Temperature Sensing to above 1500 °C Using Y_2SiO_5:Er Phosphor Thermometry

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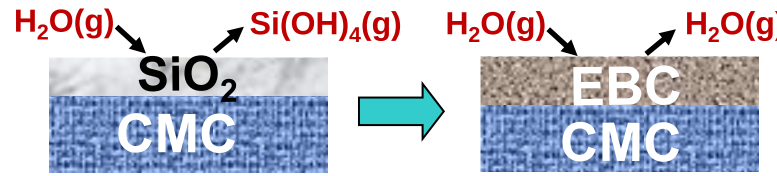
Background

- SiC/SiC ceramic matrix composites (CMCs) are being developed for the next generation of turbine engine components to utilize their advantages of higher temperature capability and lower weight compared to metallic components.
- Environmental barrier coatings (EBCs) are essential for reducing CMC recession due to volatilization of silica scales by water vapor.

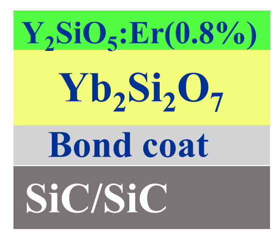


Objectives

- Meet challenges to develop phosphor thermometry EBC temperature mapping capability for evaluation of EBC performance and cooling strategies:
  - Transition from <1200 °C metallic component surface to 1300 to 1500 °C temperature range for EBC-coated CMC surfaces.
    - Intense thermal radiation background can overwhelm luminescence emission.
    - Phosphor compatibility with EBC at temperatures where “everything reacts with everything” and phosphor coatings less likely to survive thermal expansion mismatches.

Choice of Y_2SiO_5:Er over $Yb_2Si_2O_7$:Er

- Y instead of Yb because major Yb content can quench high temperature luminescence.
- Y_2SiO_5 instead of $Y_2Si_2O_7$ for stability because surface $Y_2Si_2O_7$ converts to Y_2SiO_5.

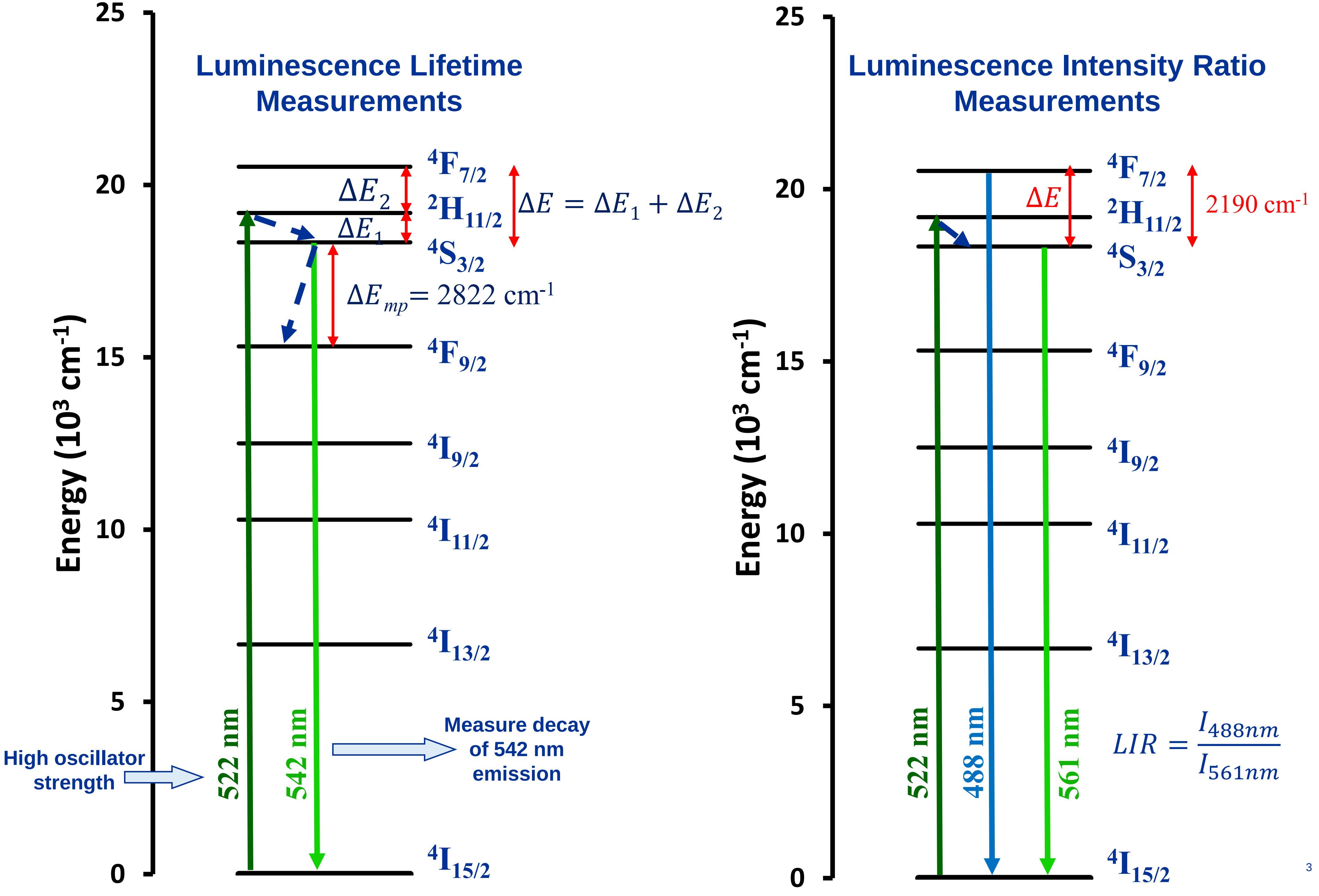


Approach

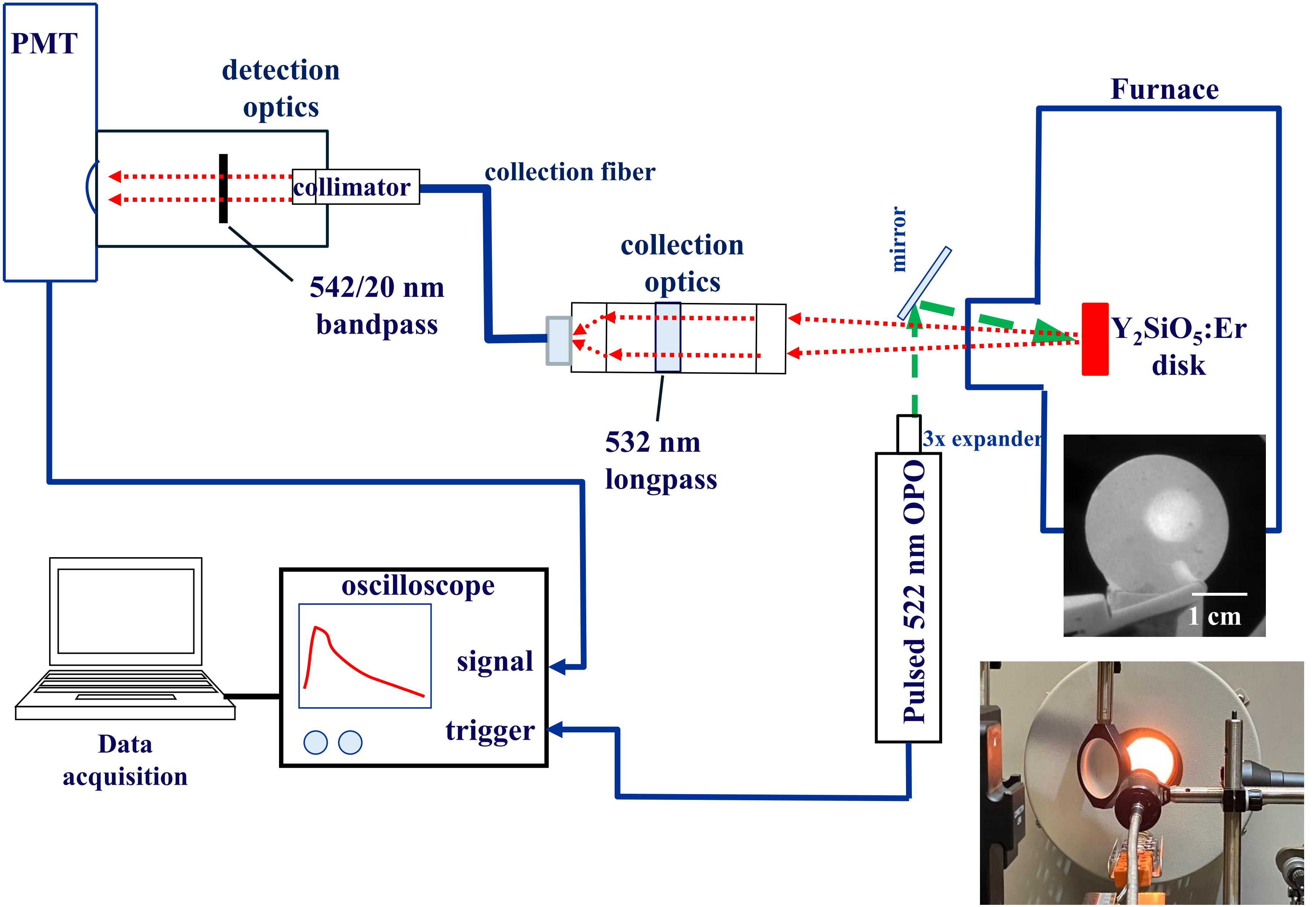
- Evaluate Y_2SiO_5:Er as potentially EBC-compatible thermographic phosphor for temperature sensing to 1500 °C based on previous success with Y_2O_3:Er.
  - Evaluate suitability for localized spot as well as full-field surface temperature measurements.
  - Compare luminescence lifetime and luminescence intensity ratio (LIR) methods and identify conditions where each method is favored.

Er^{3+} Electron Energy Levels in Y_2SiO_5

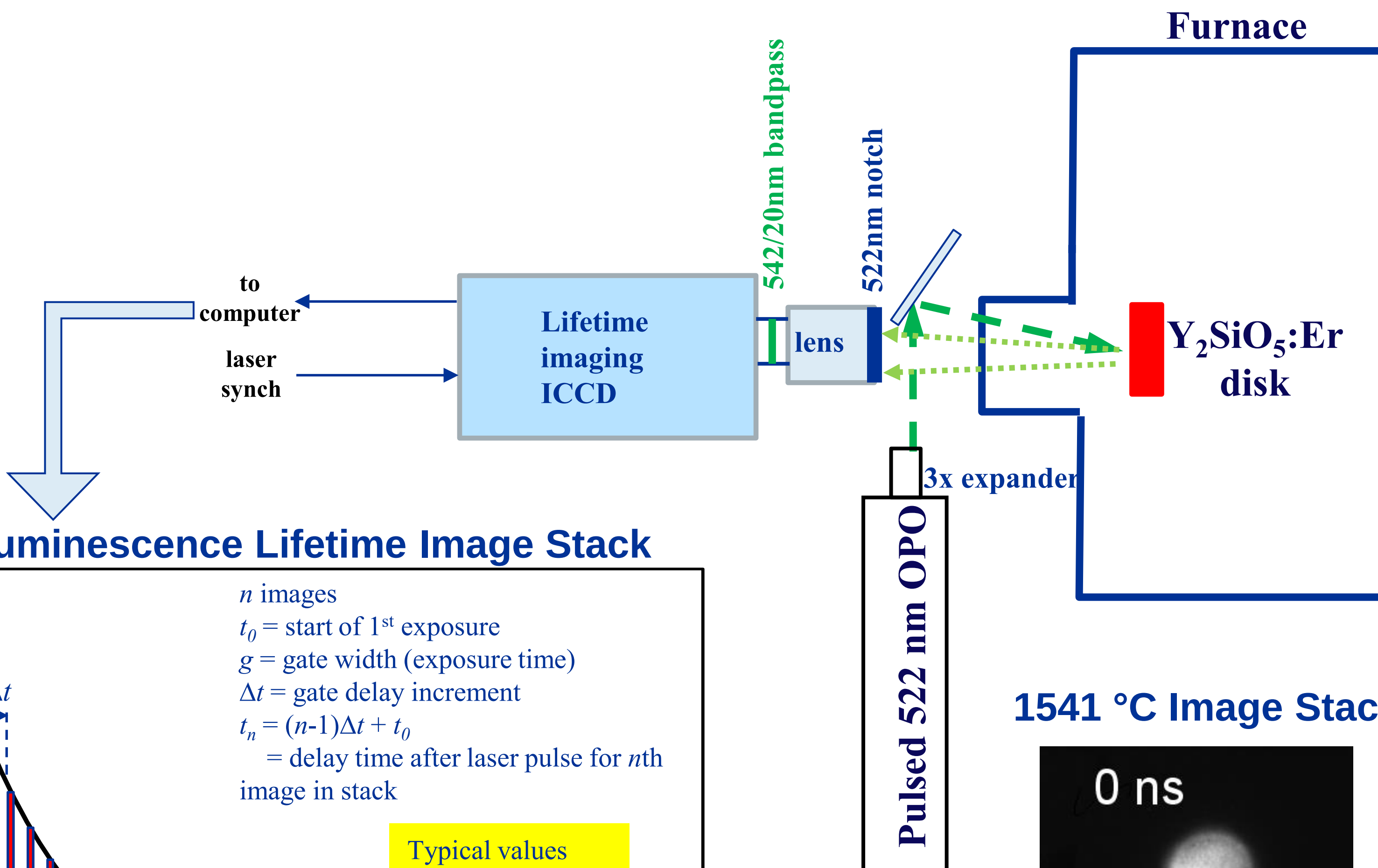
Transitions Involved in Luminescence Lifetime and LIR Measurements



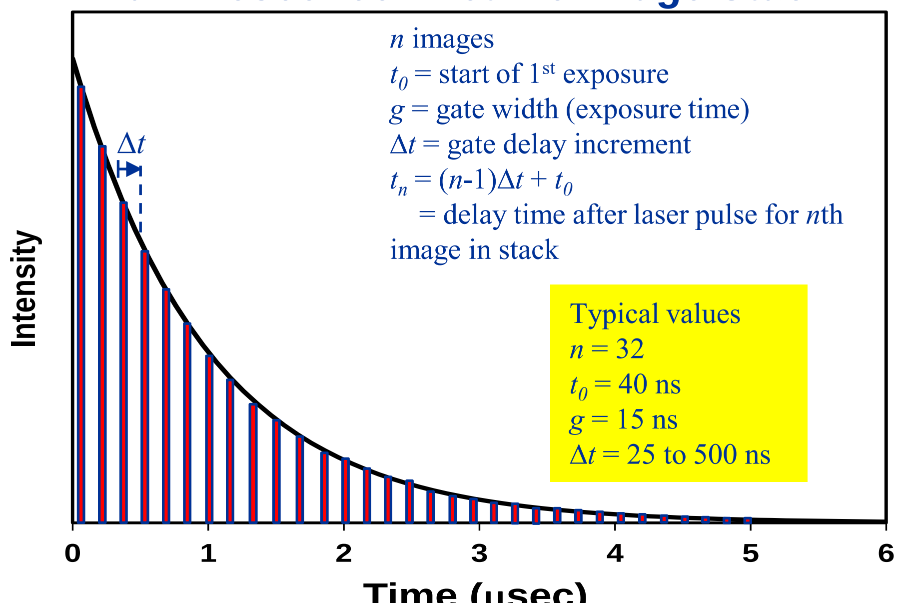
Luminescence Decay Local Measurements



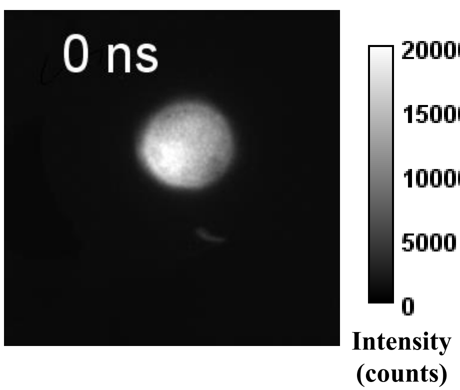
Luminescence Lifetime Imaging



Luminescence Lifetime Image Stack

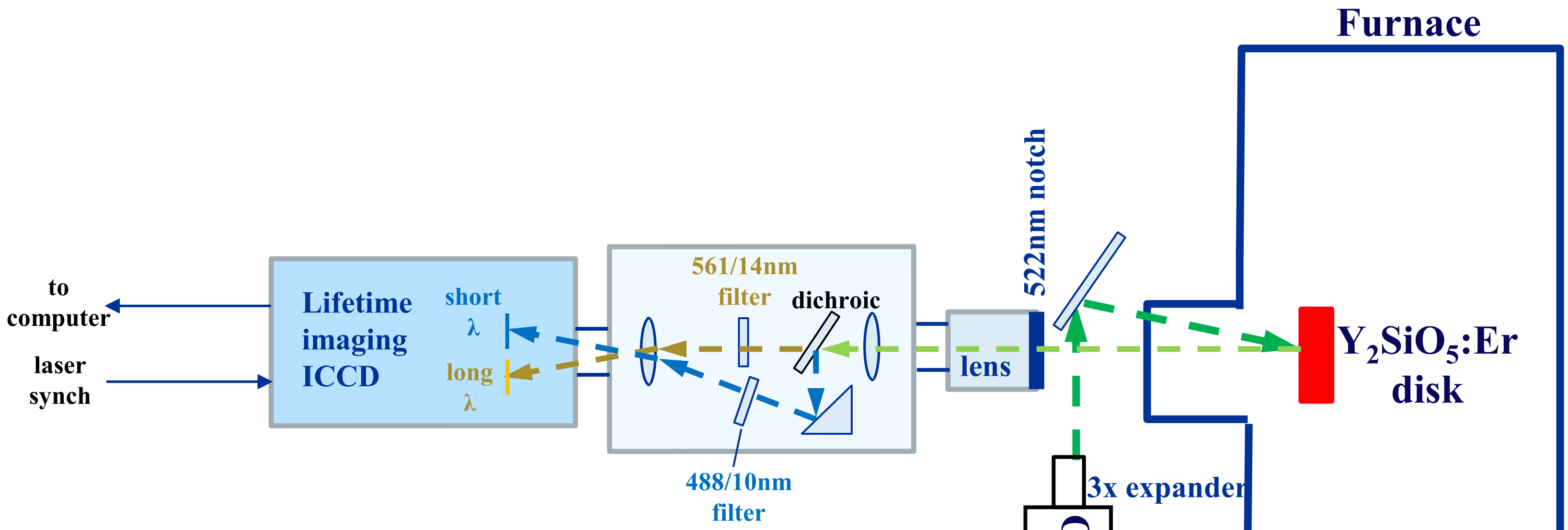


1541 °C Image Stack

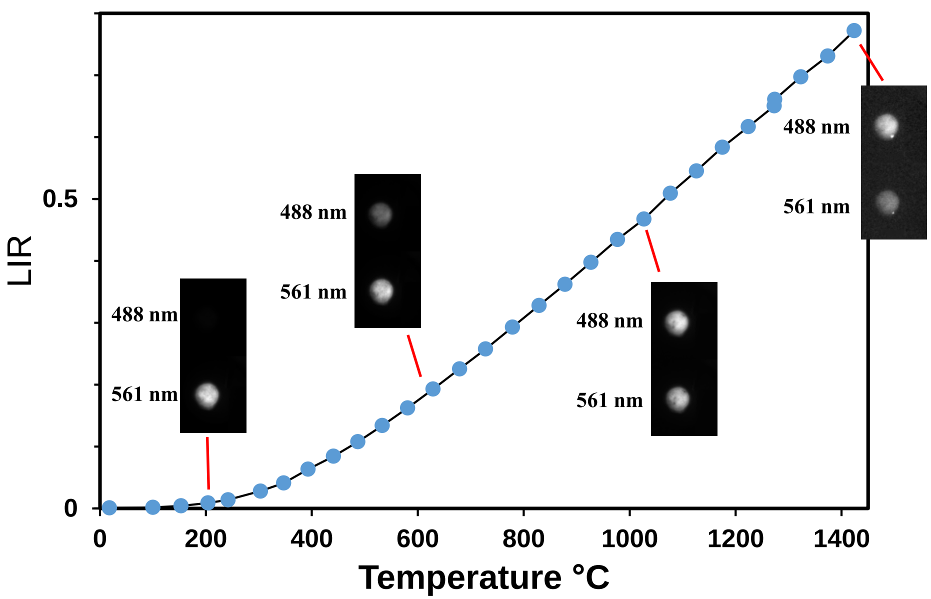


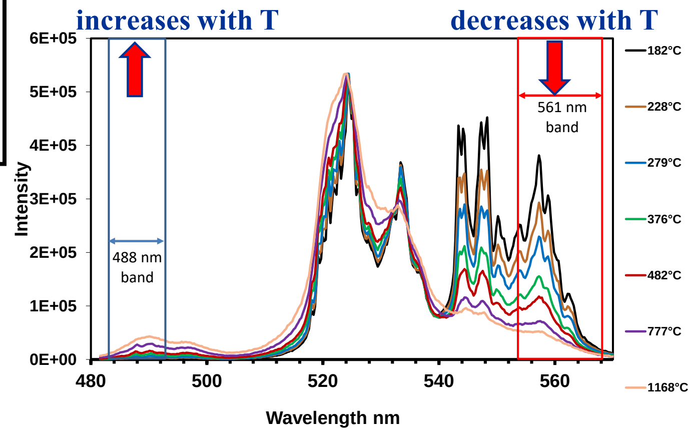
Prior to background subtraction!

Luminescence Intensity Ratio Imaging



LIR Temperature Dependence

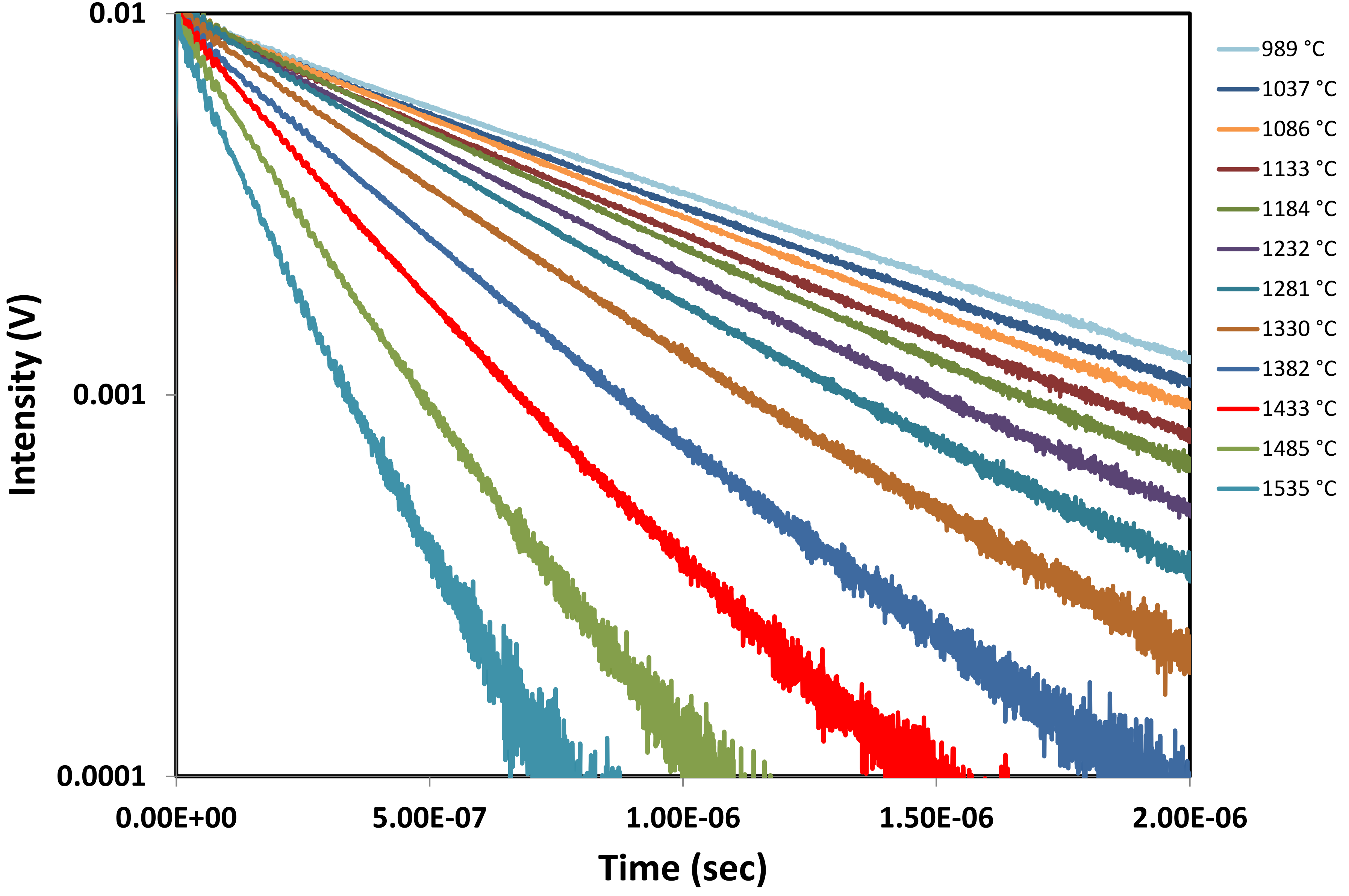




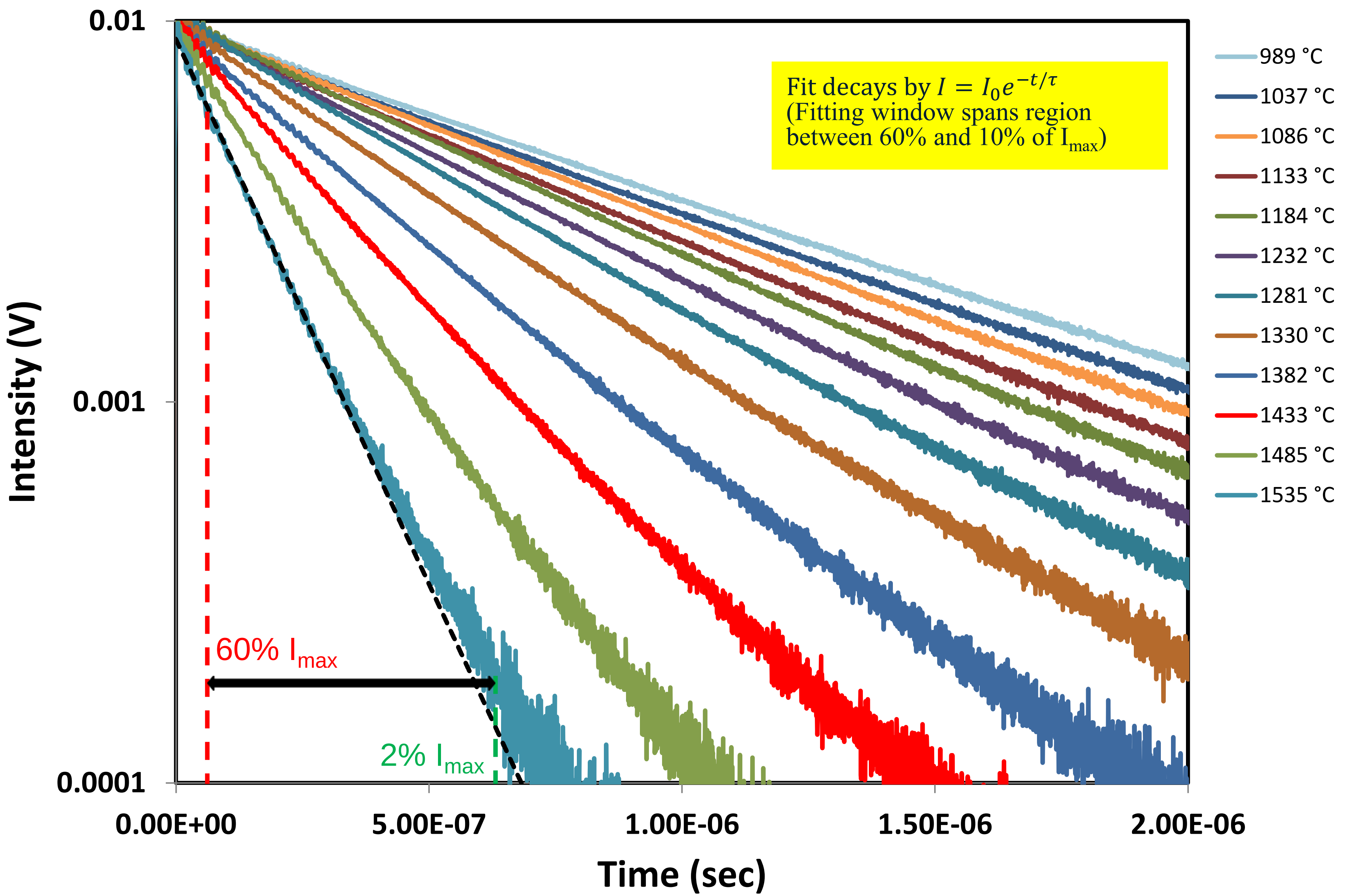
Luminescence Lifetime Measurements

Y_2SiO_5:Er(0.8%) Emission Decay Curves

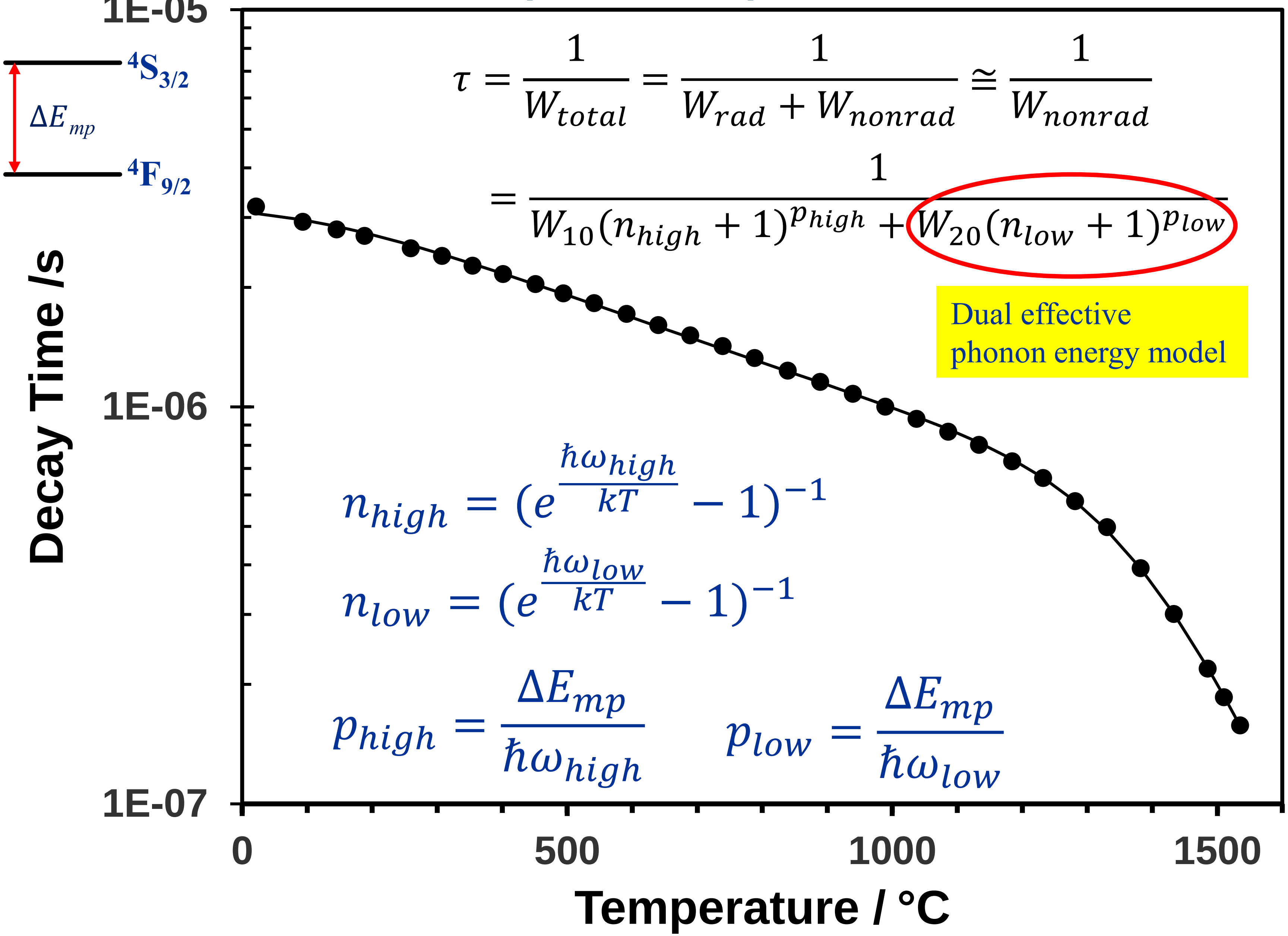
Temperature Dependence



Y_2SiO_5:Er(0.8%) Emission Decay Curves
Temperature Dependence



Y_2SiO_5:Er(0.8%) Decay Time
Temperature Dependence



$$\tau = \frac{1}{W_{total}} = \frac{1}{W_{rad} + W_{nonrad}} \cong \frac{1}{W_{nonrad}}$$

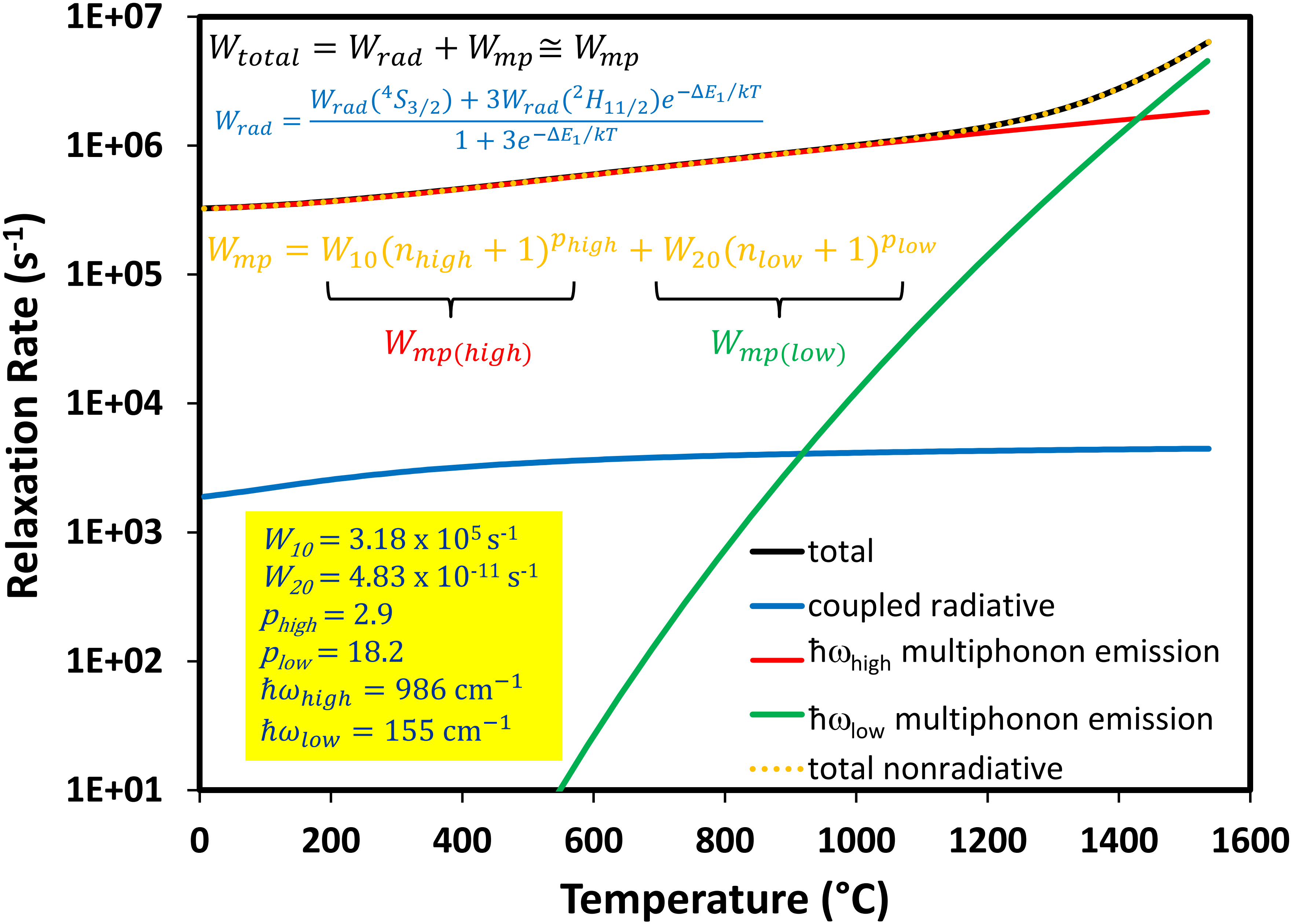
$$= \frac{1}{W_{10}(n_{high}+1)^{p_{high}} + W_{20}(n_{low}+1)^{p_{low}}}$$

$$n_{high} = \left(e^{\frac{\hbar\omega_{high}}{kT}} - 1\right)^{-1}$$

$$n_{low} = \left(e^{\frac{\hbar\omega_{low}}{kT}} - 1\right)^{-1}$$

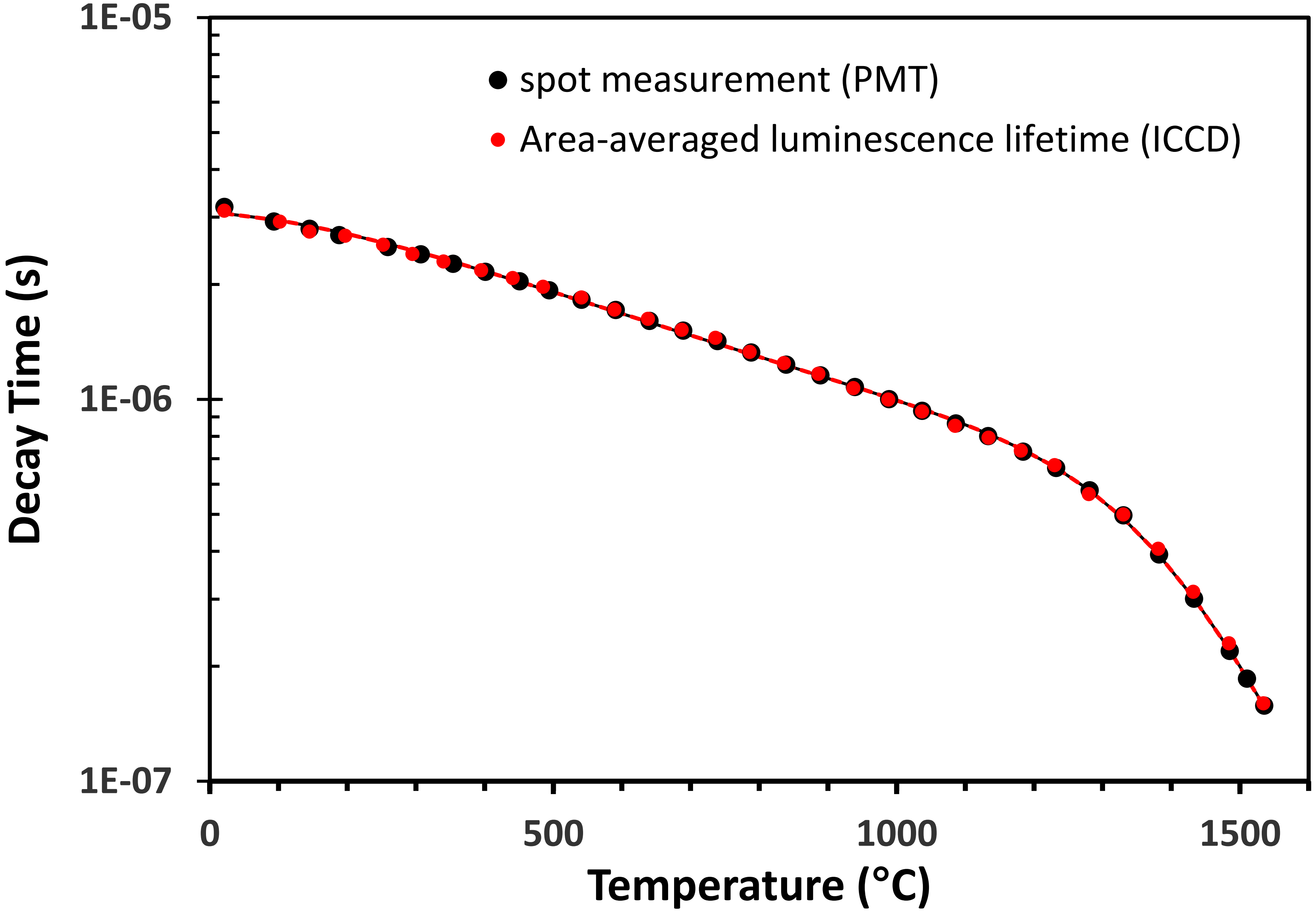
$$p_{high} = \frac{\Delta E_{mp}}{\hbar\omega_{high}} \qquad p_{low} = \frac{\Delta E_{mp}}{\hbar\omega_{low}}$$

Competing Relaxation Rates from $^4S_{3/2} \rightarrow ^4I_{15/2}$ Transition Associated with Y_2SiO_5:Er 542 nm Emission Excited at 522 nm



Y_2SiO_5:Er(0.8%) Luminescence Lifetime Measurements

Spot (PMT) vs. 2D(Image Stack) Comparison



2D Temperature Maps from Luminescence Lifetime Imaging*

- Step 1: Acquire image stack of background-corrected exposures.
- Step 2: Fit single exponential decay to luminescence decay curve at ***each pixel*** to produce decay time map. Fitting window spans region between 60% and 10% of initial intensity.

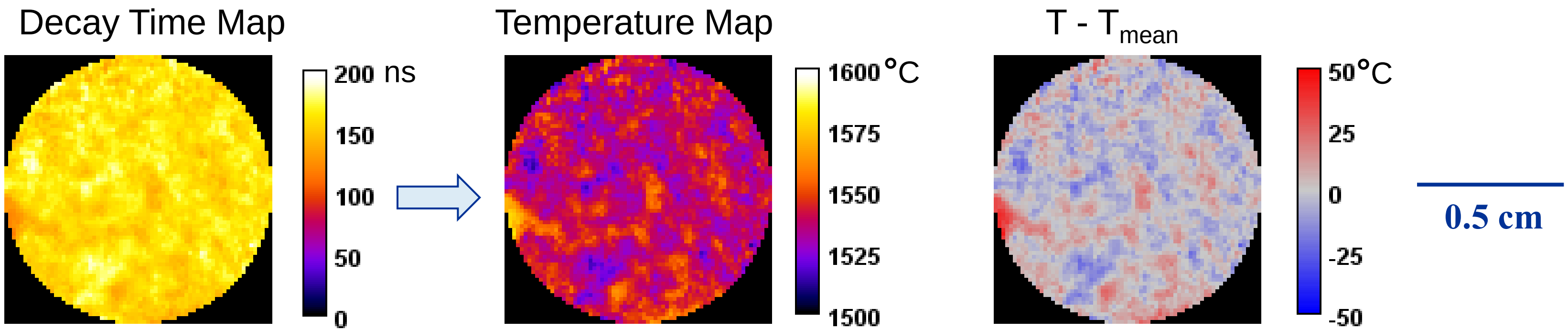


*Image processing developed by Adam Wroblewski at NASA GRC.

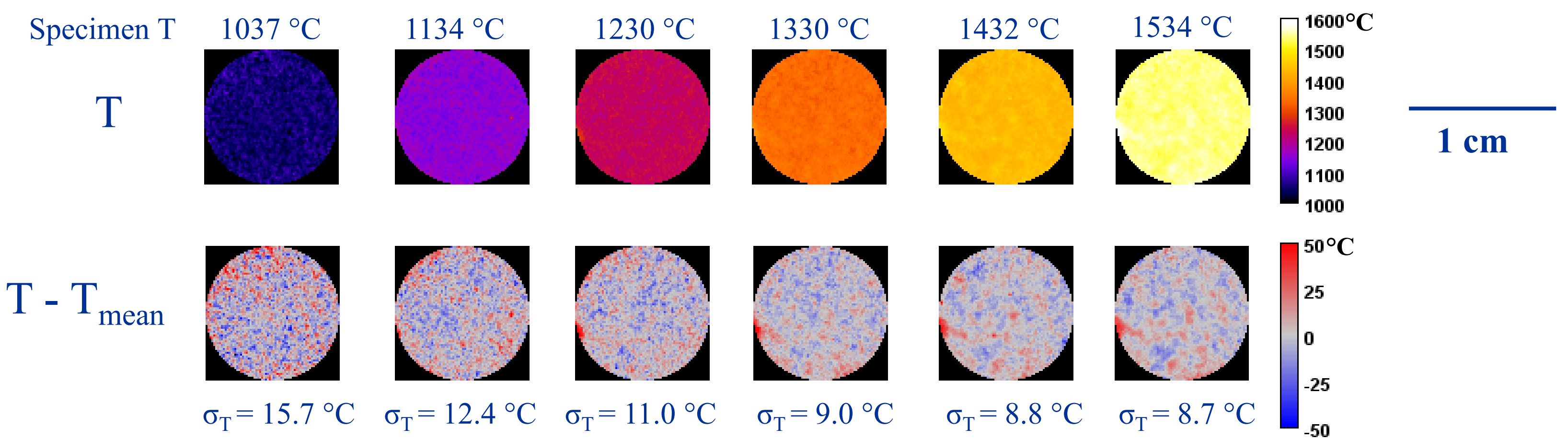
σ_T = 8.7 °C (0.5% relative precision)

- Step 3: Use furnace calibration to convert decay time map to temperature map.

$$\tau = [W_{10}(1 - e^{-\frac{\Delta E}{p_{high}kT}})^{-p_{high}} + W_{20}(1 - e^{-\frac{\Delta E}{p_{low}kT}})^{-p_{low}}]^{-1}$$

Dual effective phonon energy model

Temperature Maps

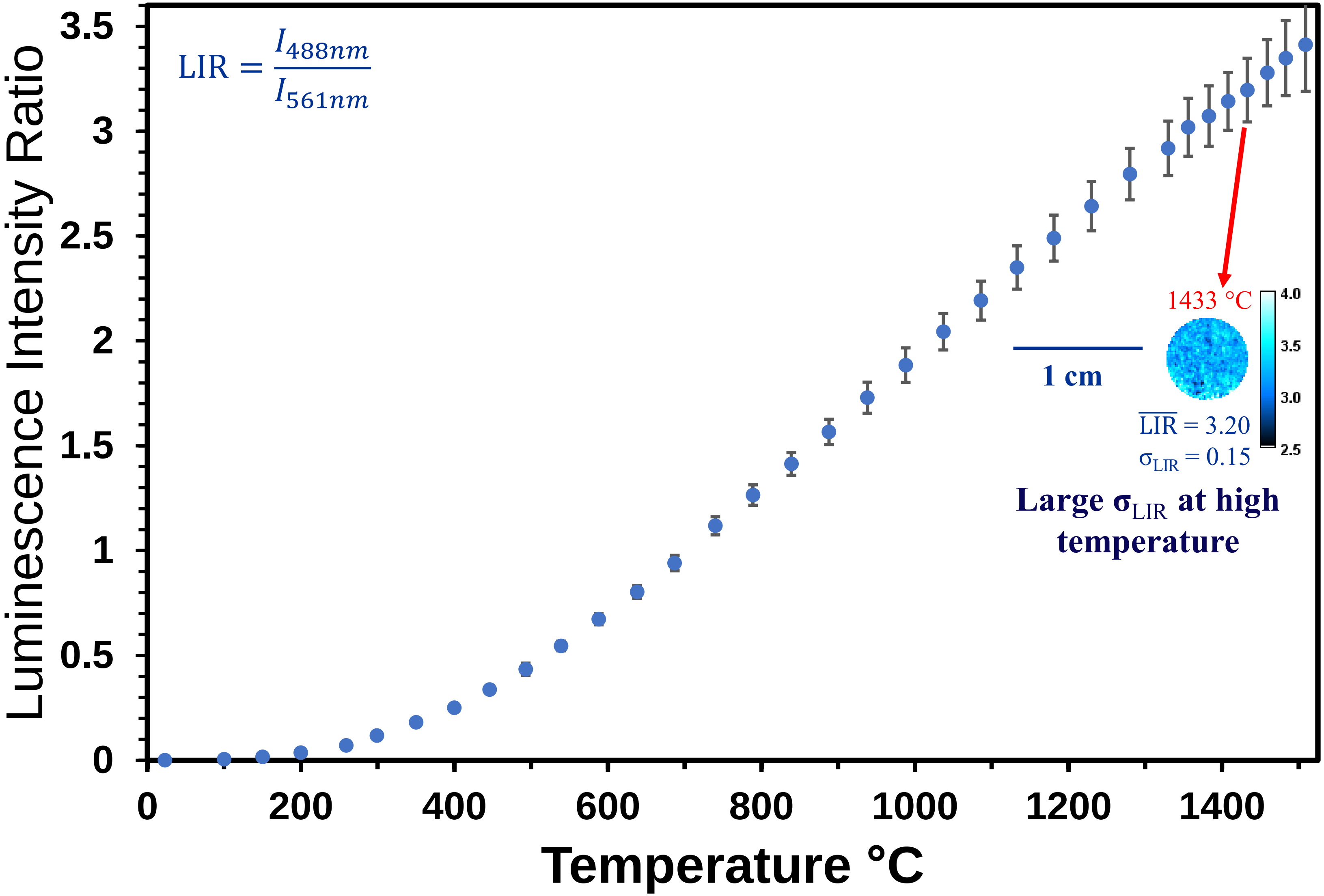


σ_T = 15.7 °C	σ_T = 12.4 °C	σ_T = 11.0 °C	σ_T = 9.0 °C	σ_T = 8.8 °C	σ_T = 8.7 °C
$\sigma_{\overline{T}}$ = 0.25 °C	$\sigma_{\overline{T}}$ = 0.20 °C	$\sigma_{\overline{T}}$ = 0.18 °C	$\sigma_{\overline{T}}$ = 0.15 °C	$\sigma_{\overline{T}}$ = 0.14 °C	$\sigma_{\overline{T}}$ = 0.14 °C

LIR Measurements

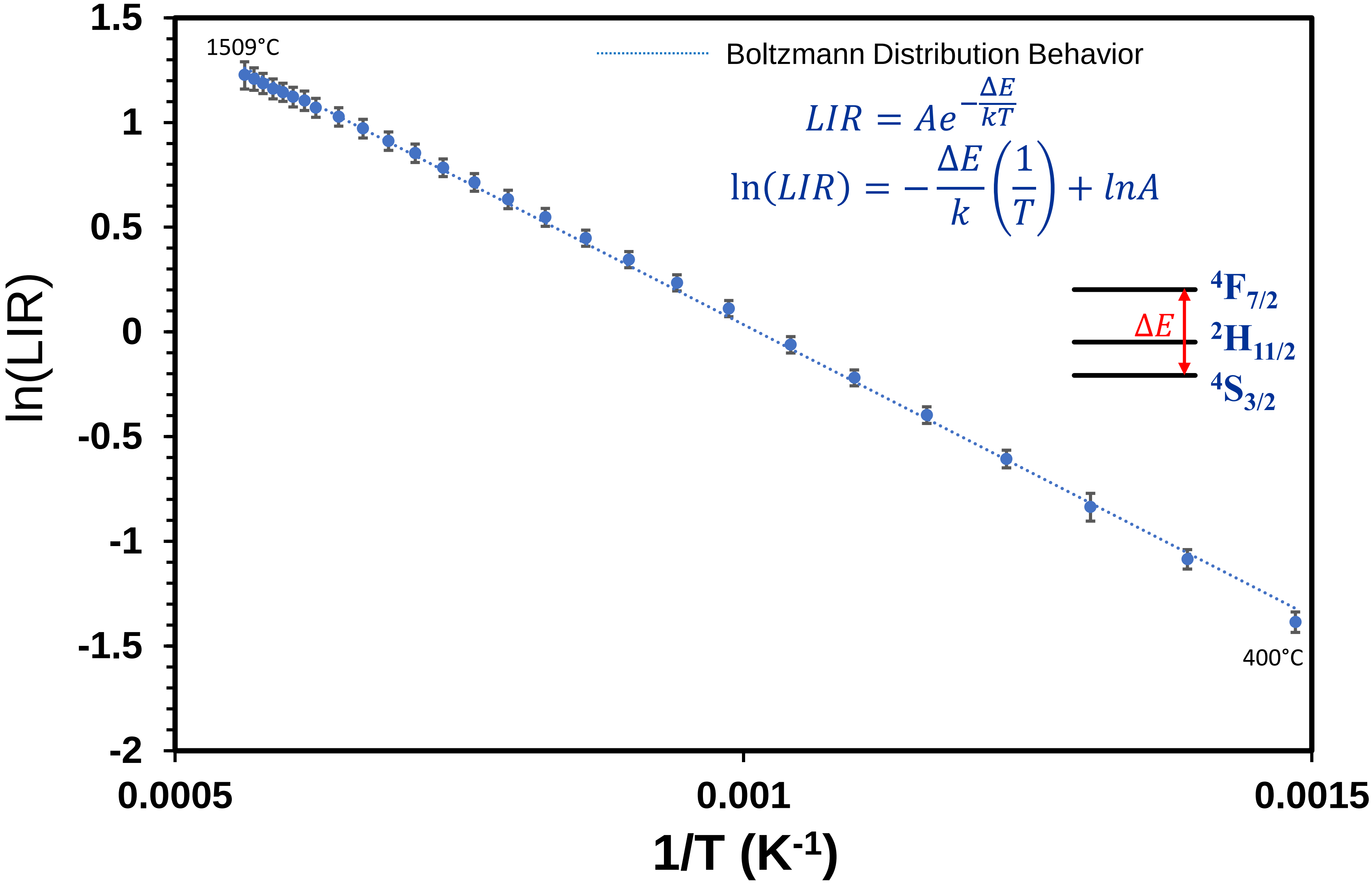
Y_2SiO_5:Er(0.8%) LIR Imaging

Area-Averaged Temperature Dependence



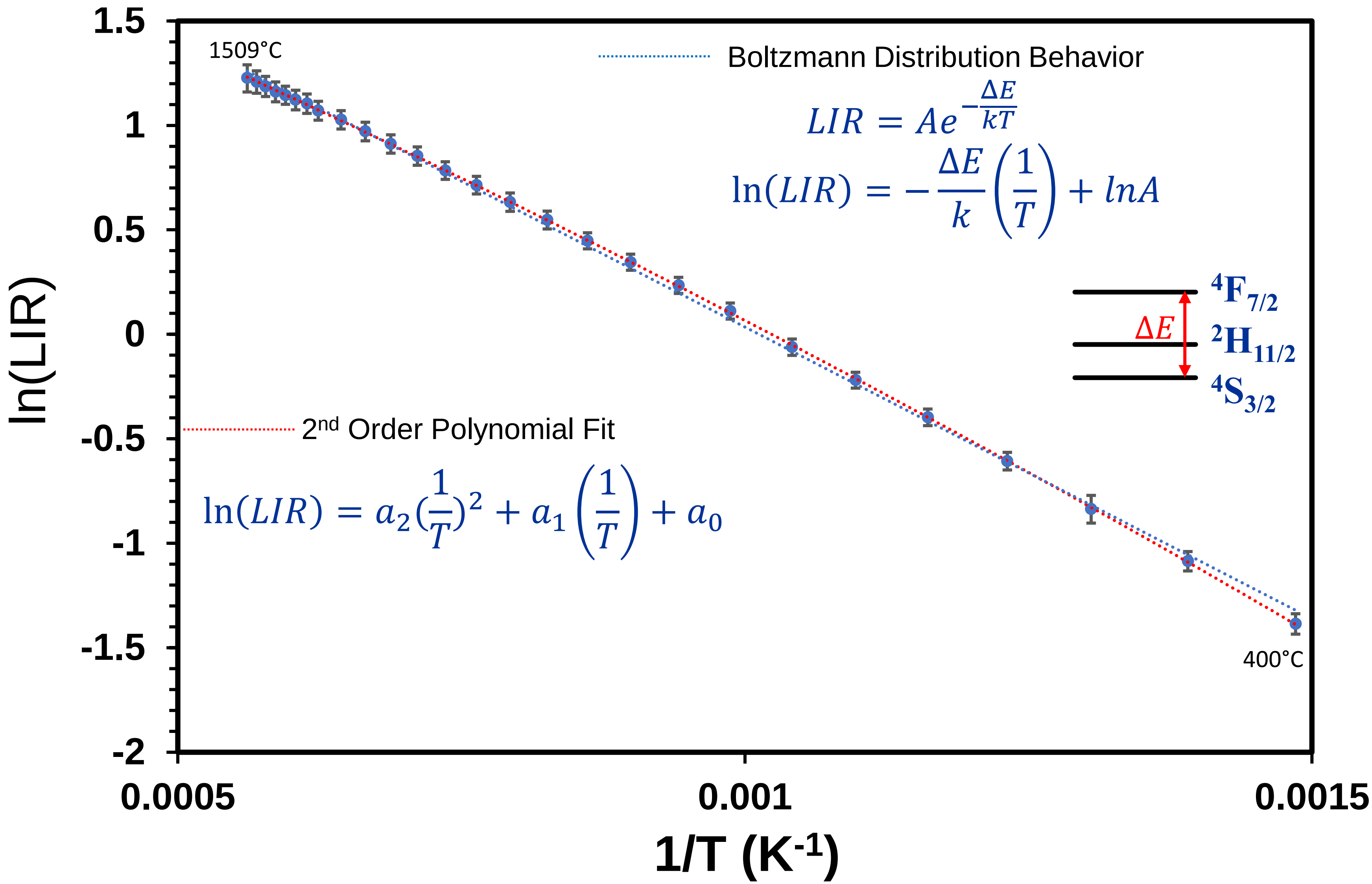
Y_2SiO_5:Er(0.8%) LIR Imaging

Area-Averaged Temperature Dependence



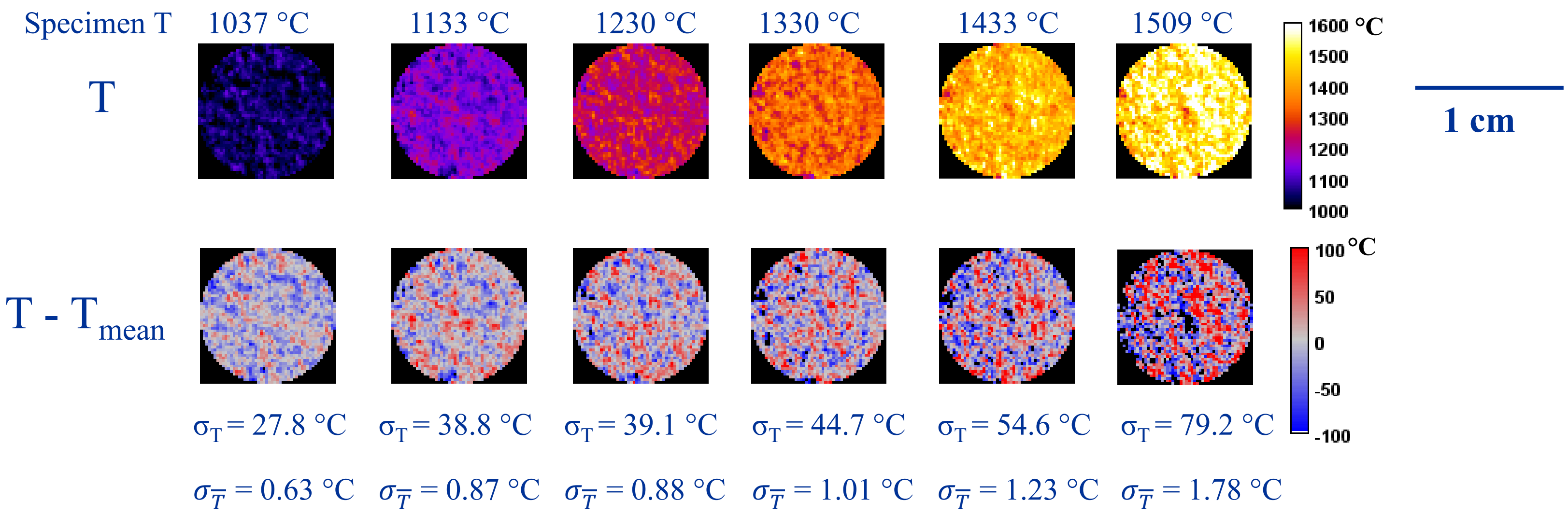
Y_2SiO_5:Er(0.8%) LIR Imaging

Area-Averaged Temperature Dependence

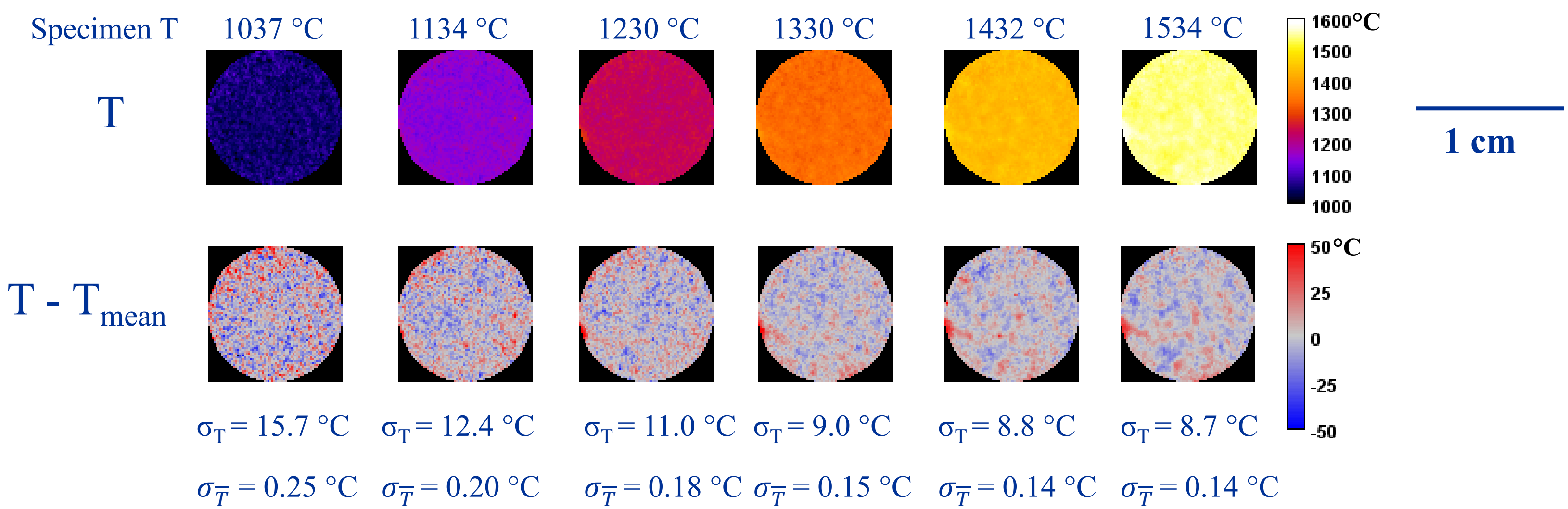


High Temperature Furnace Calibrations

Y_2SiO_5:Er(0.8%) LIR Temperature Maps

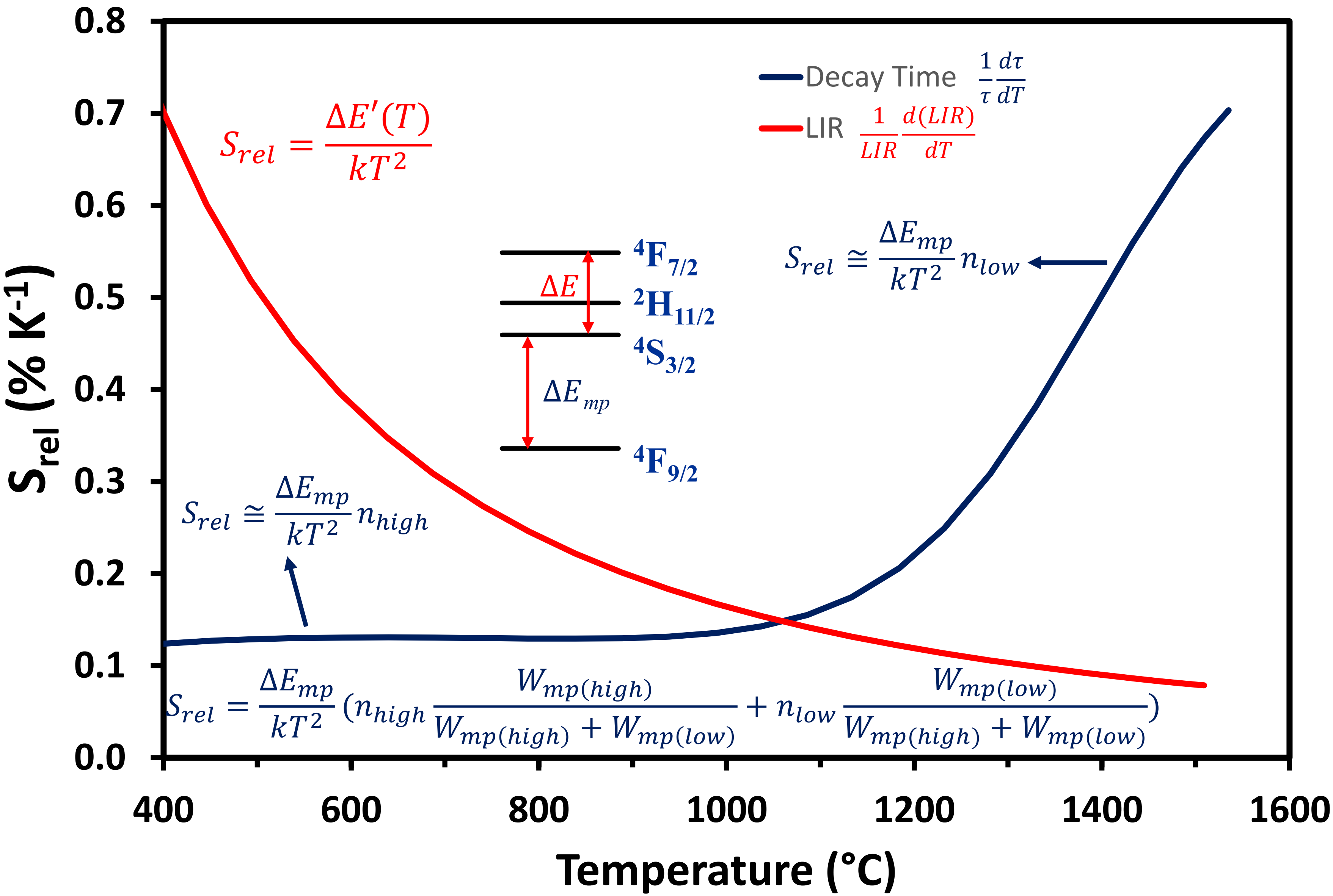


Y_2SiO_5:Er(0.8%) Luminescence Lifetime Temperature Maps



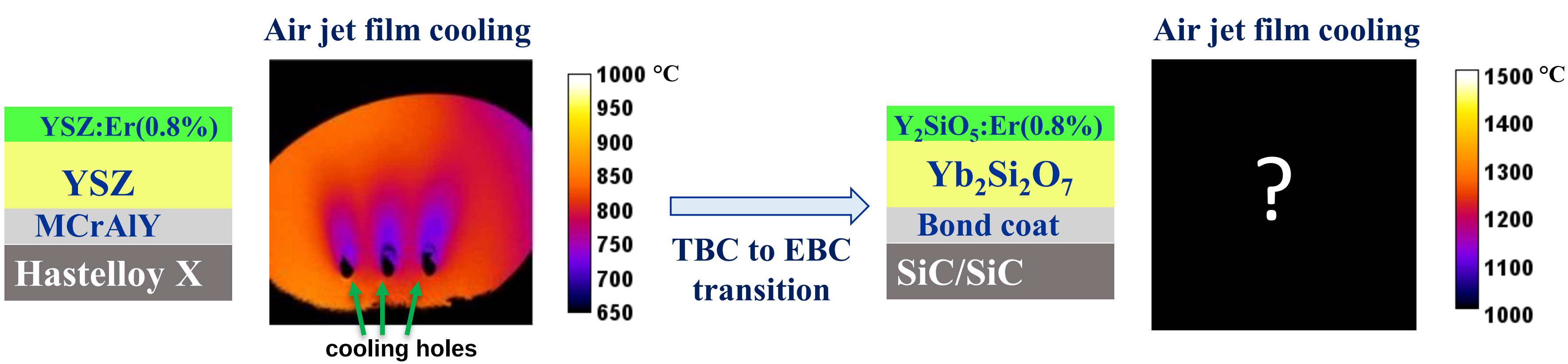
Relative Temperature Sensitivity Temperature Dependence

Luminescence Lifetime vs. LIR Comparison



Conclusions

- Y_2SiO_5:Er shows temperature mapping potential for EBC-relevant temperatures (1300-1500 °C).
  - Luminescence lifetime useful for local and steady-state full-field temperature measurements.
  - LIR may have advantage for dynamic full-field temperature measurements, but with lower temperature sensitivity/precision.
- Conflicts with conventional guidance on selecting phosphors for high-temperature sensing.
  - Low quantum efficiency, producing mostly nonradiative relaxation even at room temperature
  - Energy gap for multiphonon emission can be bridged by as few as 3 phonons.
- Temperature sensing performance >1300 °C enabled by:
  - High oscillator strength of excitation transition
  - Transition to low effective phonon energy (986→155 cm^{-1}) for multiphonon relaxation above 1300 °C increases temperature sensitivity.
  - Very slow decrease in decay time and intensity with temperature until ~1300 °C



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