Optical Refrigeration for LIGO Instruments

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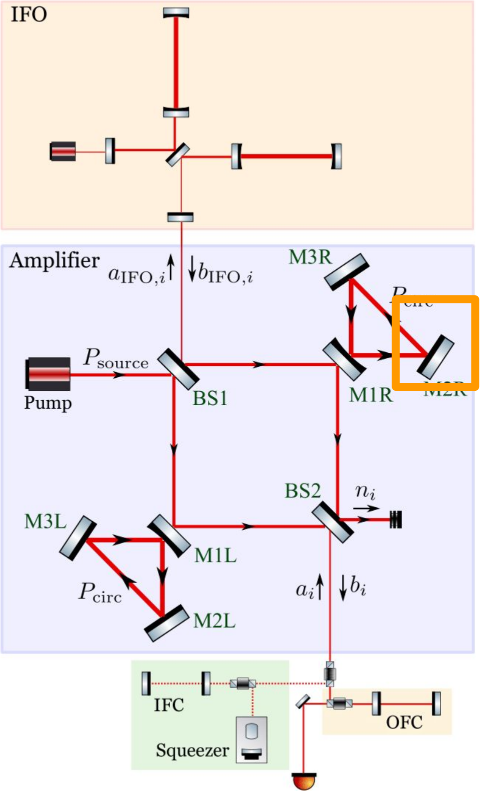
Optical Refrigeration for LIGO

- LIGO- Interferometer to detect gravitational waves (GW)
- Next version of LIGO needs to be cooled and maintained at 123 K
- Any cooling must be done without vibrations or moving parts
- Optical refrigeration (OR) - cooling with [laser] light
- We show that OR may outperform other cooling methods for certain components of LIGO

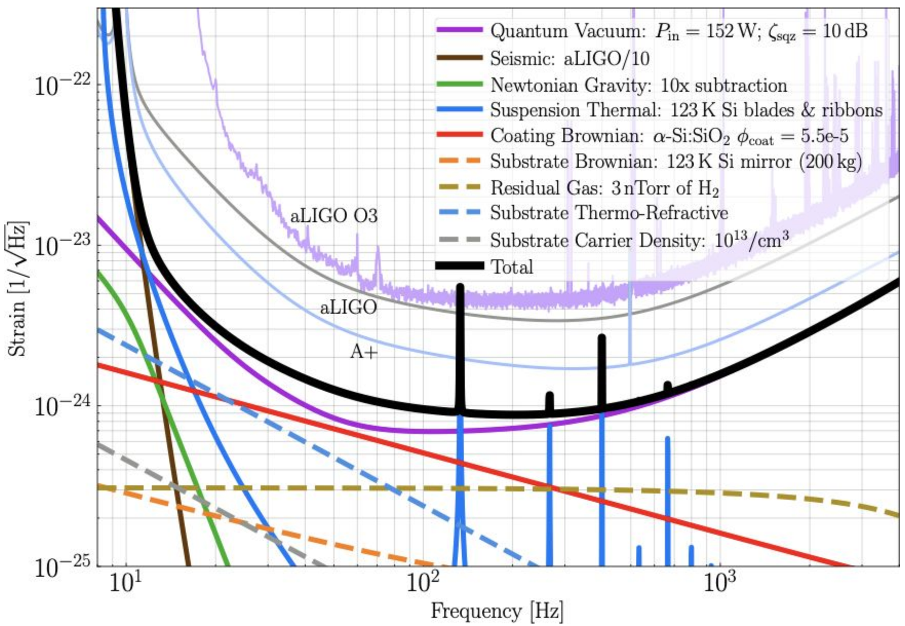


PSOMA*
Mirror

*A Phase-Sensitive Optomechanical Amplifier... Bai et al. (2020)

LIGO Voyager and Strain Sensitivity

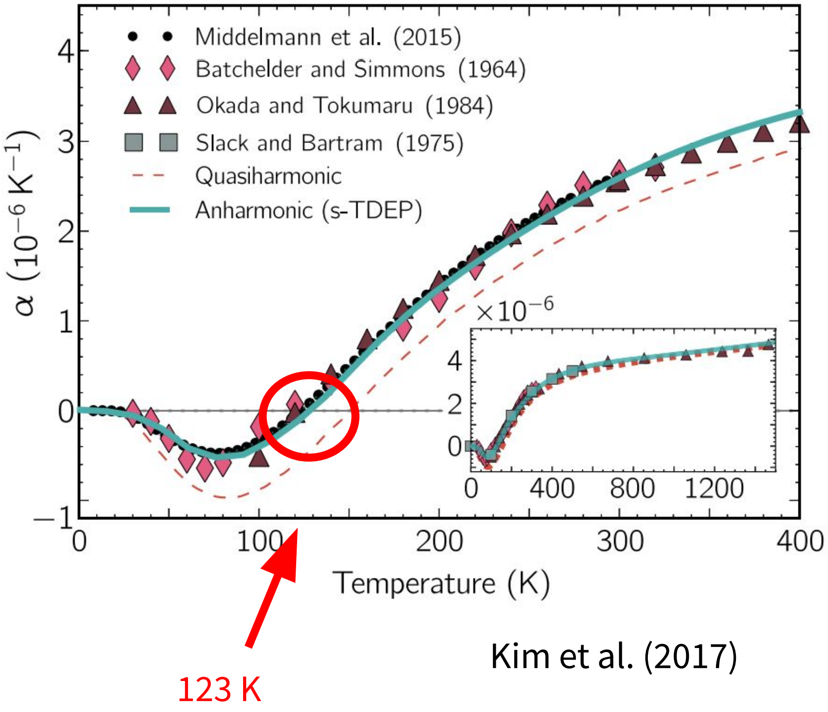
- To detect GW, LIGO must be extremely sensitive
- Quantum noise [purple] remains the limiting factor at most detection frequencies
- Can decrease quantum noise by
  - Mitigating optical losses [PSOMA, more later]
  - Increasing interferometer (IFO) input power by cooling test mass



R. Adhikari et al. (2019)

Cryogenic Voyager LIGO

- Next generation of LIGO observatories
- Test masses made of silicon to leverage vanishing coefficient of thermal expansion (CTE)
- IFO must be run at 123 K for vanishing CTE
- Important to minimize scattering and lensing due to small deformities in the mirrors



Kim et al. (2017)

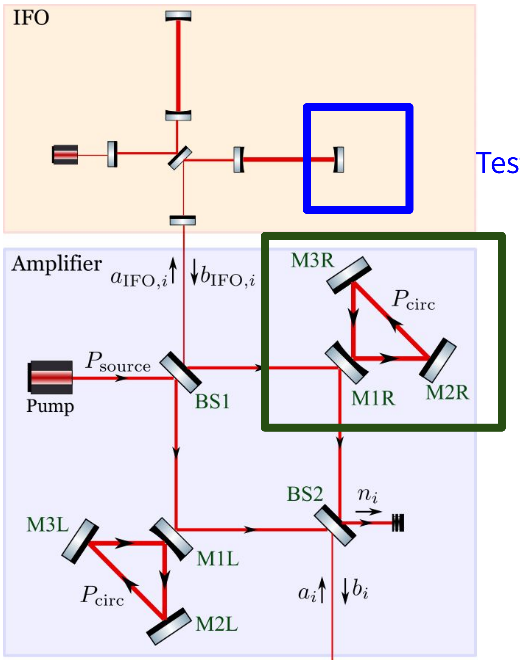
Potential Cooling Choices

Type of Cooling	Vibration Free?	Can Cool at 123 K?	Sufficient Power at 123 K?
Mechanical: Pulse tube/Stirling Cycle	No	Yes	Yes
Thermoelectric Cooling	Yes	No (limit of ~155 K)	No
Radiative Cooling	Yes	Yes	In some cases
Optical Refrigeration	Yes*	Yes*	Yes*

*With some caveats

Limits of Radiative Cooling for Small Objects

- Governed by Stefan-Boltzmann law
  - $P_c \simeq \sigma A(T^4 - Tc^4)$
- Leads to strong geometrical limits when trying to keep elements light
  - For Voyager's test masses, up to ~10 W of radiative cooling is possible
  - For 30 g PSOMA mirrors, maximum of about 40 mW, which allows for 40 kW of cavity power, which we want to maximize
- This is where optical refrigeration could be useful, as there is no fundamental limit on the cooling power due to the size of the mirrors



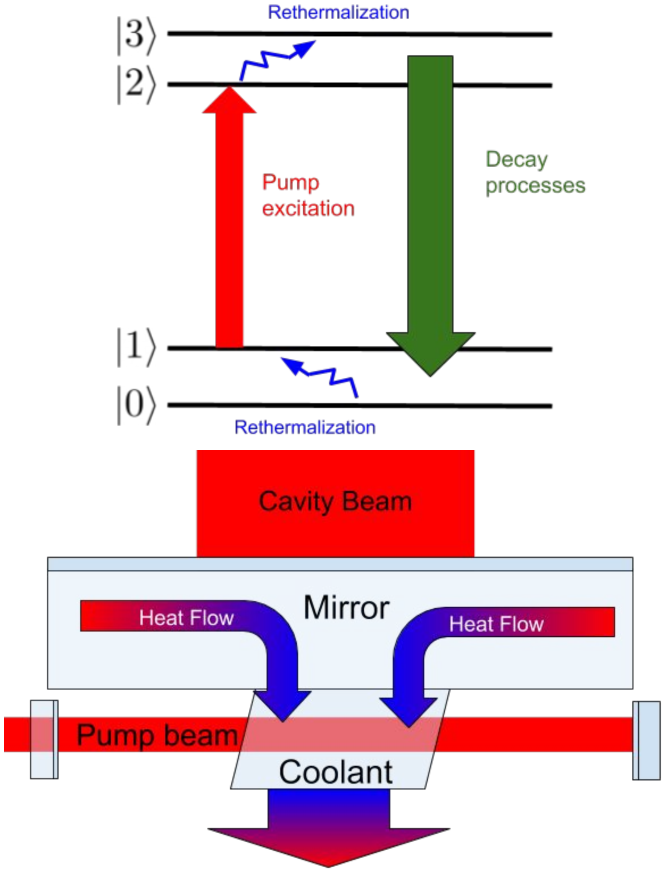
Test mass

PSOMA Cavity Mirrors

Bai et al. (2020)

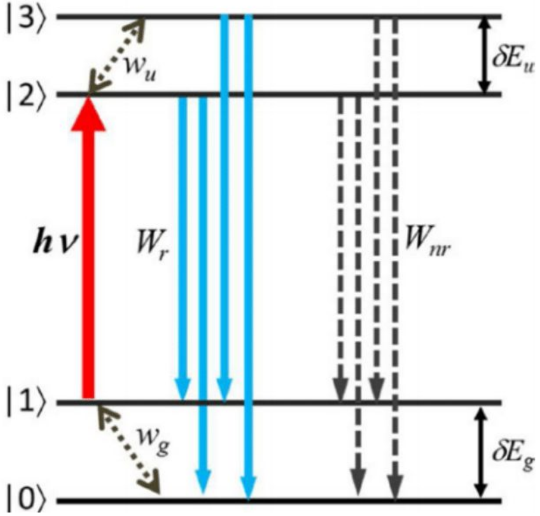
Optical Refrigeration Basics

- Cooling with a laser- familiar ideas from cooling of gases
- Not Doppler shift, but anti-Stokes
  - Mean fluorescence event is of lower wavelength/higher energy than the pump light
- Crystal doped with certain rare earth (RE) ions
- Extra energy comes from phonon bath in host crystal
- Conductively couple crystal to load [mirror] to cool it



OR Cooling Model

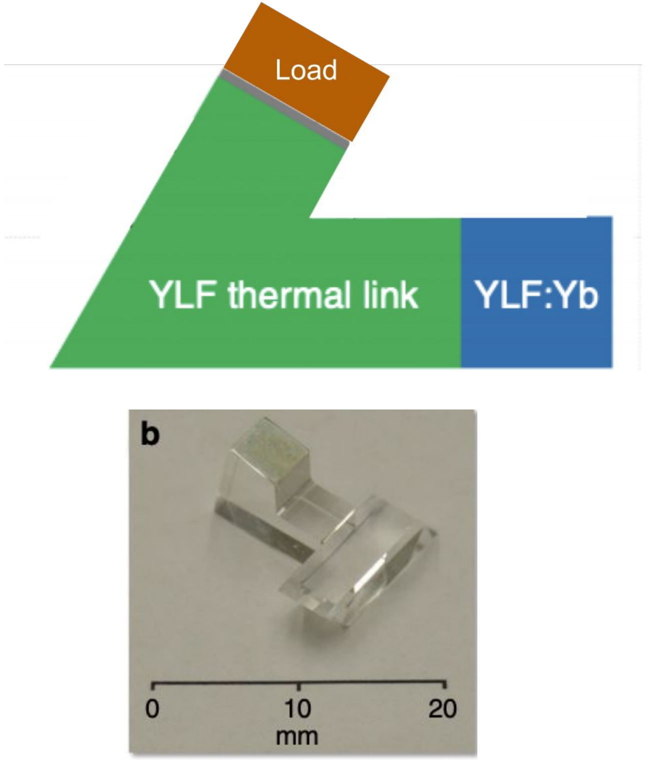
- Model of level structures for optical coolant ions
- |0⟩-|1⟩ and |2⟩-|3⟩ transitions happen much faster than relaxations
    - These gaps are also **much** smaller than the decay ones
- Boltzmann quasi-equilibrium, mediated by phonons
- Need systems that can approximate this 4-level model
- Quantum efficiency– limited by nonradiative decay–is the main limiter on cooling power
- Cooling power and cooling efficiency, the most relevant figures of merit, can be derived from this and some material properties



Seletskiy et al. (2016)

Fluorescence Heating

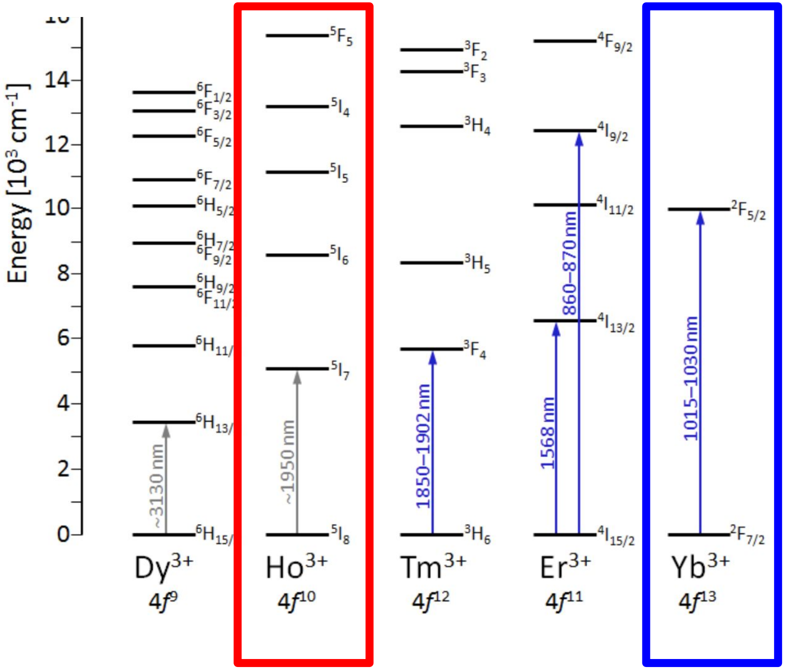
- Resulting from the cooling mechanism, the fluorescence will be of a much higher power than the cooling
- “it is as though one wants to use a [100 mW] refrigerator that had [an 80 W] refrigerator light bulb that can‘t be turned off.” (Seletskiy et. al, 2016)
- Can be mitigated
  - Shielding
  - Transparency



Hehlen et al. (2018)

Important dopants

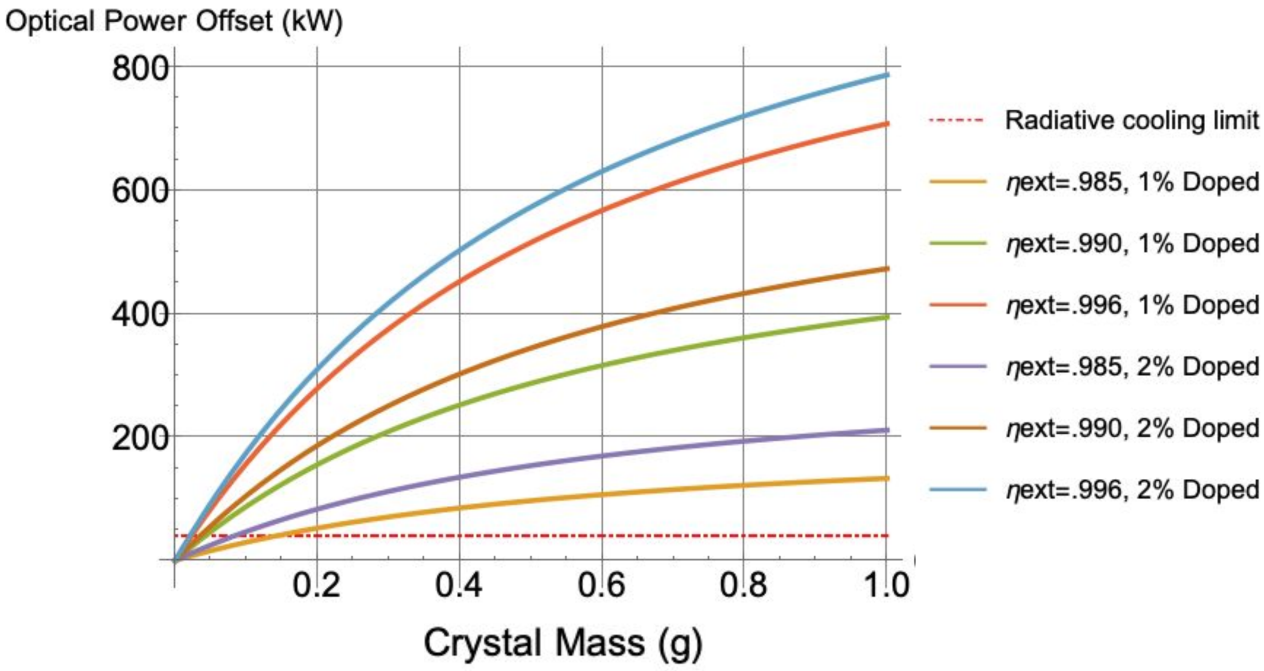
- Ytterbium (Yb^{3+})
  - Cheap
  - Effective
  - Proven
  - Cooled down to 91 K, 135 K with load
- Holmium (Ho^{3+})
  - Newer
  - No cryogenic cooling demonstrated to date
  - Potential for higher cooling power
  - Current crystals can cool to ~130 K
  - **SIlicon transparent to its fluorescence**



Hehlen et al. (2014)

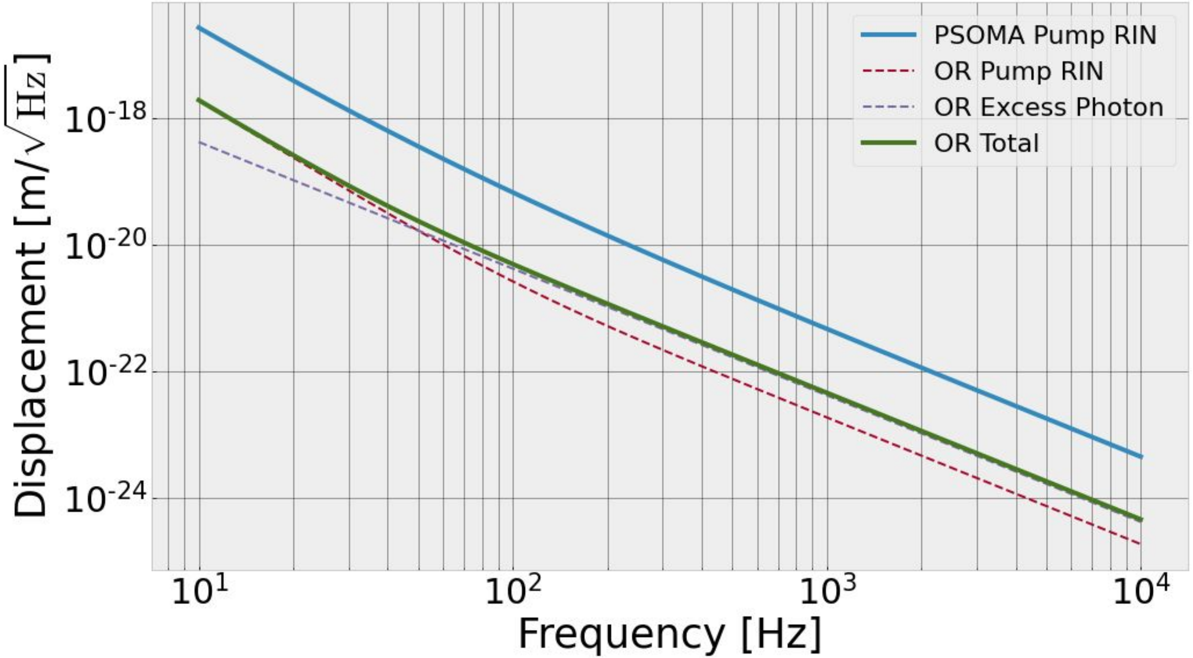
Optical Cooling Power for PSOMA

- Evaluated for real and theoretical crystals
- With some reasonable improvements in crystal quality, optical refrigeration offset **significantly** more power than radiative cooling



Radiation Pressure Noise

- ~ 3.5 W of fluorescence hits the highly reflective mirror surface
- Fluorescence is noisy
  - Pump laser noise
  - “Wave interaction/Excess photon noise” due to linewidth of fluorescence
- RP noise may be a concern in implementation



Conclusions

- OR may be more effective than radiative cooling in cooling PSOMA mirrors or other small optomechanical components
- May have to work on eliminating contributions of fluorescence radiation pressure to noise
- Practicality relies on some improvements in crystal growth, expected to come in the next several years. (Rostami et al. 2019)

Acknowledgements

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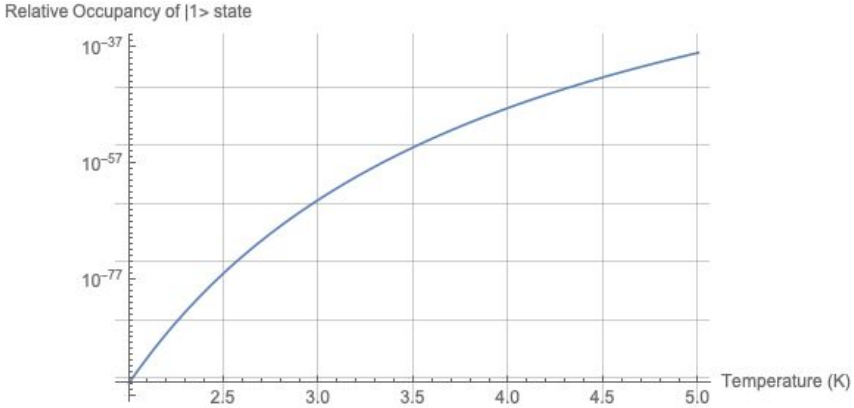
- LIGO Lab, the Caltech LIGO SURF program, and the broader NSF REU program

Appendix I - Low-Temperature OR?

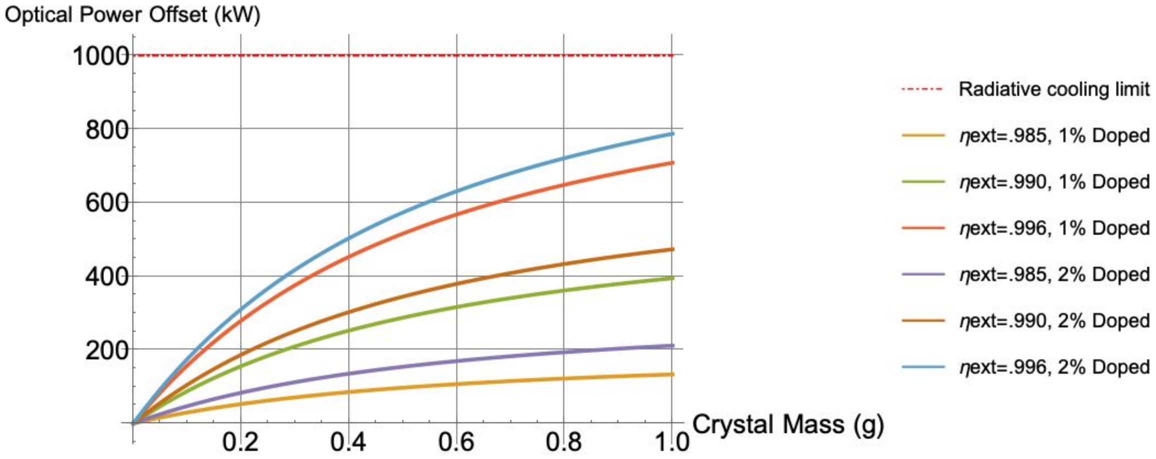
- Can you optically cool test masses for a ~4 K interferometer?
    - **Almost definitely not.**
- The limits become clear when looking at the low temperature Boltzmann populations
- Would have to find a material with an extremely narrow ground state that will still anti-Stokes fluoresce and show extremely low background absorption



Excited level of ground state occupancy relative to lowest level occupancy (Boltzmann factors) at low temperatures for Ho:YLF. At 4 K, this figure is about 10^{-50}.

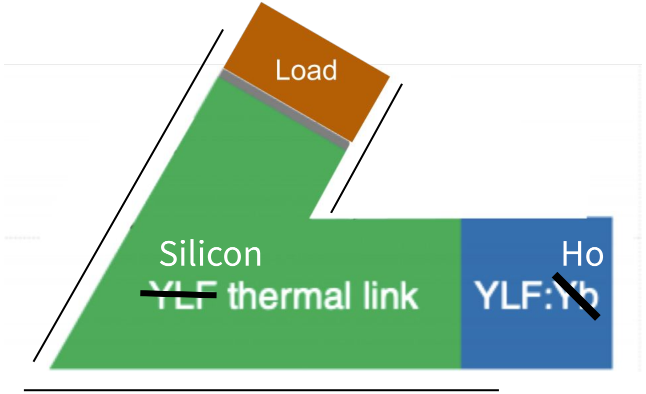
Appendix II - Cooling Test Masses

- Could work, but clearly outshone by radiative cooling
- RP noise could be less of an issue, but the cooling power contribution is just not significant enough



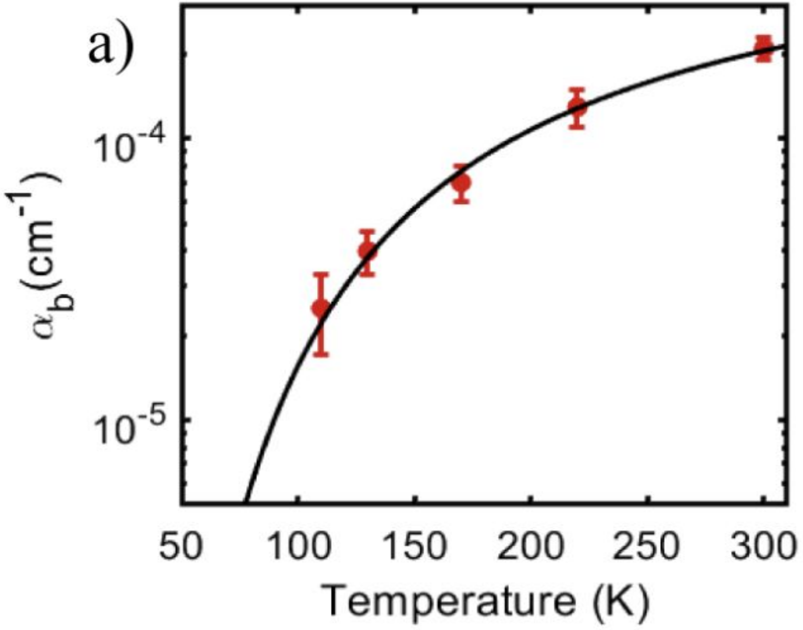
Appendix III - RP Noise Mitigation

- Silicon thermal link (pictured)
  - Potentially surrounded by (non-suspended) cooled absorbing surfaces
- Introducing symmetry
  - Placing another reflecting surface on the other side of the mirror
  - Should eliminate classical noises- shot noise not significant



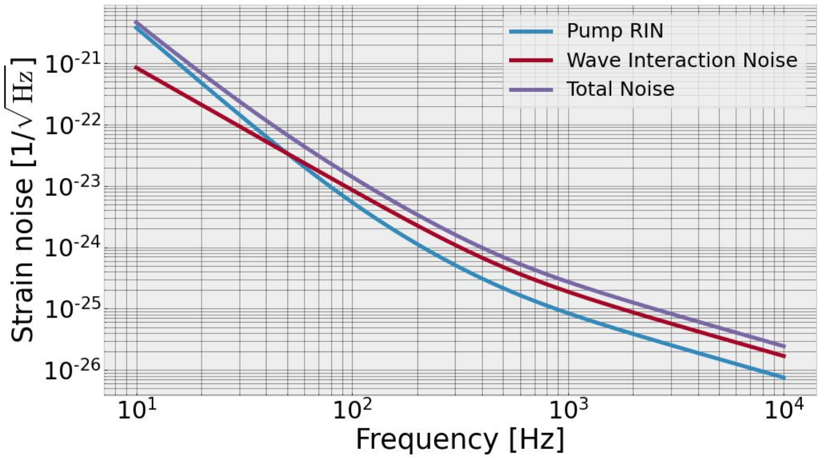
Appendix V- Deviations from Optimal P_{cool}

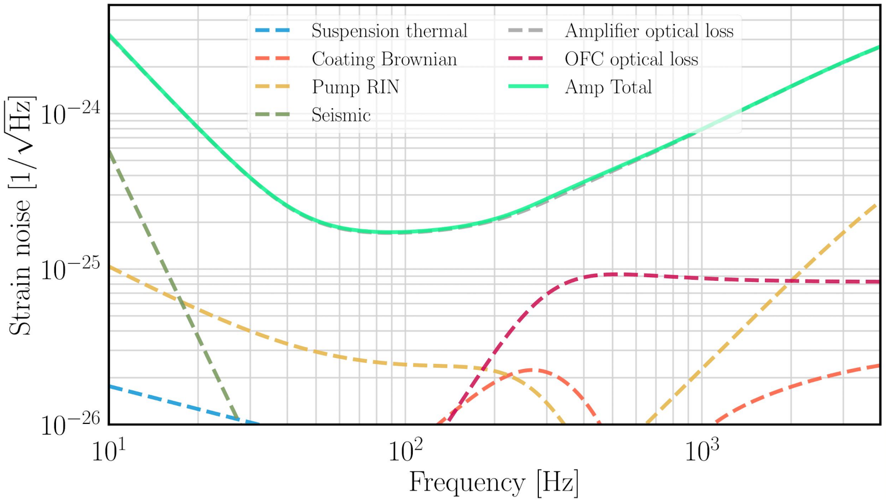
- Saturation- not well studied and largely ignored in most OR experiments
- Oddities with background absorption
  - Not yet studied with Ho:YLF
- Absorption by adhesives



Volpi et al. (2019)

Appendix IV- More on Noise





Bai et. al (2020)