Advances in the Physical Understanding of Laser Surgery at 6.45 microns

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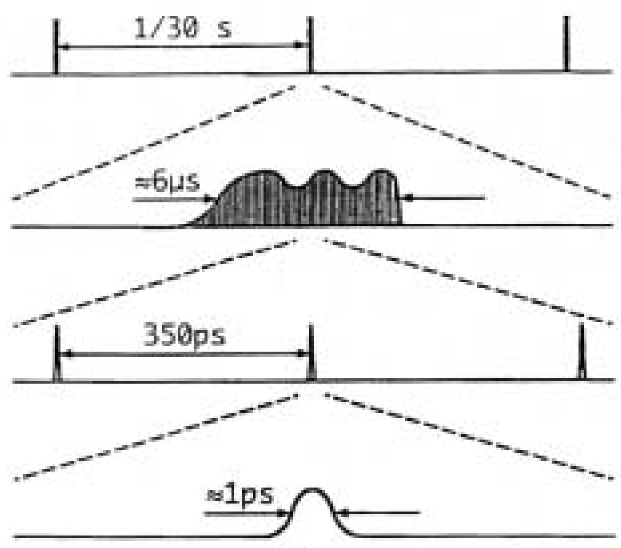
Mid-IR FEL Laser Surgery



The Vanderbilt Mark III FEL has been used successfully in human surgery.

6.45 μm,
5-50 J/cm^2
~5 μs superpulses at 4-30 Hz

How do we translate this success into a cost-effective, compact, and dedicated surgical laser system?

Outline

Background: A ThermoPhysical Model of mid-IR Laser Ablation

- Energy-partitioning and thermal diffusion
- Explosive vaporization
- Protein denaturation
- A better represention of tissue ultrastructure

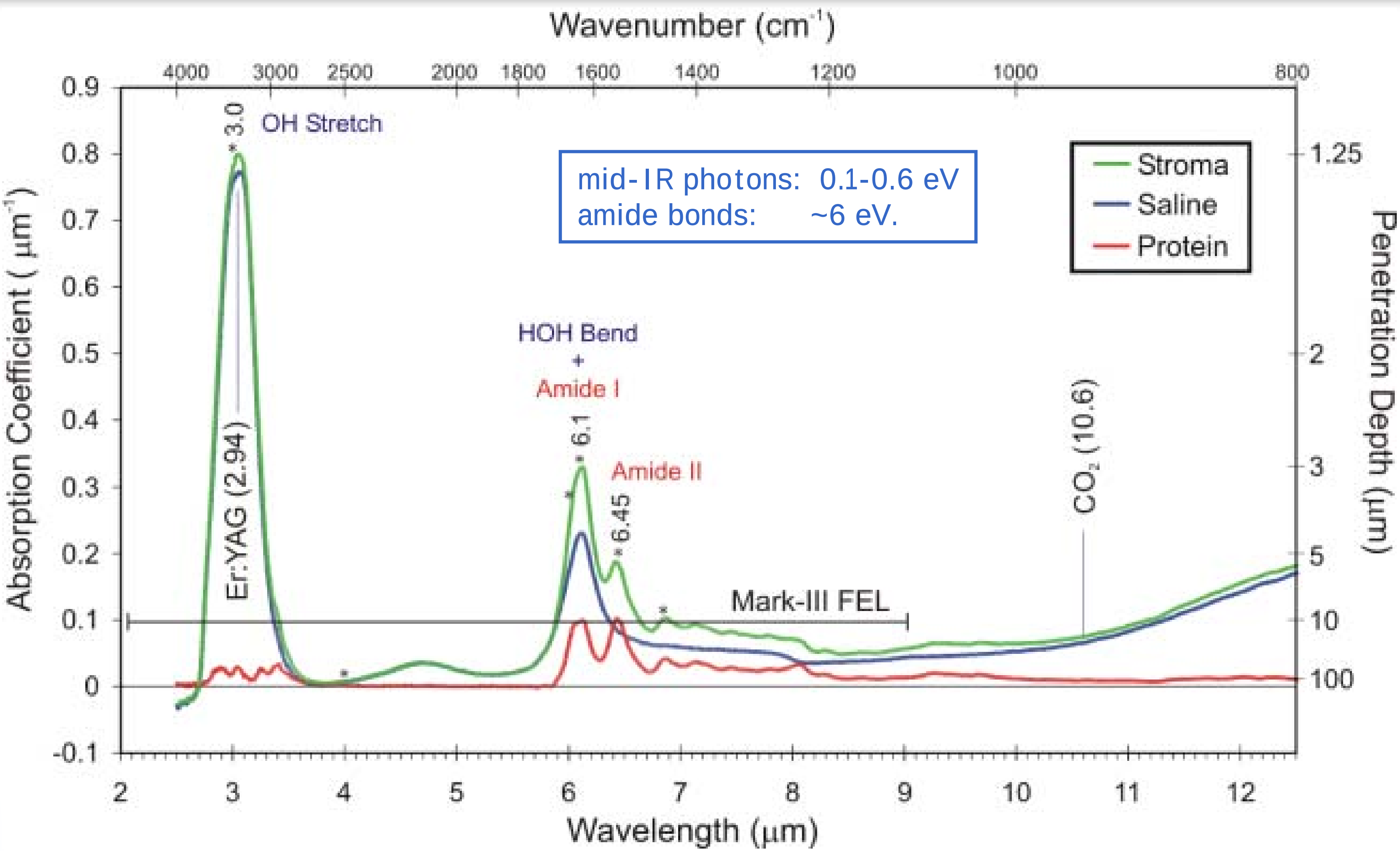
Results: Predictions of the model

- Sweet-spots in parameter space
- Fractional Denaturation at Vaporization (FDV), dependence on λ and **Intensity**

Discussion:

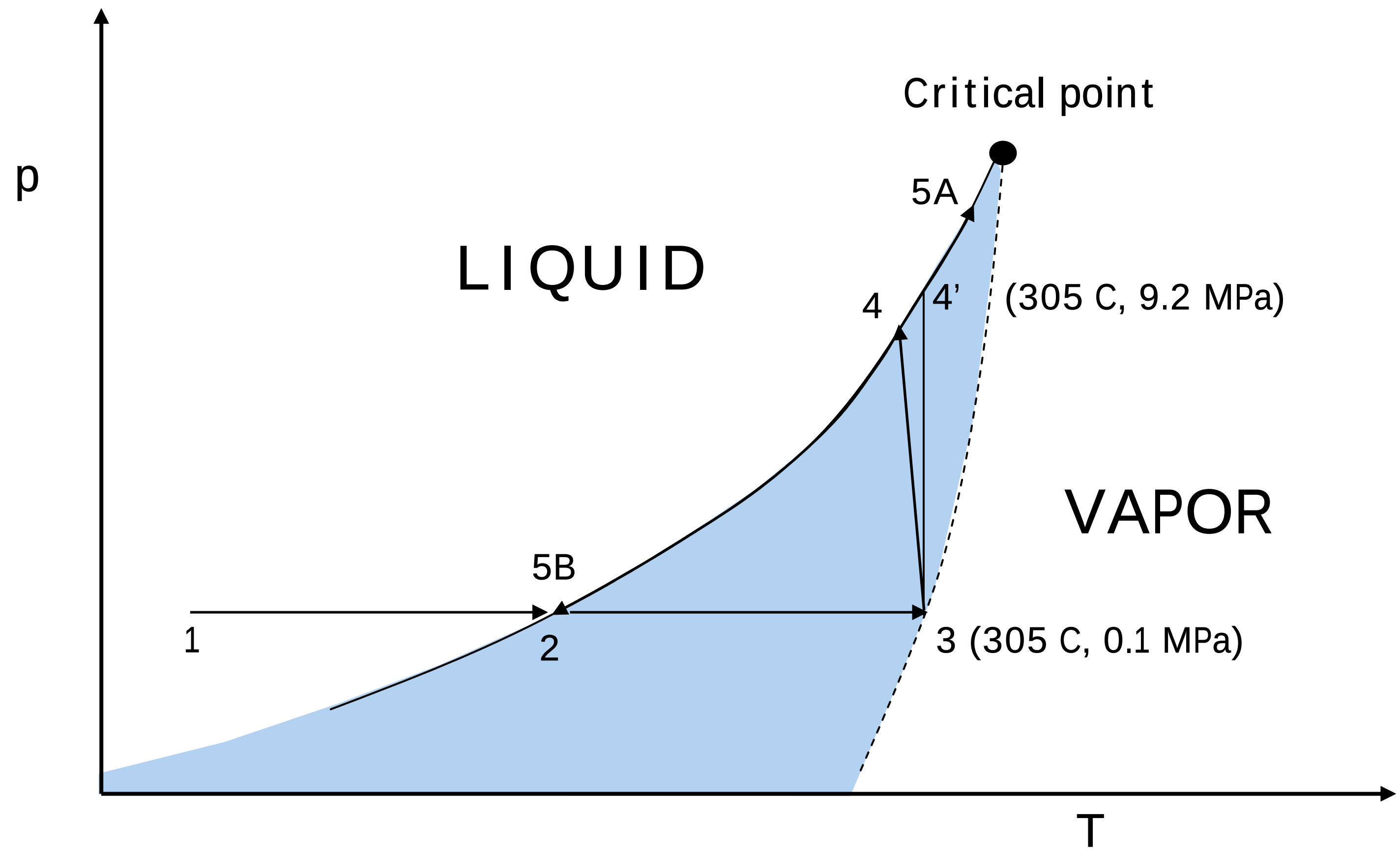
- Can conflicts in previous experimental data be resolved?
- What new experiments are needed to test the model?
- What are the prospects for PASSAT's new 6.45-μm laser?

Energy-Partitioning



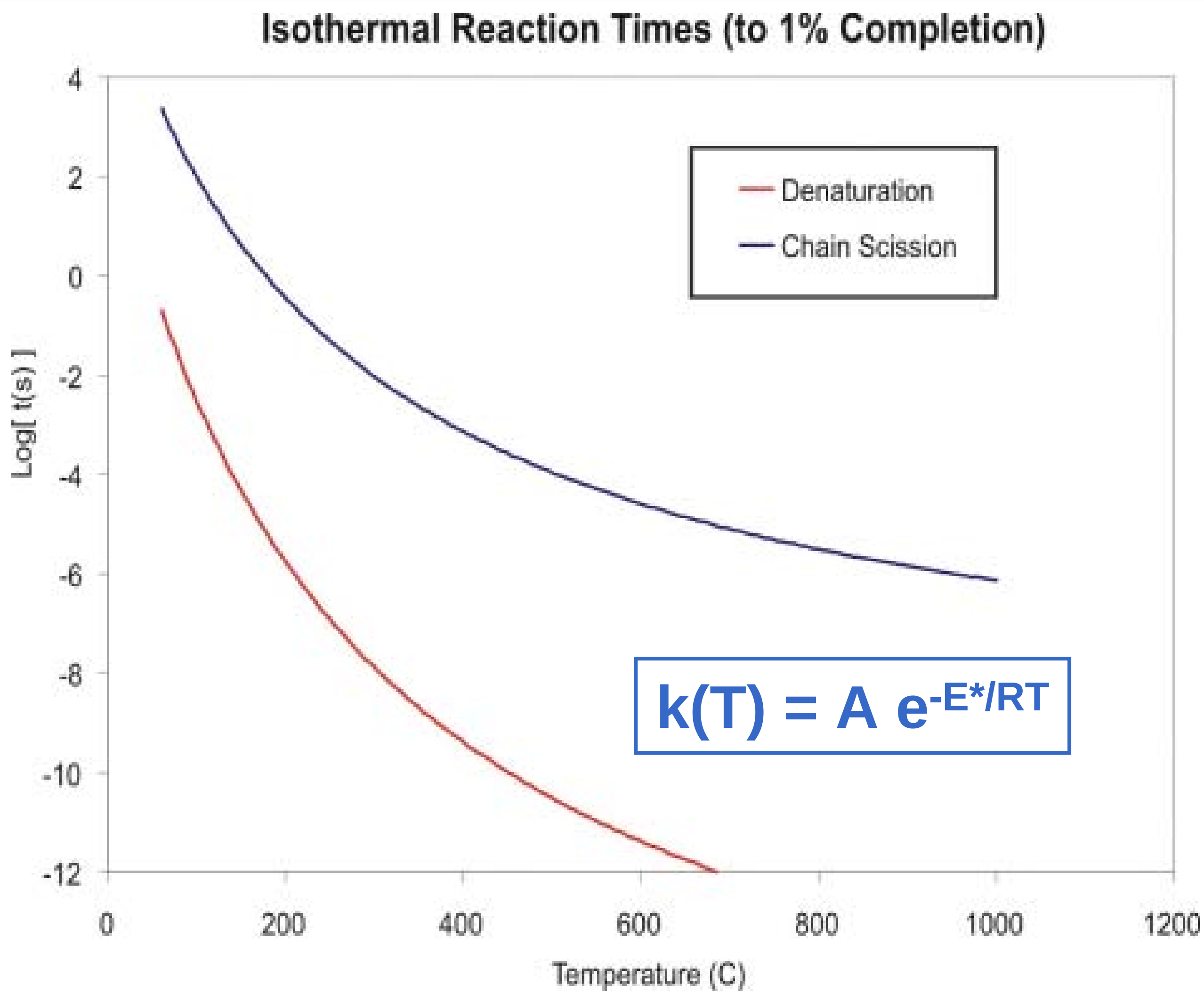
mid-IR photons: 0.1-0.6 eV
amide bonds: ~6 eV.

Explosive Vaporization



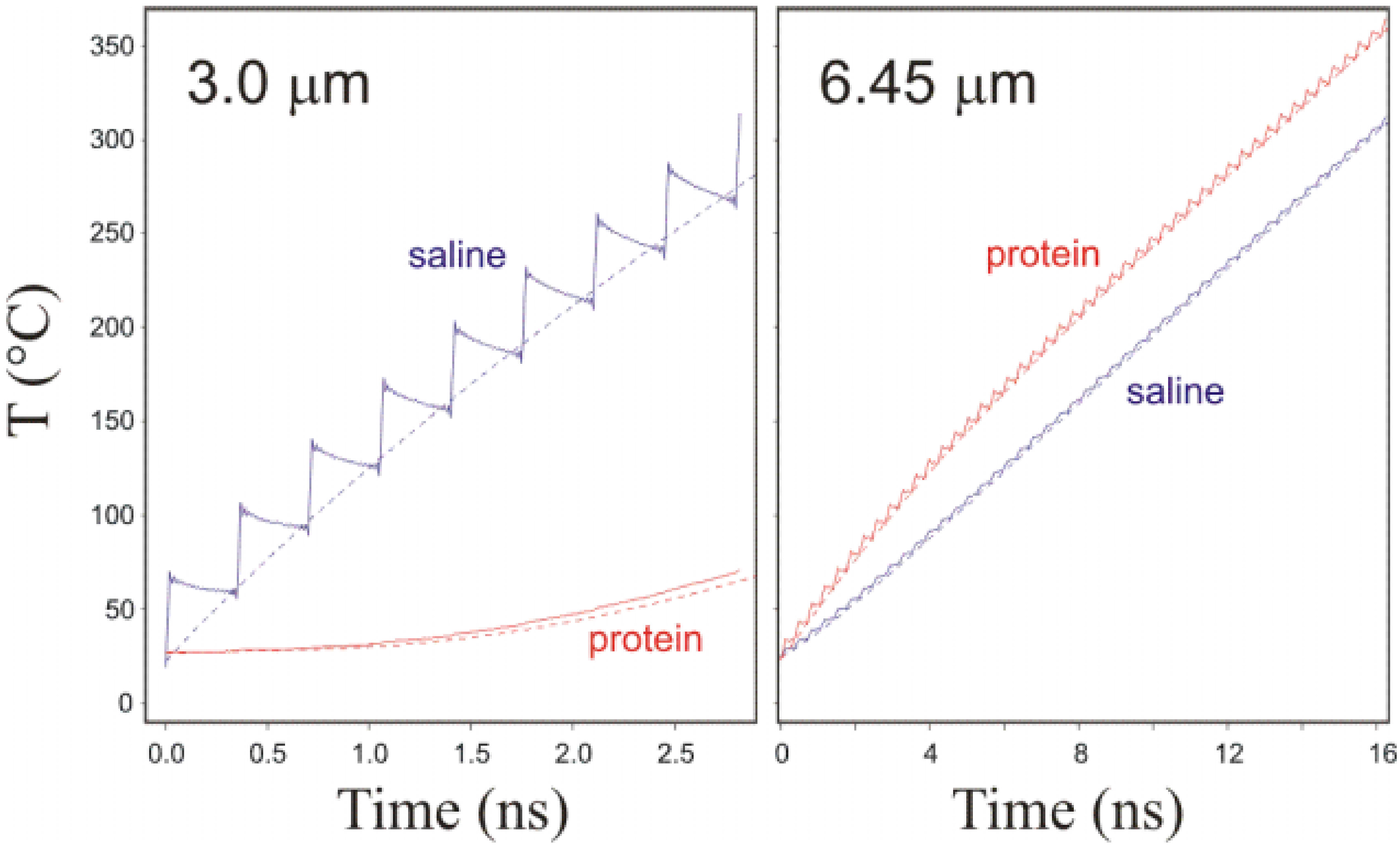
A. Vogel and V. Venugopalan (2003), Chem. Rev. 103: 577-644.

Protein Denaturation



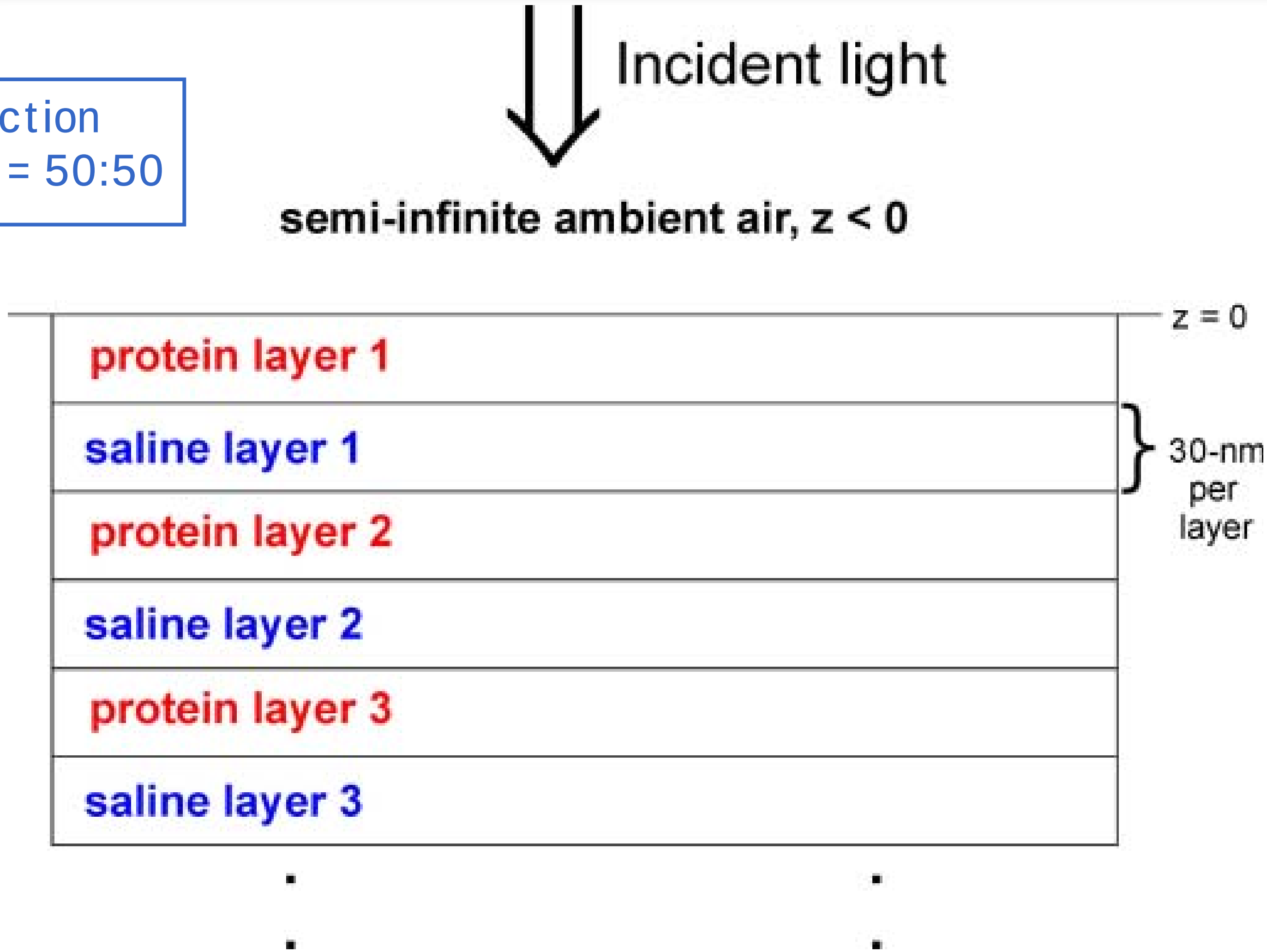
$$k(T) = A\,e^{-E^*/RT}$$

How important are ps pulses?



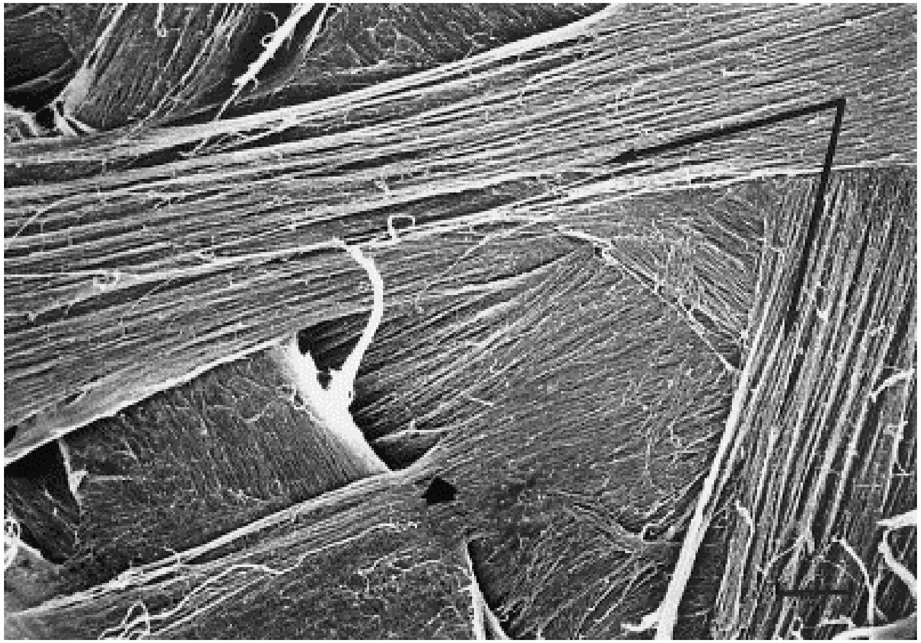
Laminar Model

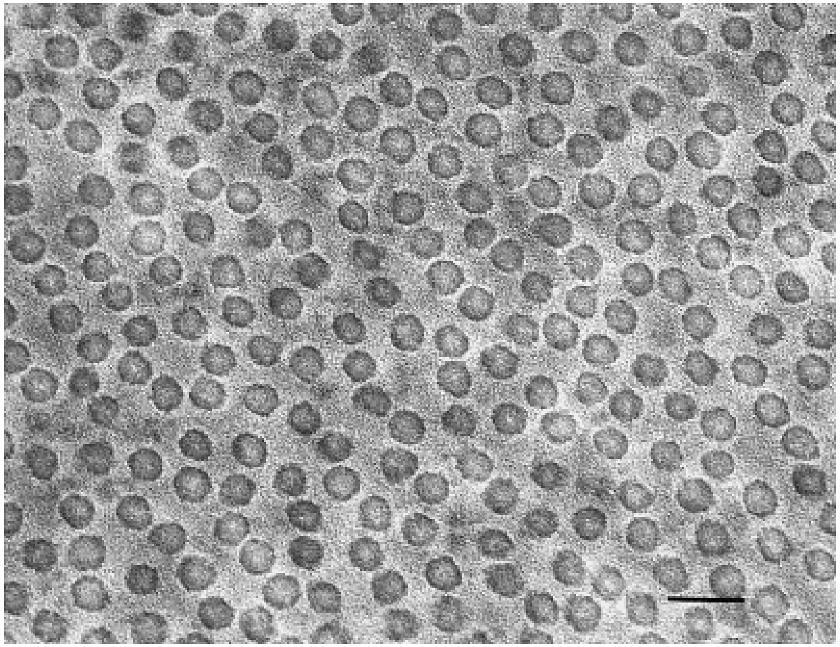
Volume Fraction
saline:protein = 50:50



Ultrastructure of Corneal Stroma

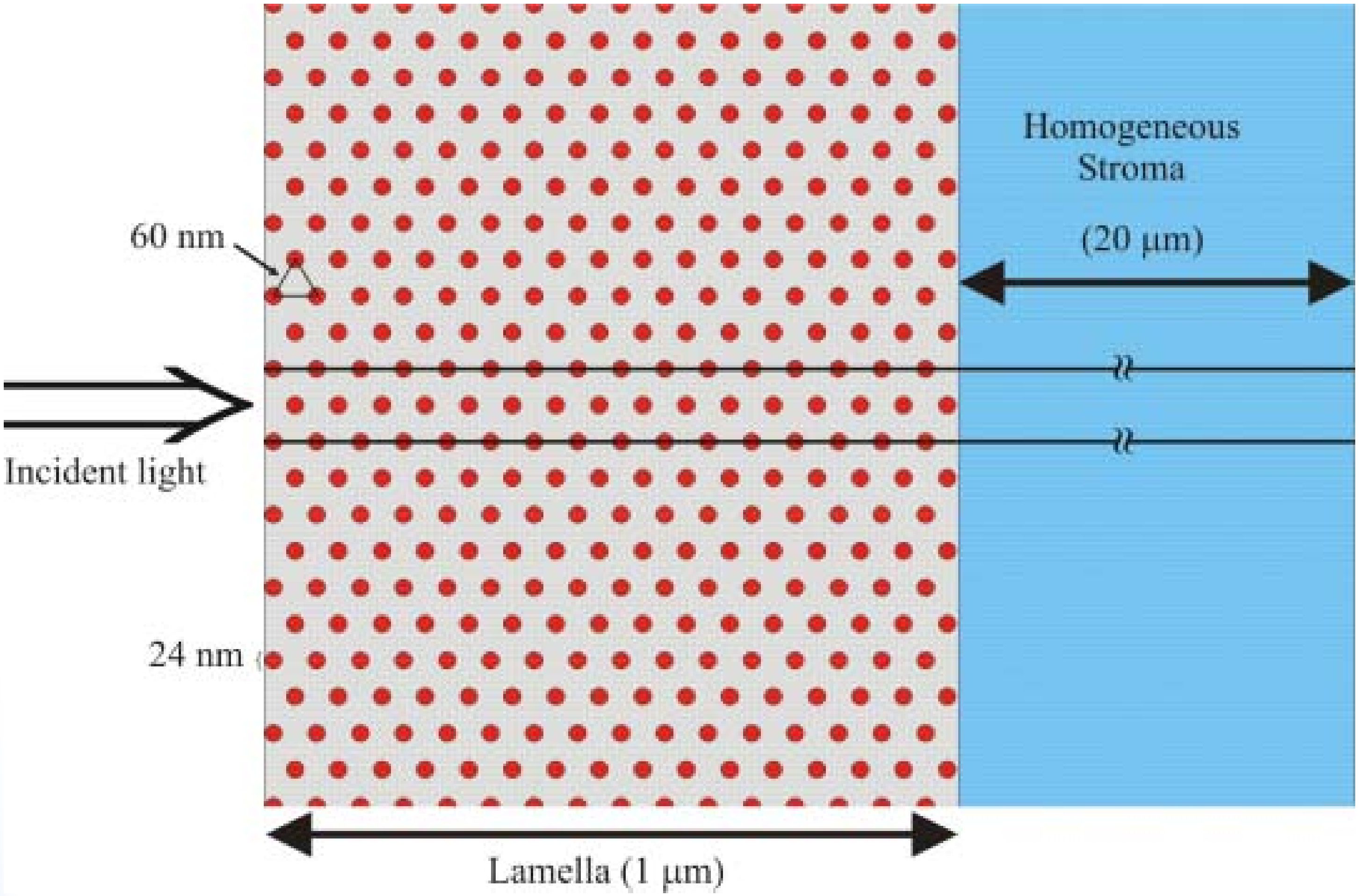
1-2 μm thick lamellae containing a quasi-hexagonal array of collagen fibrils





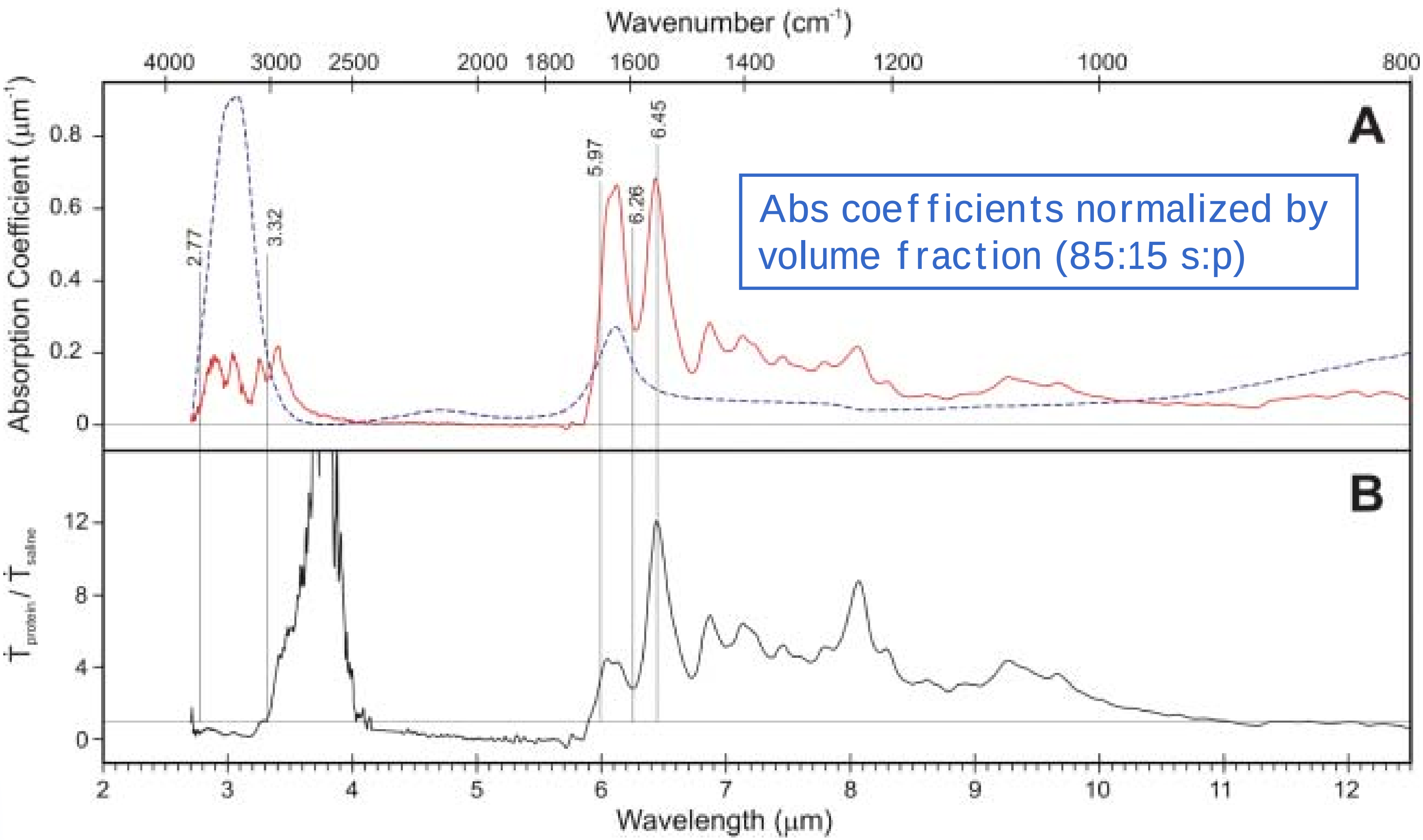
Meek et al, 2001.

Hexagonal Array Model

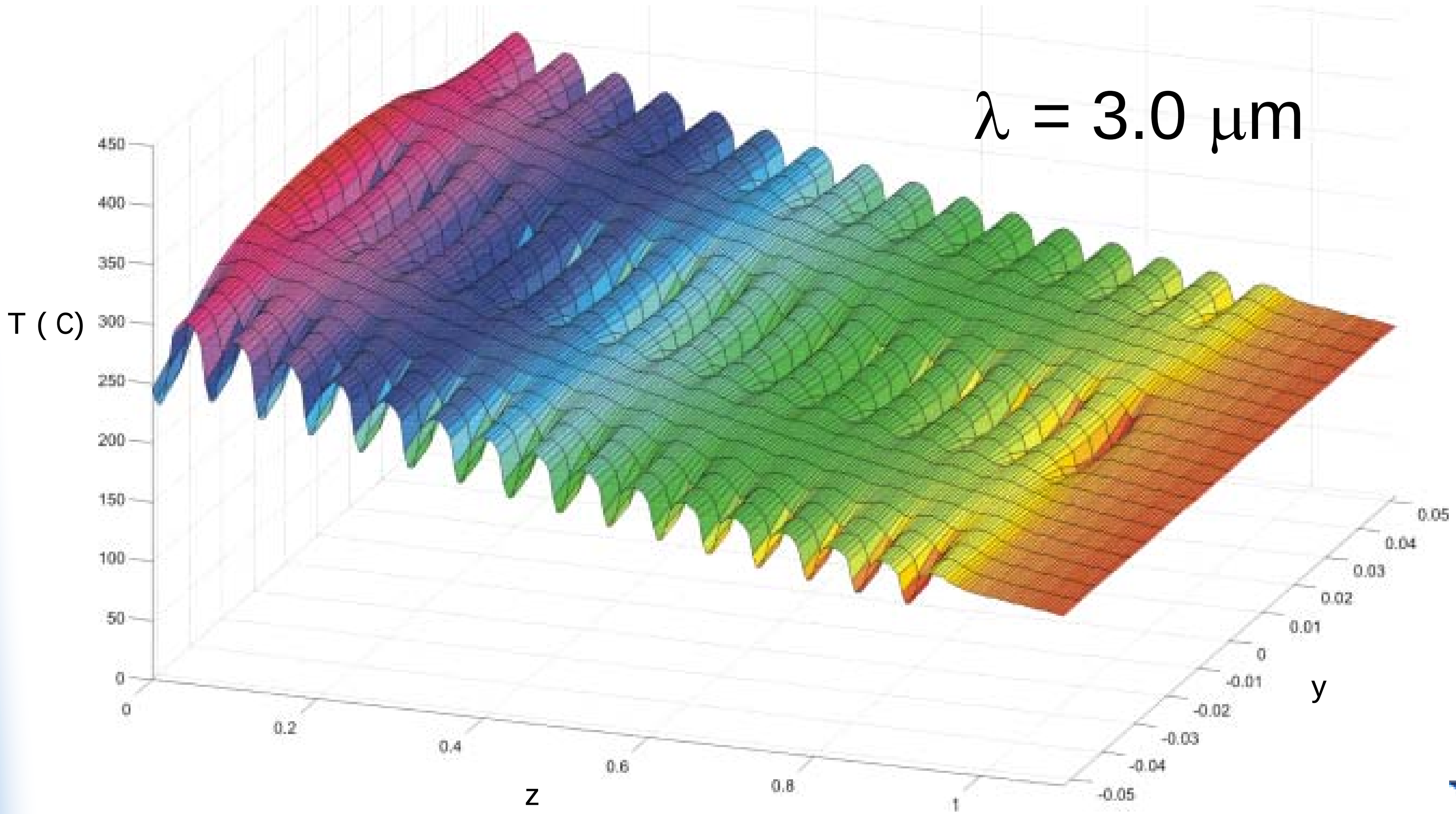


Volume Fraction
(saline:protein)
85:15

Relative Energy Densities



T Profile at Superheat Limit



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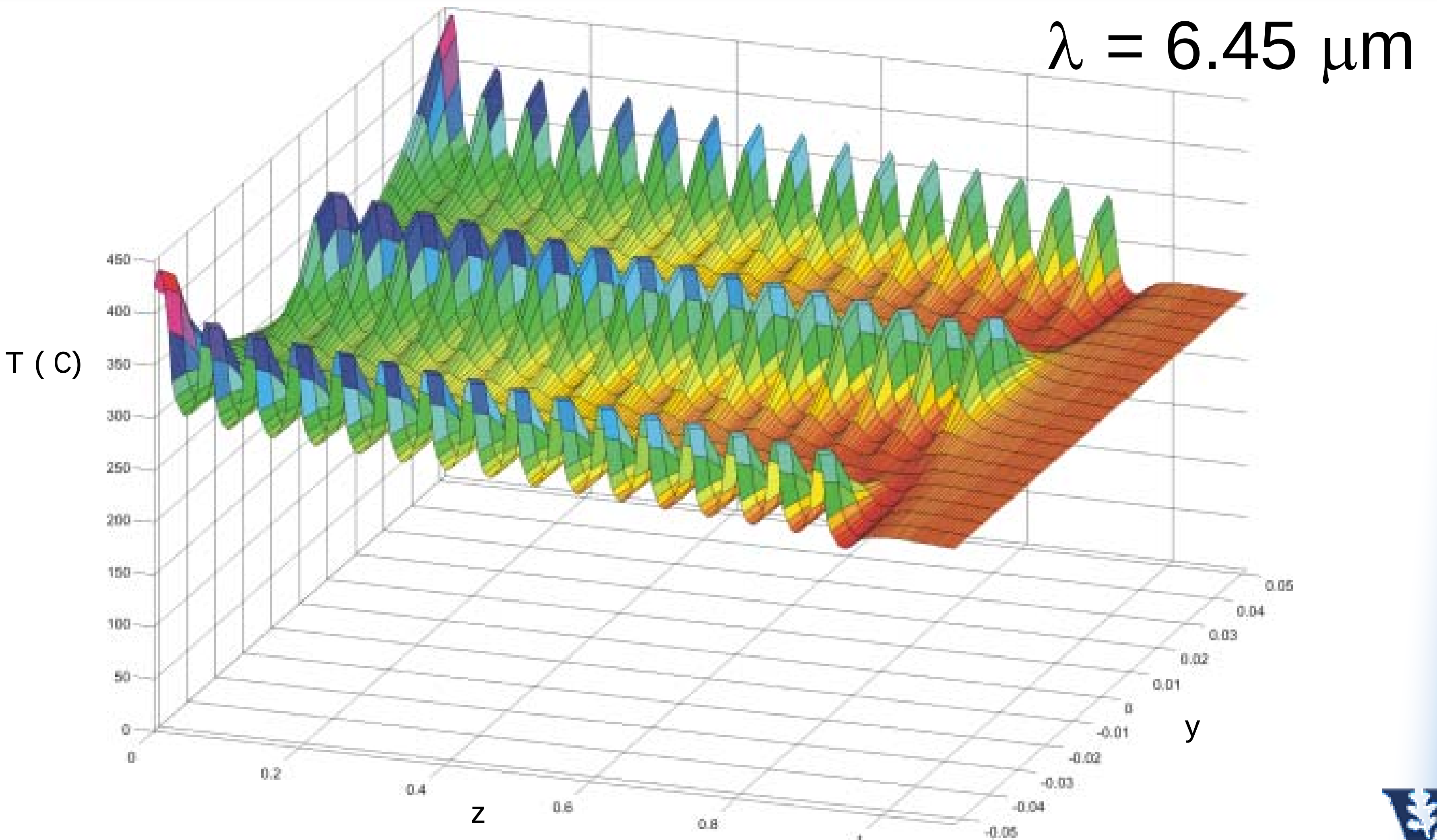

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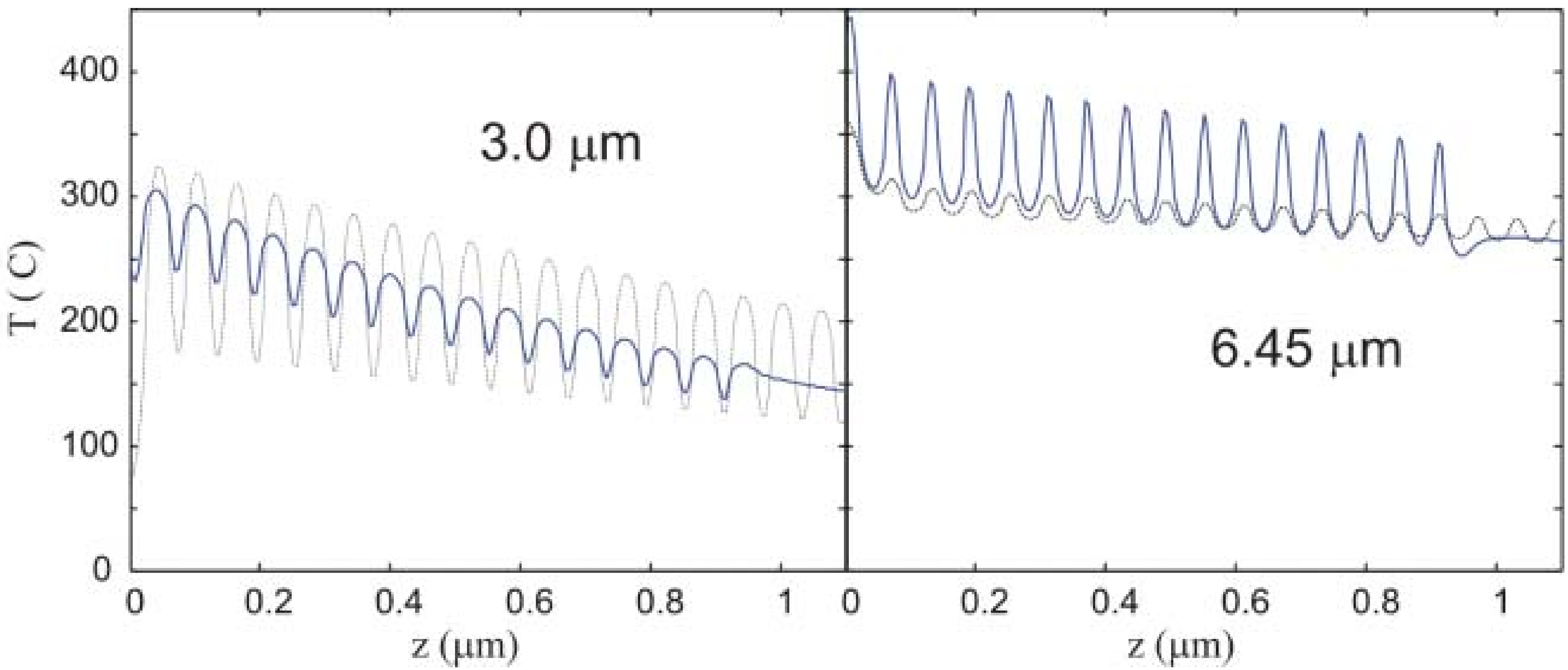
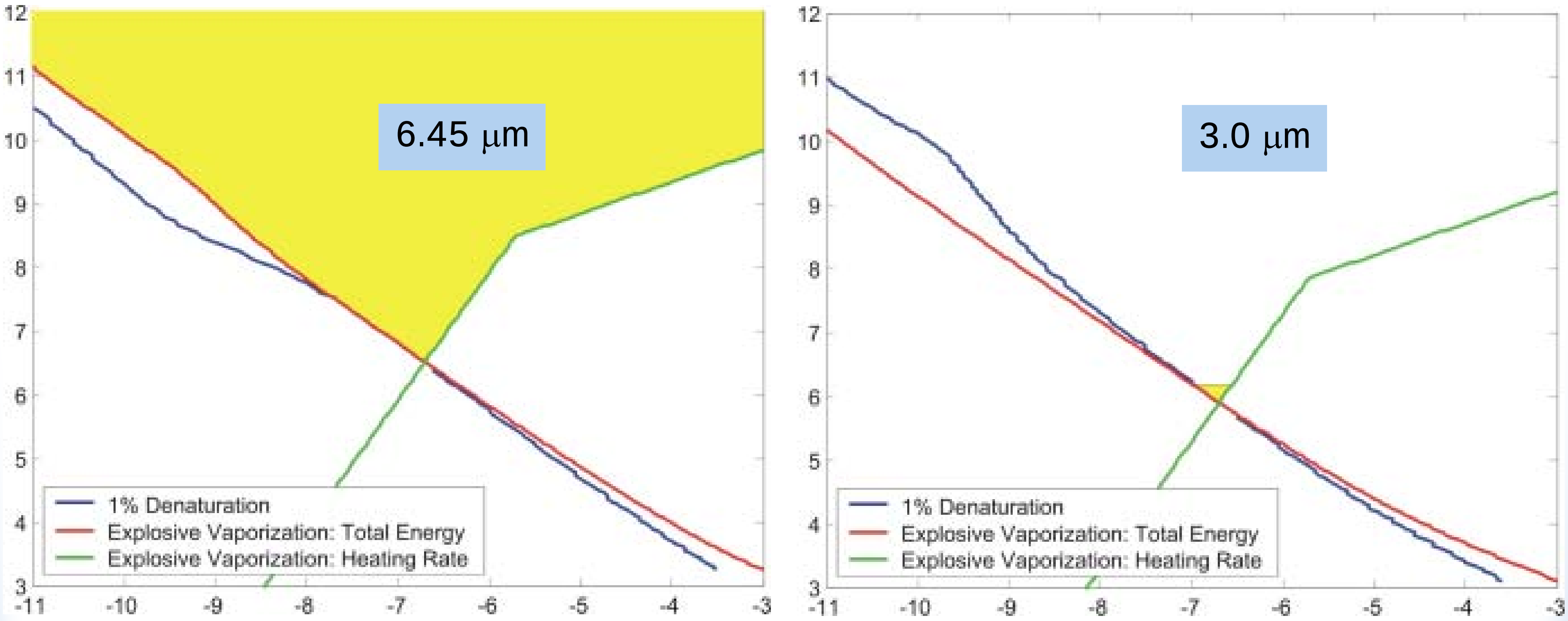


Sweet-spot Plots



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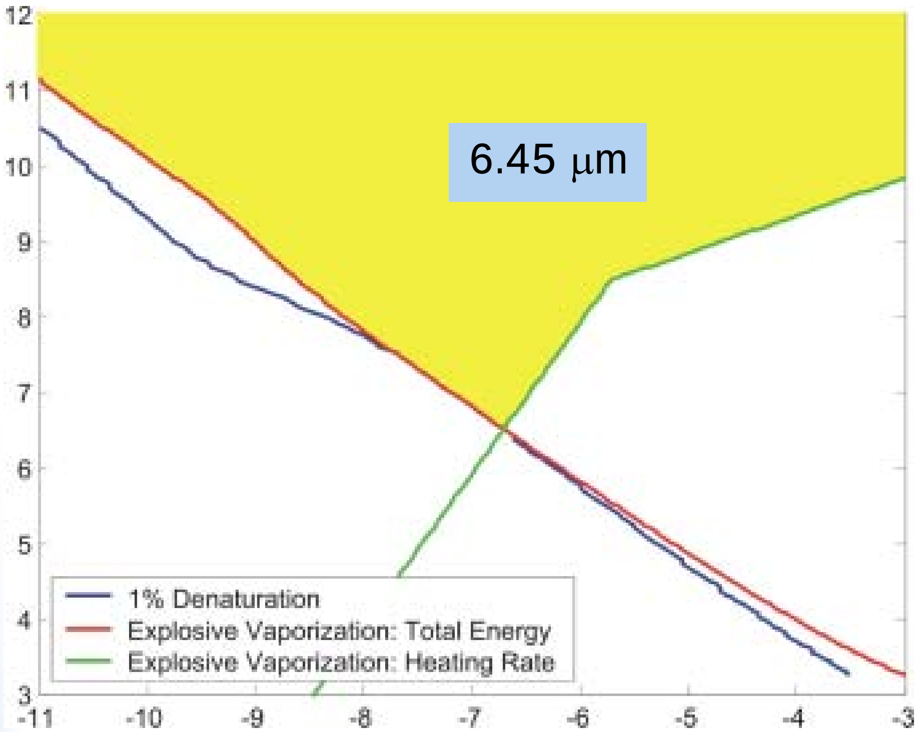
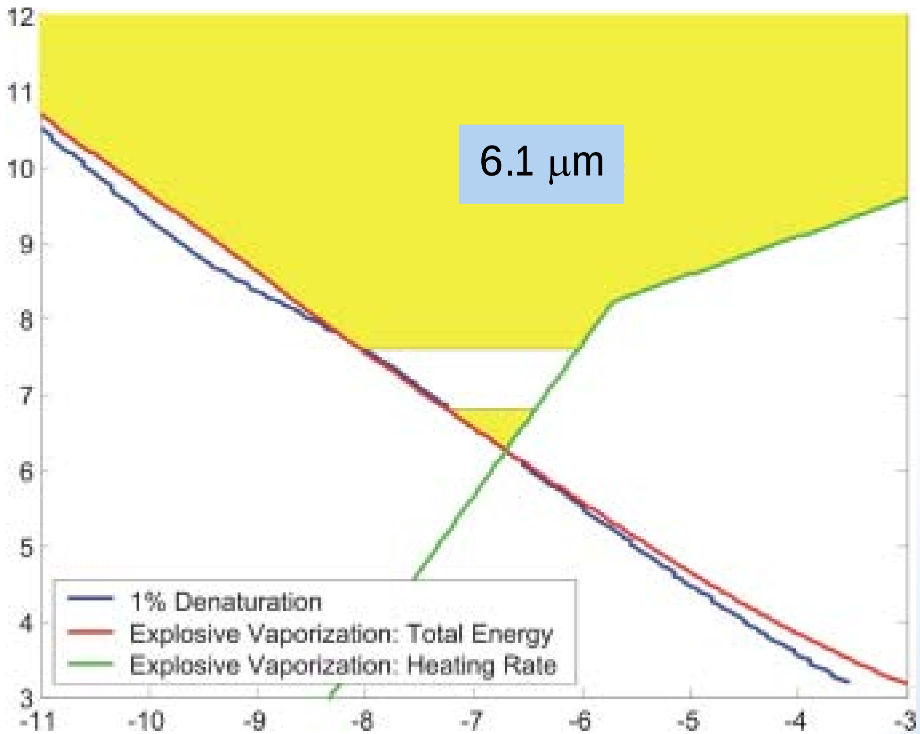
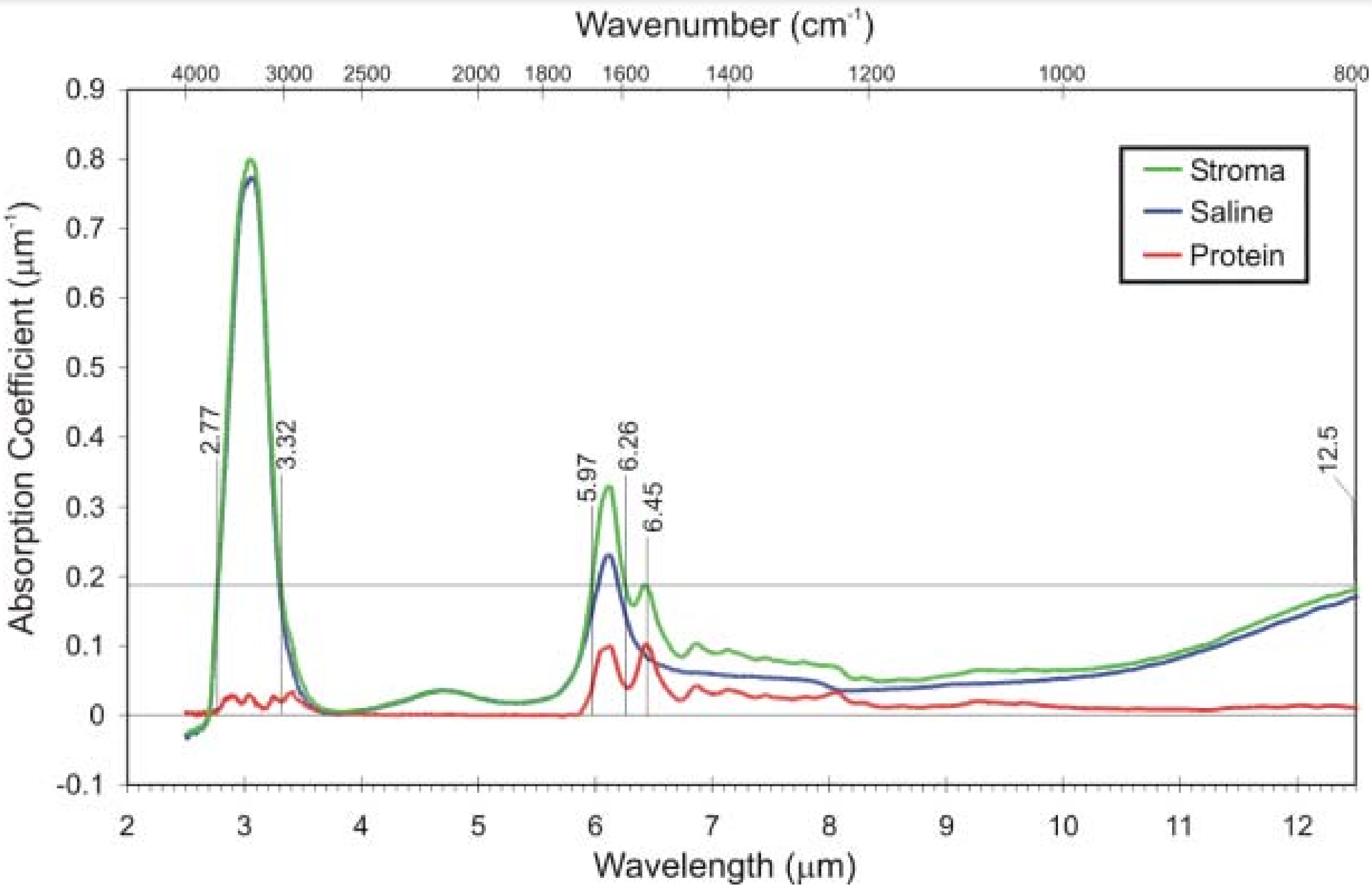
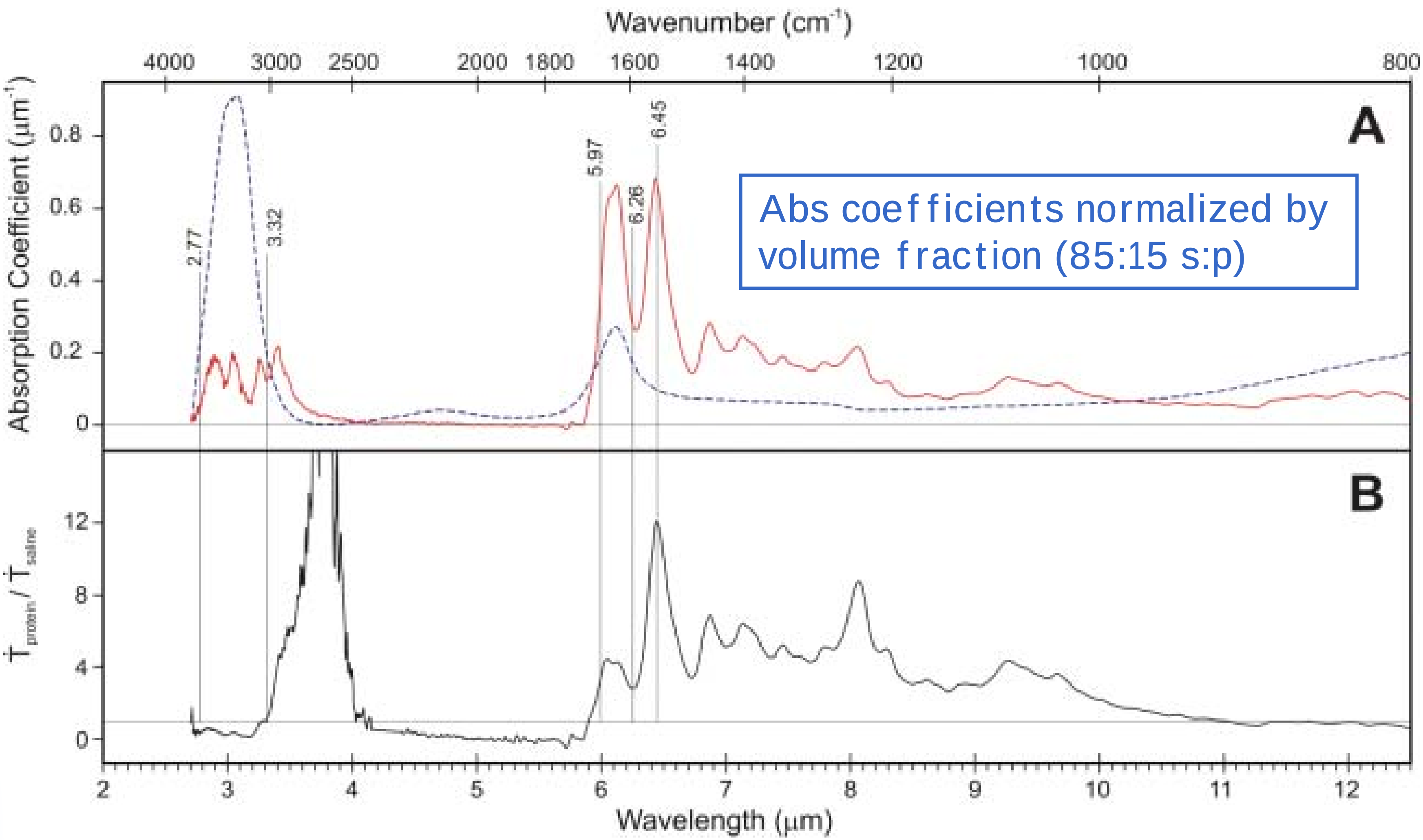




Mid-IR λ's Matching α(6.45 μm)



Relative Energy Densities



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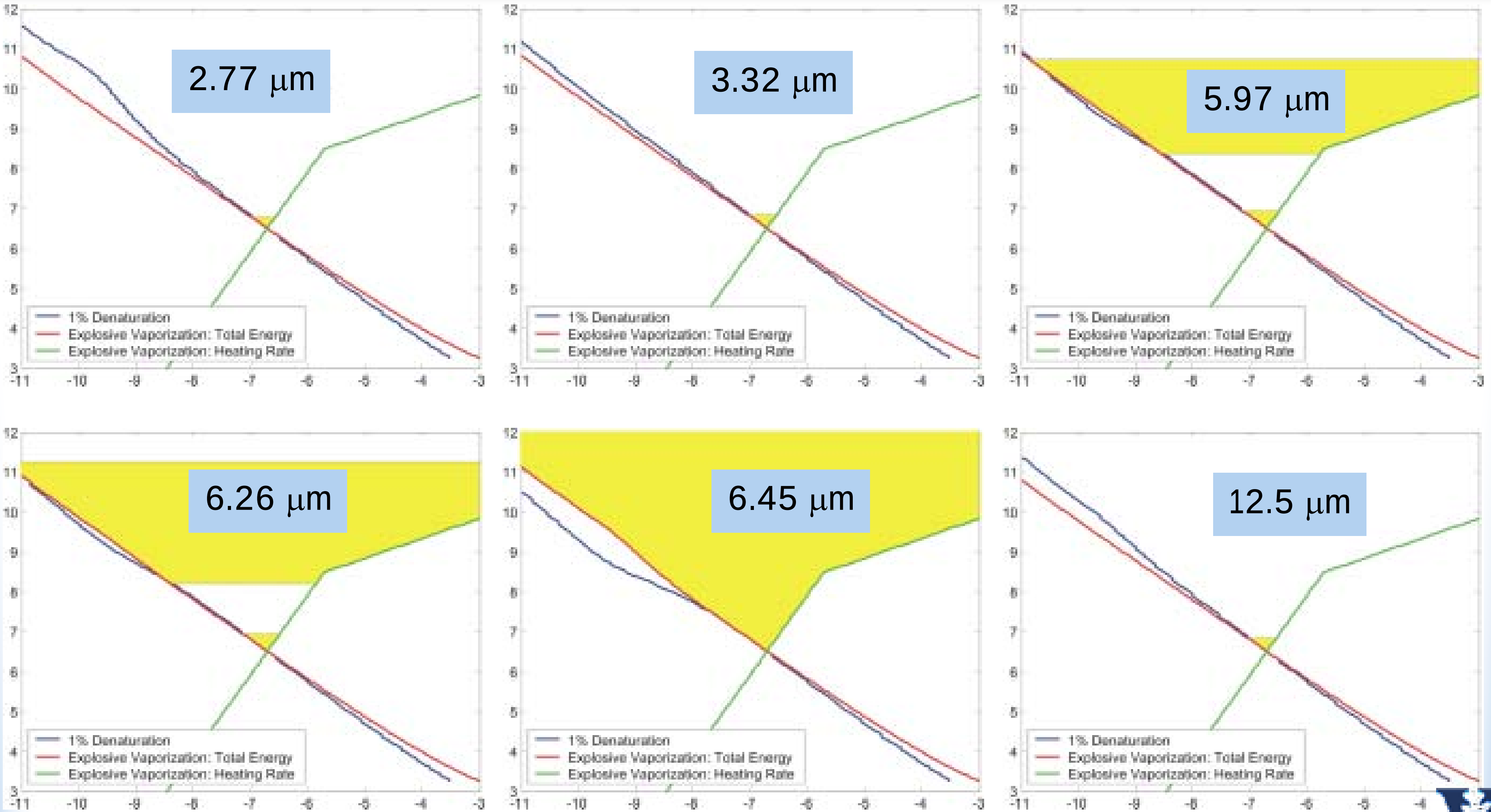
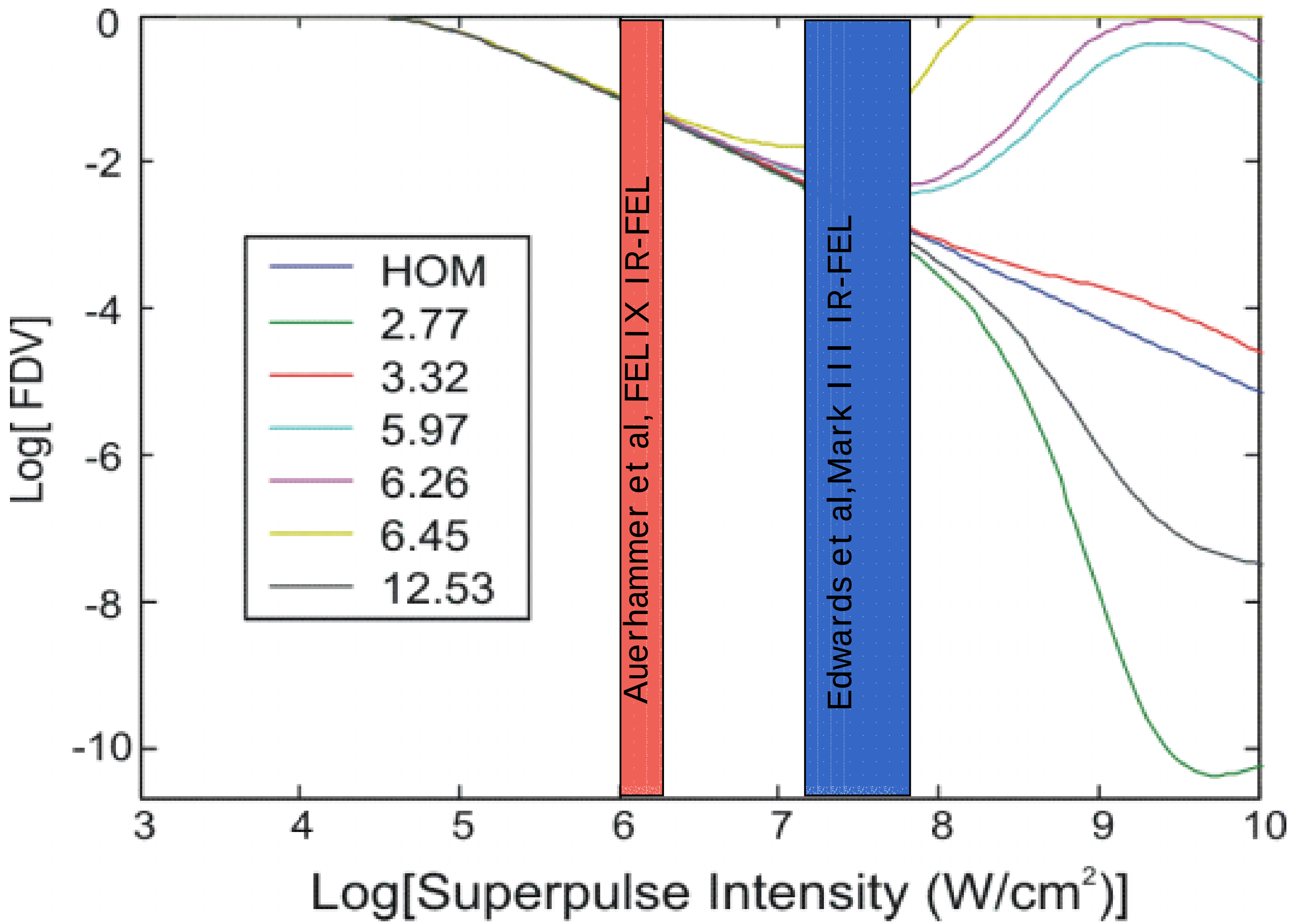


FDV versus Superpulse Intensity



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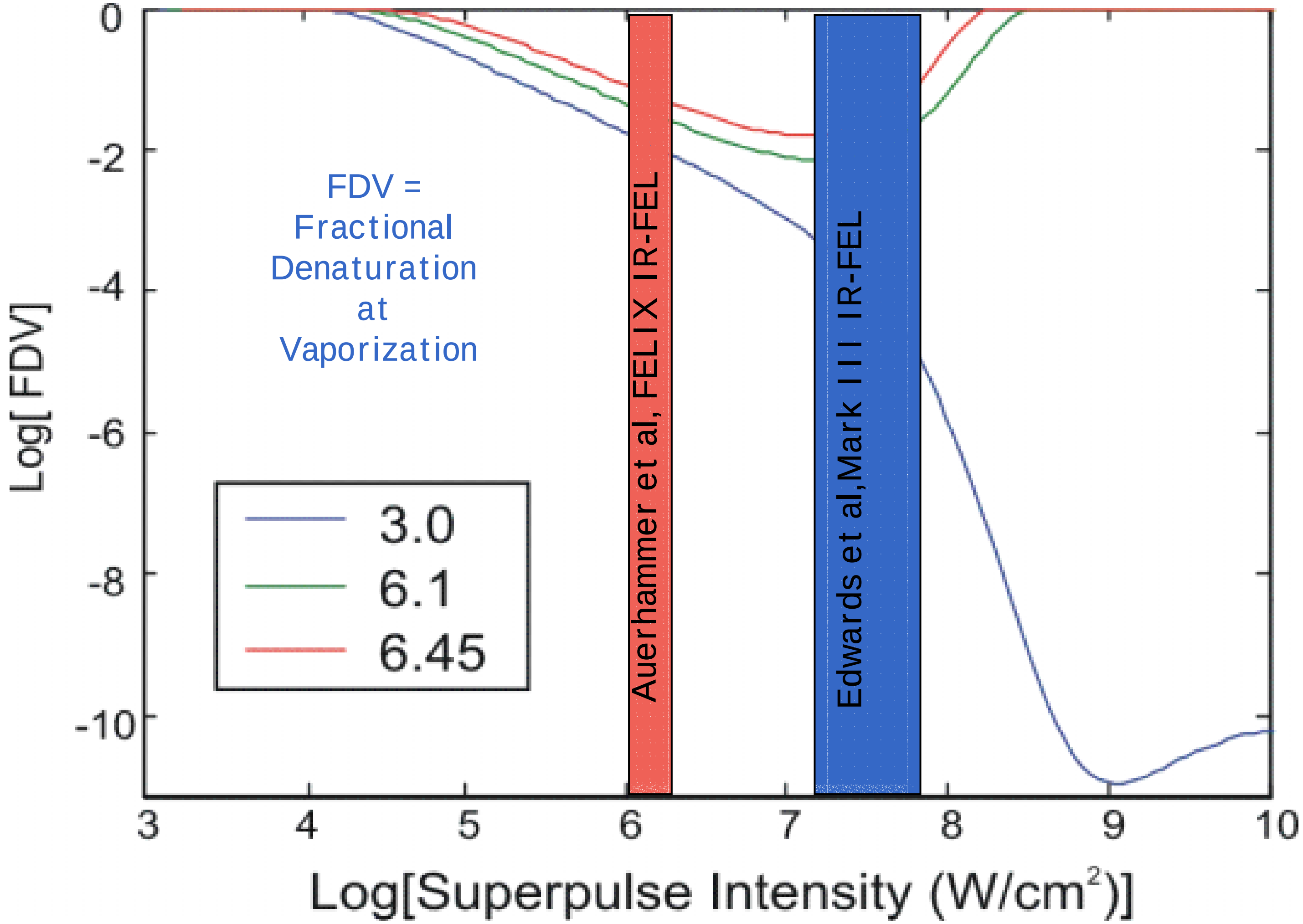


Experiments Needed

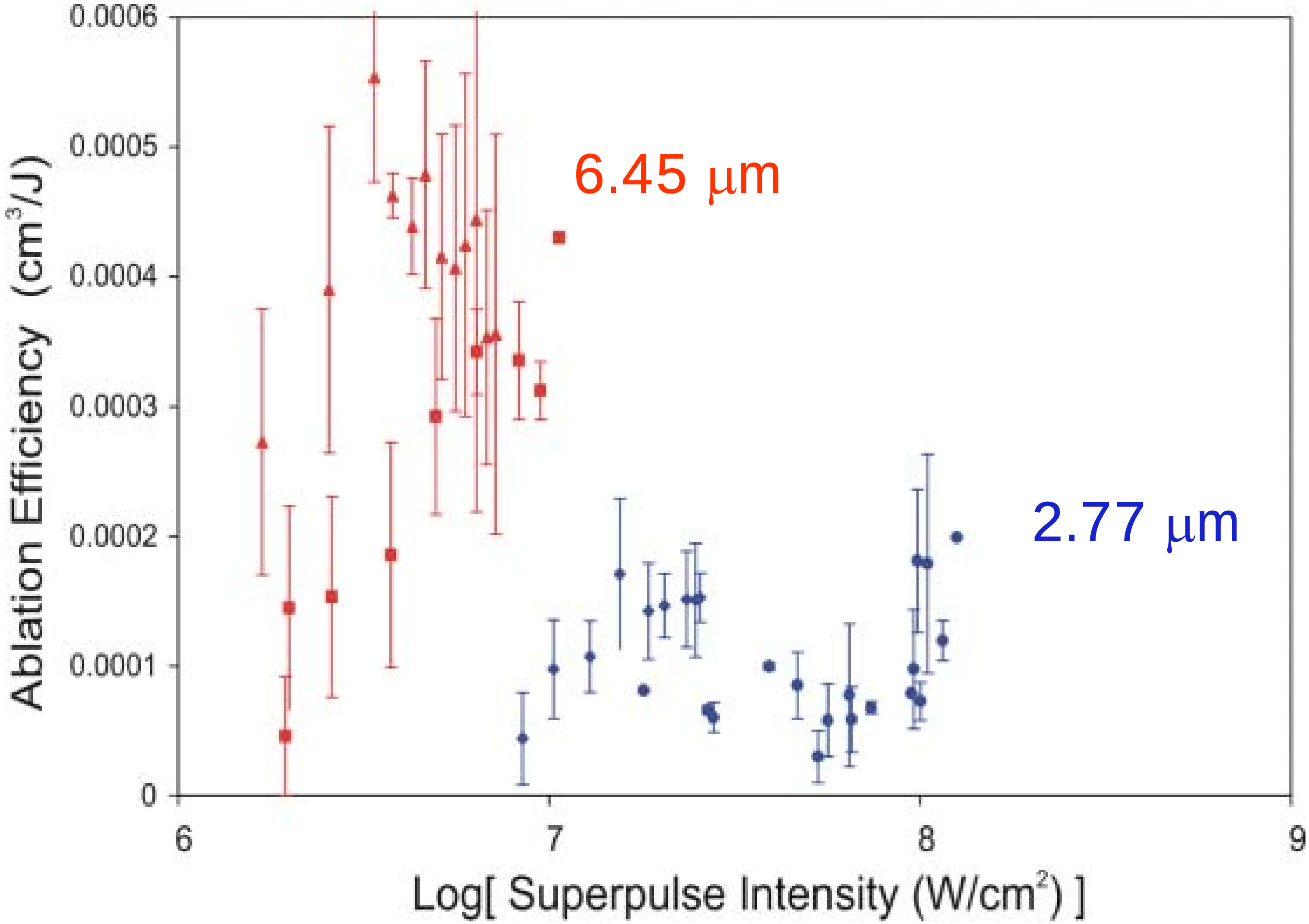
Wavelengths (e.g. 6.45 and 2.77 microns) with:

1. matched absorption coefficient, but
2. very different energy partitioning.

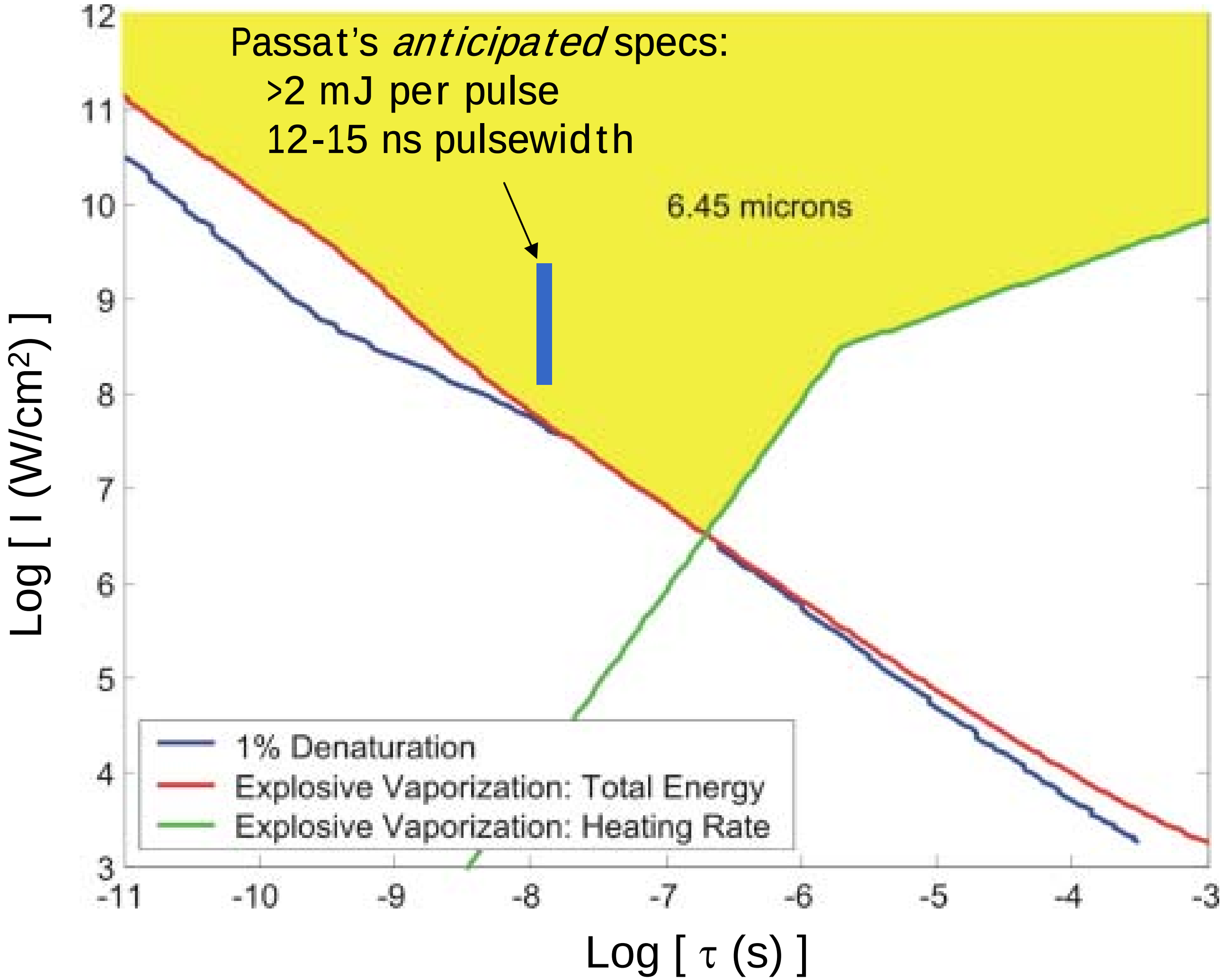
Measure:

- Ablation efficiency versus superpulse intensity
- Collateral damage versus superpulse intensity
- Ablation threshold fluence versus pulsewidth

Perforation of Porcine Cornea



Other 6.45 Micron Sources?



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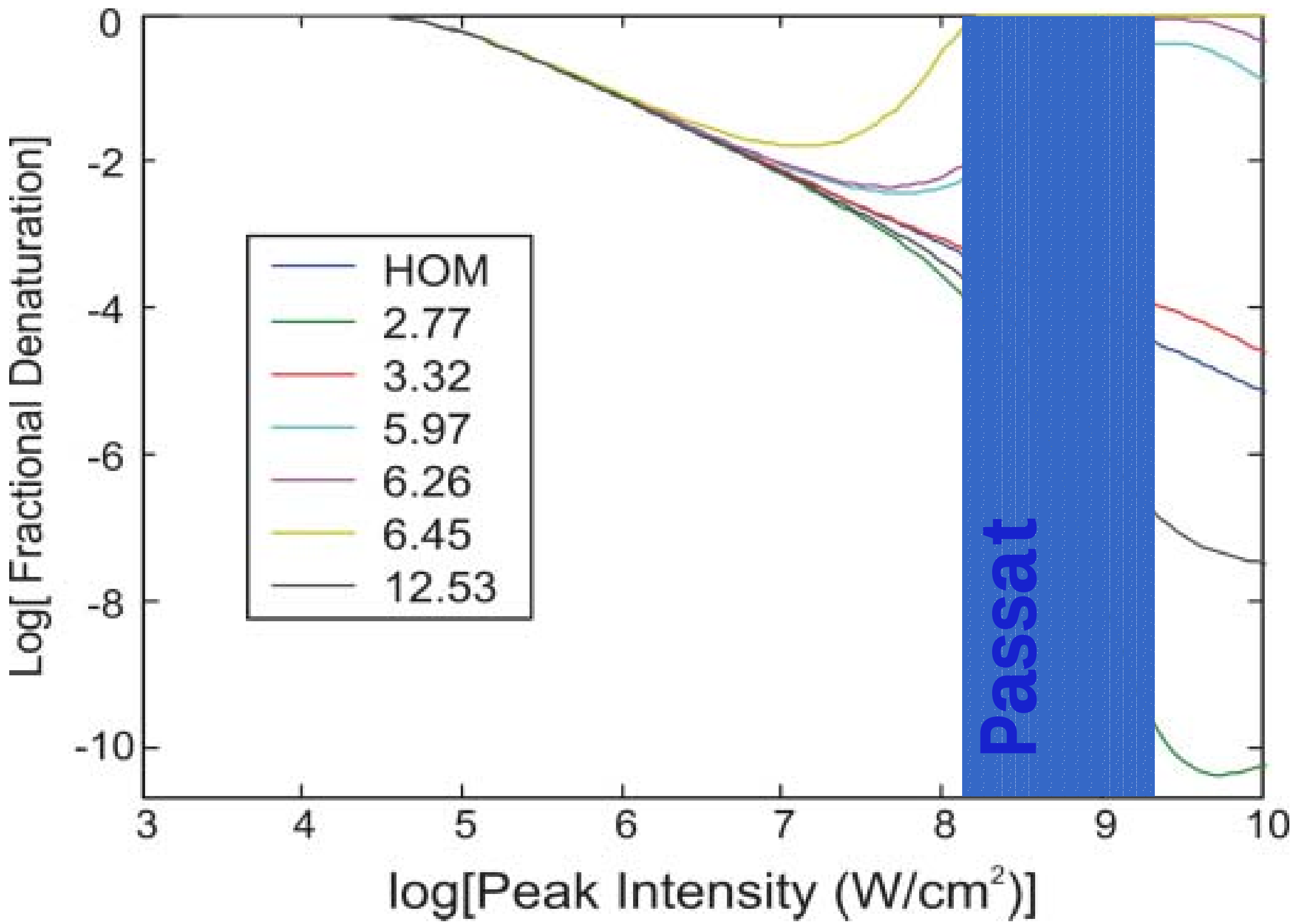
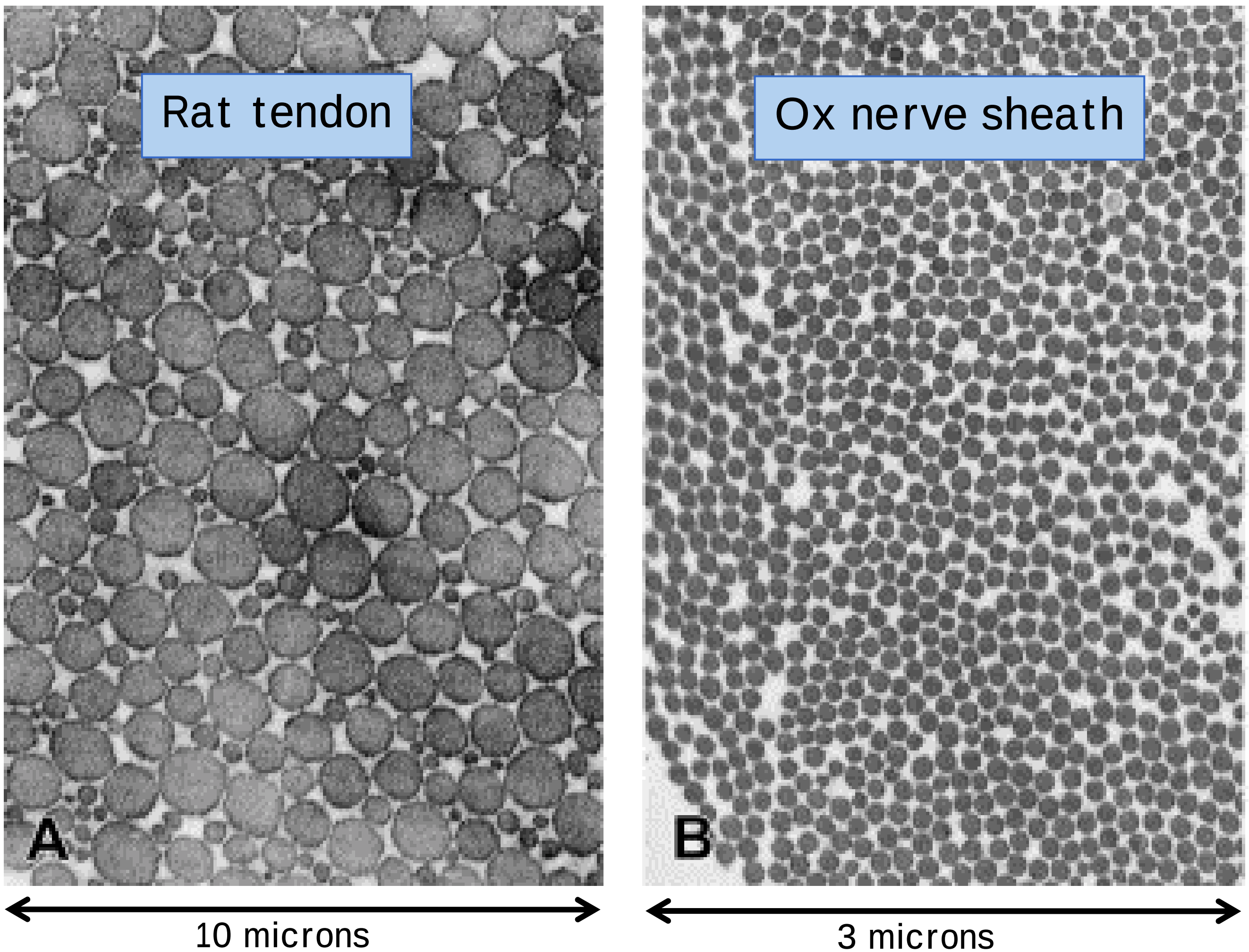


Other Tissues?



Ottani et al, 2002.

Summary

- Protein is heated more rapidly than saline for a wide range of mid-IR wavelengths (3.4-4 μm and 6-10 μm).

- Thermophysical model predicts that measurements of ablation metrics versus λ will be **strongly dependent on the superpulse intensity.**

  all λ's show decreasing FDV for $I > 10^5$ W/cm^2

  λ's that target protein then show an increase for $I > 10^7$ W/cm^2

- PASSAT's 6.45-μm laser falls into a very interesting intensity range, $I \sim 10^8$ to 10^9 W/cm^2 (eagerly awaiting experiments to evaluate!)

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