Optical Refrigeration for an Optomechanical Amplifier

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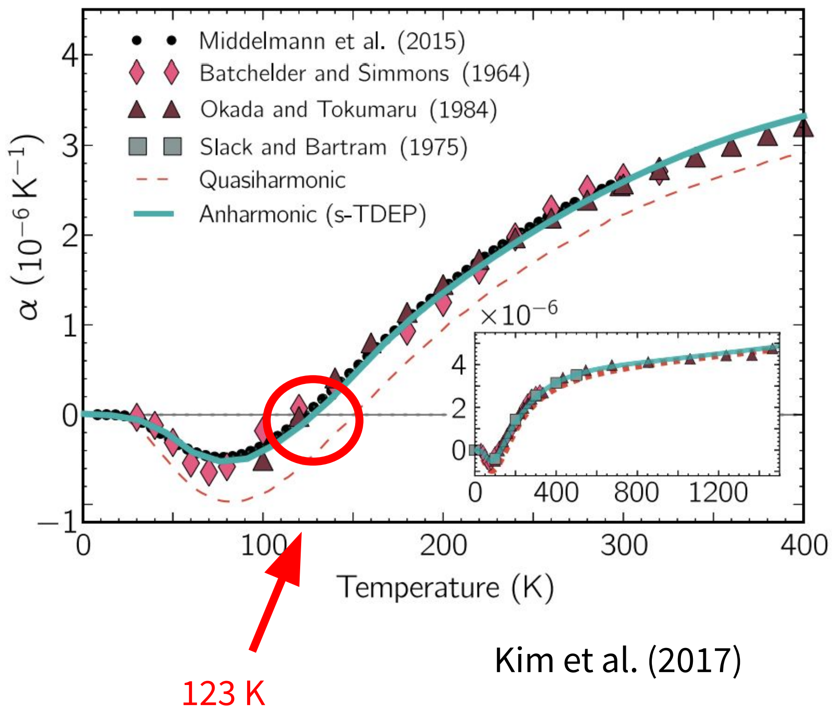
Cryogenic Voyager LIGO

- Next generation of LIGO observatories
- Test masses will be made of silicon at 123K to leverage vanishing coefficient of thermal expansion



Kim et al. (2017)

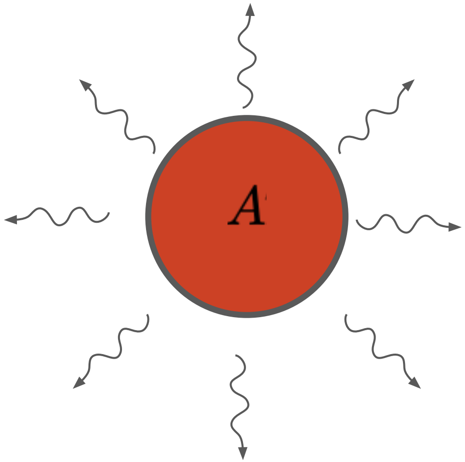
Potential Cooling Choices

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

*With some caveats

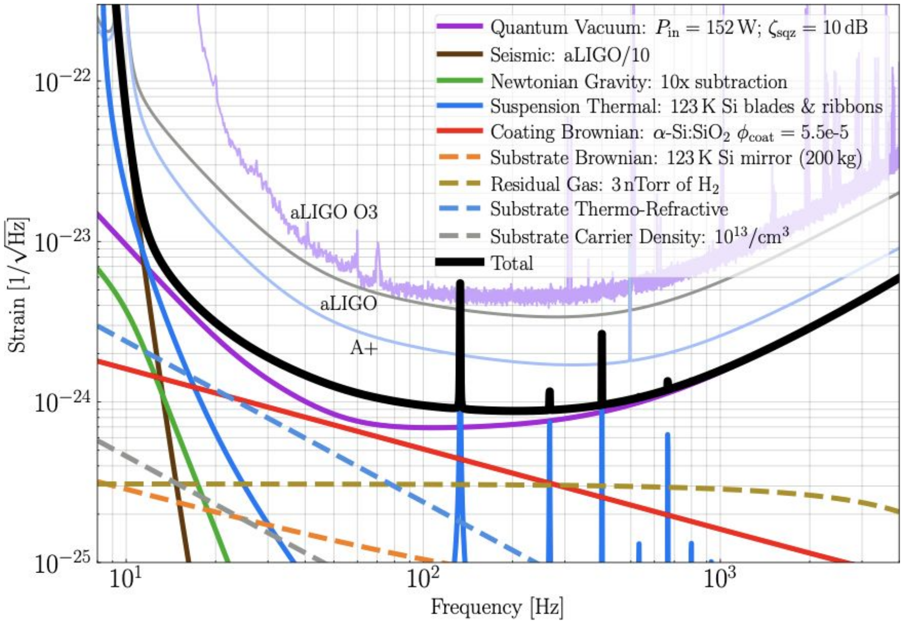
Limits of Radiative Cooling for Small Objects

- Governed by Stefan-Boltzmann law
  - $P_c \propto AT^4$
- 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 gram scale mirrors, it is not very efficient
- 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



LIGO Voyager and Strain Sensitivity

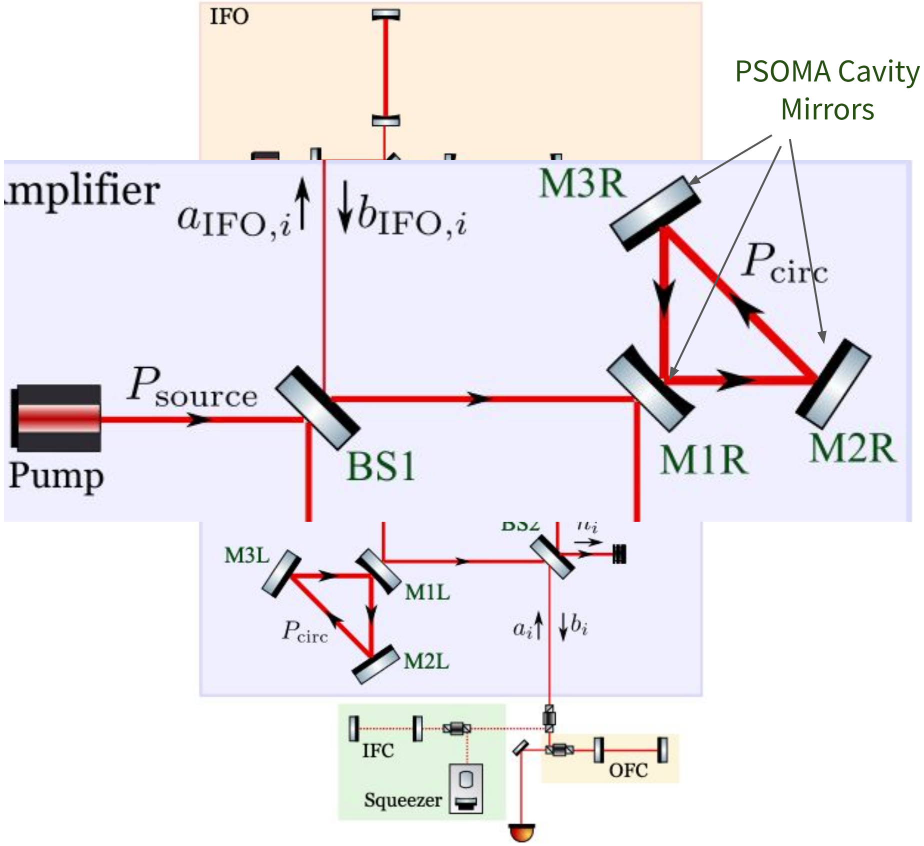
- Quantum noise remains the limiting factor at most detection frequencies
- Squeezed vacuum is the solution (other than increasing laser power)
- Loss degrades squeezing
- In current detectors loss occurs mainly due to mode mismatch between cavities (e.g. OMC)



R. Adhikari et al. (2019)

Phase-Sensitive Optomechanical Amplifier (PSOMA)

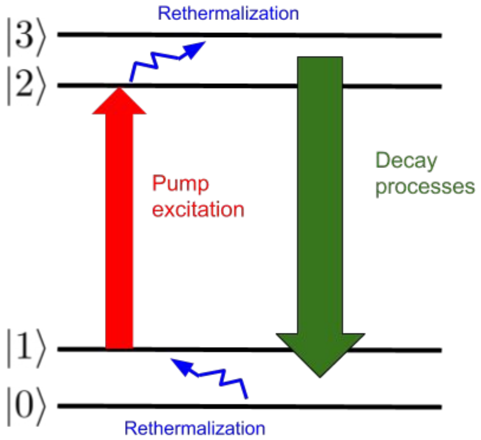
- Need to compensate for losses in the readout chain (e.g. OMC mode mismatch)
- Radiation pressure can be used to amplify weak signals using lightweight mirrors
- Radiative cooling can lift a maximum of about 40 mW of heat from 30g PSOMA mirrors, which allows for 40 kW of circulating power



Bai et al. (2020)

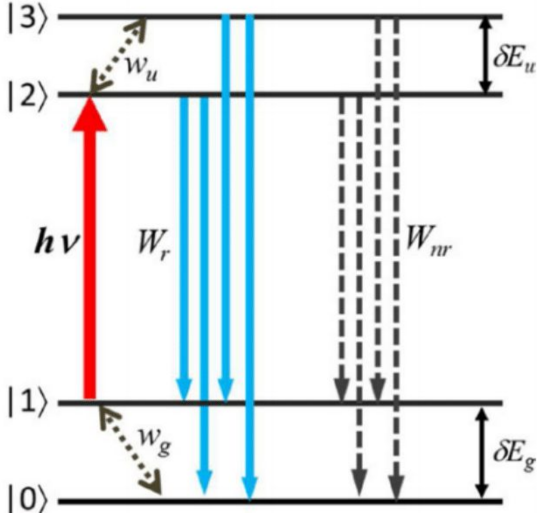
Optical Refrigeration Basics

- 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



Optical Regrigeration Cooling Model

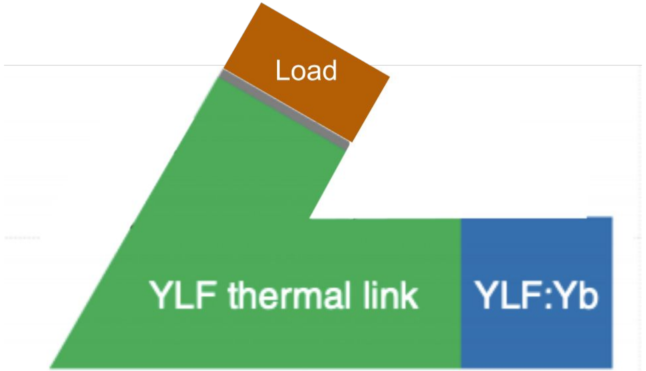
- $|0\rangle$-$|1\rangle$ and $|2\rangle$-$|3\rangle$ transitions happen much faster than relaxations
- Boltzmann quasi-equilibrium, mediated by phonons
- Cooling power and cooling efficiency, the most relevant figures of merit, can be derived from this and some material properties
- Quantum efficiency– limited by nonradiative decay–is the main limiter on cooling power

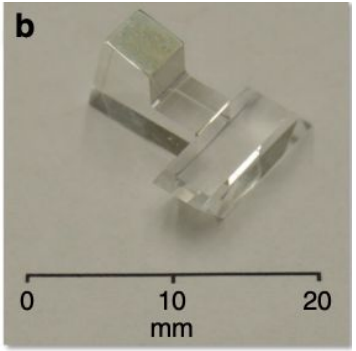


Seletskiy et al. (2016)

Fluorescence Heating

- Resulting from the cooling mechanism, the fluorescence will be of a much higher power than the cooling
- Can be mitigated
    - Shielding
    - Transparency
- “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)

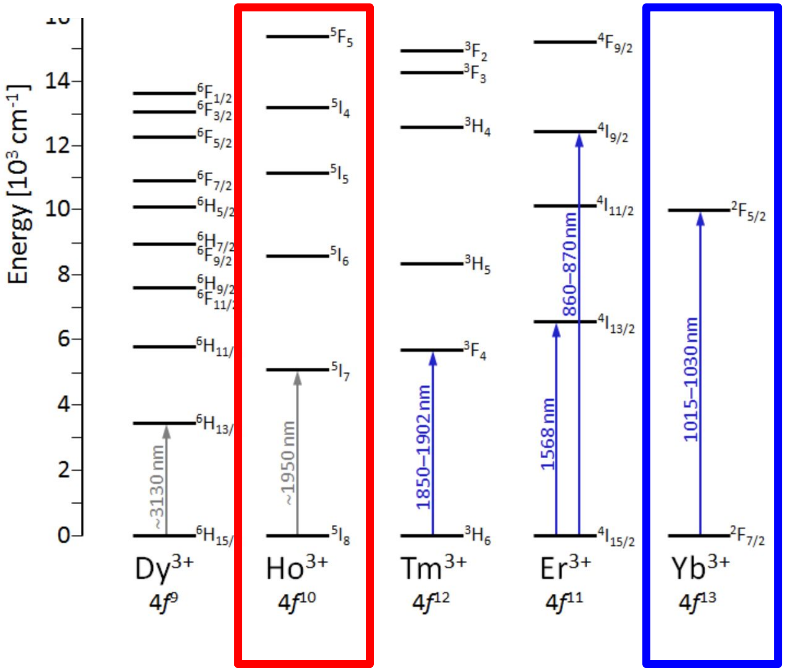




Hehlen et al. (2018)

Important Dopants

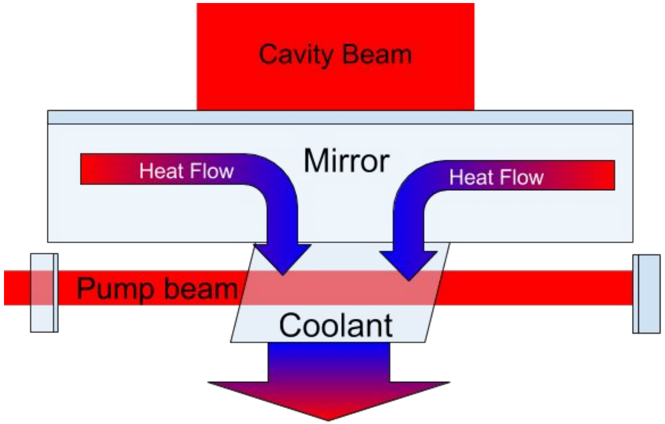
- Ytterbium (Yb^{3+})
  - Cheap
  - Effective
  - Proven
  - Cooled down to 91 K, 135 K with load
- Holmium (Ho^{3+})
  - Newer
  - No cryogenic cooling demonstrated to date
  - Potential for higher cooling power
  - Current crystals can cool to ~120 K
  - **SIlicon transparent to its fluorescence**



Hehlen et al. (2014)

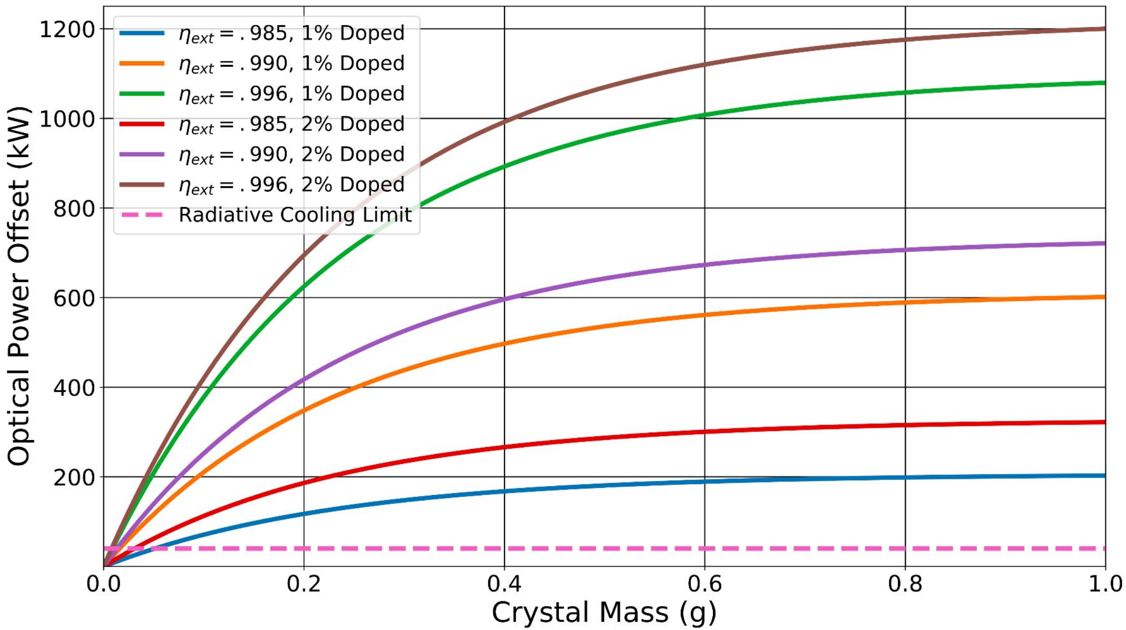
Design Considerations

- Shield against fluorescence
  - Choose Ho^{3+} for transparency and potential for high cooling efficiency
- Good thermal contact with mirror (short thermal link)
- Multipass configuration
- Minimize radiation pressure noise
- Minimize readout contamination (work in progress)



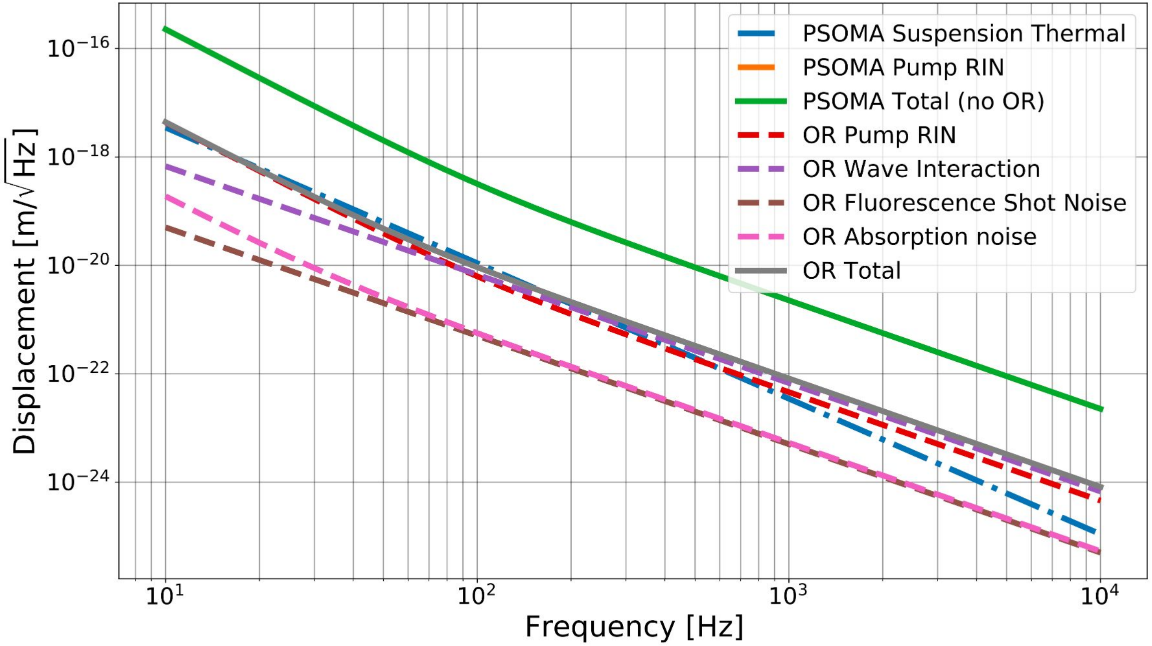
Optical Cooling Power for PSOMA (Ho:YLF)

- 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

- ~ 7.7 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

- Optical refrigeration may be more effective than radiative cooling in cooling PSOMA mirrors or other small optomechanical components
- Practicality relies on some improvements in crystal growth, expected to come in the next several years. (Rostami et al. 2021)
- Preliminary results show that high performance optical refrigeration does not add significant noise to PSOMA