Cryogenic Silicon for LIGO

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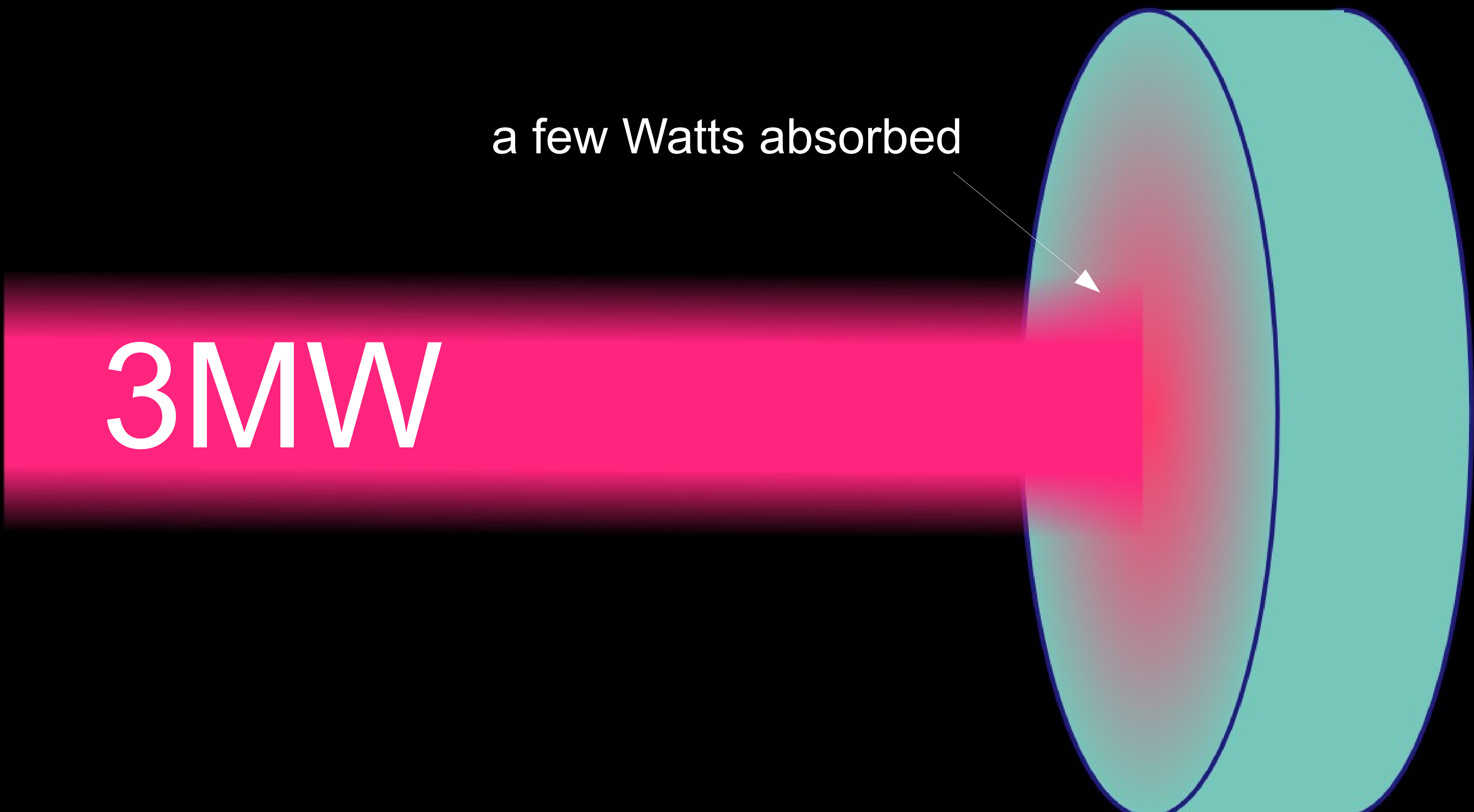
Caltech
GWADW 2013

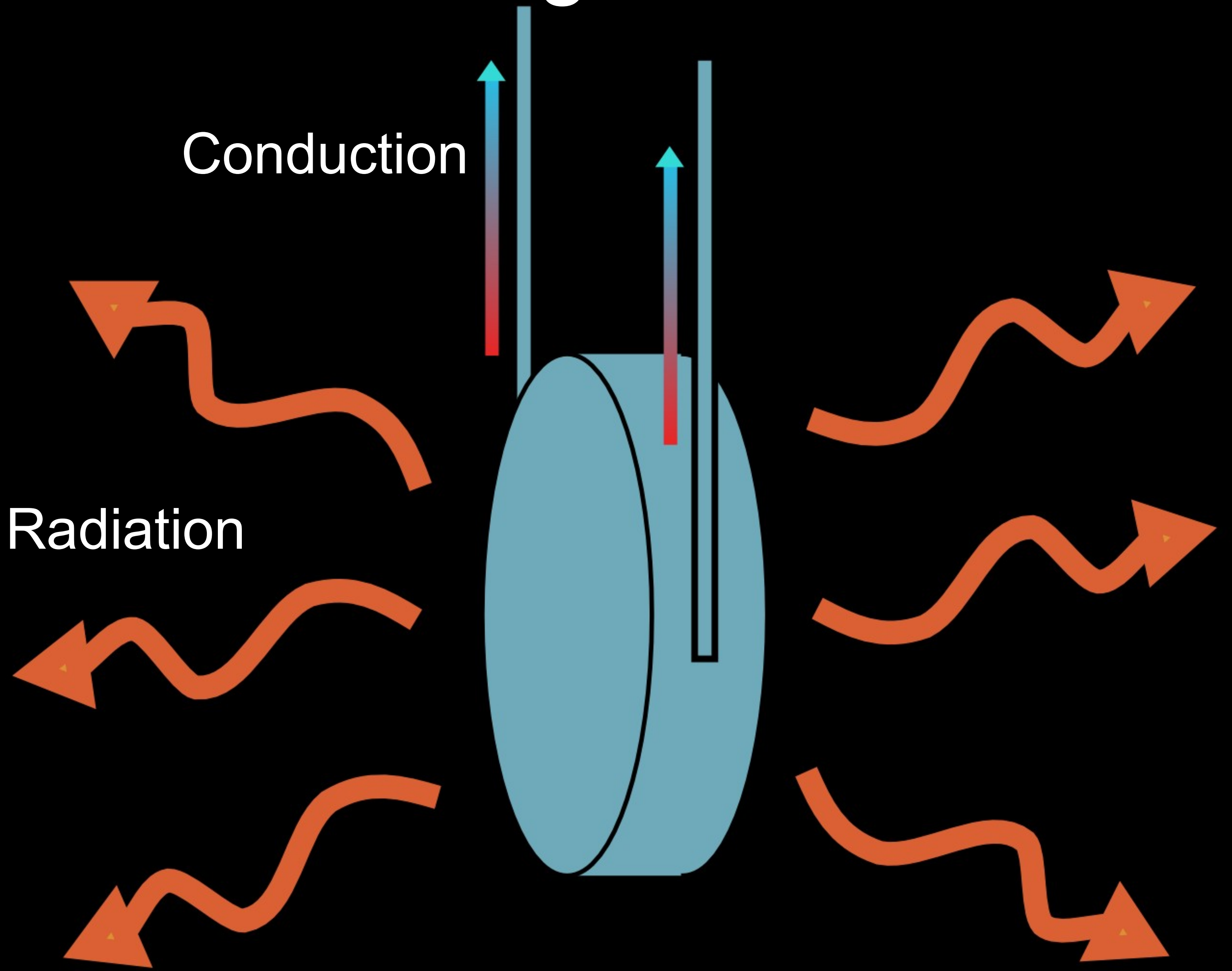
Outline

- How can one keep the interferometer cold?
- Research that is being done regarding cryogenic silicon suspensions.
- A bid for interest in non-equilibrium thermal noise.

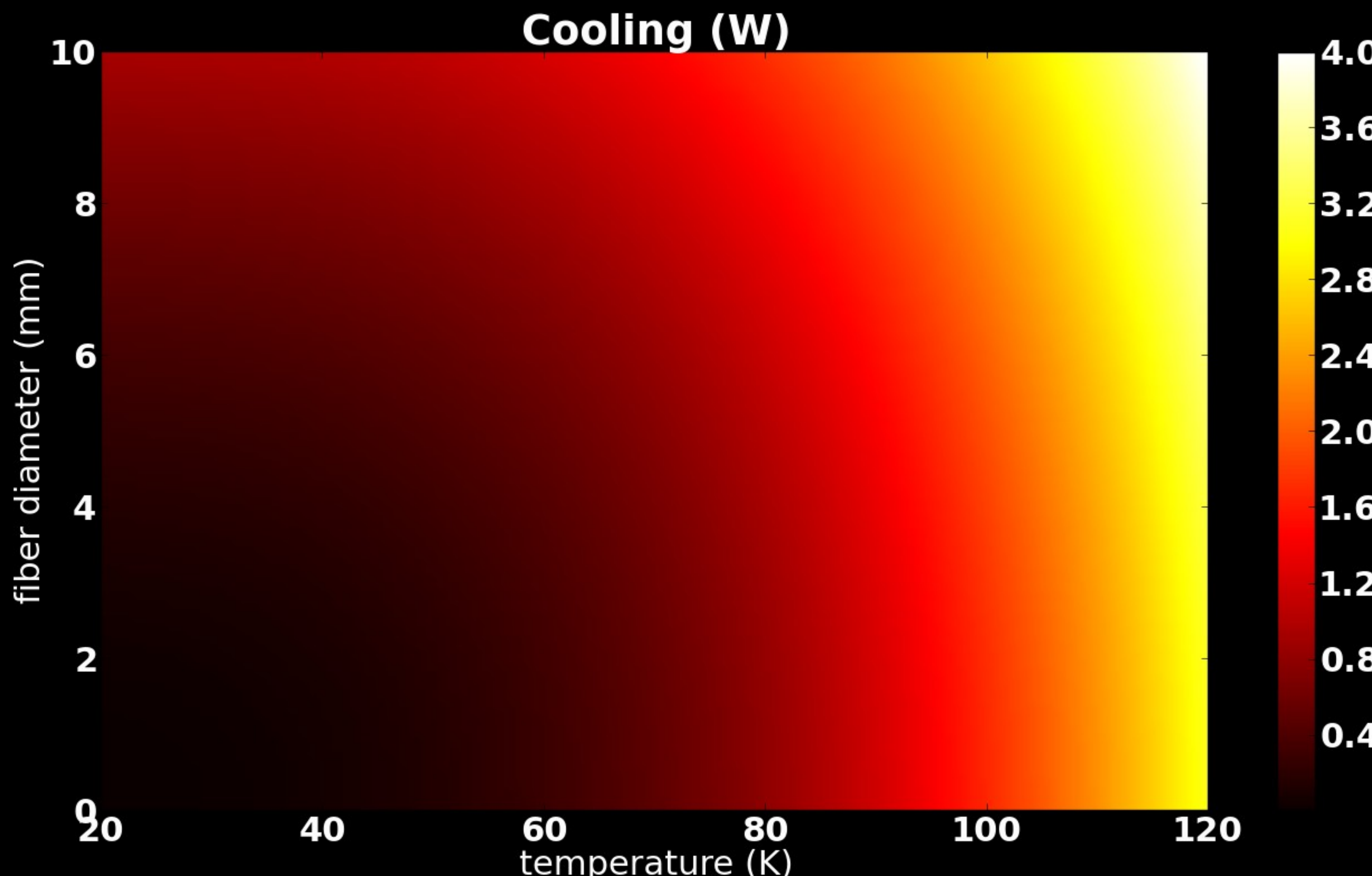
Cryogenics in Gravitational Wave Interferometers: the cooling problem



Cooling methods



Cooling power as a function of fiber diameter and temperature



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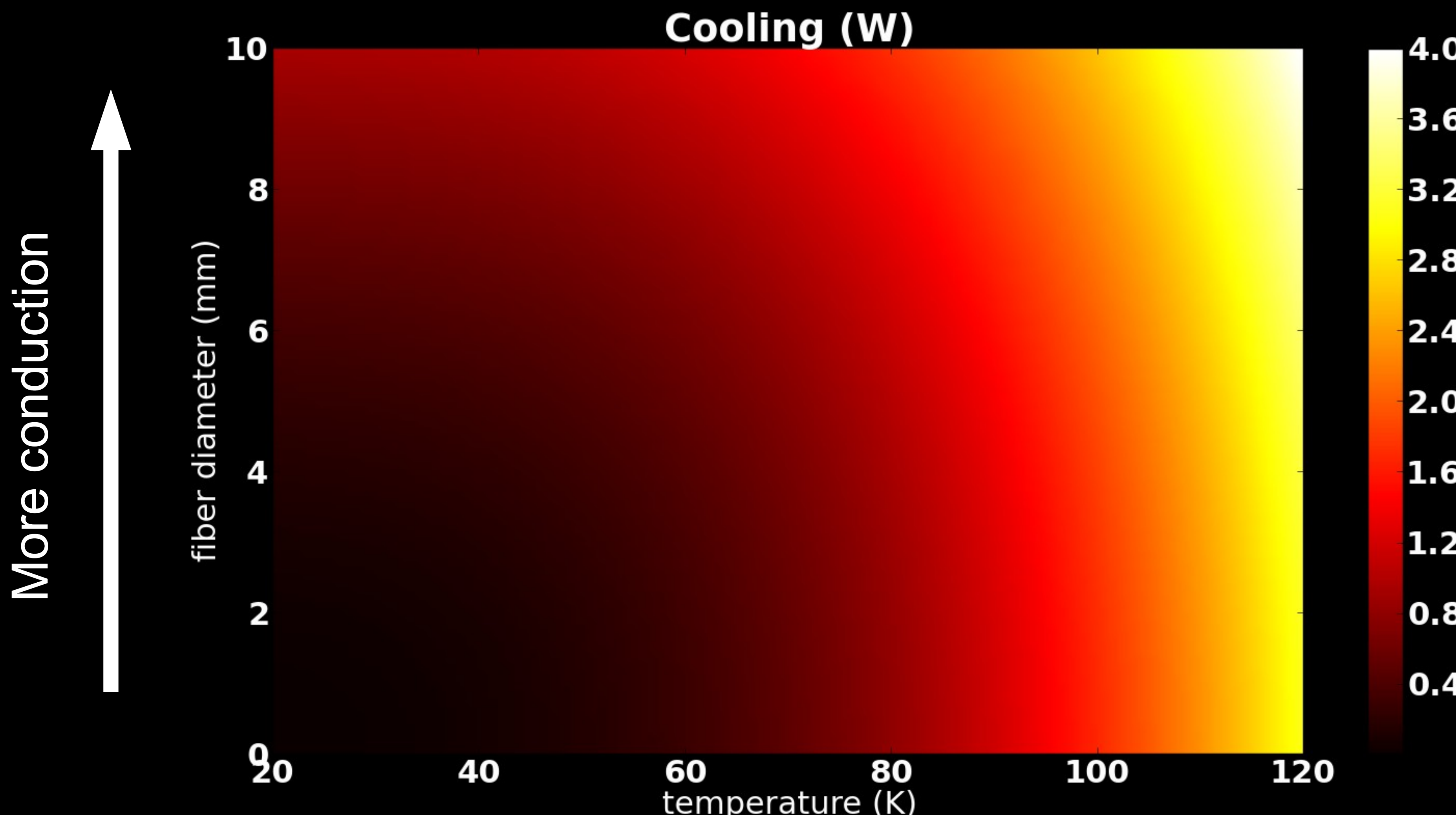

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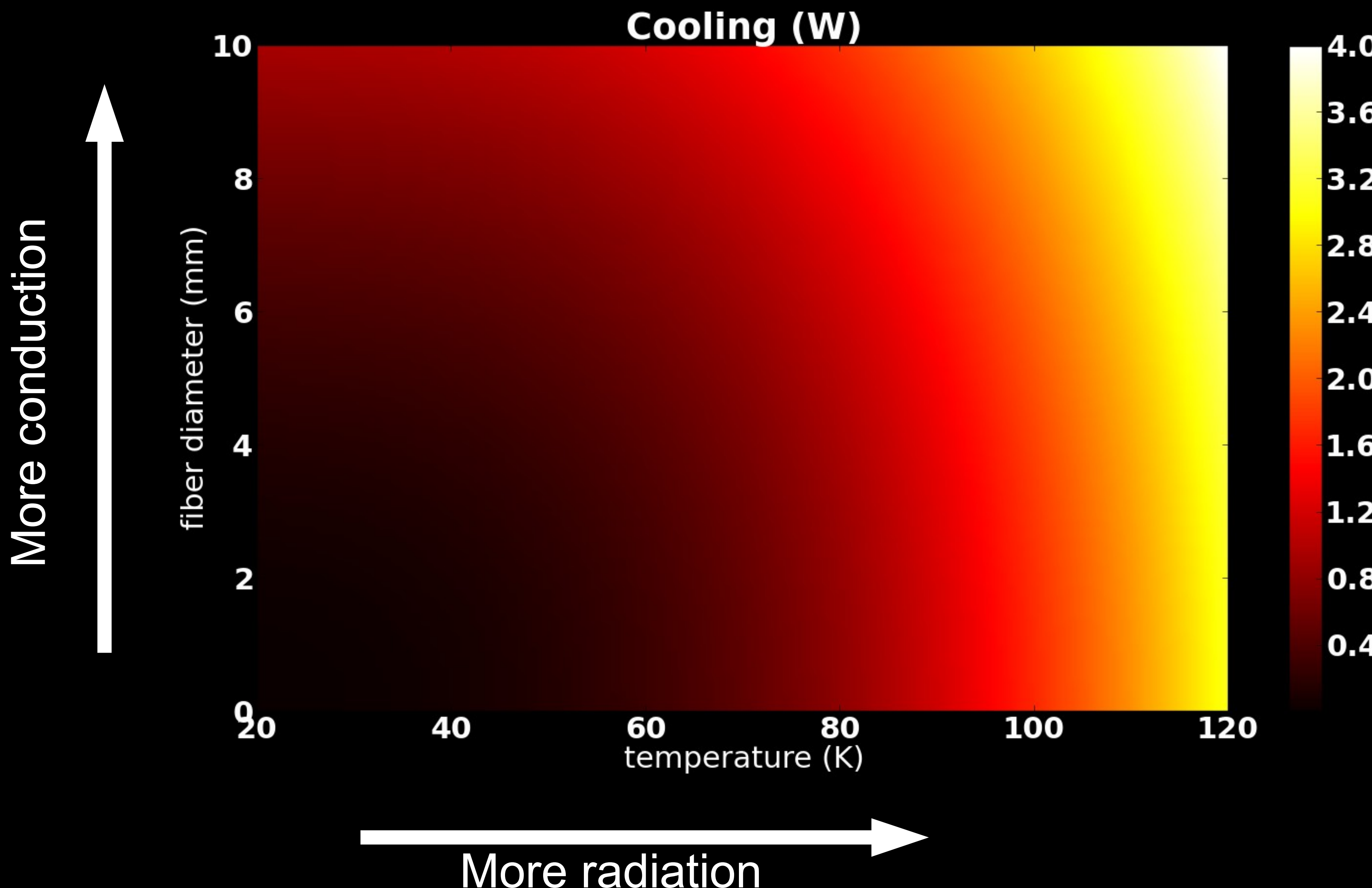
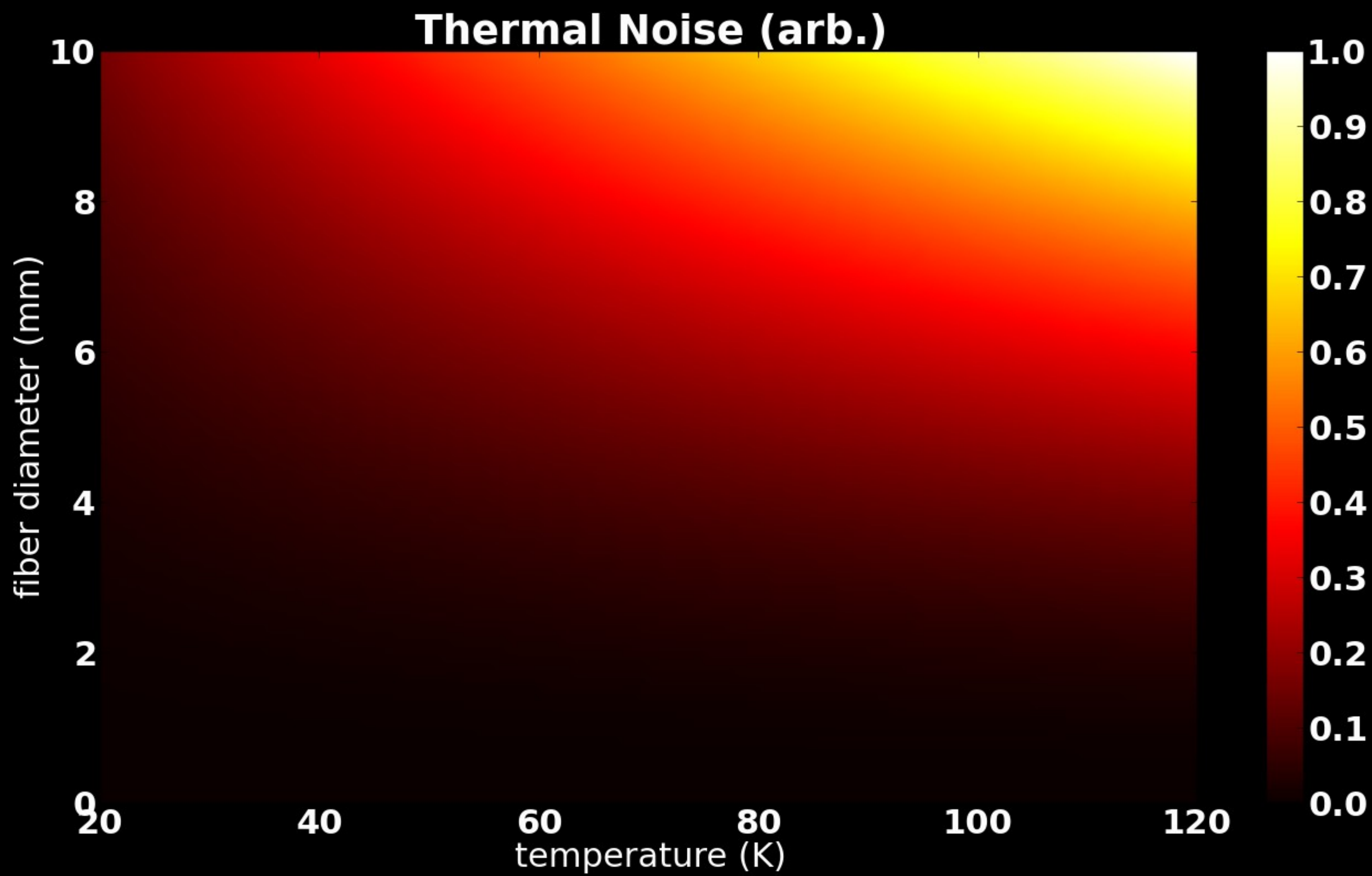


Thermal Noise as a function of fiber diameter and temperature



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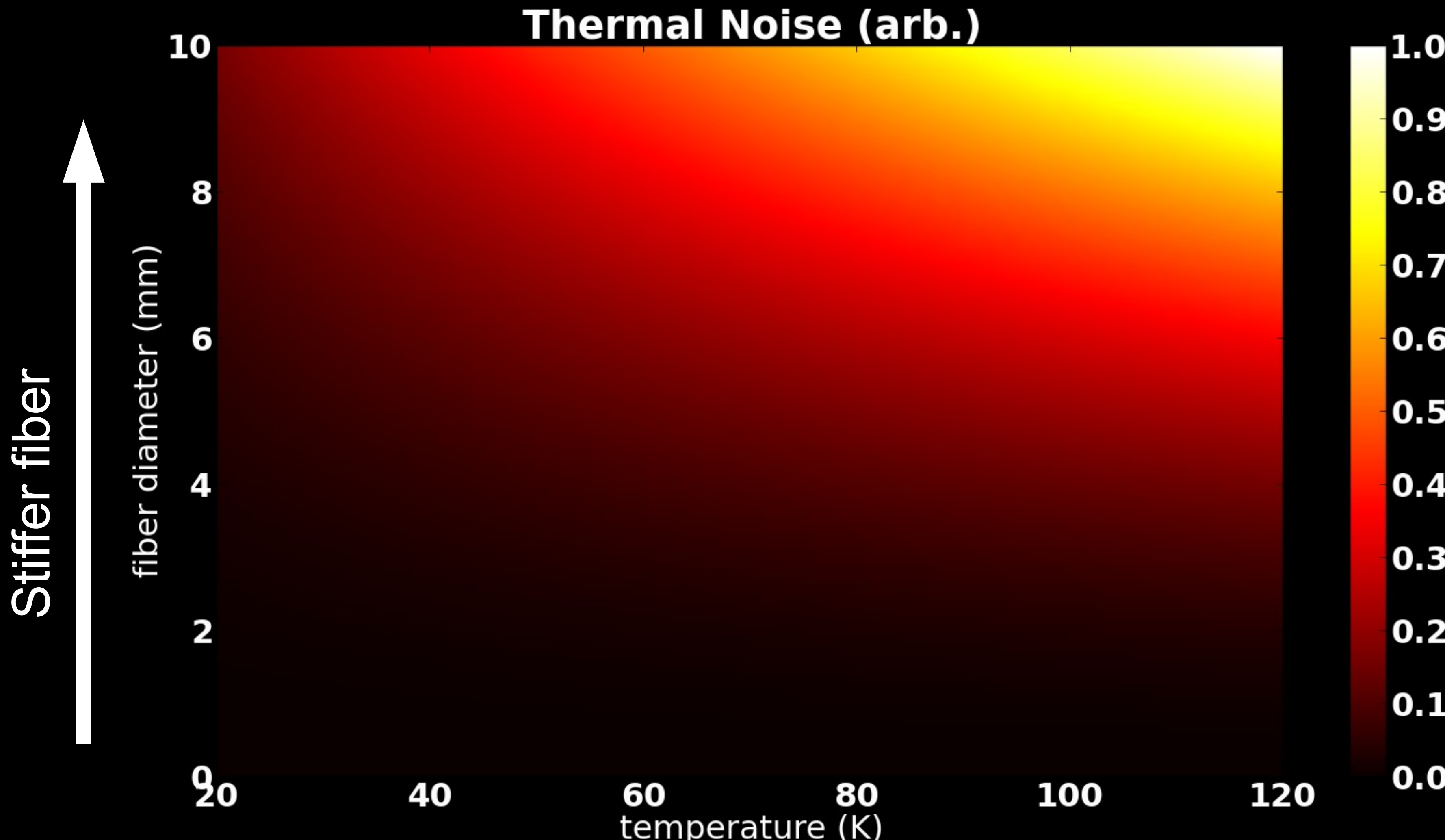

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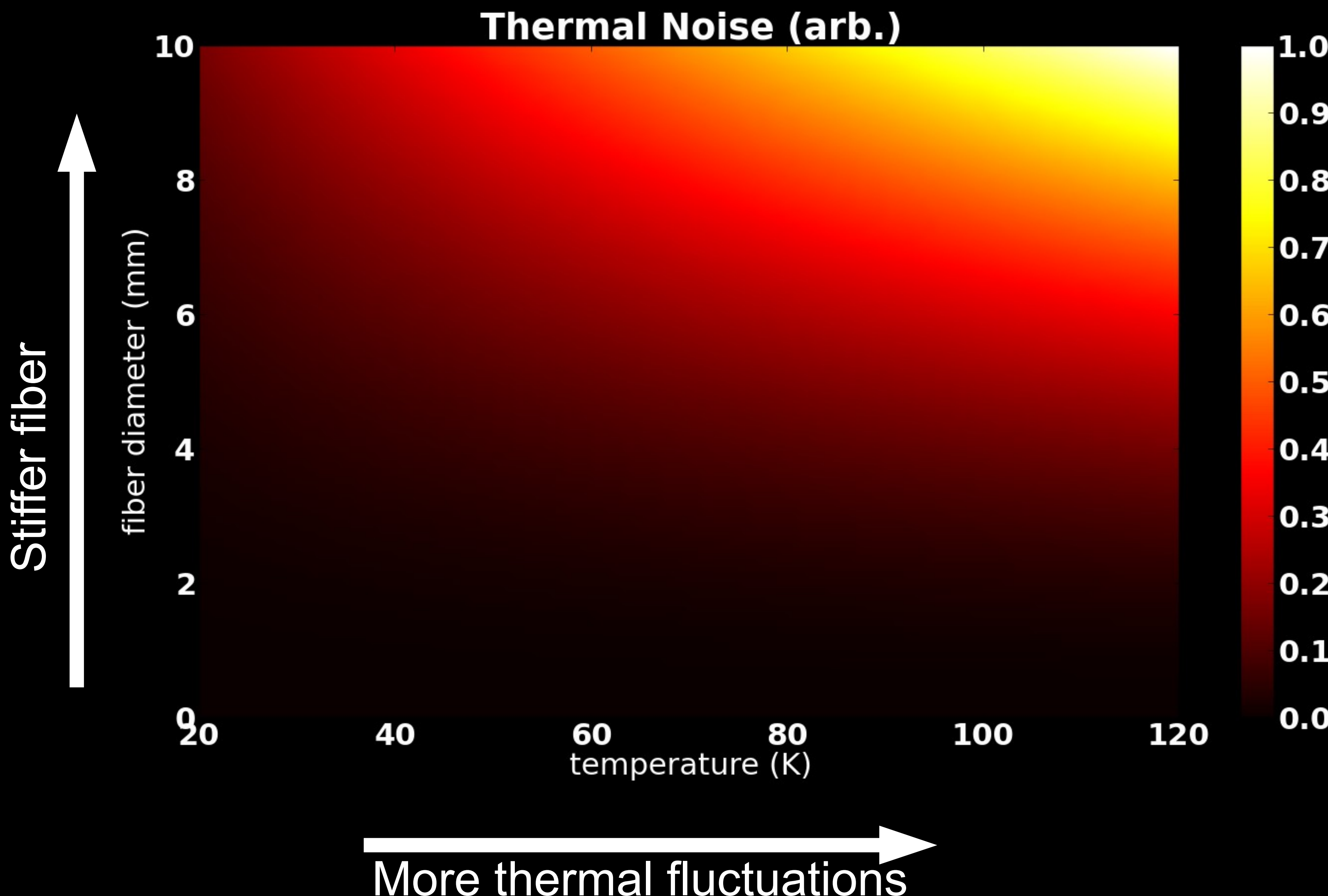
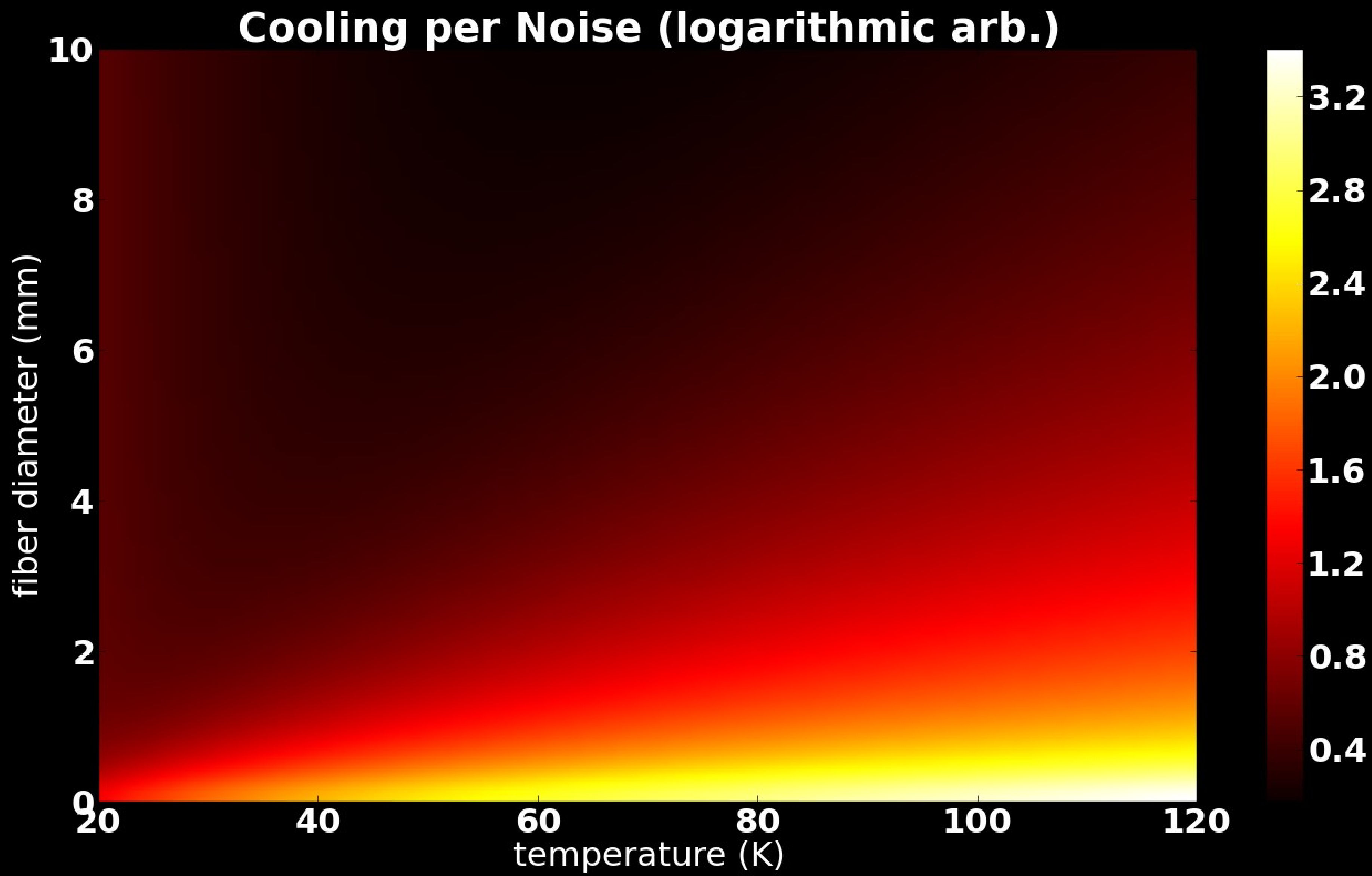


Cooling vs Noise trade-off



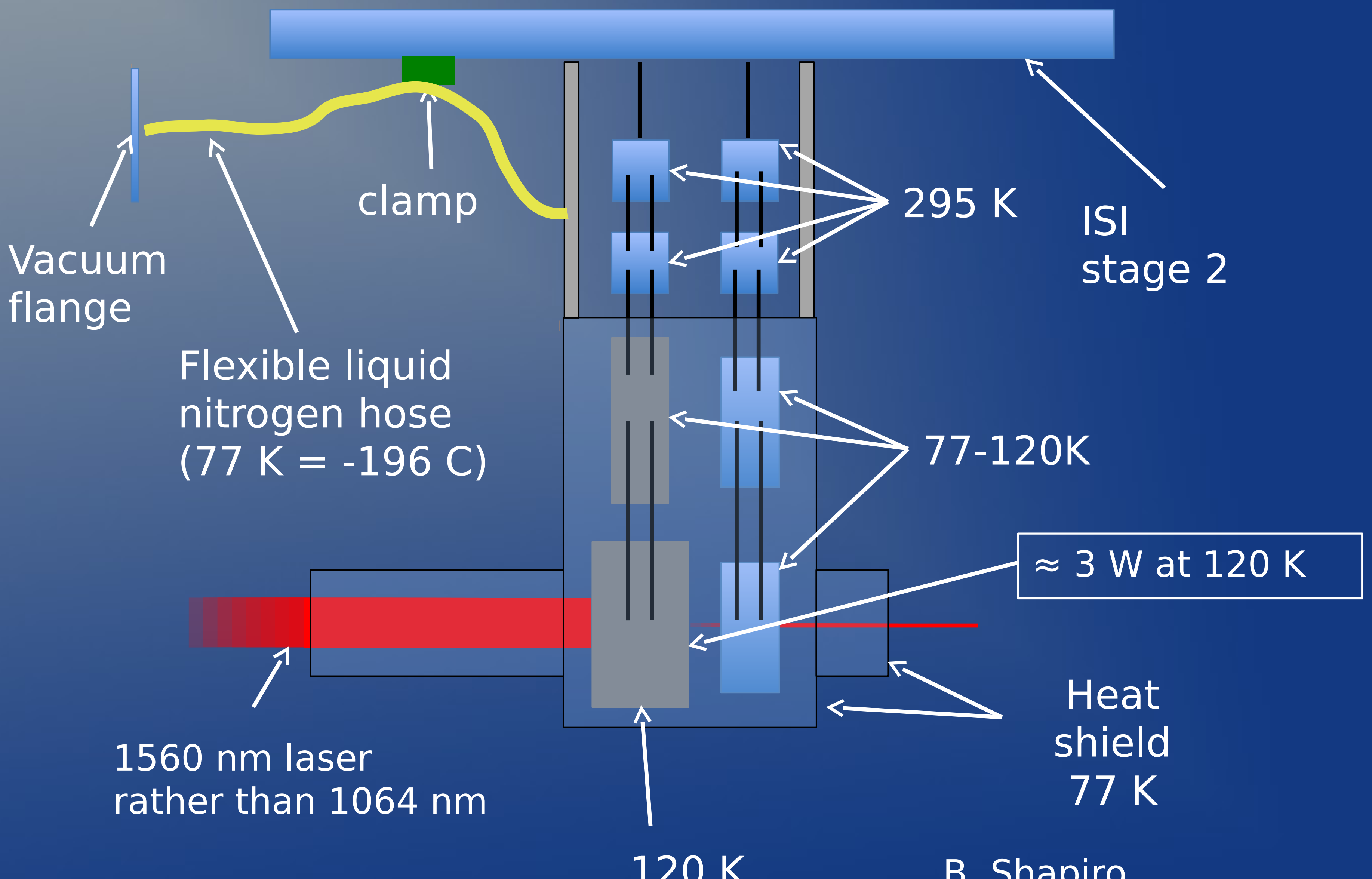
Temperature and cooling trade-off

- Differing approaches
- KAGRA - Sapphire 20K Thick fibers (higher thermal noise than thin)
- ET - Silicon 20K Low power (requires two independent interferometers)
- LIGO3 Blue - Silicon 120K radiative cooling (not as cold)

120K Silicon

- The only way for one detector to achieve significant broadband improvement over advanced detectors (high power AND low thermal noise)
- Low frequency improvement due to thermal noise (zero thermo-elastic noise)
- High frequency improvement due to high stored arm power
    - 120K Silicon has higher thermal conductivity than copper, thermal distortion greatly reduced

Silicon Quad Suspension

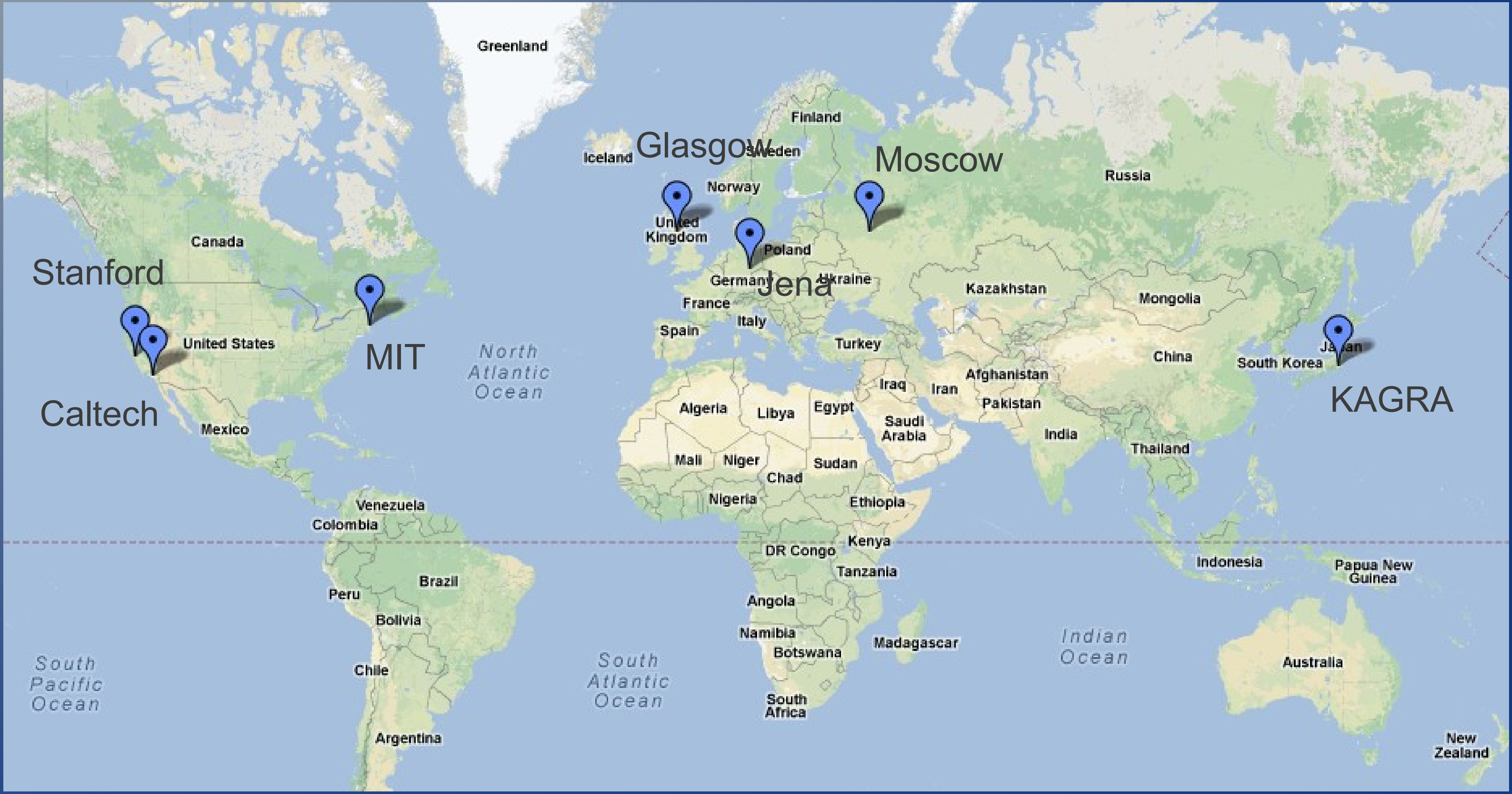


B. Shapiro

Some unknowns

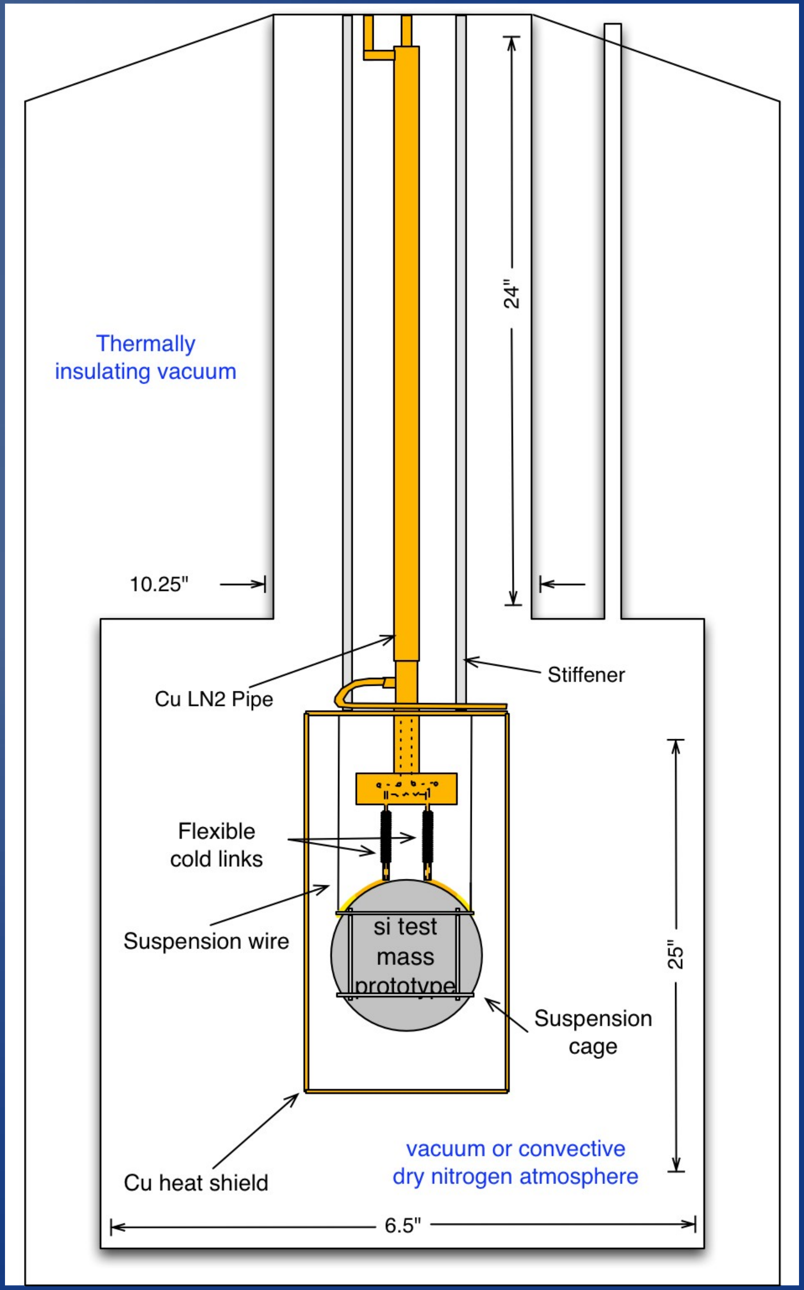
- Initial cooling method
- Laser techniques at 1550nm
- High emissivity coating
- How to mitigate surface losses
- Bonding of silicon to silicon
- How to create high purity masses at LIGO3 scale
- Unknown unknowns

Who's working on it?



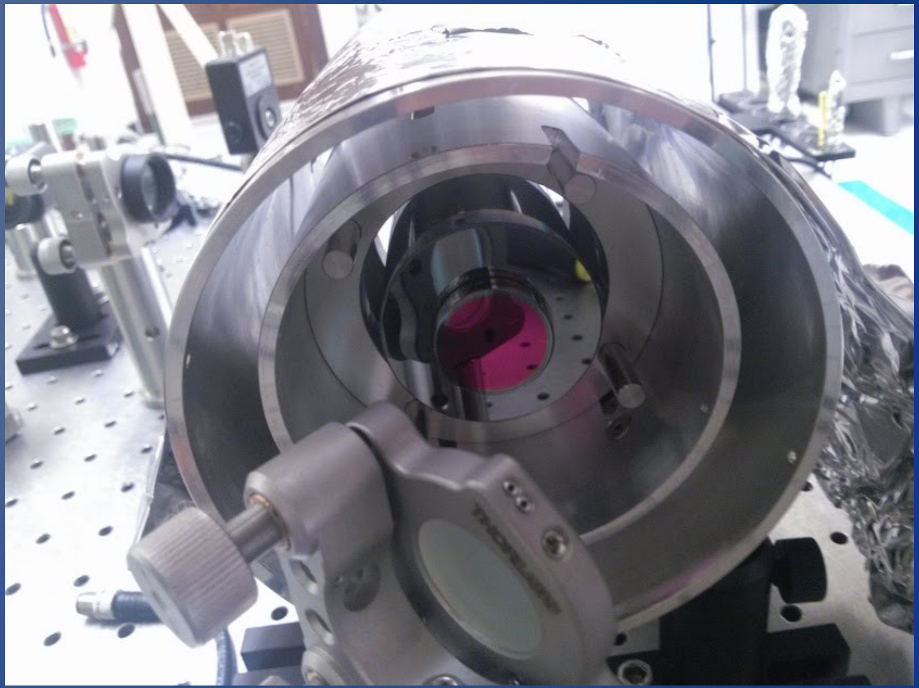
Initial test mass cooling @ Stanford

B. Shapiro

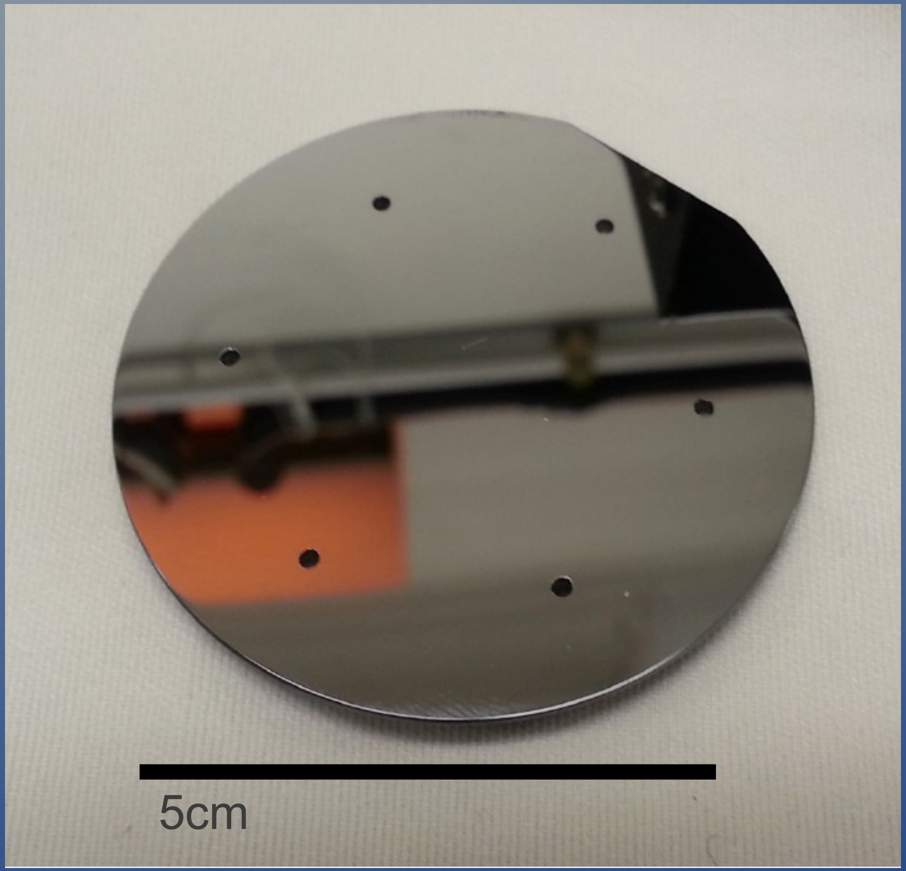


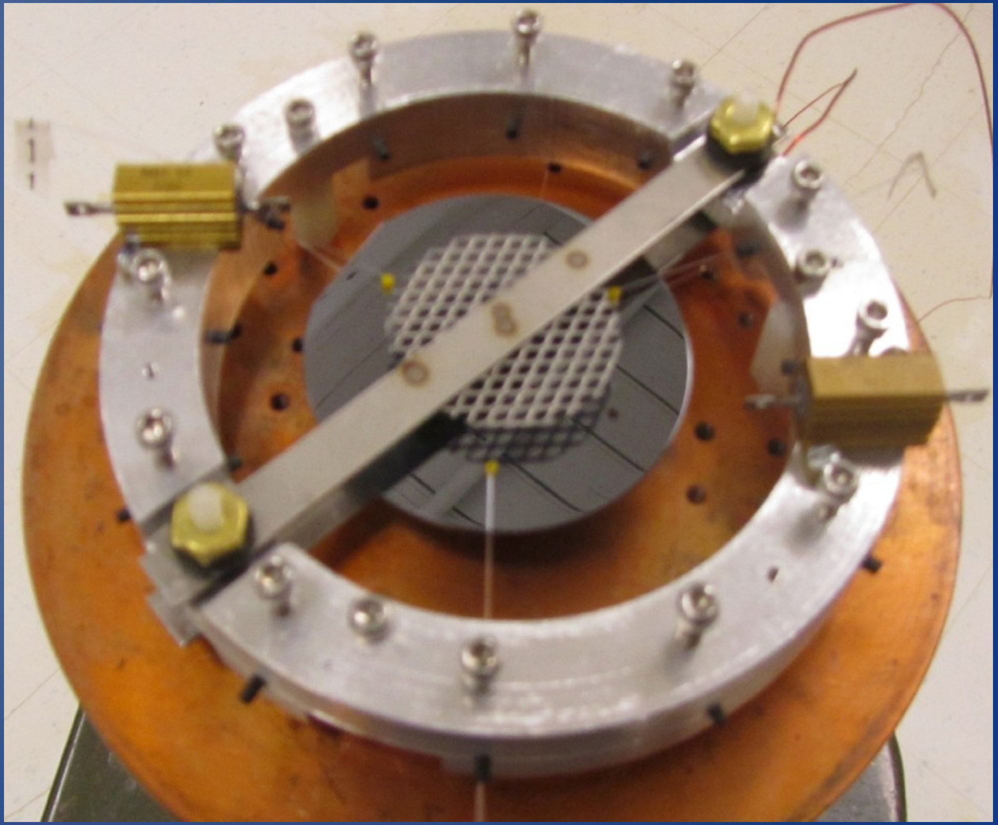
Cryogenic Reference Cavities @Caltech

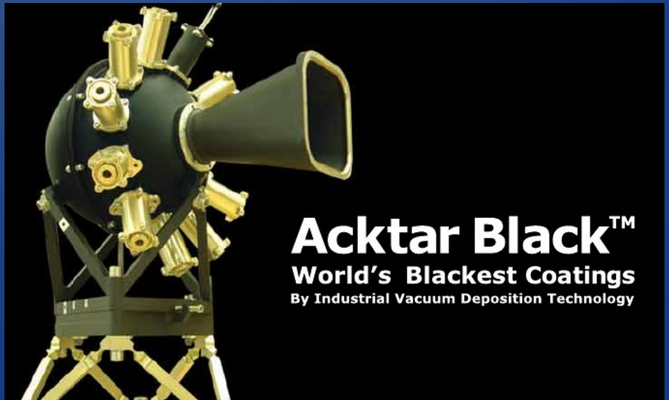
- Provides experience for many relevant technologies
- Ultra-stable DC frequency reference
- Potentially interesting system for studying macroscopic quantum mechanics



High emissivity coating experiment @MIT

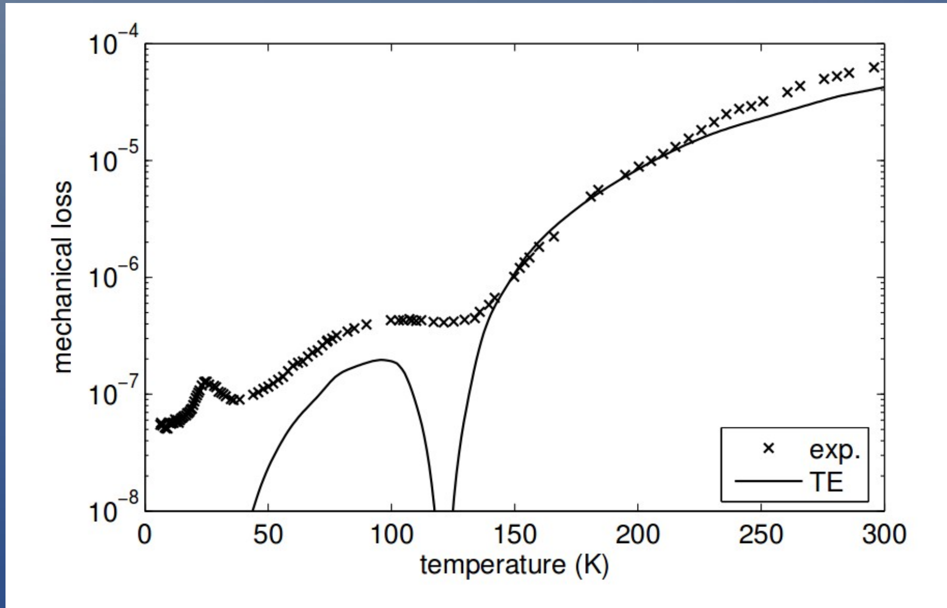






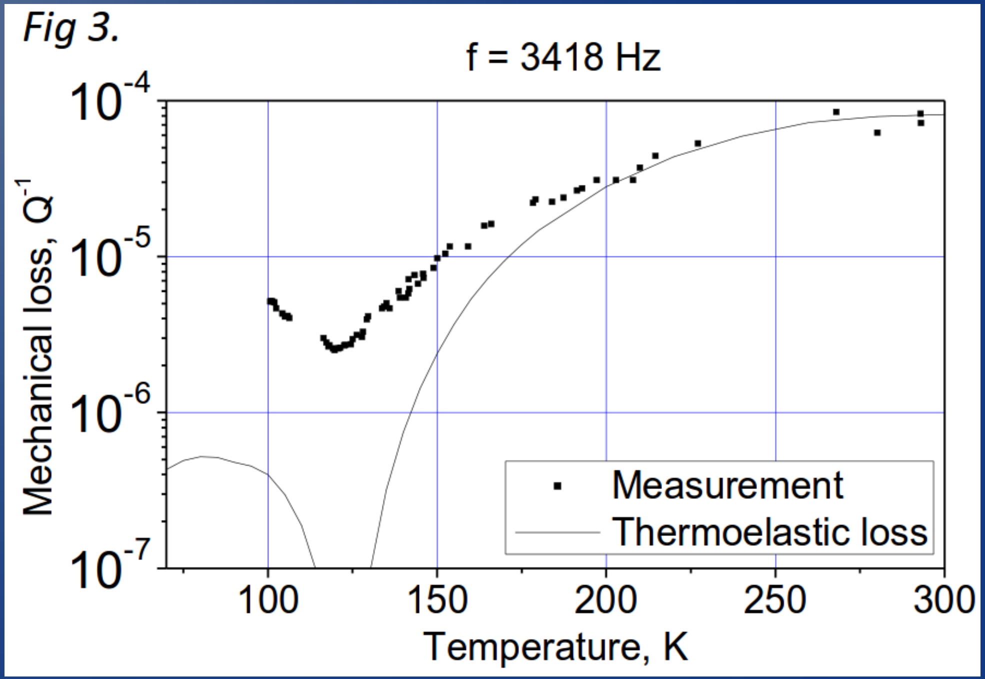
Losses in Silicon Samples @Jena/Glasgow/Moscow

- 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

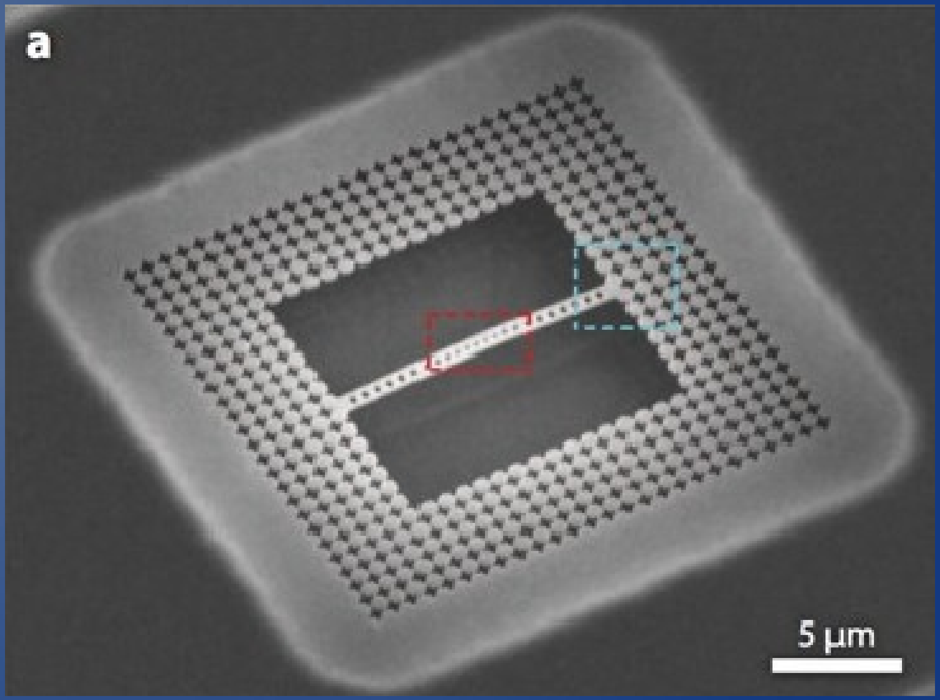
Silicon Cantilever @ Jena/Glasgow
Nawrodt et al. arXiv:1003.2893



Silicon Wafer @ Moscow
Prokhorov, Mitrofanov

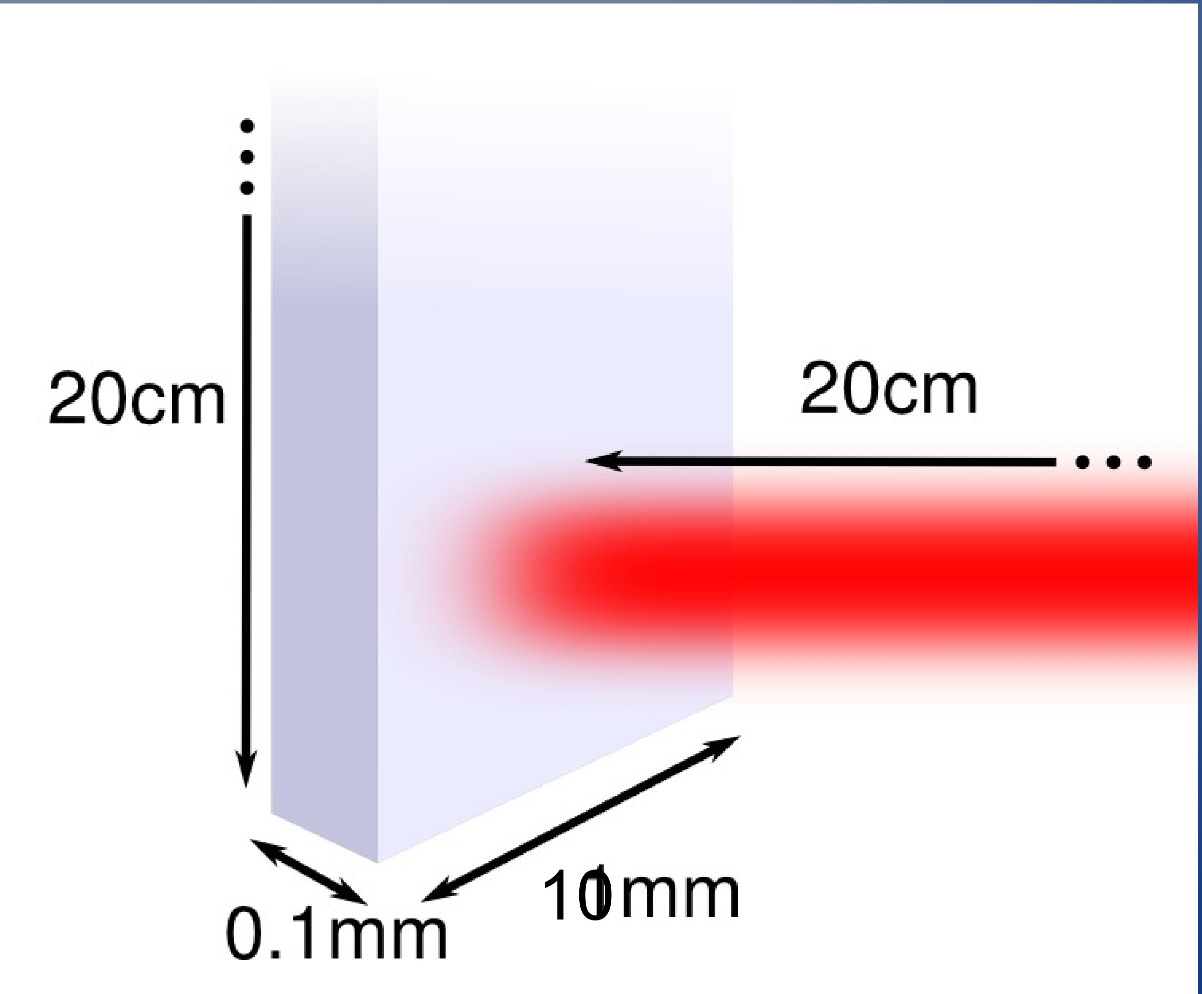
Oskar Painter Silicon Etching @Caltech

- Micro-mechanical silicon structures
- Demonstrated laser cooling of mechanical oscillator to quantum ground state
- Willing to collaborate with us on Silicon etching techniques for low surface losses



Silicon macro-mechanical cantilever @Caltech

- Allows direct measurement of thermal noise at cryogenic temperatures



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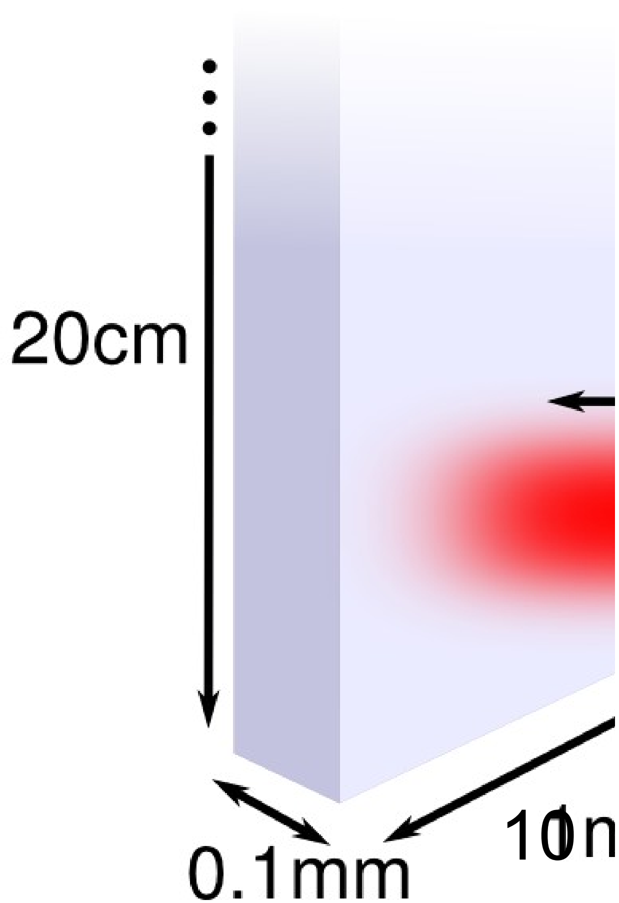
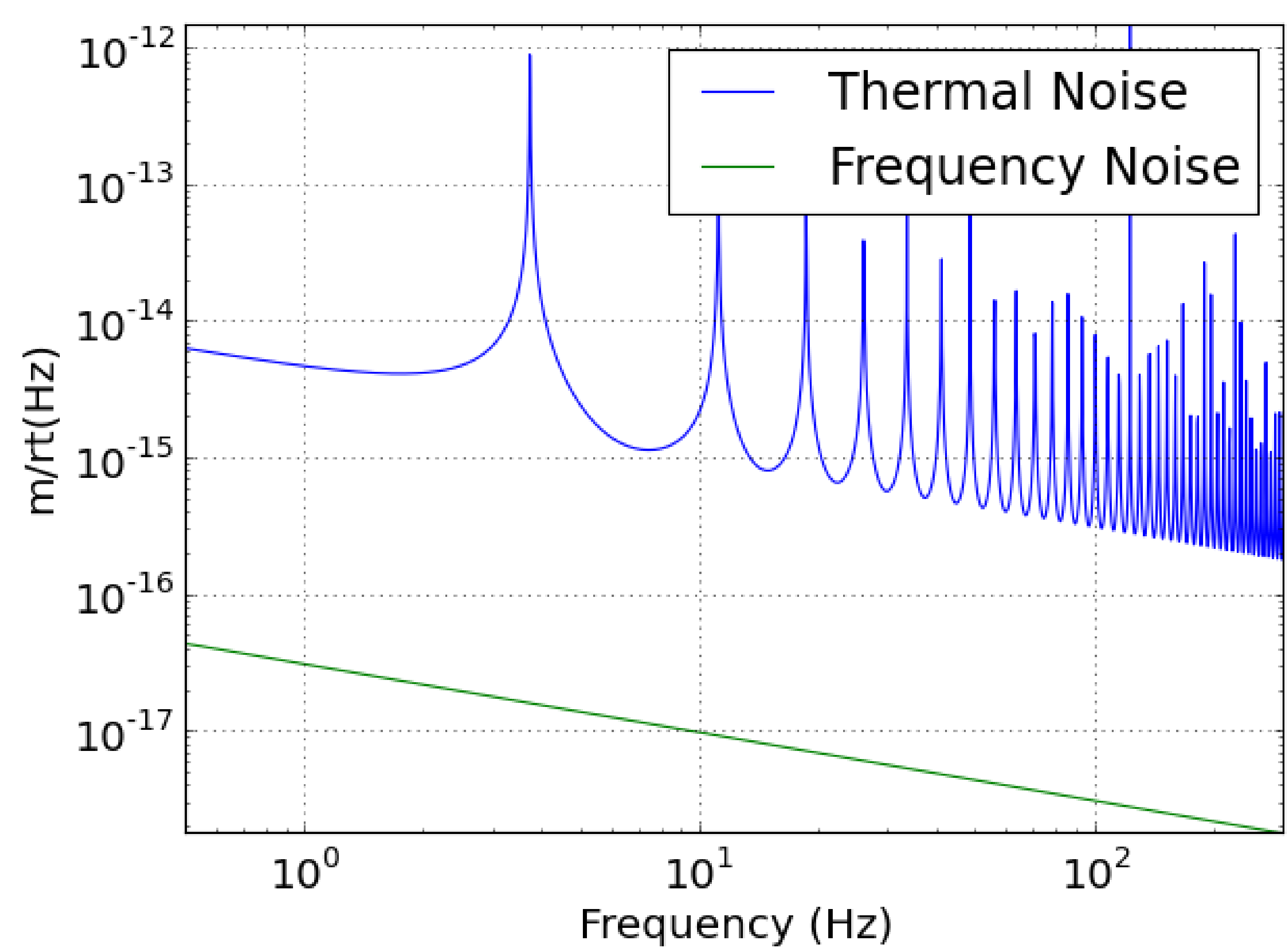
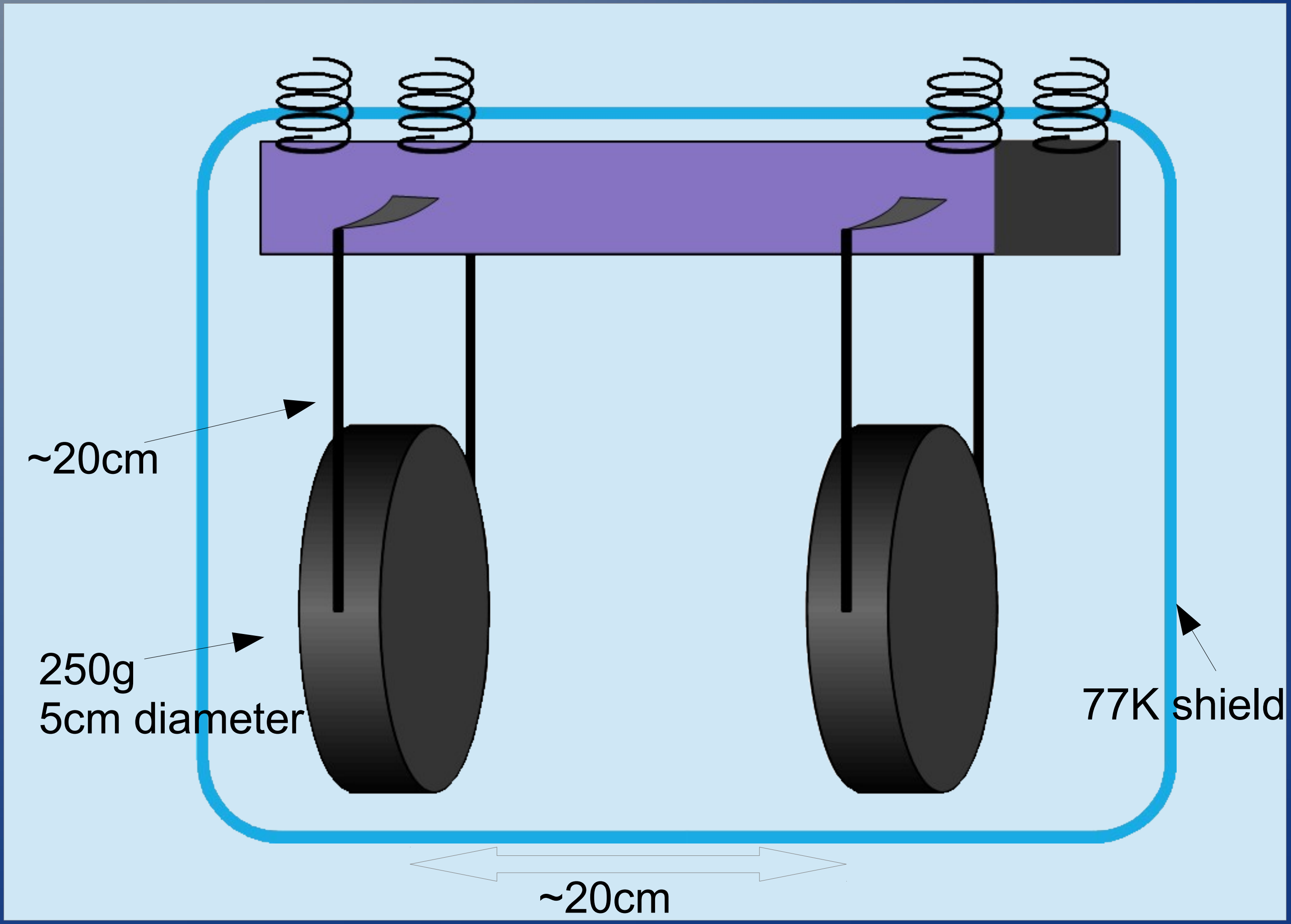




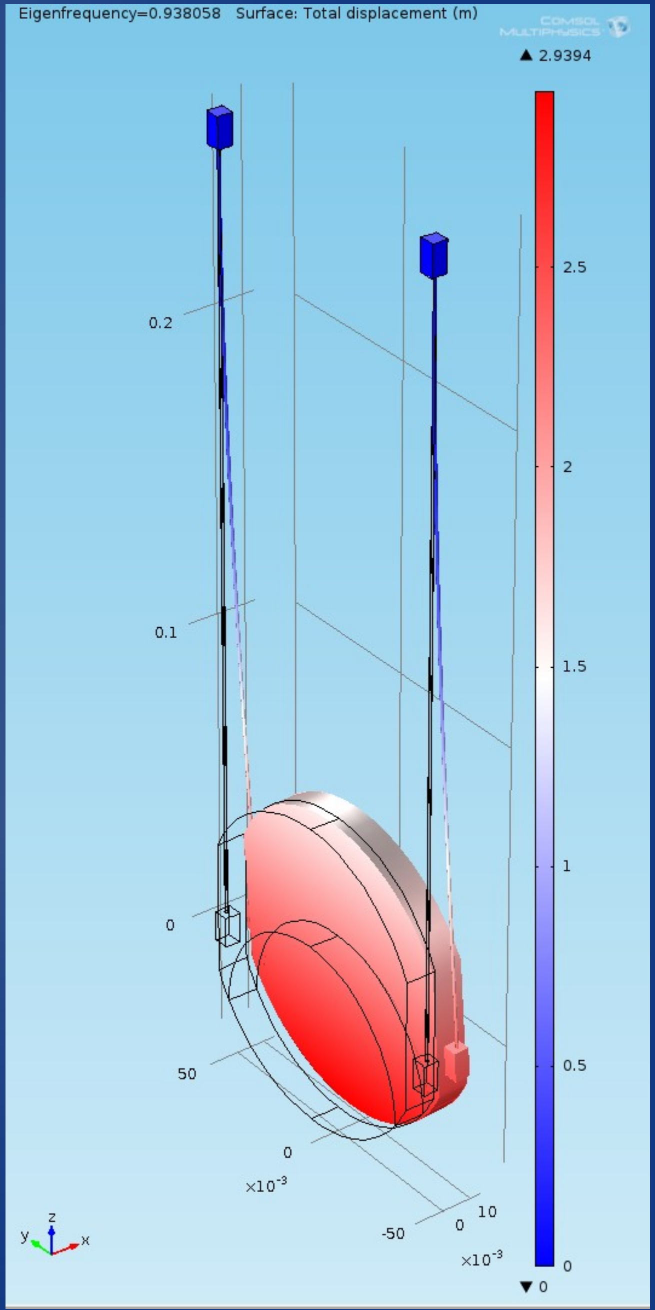
Prototype suspension @Caltech

- Good for developing fabrication techniques, though likely difficult to see thermal noise



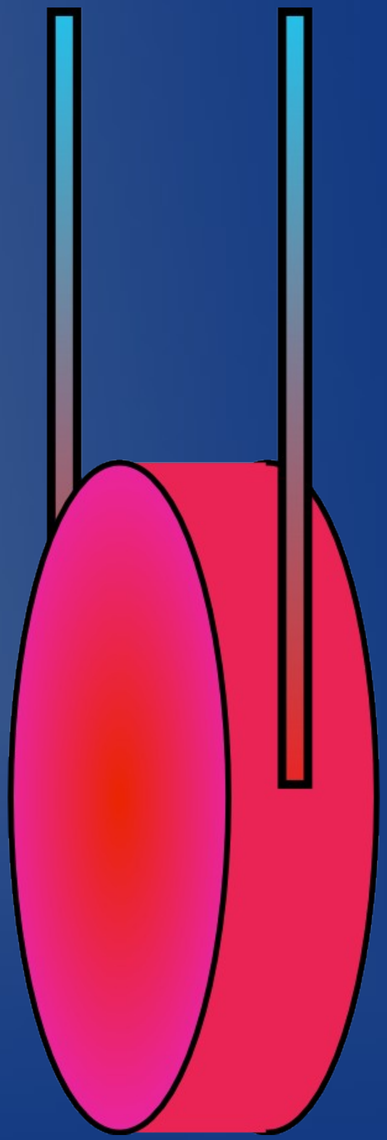
Thermal Noise Modeling

- The dream: design your suspension in an FEA tool, and directly predict the thermal noise
  - Prevents bookkeeping errors
- A Cumming et al 2009 Class. Quantum Grav. 26 215012
- Abraham R Neben et al 2012 New J. Phys. 14 115008



An Open Question in Thermal Noise Modeling: Non thermal equilibrium

- Cryogenic interferometers will have thermal gradients along the suspension wire
- It is not yet settled how to calculate the noise correctly



The Thermal Noise Cookbook: Single degree of freedom oscillator

- Use the expression from Saulson (1990)

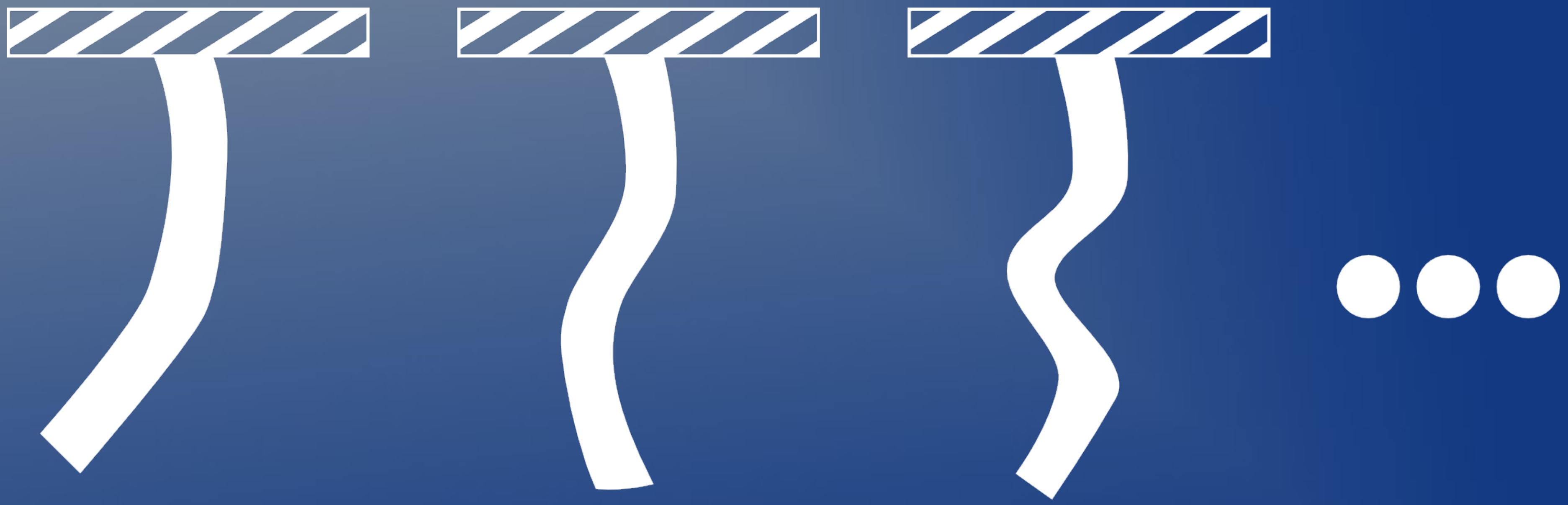
$$S_x(f) = \frac{4k_B T\omega_0^2\phi}{m\omega([\omega_0^2 - \omega^2]^2 + \omega_0^4\phi^2)}$$

Multiple degree of freedom system

- System may have many 'modes' but you are only interested in the thermal noise measured by some degree of freedom (x)
- There are multiple recipes in the Cookbook to approach this
- My example: the position of the end of a beam

Muti-DOF system: the modal approach

Step 1:
Break the system into the normal mode DOFs



$|\Psi_1\rangle$ $|\Psi_2\rangle$ $|\Psi_3\rangle$ $|\Psi_n\rangle$

Muti-DOF system: the modal approach

Step 2:
Find the thermal amplitude of each mode (from Saulson)

$$S_{\Psi_n}(f)$$

Muti-DOF system: the modal approach

Step 3:
Find overlap of each mode with desired DOF, and combine them.

$$S_x(f) = \sum_n \langle x | \Psi_n \rangle^2 S_{\Psi_n}(f)$$

- Major drawback: not straightforward to use when loss angle is function of position

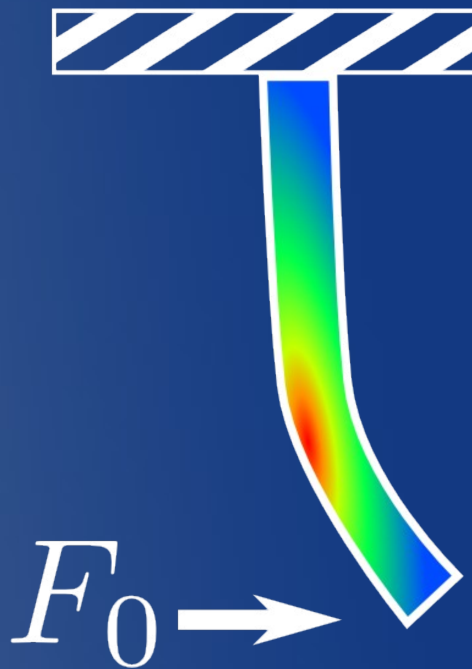
The Levin approach

- Uses the fluctuation dissipation theorem while treating the system holistically

Step 1.
Convert your desired DOF into a conjugate force and apply that force to the system

The Levin approach

Step 2.
Calculate the dissipation 'experienced' by the force



$$W_{\mathrm{diss}} = 2\pi f \int_V \rho(\vec{r})\phi(\vec{r})\mathrm{d}^3\vec{r}$$

The Levin approach

Step 3.
Plug into formula

$$S_x(f) = \frac{4k_B T W_{\mathrm{diss}}}{\pi^2 f^2 F_0^2}$$

$$W_{\mathrm{diss}} = 2\pi f \int_V \rho(\vec{r})\phi(\vec{r})\mathrm{d}^3\vec{r}$$

Sum over volume elements instead of sum over modes

A new recipe

- Use a Levin-like approach to find the coupling of each volume element to your degree of freedom
- Allow each volume element to have its own temperature (and loss angle)

The Gradient Effect

- Does the thermal gradient contribute an additional effect to the noise?

$$S_x(f) = \frac{4k_B}{\pi f F_0^2} \times$$

$$\int_V \rho(\vec{r}) \left[T(\vec{r}) + H(\vec{\nabla} T(\vec{r})) \right] \phi(\vec{r}) \mathrm{d}^3\vec{r}$$

The Need to Complete the Cookbook

- The problem of thermal noise in non-thermal equilibrium is very relevant for cryogenic interferometers
- Very interesting results presented here suggest some (large) effects due to thermal gradients
- Talk by Claudia Lazzaro and poster by Rossana De Gregorio

Fin

Thanks to:
Caltech: Rana Adhikari, Alastair Heptonstal, Norna Robinson, Eric Gustufson
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Stanford: Brett Shapiro
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