Solid-State Optical Cryocoolers

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Optical cryocooling is the coolest solid-state refrigerator

Has advantages over other cryocoolers

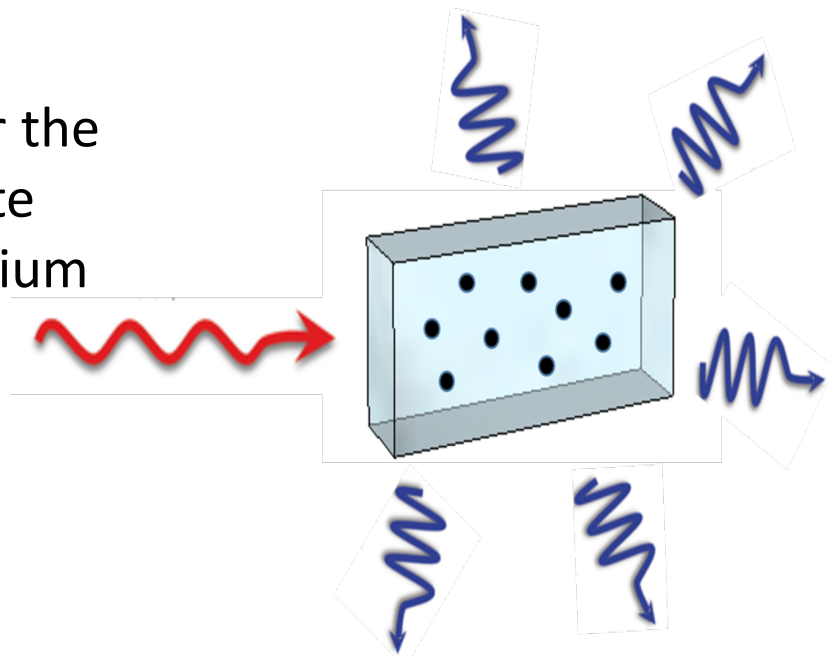
Almost ready for "real-world" applications.

Ytterbium-based Laser Cooling

- **Anti-Stokes Fluorescence**

Excited ytterbium atoms absorb energy from the solid and emit higher energy photons. **This creates cooling.**

Lower energy photons enter the solid and excite dopant ytterbium atoms

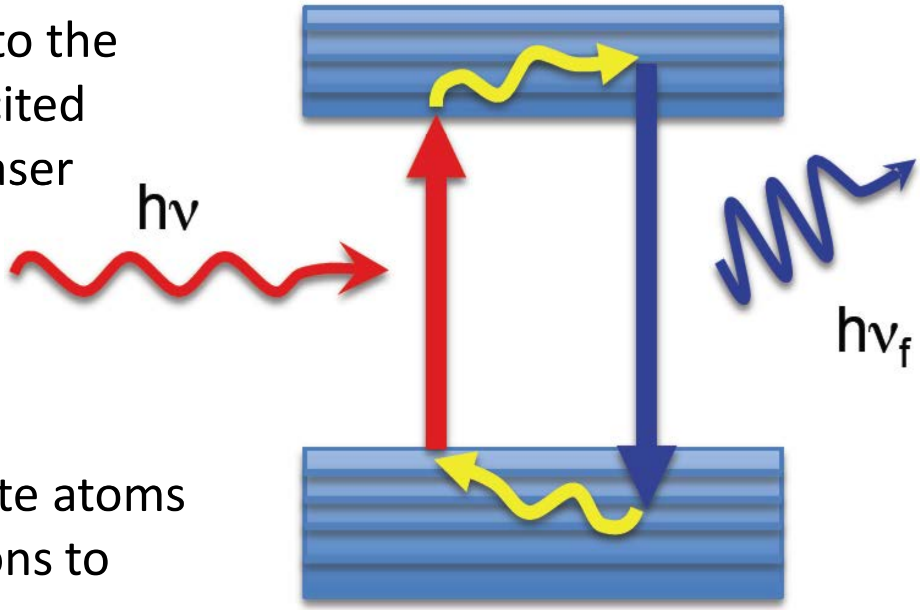


Prediction: P. Pringsheim, *Z. Physik* ***57*** (1929).
Theory: L. Landau, *J. Phys*. (Moscow) **10**, (1946).
Observation: R.I. Epstein, et.al. *Nature*, **377**, 500 (1995) (Los Alamos, USA)

Cooling Cycle

1) Atoms are excited from the top of ground state to the bottom of excited state by the laser

2) Excited atoms absorb phonons to reach thermal equilibrium with lattice host



3) Spontaneous fluorescence at a greater photon energy ($h\nu_f > h\nu$) brings atoms back to ground state

4) Ground state atoms absorb phonons to thermalize

Ideal cooling efficiency:

$$\eta_c = \frac{h\nu_f - h\nu}{h\nu} = \frac{\lambda}{\lambda_f} - 1$$

Fighting Background Absorption

$$\eta_c \; ; \; \eta_{abs}\frac{h\nu_f}{h\nu}-1>0 \text{ for cooling}$$

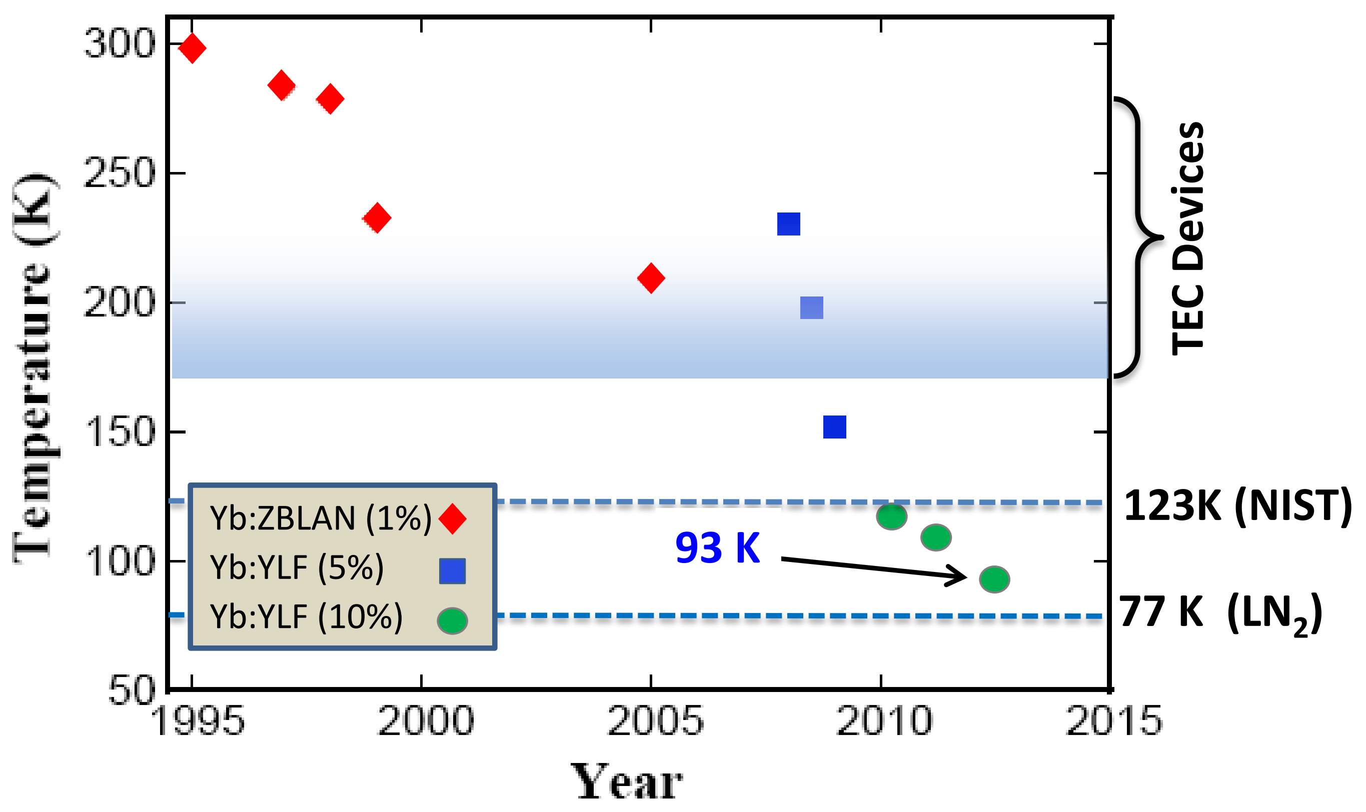
$$\eta_{abs}=\frac{\alpha_r(\nu)}{\alpha_r(\nu)+\alpha_b}=\frac{1}{1+\alpha_b/\alpha_r(\nu)}$$

Competition between **resonant absorption** $\boldsymbol{\alpha_r}$
And parasitic **background absorption** $\boldsymbol{\alpha_b}$

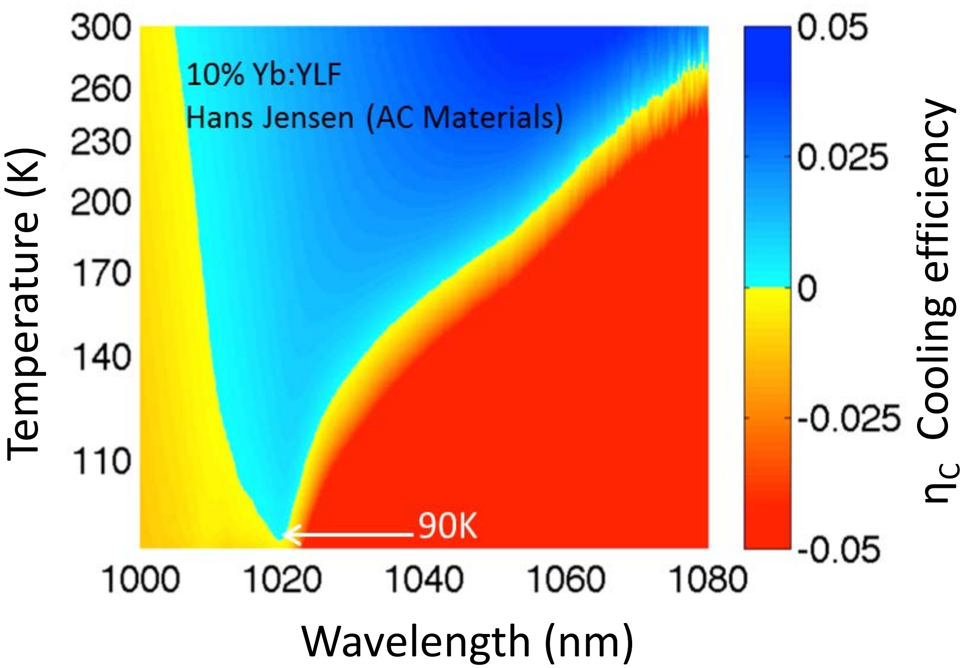
Resonant absorption:
Converts ~ 1% of absorbed laser power into cooling heat lift

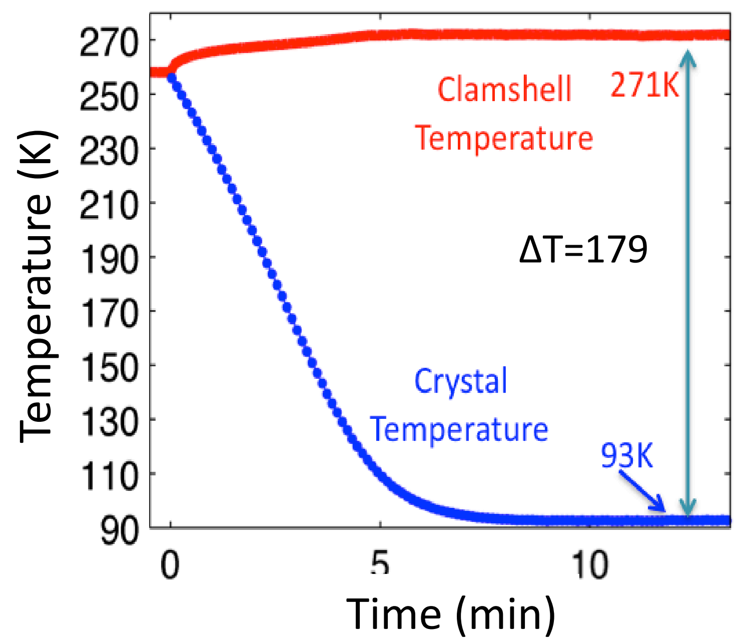
Background absorption:
Converts 100% of absorbed power into heat

Lower and Lower Temperatures



Best Cooling Material To Date

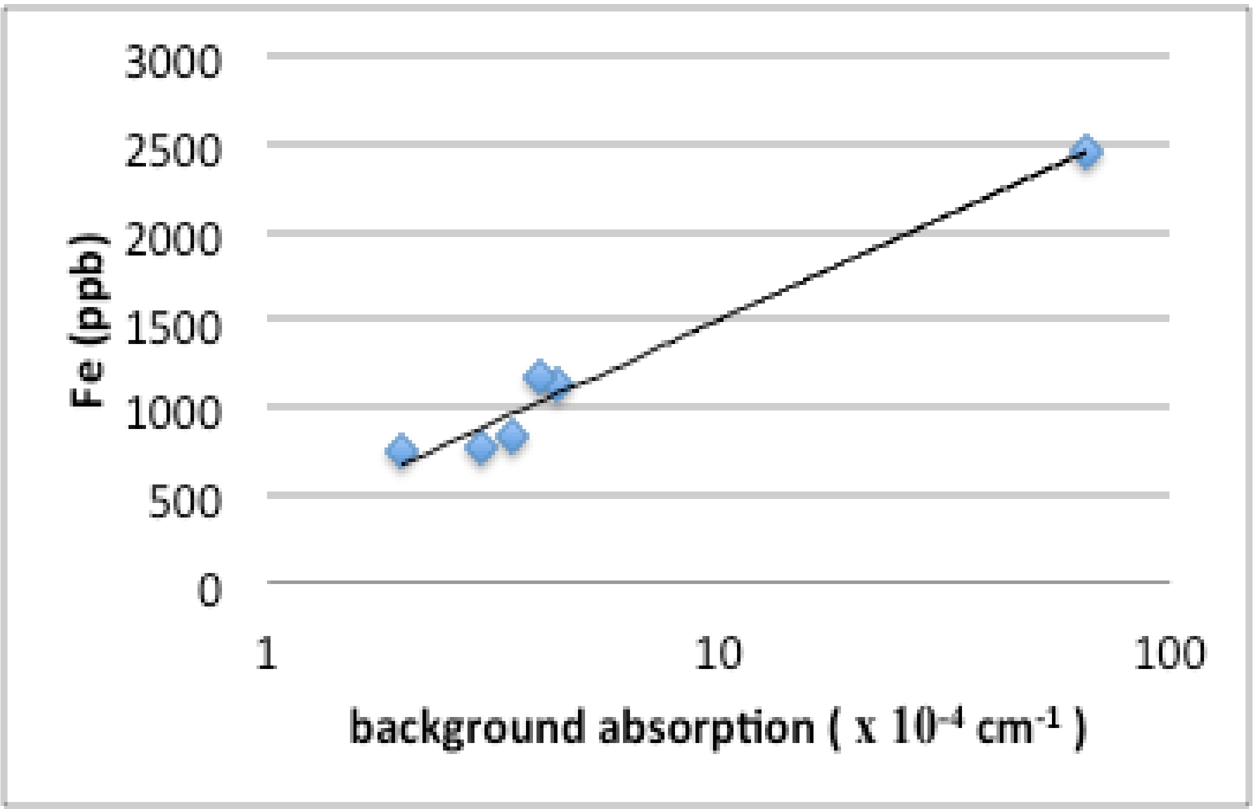




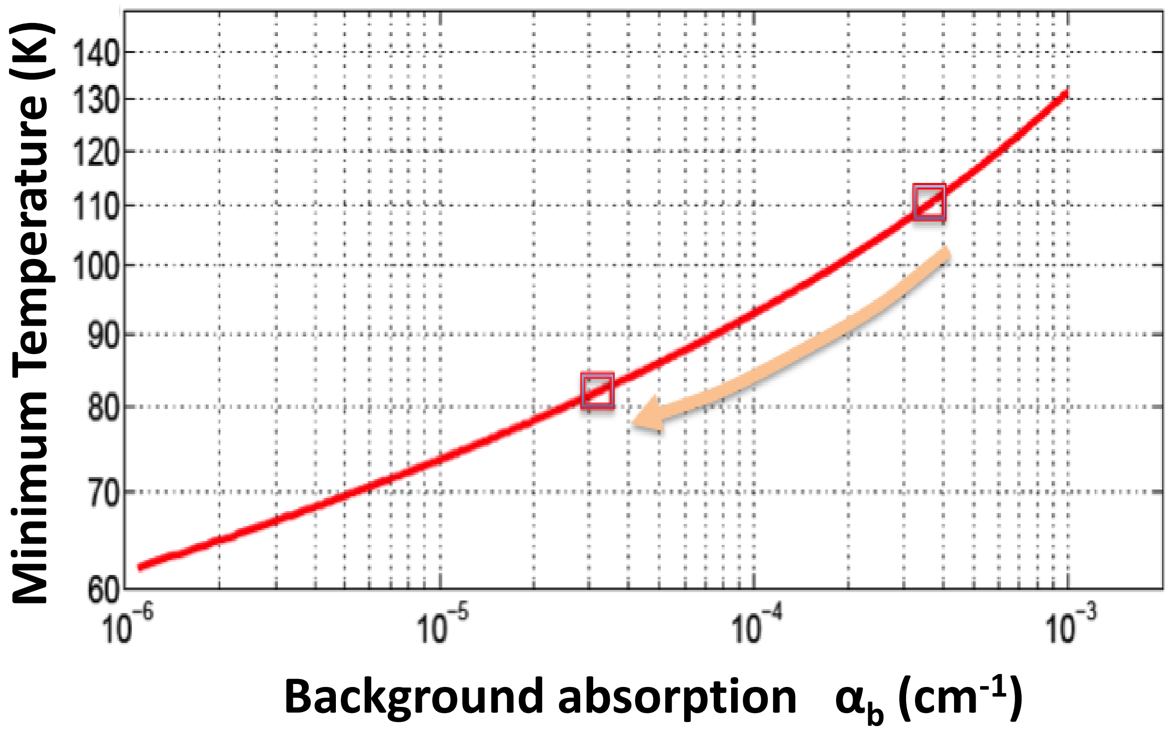
Plot of η_C for a Yb:YLF crystal
Yb doping = 10% wt.
Background absorption: α_b = 2.0 x 10^{-4} cm^{-1}

Cooling measurements with
54 W laser tuned to 1020 nm

Origin of Background Absorption? Iron May be the Main Problem



Paths to Lower Temperatures



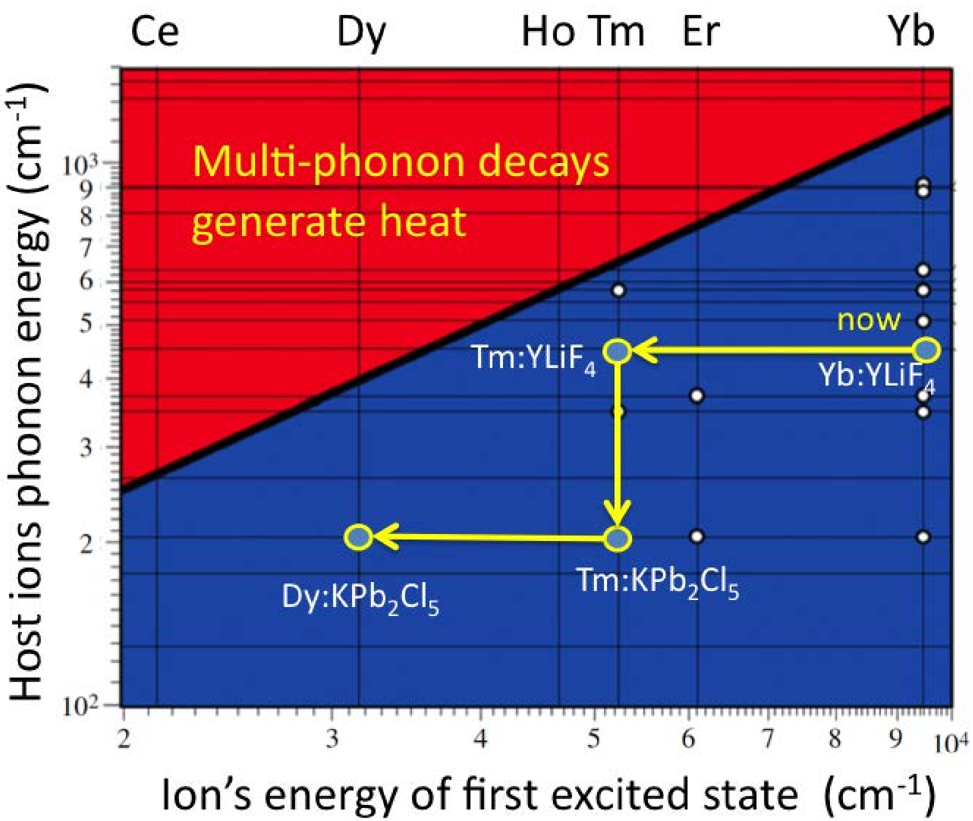
Iron may be removed by
Chelation Assisted Solvent Extraction or by
Electrochemical Purification

Paths to Higher Efficiencies

Lower pump energies allow higher efficiencies

Choose Active Ions and Crystal Hosts

← Higher Quantum Efficiency



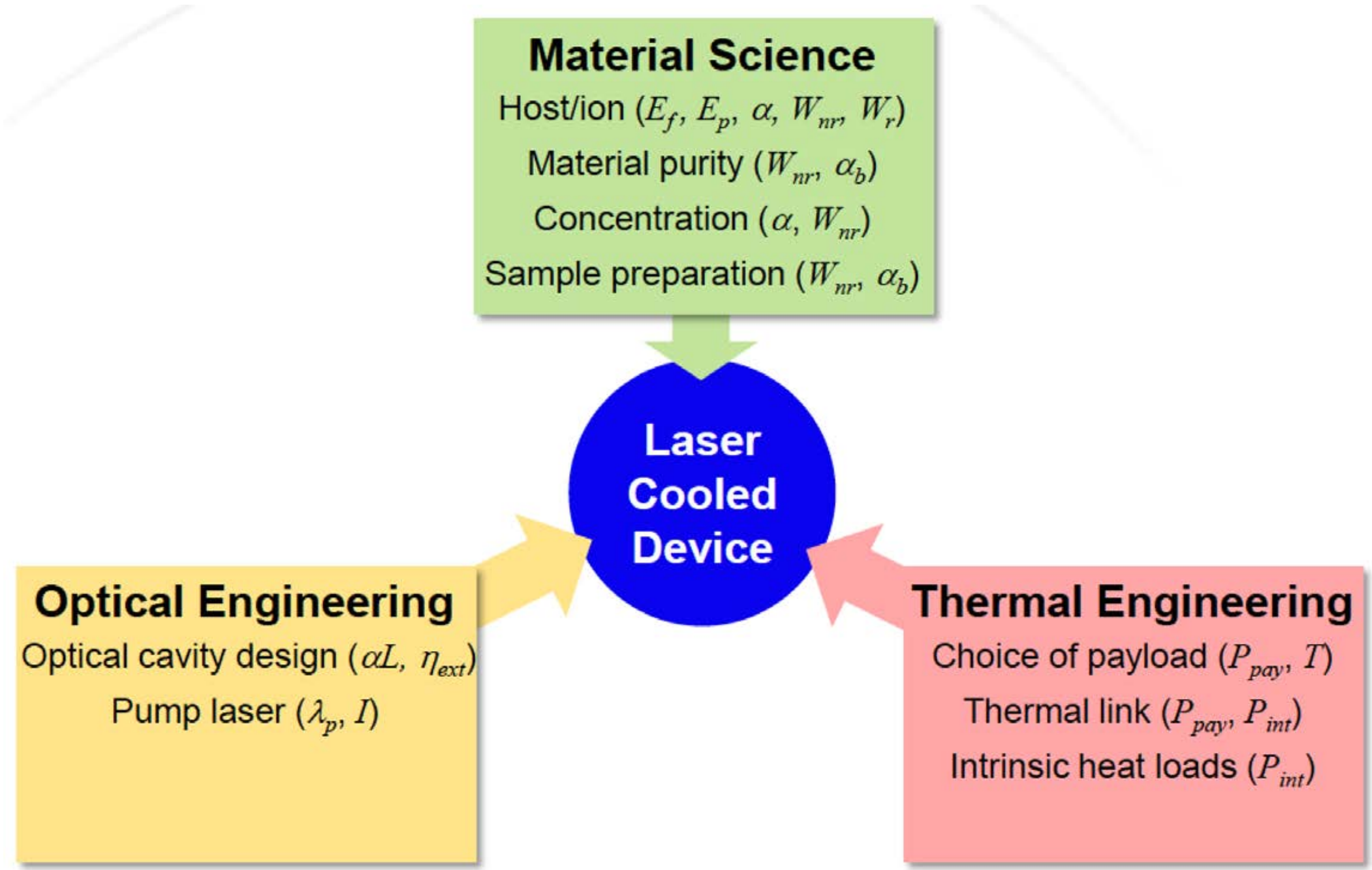
← Higher Cooling Efficiency

Photon energy shift is limited by thermal excitations

$$\eta_c \sim \frac{h\nu_f}{h\nu} - 1 \sim \frac{kT}{h\nu}$$

Dopant Ion	Pump Energy	Cooling Efficiency
Yb^{3+}	1.21 eV	~1.5%
Tm^{3+}	0.62 eV	~2.9%
Dy^{3+}	0.37 eV	~4.9%

Multidisciplinary Challenges



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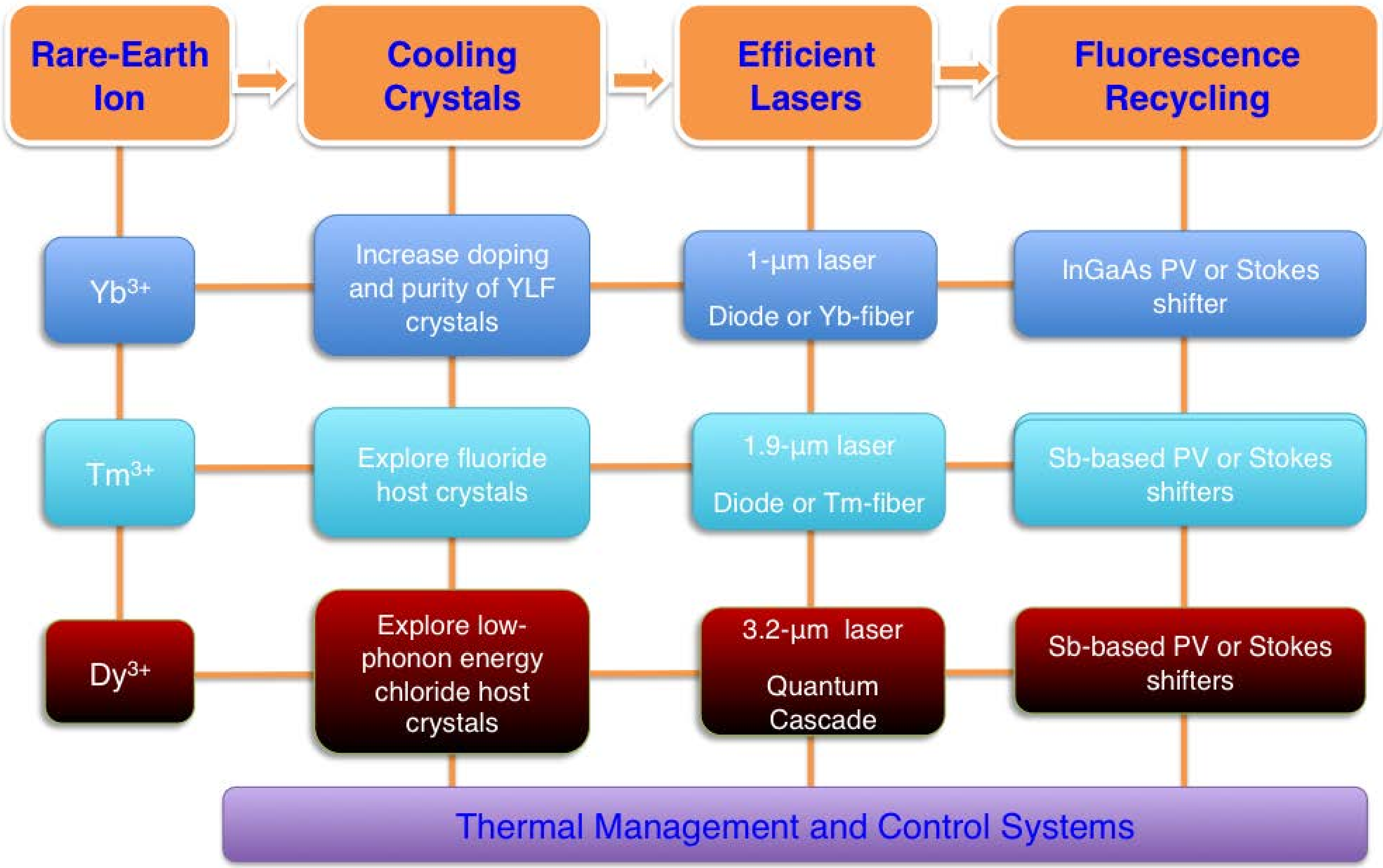
Roadmap for High-Efficiency RE-Based Optical Cryocoolers



Additionally – there have been major breakthroughs in cooling semiconductors by Prof. Qihua Xiong's group from Nanyang Technological Univ. in Singapore

Advantages Optical Cryocoolers

- **Solid-State**
  - **No vibrations**
  - **Reliable – no moving parts**
- **Compact and low mass**
- **Novel thermal management**
  - **Pump laser can be far from cooler head**
  - **Waste fluorescence can be radiated away or recycled into electrical power**
- **No EMI**
- **Insensitive to strong magnetic fields**

Initial Uses for Optical Cryocoolers

Ultra-stable frequency standards

no vibrations, T_{cooler} ~ 124K

Infrared cameras (space-based and terrestrial)

no vibrations, compact, reliable, T_{cooler} < 150K

Germanium-based gamma-ray spectrometers

no vibrations, T_{cooler} < 120K

Electron microscopes

no vibrations, T_{cooler} ~ 160K

Low-noise amplifiers for antennas

low mass, T_{cooler} < 120K

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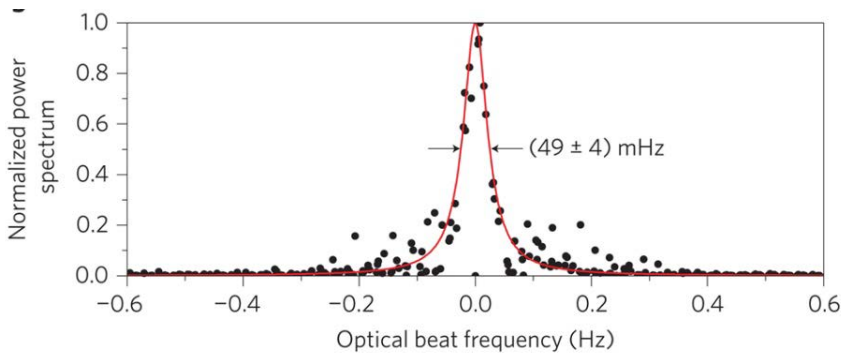
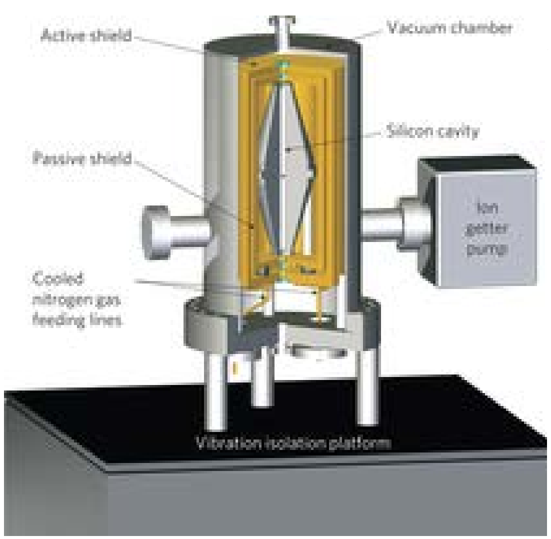
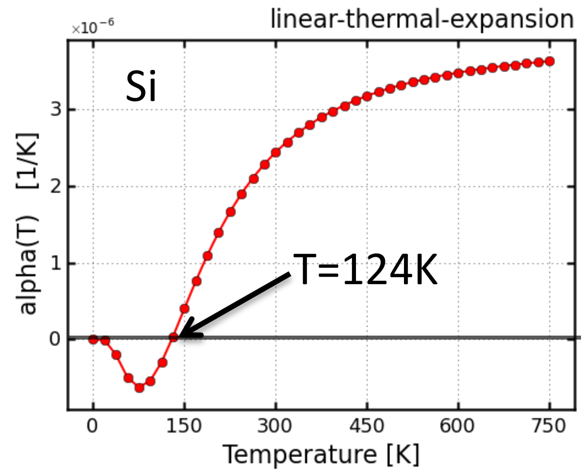
Ultrastable Laser Cavity Frequency Standard

A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity

Kessler et al., *Nature Photonics* **6**, 687–692 (2012)







Requires vibration-free cooling at 124 K

Collaboration with Prof. Jun Ye (NIST)

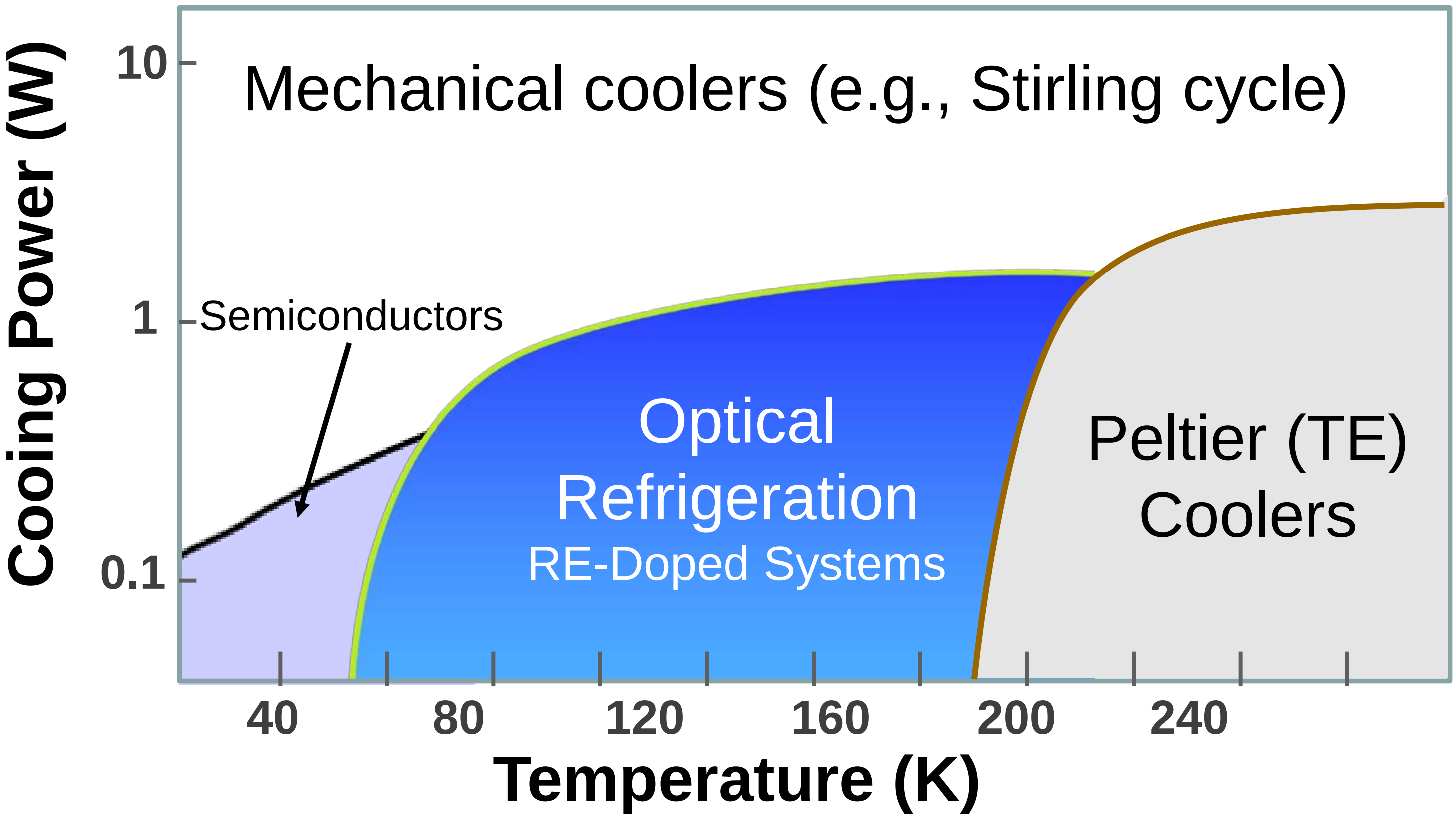
IR Imaging from Space

Cryocoolers for IR cameras on satellites should produce *very little vibration* and be *extremely reliable*

MTI multi-thermal image of SF Bay

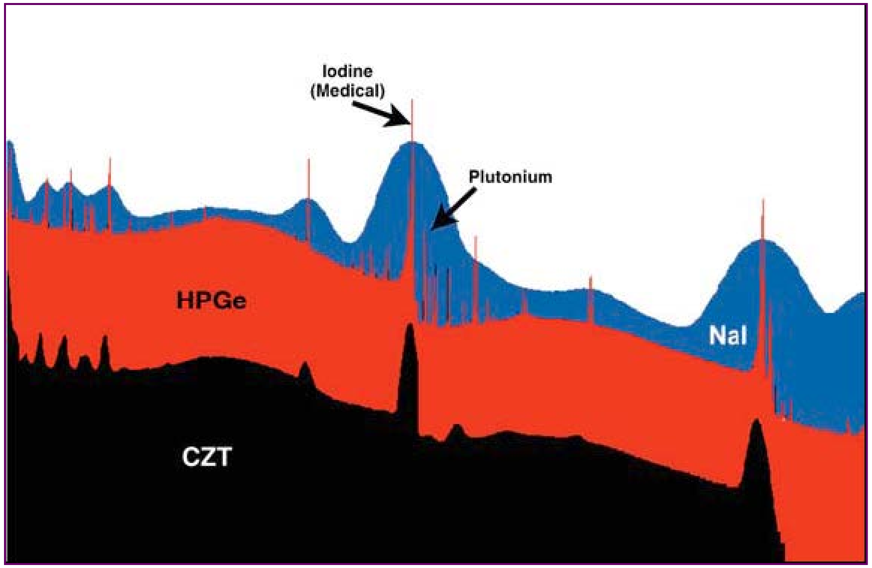
Optical Cryocoolers can Decrease Mission Weight

Lowest Mass for Space-Borne Coolers
(including solar panels etc.)



Adapted from a study by
Ball Aerospace & Technologies Corp.

Gamma-Ray Spectroscopy

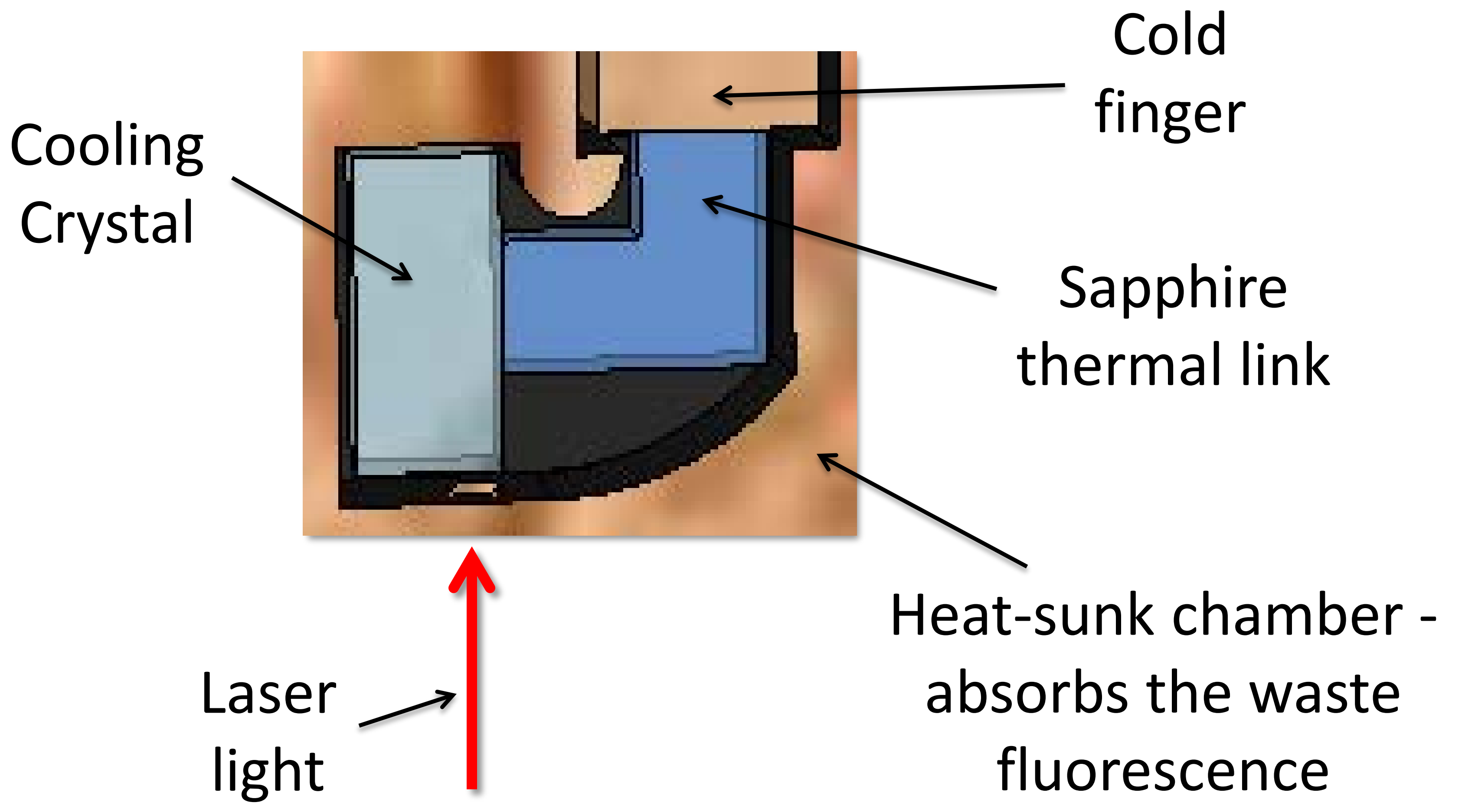


High-Purity Gamma Ray Spectrometers have extremely high energy resolution at T<120K

But – the spectra are severely degraded by *vibrations and microphonics*.

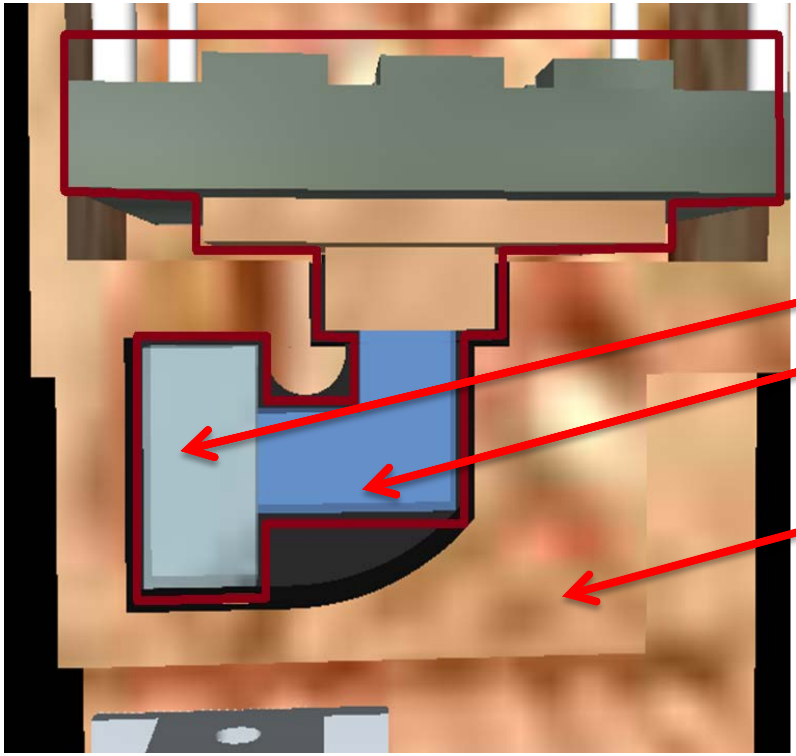
Solid-state cryocooling could enable portable, high-energy-resolution gamma-ray spectrometers.

The Essential Parts of an Optical Cryocooler



Very Little Cold Material

Rapid cool-down and low inertial



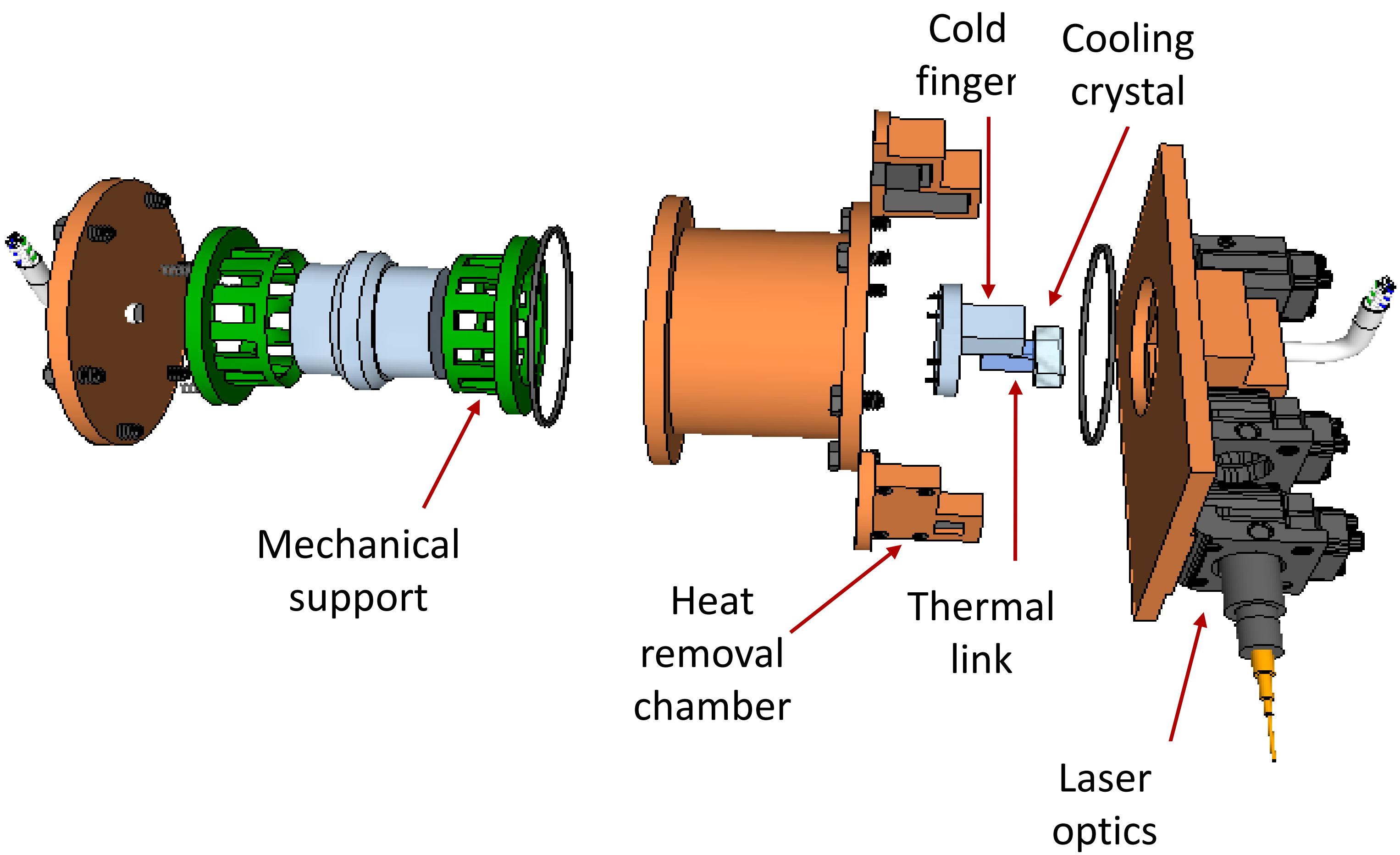
Total cold mass ~ 10 g

Cooling Crystal

Thermal Link

Chamber at ~300 K

Building a General Prototype



Summing-up

Optical cryocooling can now achieve sub-100 K temperatures, and there are strategies for getting below LN2

Advantages: Solid-state cooling, no moving parts, no vibrations, low mass and compact.

Applications: Laser metrology
IR detectors:
Gamma-ray spectrometry
Cold electronics.

If you have other ideas, let's talk!

Team

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email me if you want some review papers

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