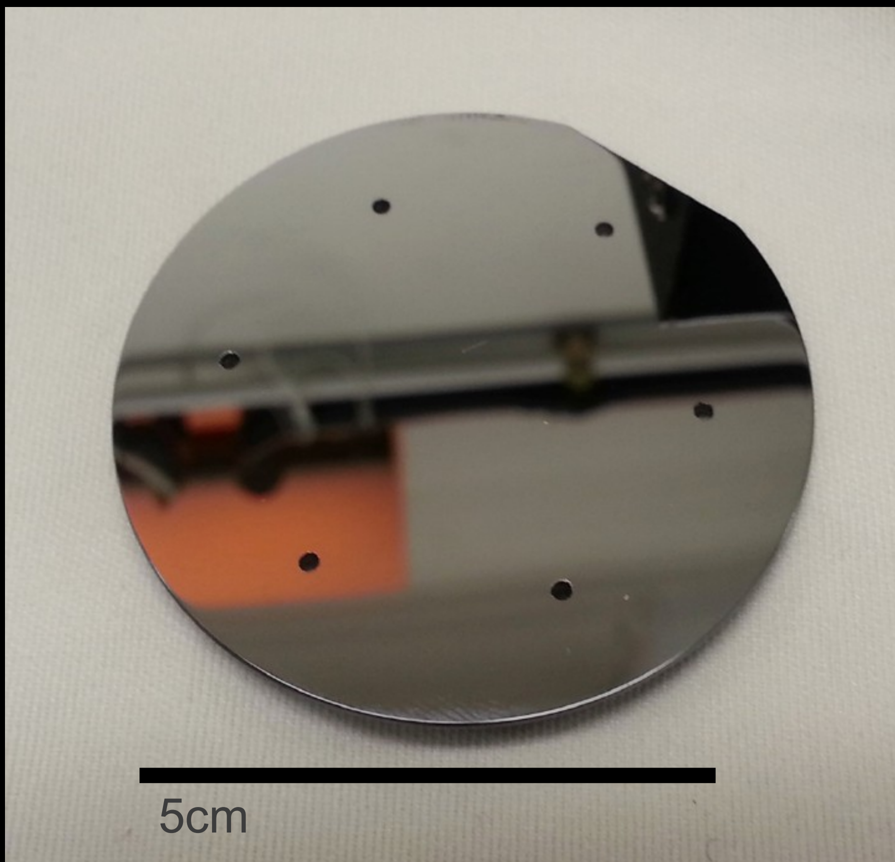
Cryogenic Reference Cavities @Caltech

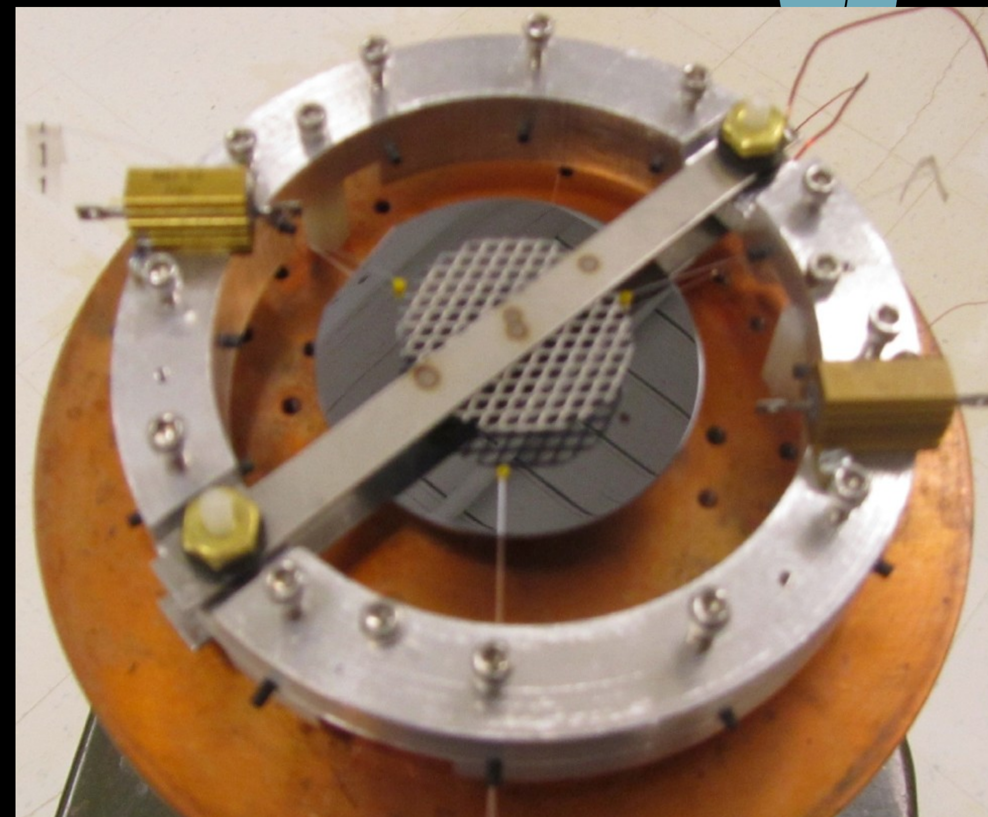


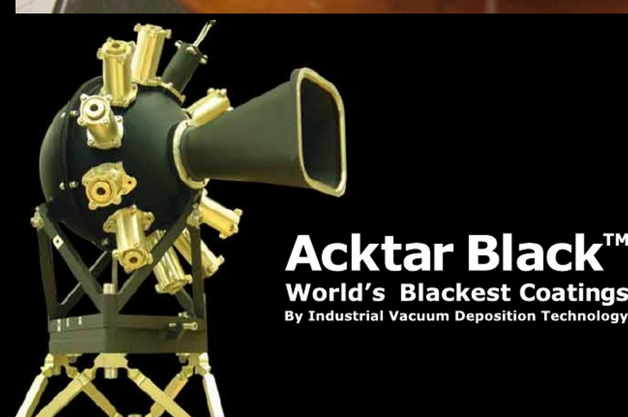
- Provides experience for many relevant technologies
- Ultra-stable DC frequency reference
- Potentially interesting system for studying macroscopic quantum mechanics



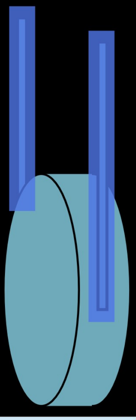
High emissivity coating experiment @MIT



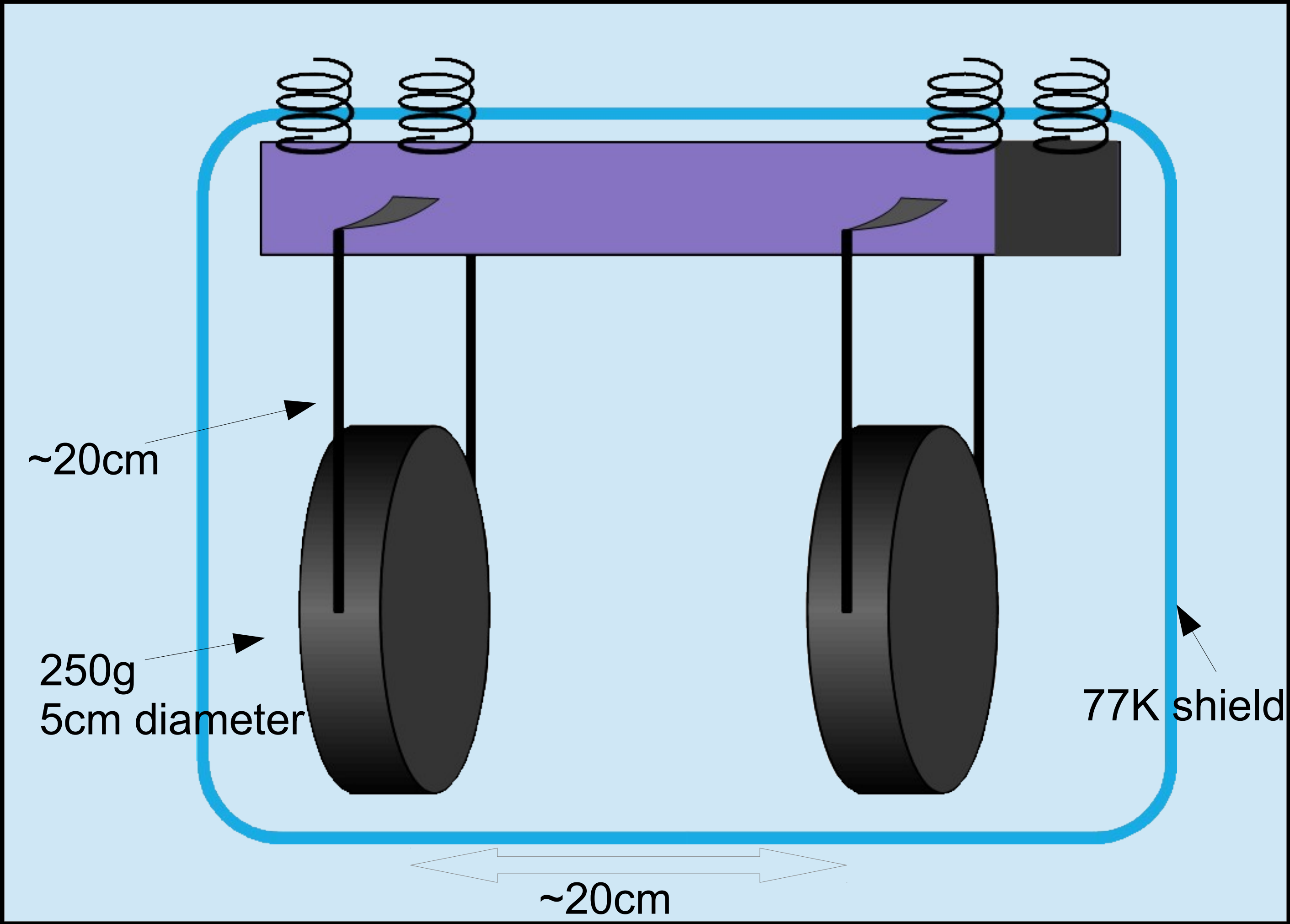




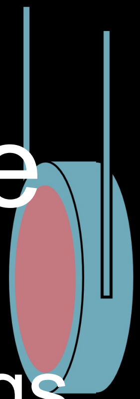
Prototype Suspension Test @Caltech



- Early planning
- Shopping for a cryostat

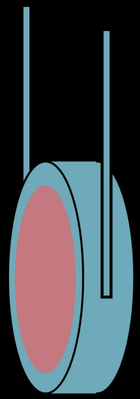


Reducing coating thermal noise



- Traditional materials used for optical coatings have relatively low Q
  - Amorphous Silica/Tantala
  - Q ~ few 10^4
- High Q optical coatings has been a major research subject for many years
- Recent results on new crystalline materials show order of magnitude higher Q
  - Very exciting!

AlGaAs Coatings



Tenfold reduction of Brownian noise in optical interferometry

Garrett D. Cole[1,2,*], Wei Zhang[3,*], Michael J. Martin[3], Jun Ye[3], and Markus Aspelmeyer[1]

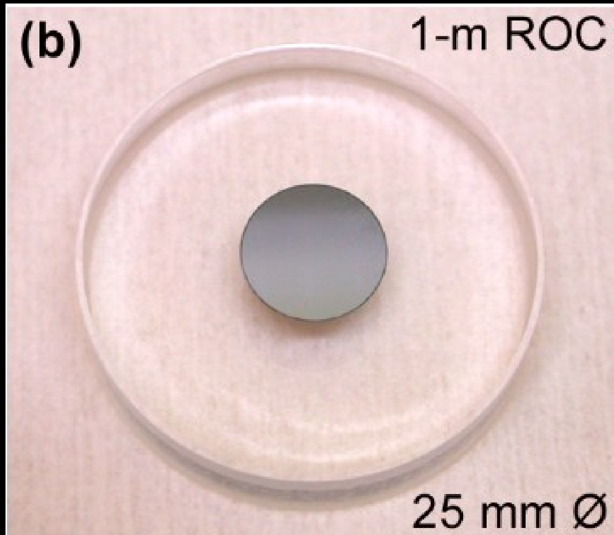
[1] *Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, A-1090 Vienna, Austria*

[2] *Crystalline Mirror Solutions GmbH, A-1090 Vienna, Austria*

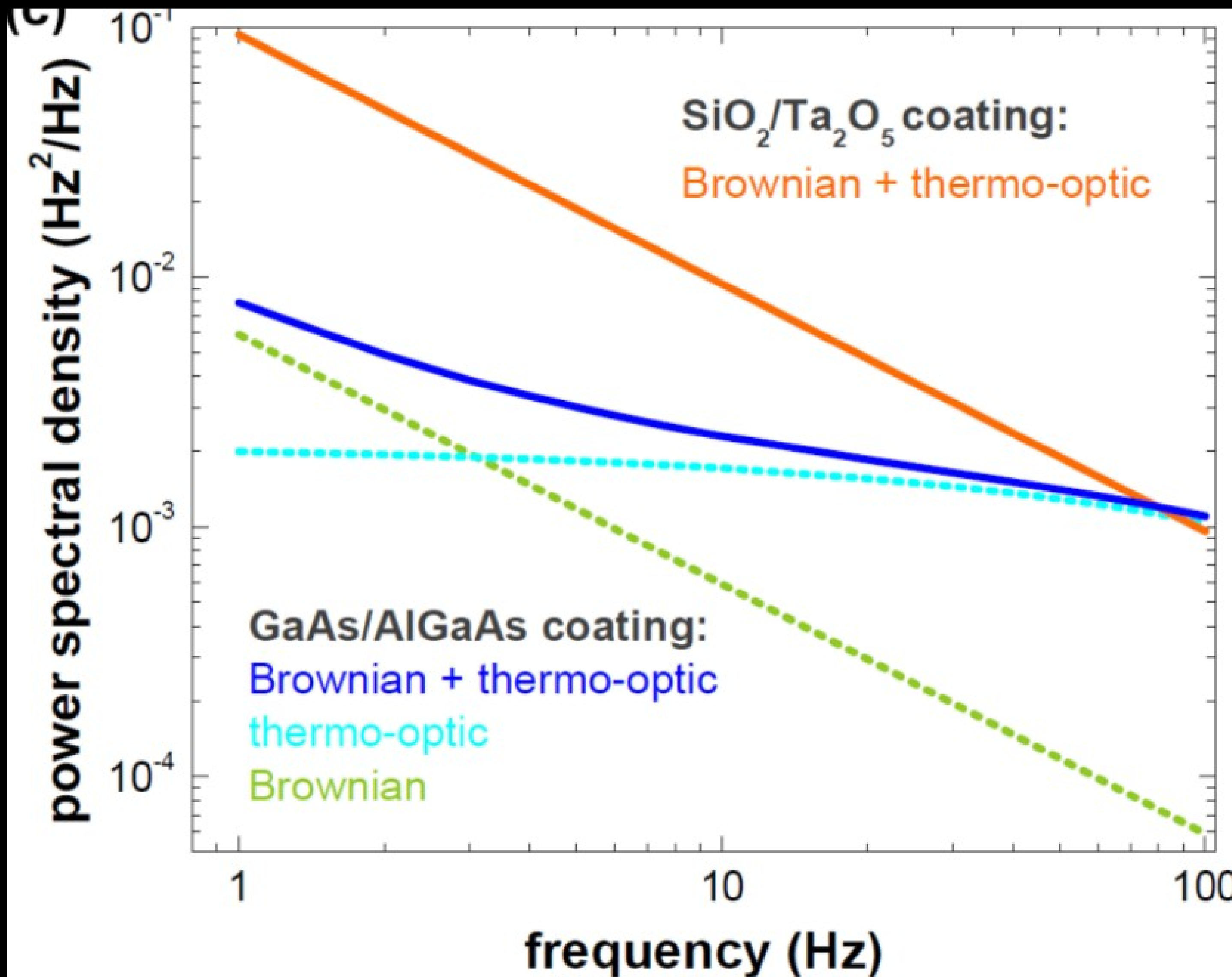
[3] *JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA*

arXiv:1302.6489

- Shown to have $Q>10^5$
- Thermal noise upper limit measured, consistent with measured Q
- Grown on GaAs substrate, lifted and bonded onto optic (any material)

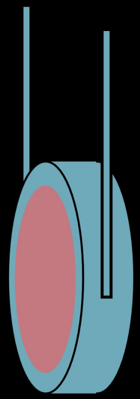


AlGaAs Thermal Noise Estimate

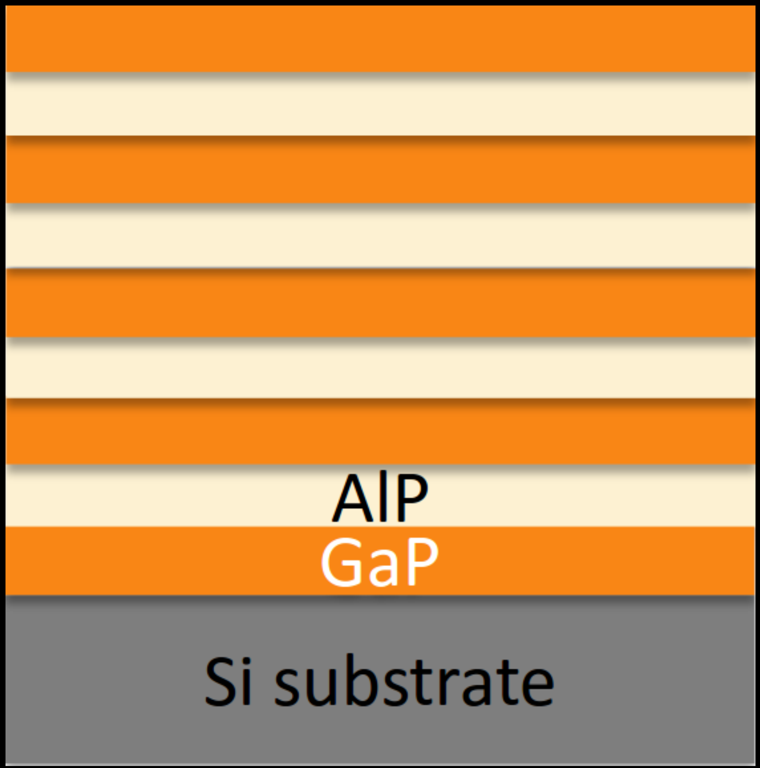


Cole et al.
arXiv:1302.6489

AlGaP Coatings

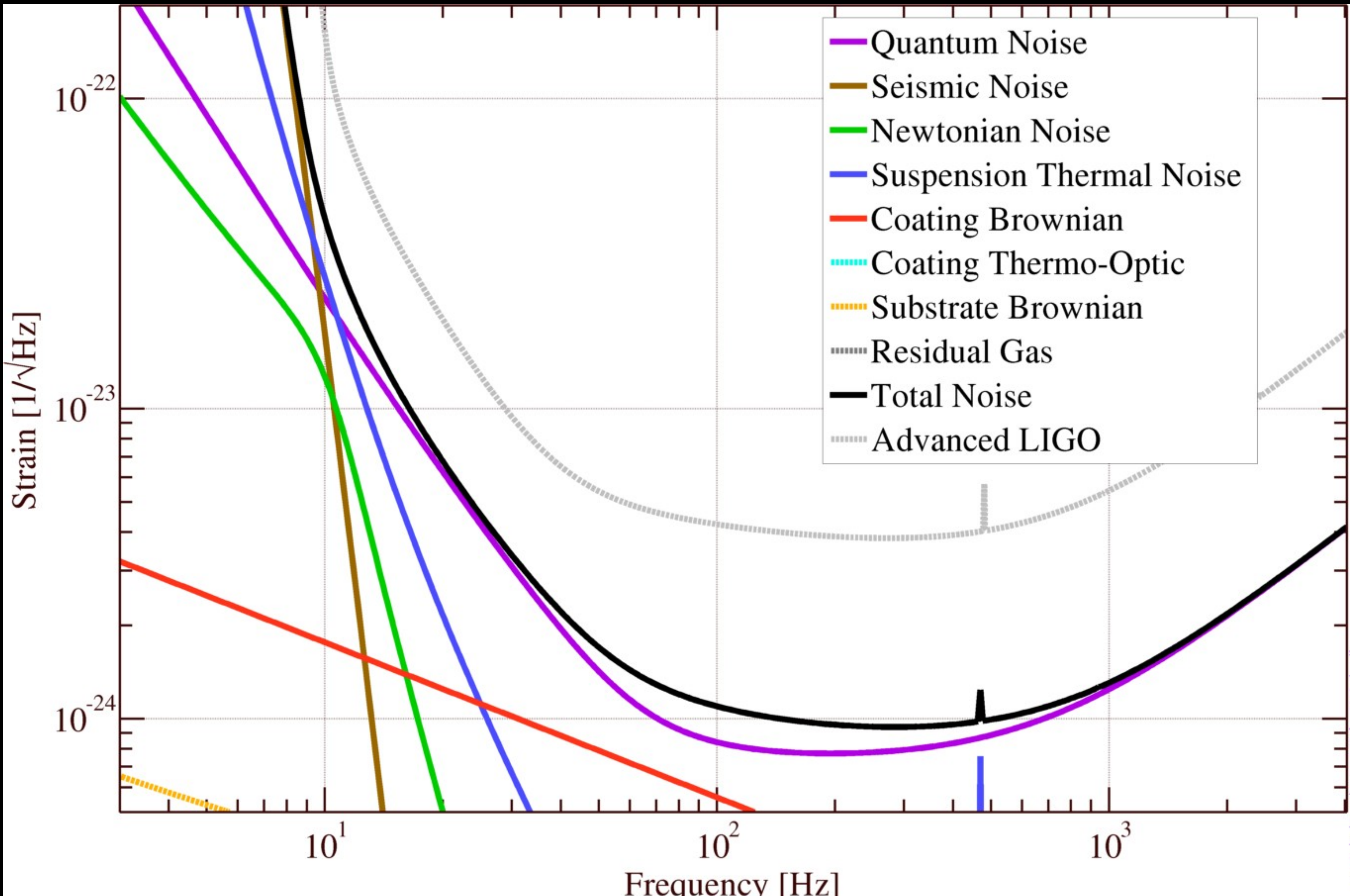


- Also high Q, though no thermal noise measurement yet
- Has the same lattice spacing as Silicon, so can be grown directly on the mirror

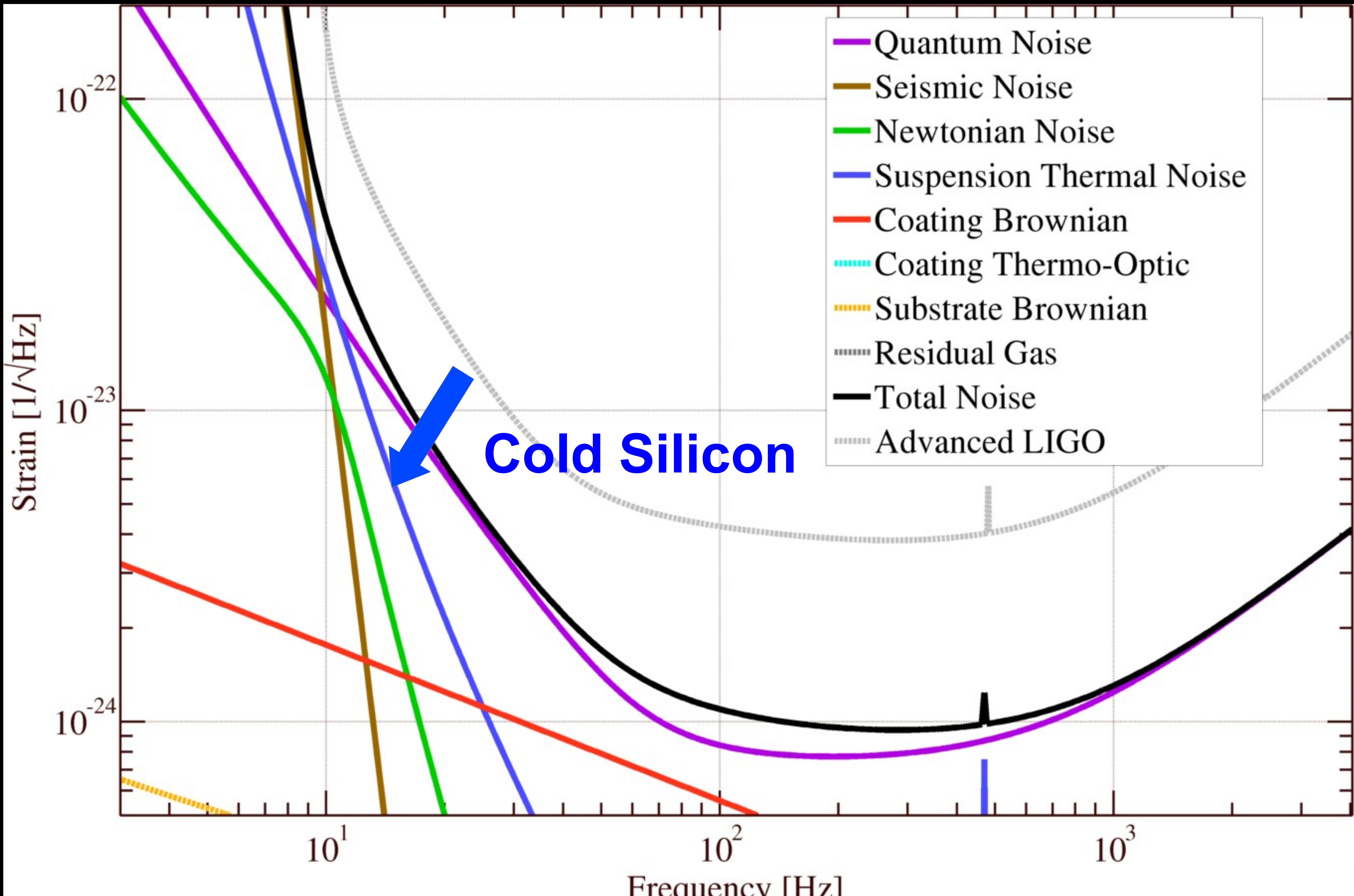


Angie Lin, Stanford

Possible Sensitivity of Future LIGO



Possible Sensitivity of Future LIGO



Possible Sensitivity of Future LIGO