Understanding the dangers of blue light: thermal and photochemical damage models

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Overview

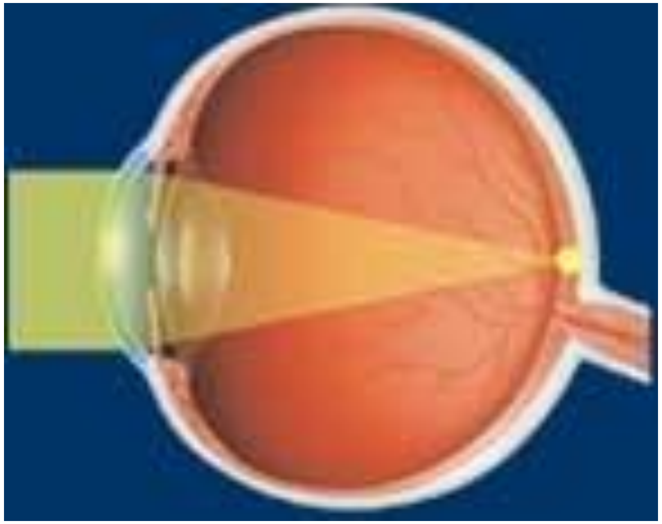
- The General Problem
- Motivation
- Laser light and the retina
- Damage models: predicting the threshold for damage
- A new model
- Conclusions

The General Problem

- Based on the exposure parameters at the cornea, will the retina be injured?
- What is the threshold for causing injury?

Cornea exposure

Can measure directly



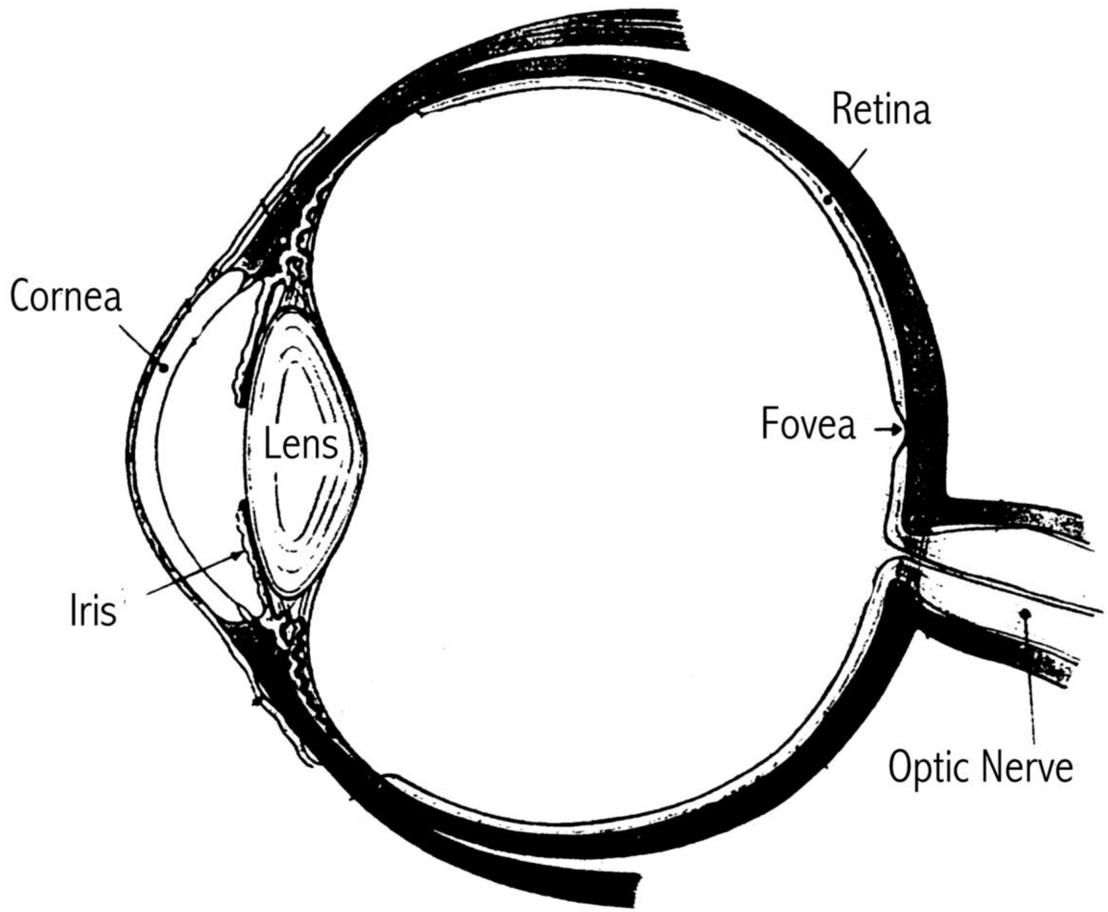
Retina Exposure

Cannot measure directly

Motivation

- Demonstrate an understanding of the underlying processes
- Supplement experiment
- Safety
  - Standards (ANSI Z136.1)
    - Laser classifications
    - Hazard zones
  - Protection
    - If we understand the process, we may be able to prevent it
- Medical
  - Surgery: controlled damage
  - Therapy: sub-threshold stimulation

Laser light and the retina



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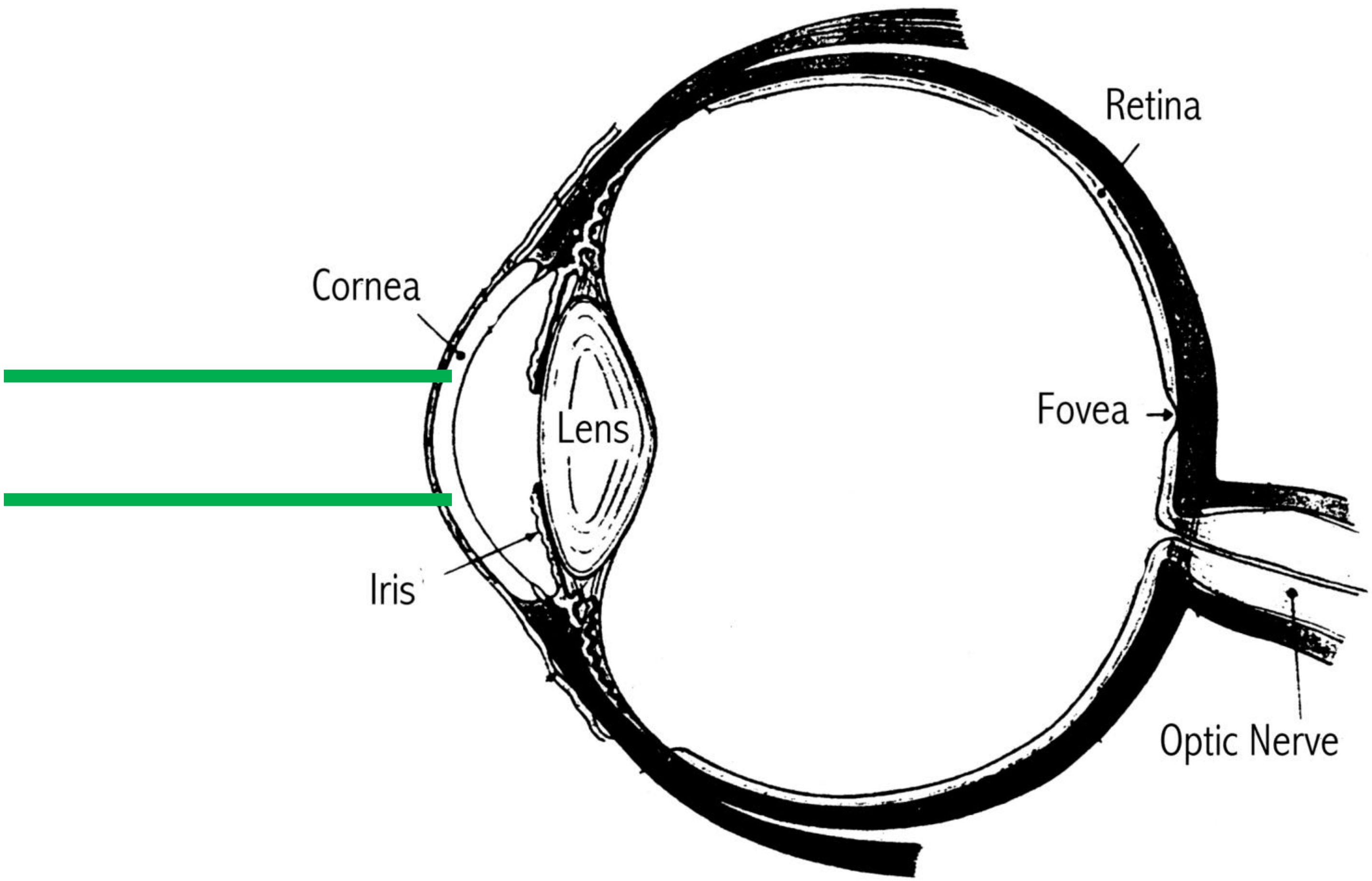

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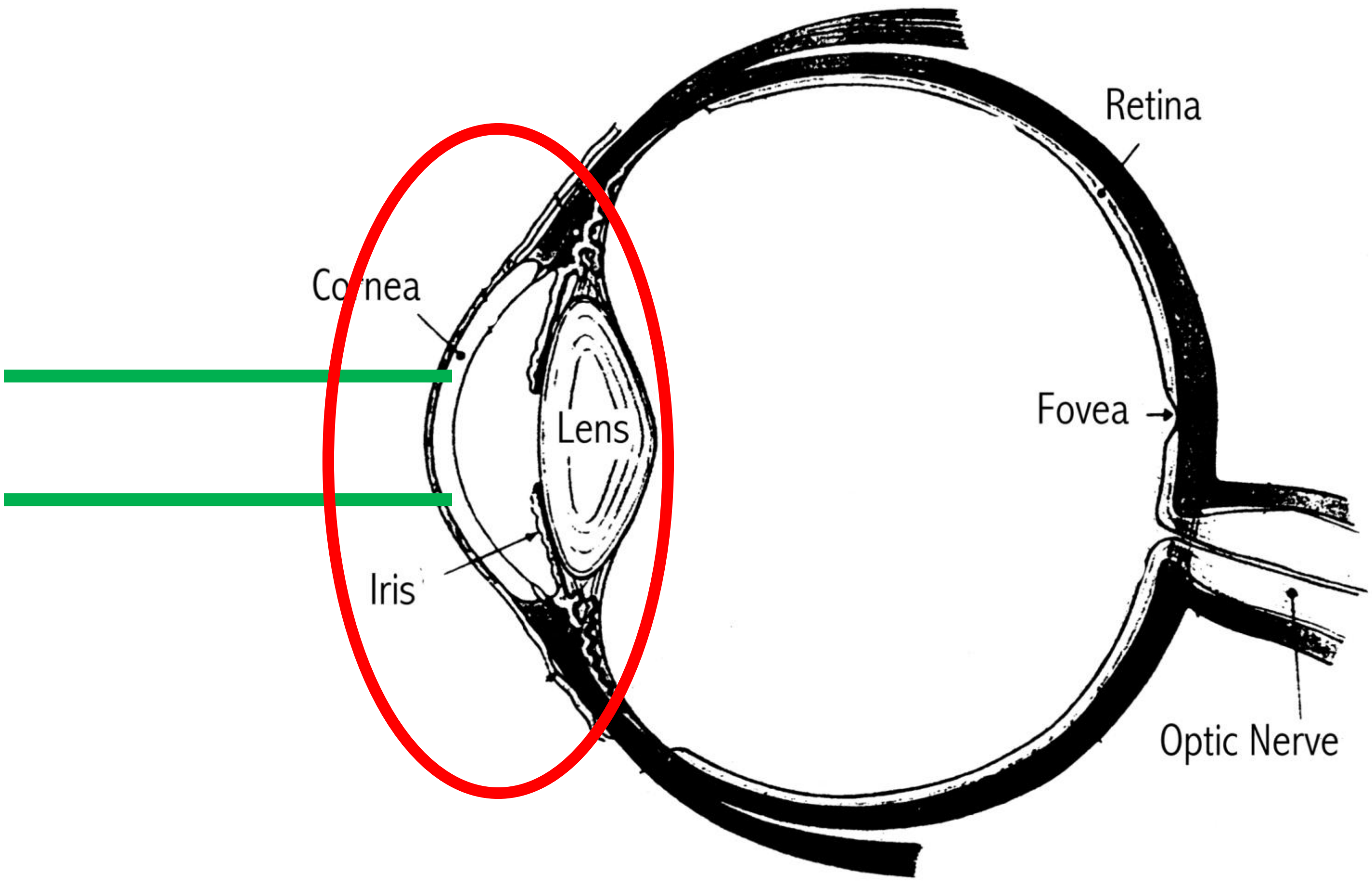

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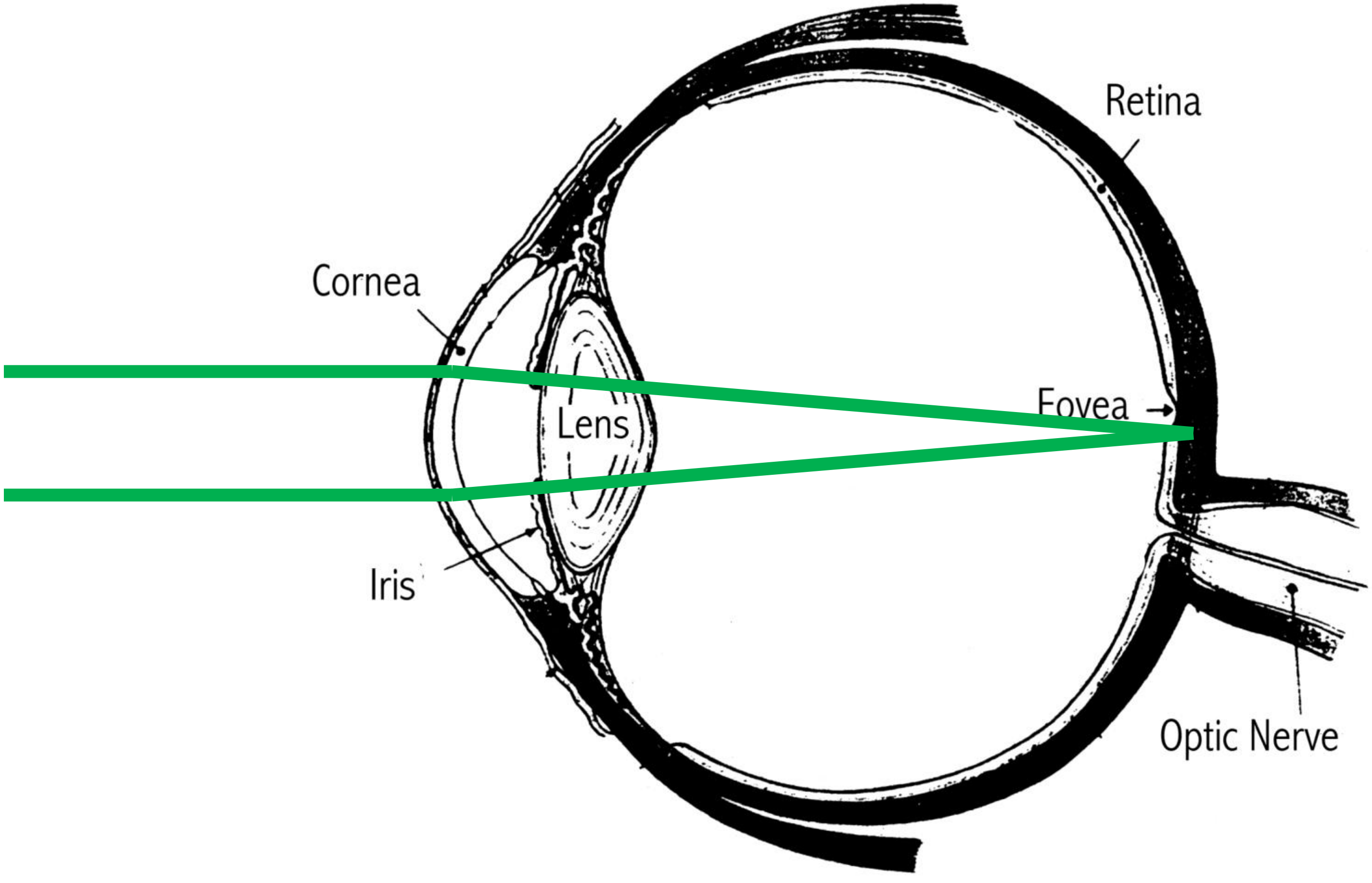
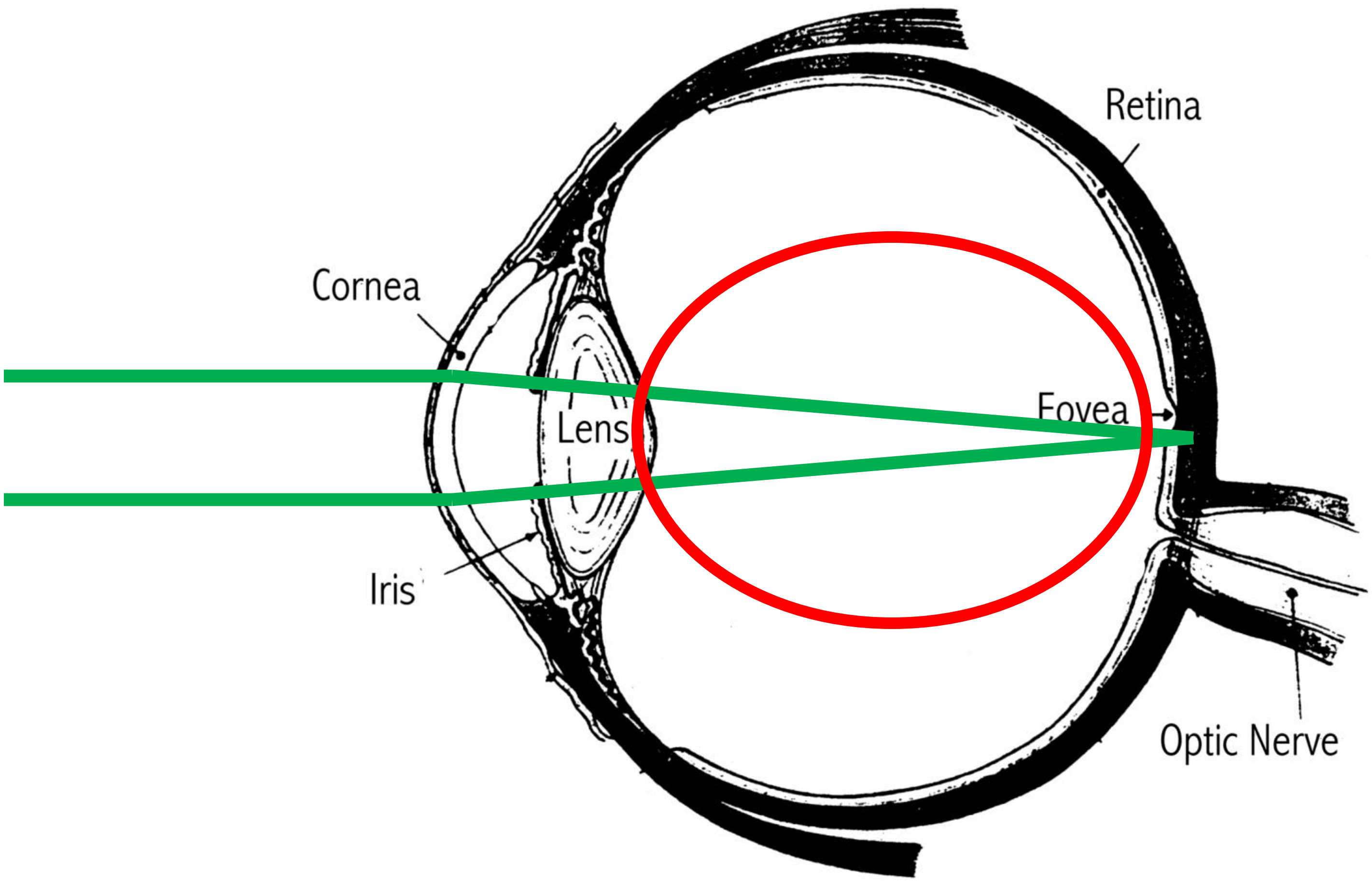


Laser light and the retina



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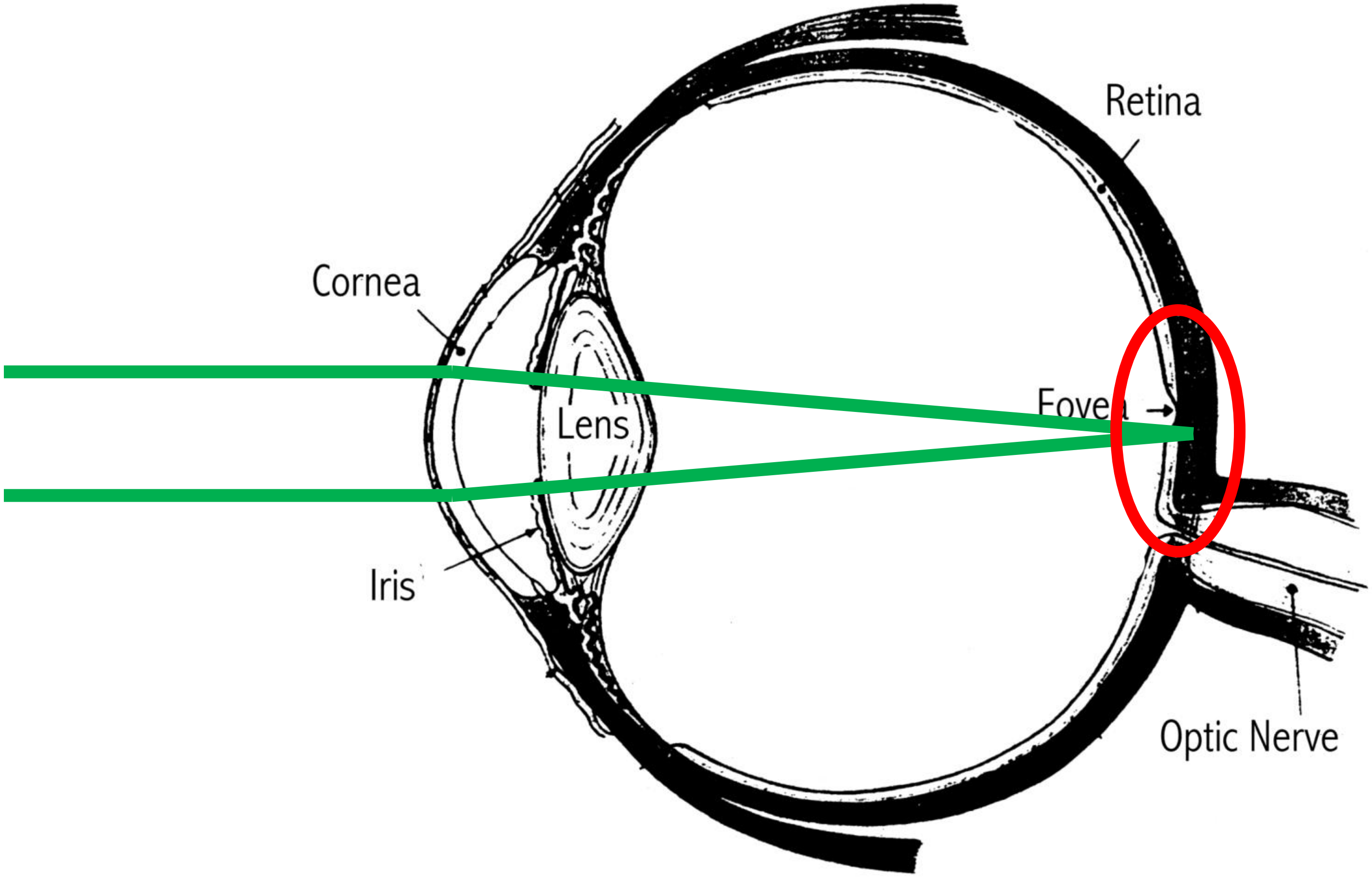

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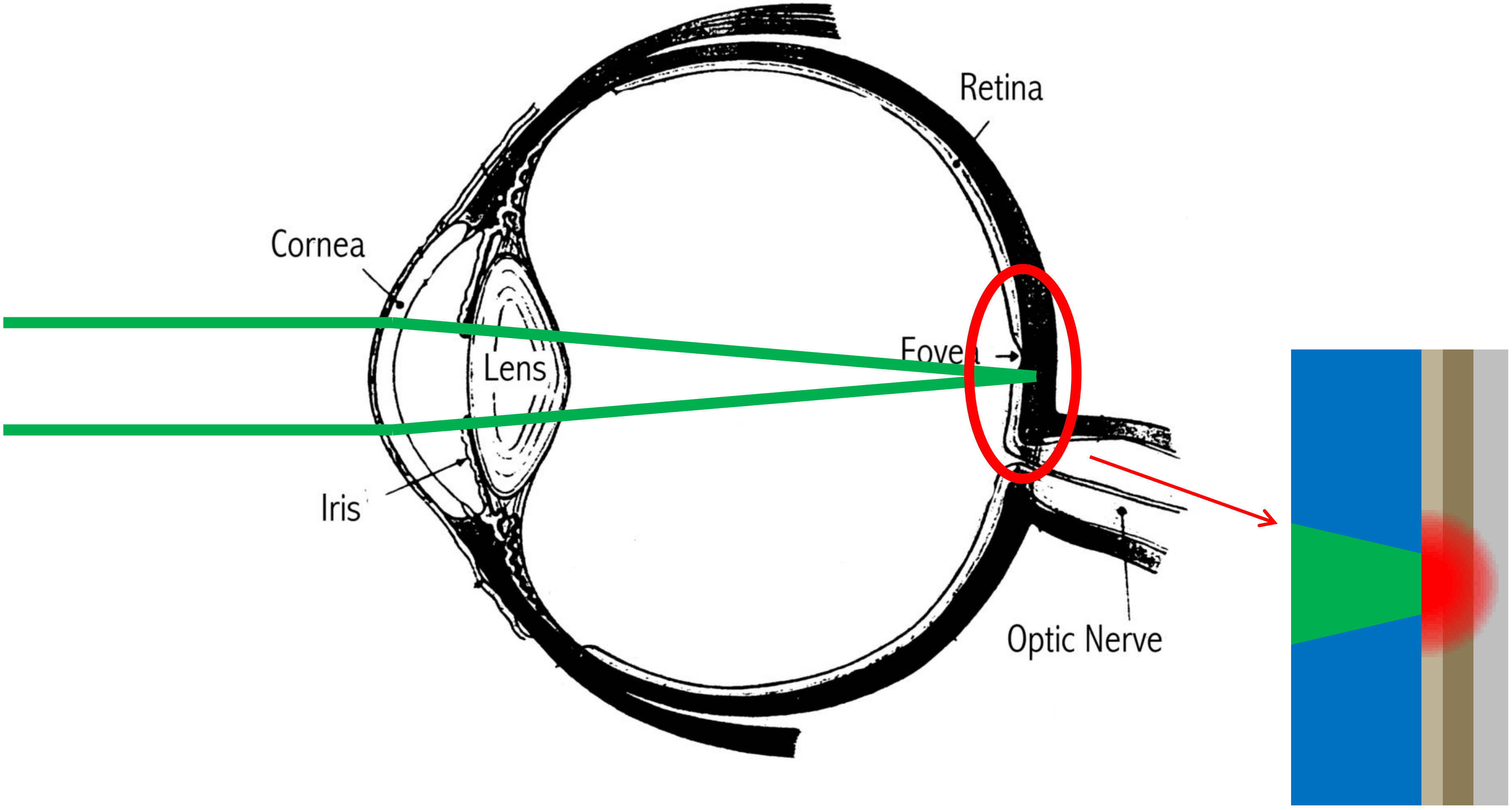
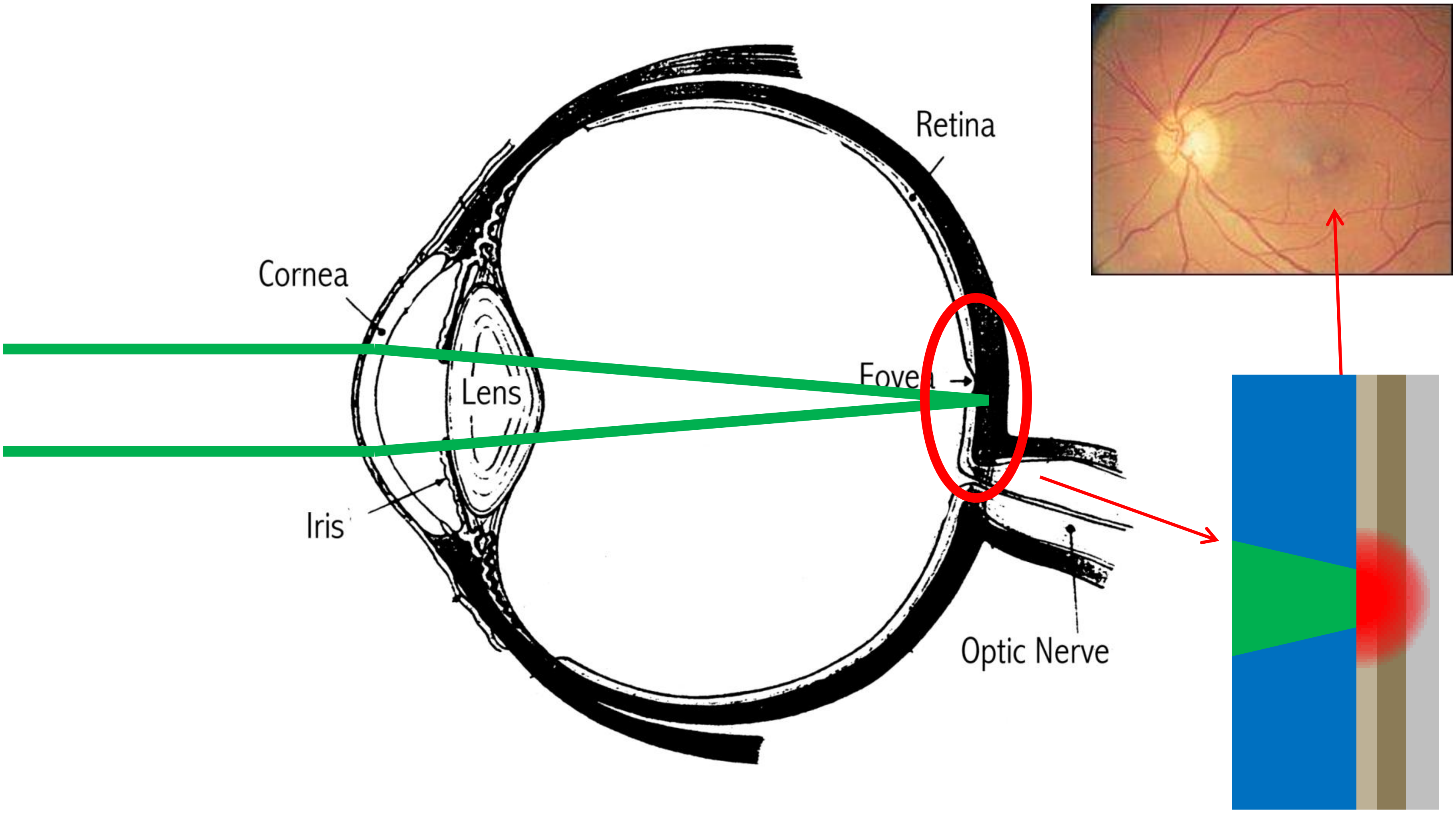
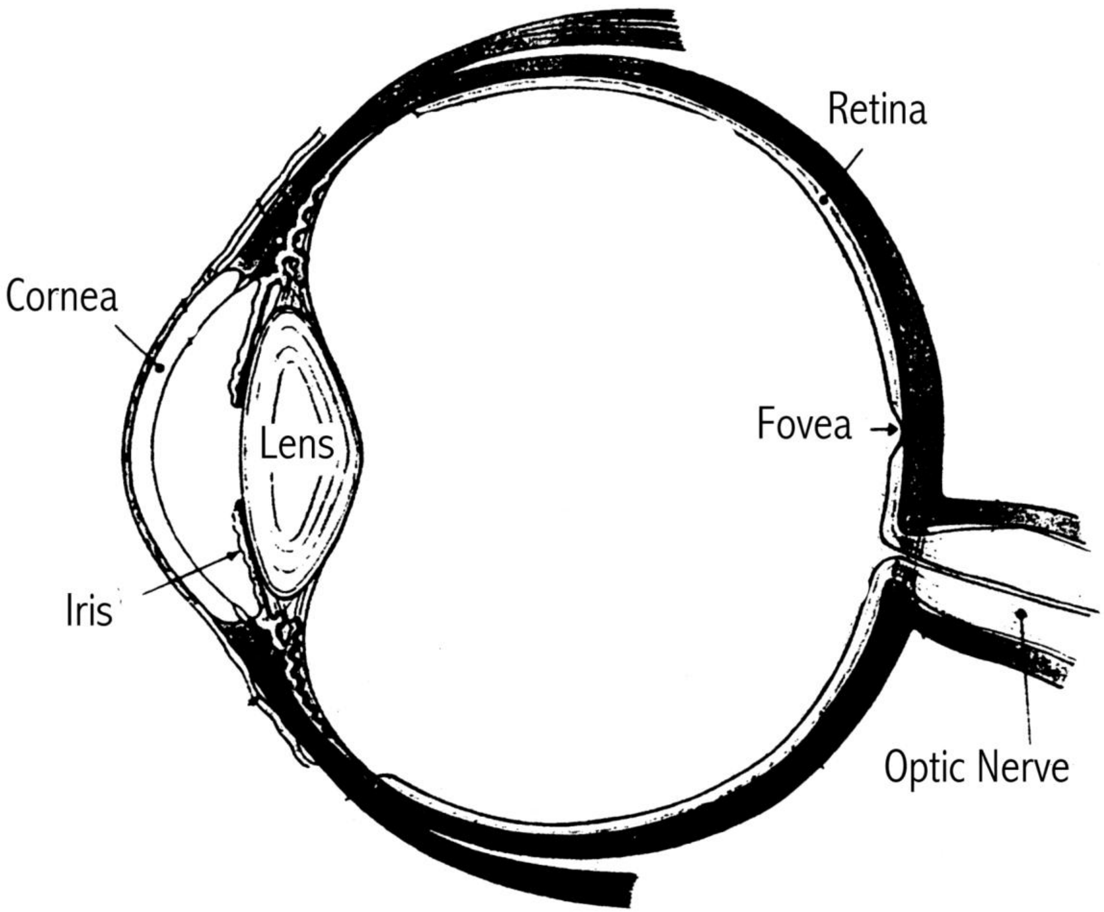


Laser light and the retina

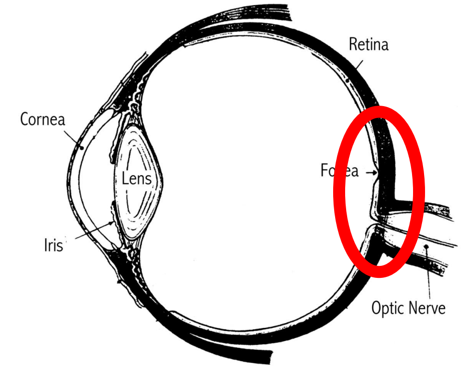


My Work

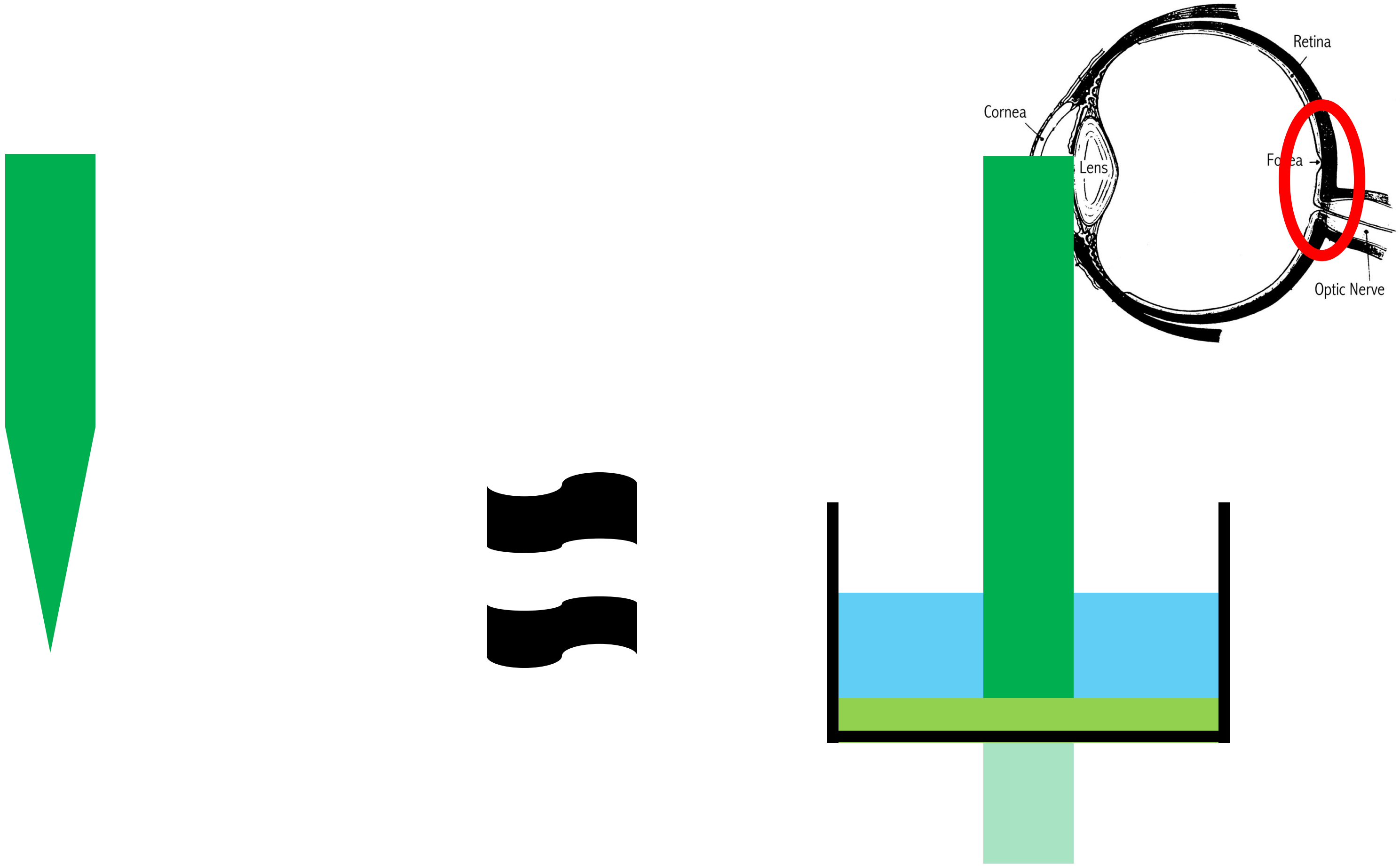


My Work

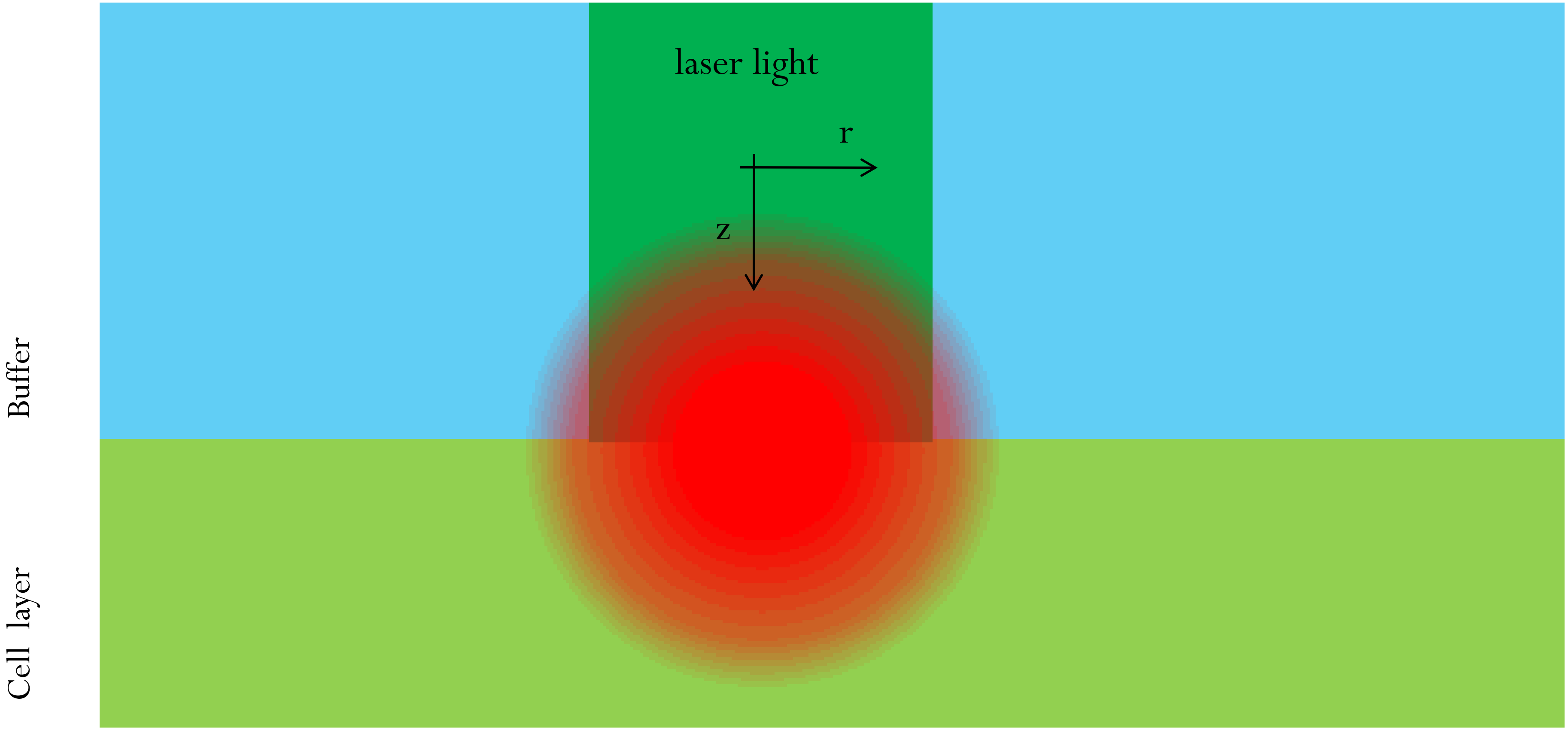
- Propagation
  - Thermal lensing
  - Ultrashort pulses
- Multiple pulse damage thresholds
- Rate Process Models
  - Photochemical damage



Cell Culture

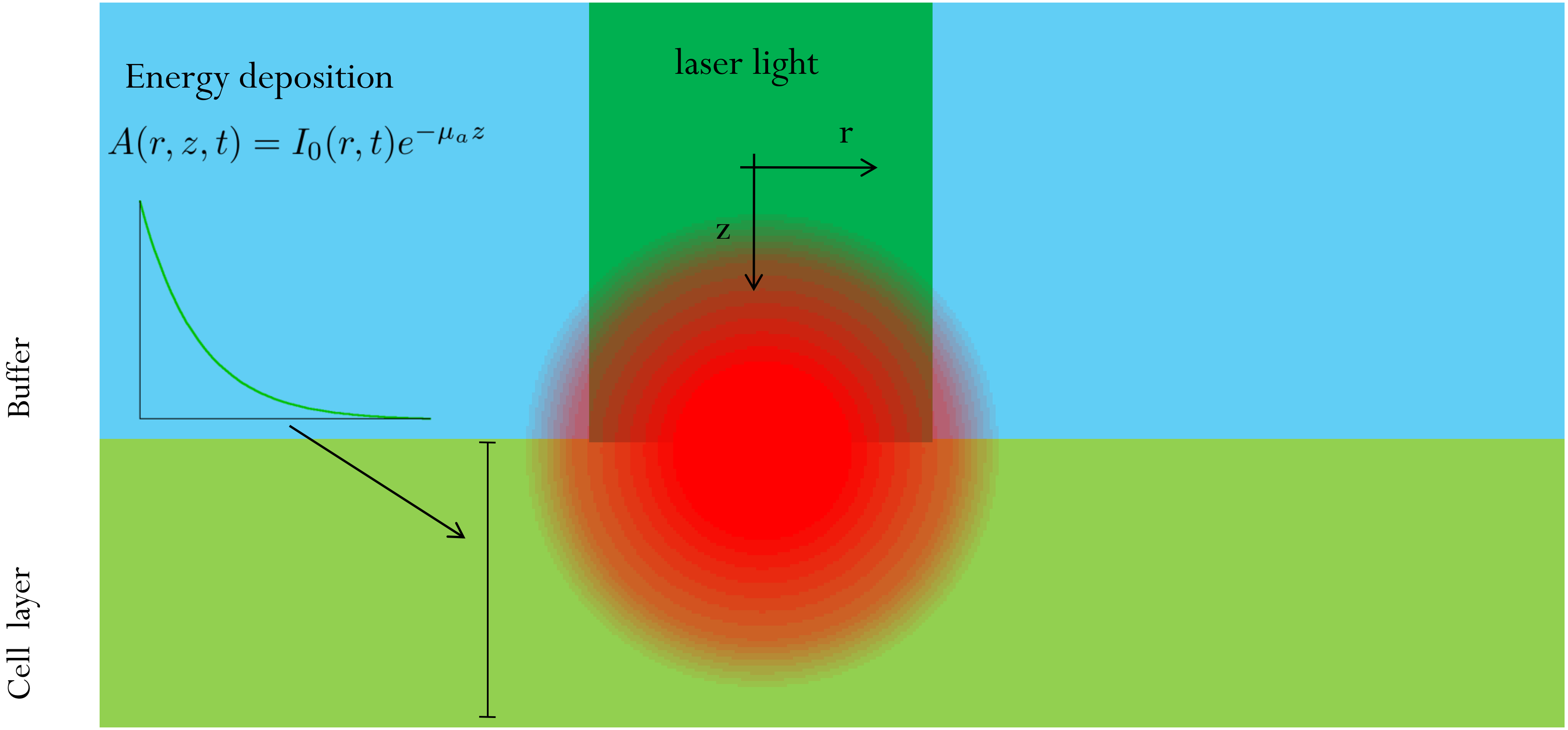


Cell Culture: Predicting Temperature



$$\rho c \frac{\partial T(r,z,t)}{\partial t} - \nabla \cdot \kappa \nabla T(r,z,t) = A(r,z,t)$$

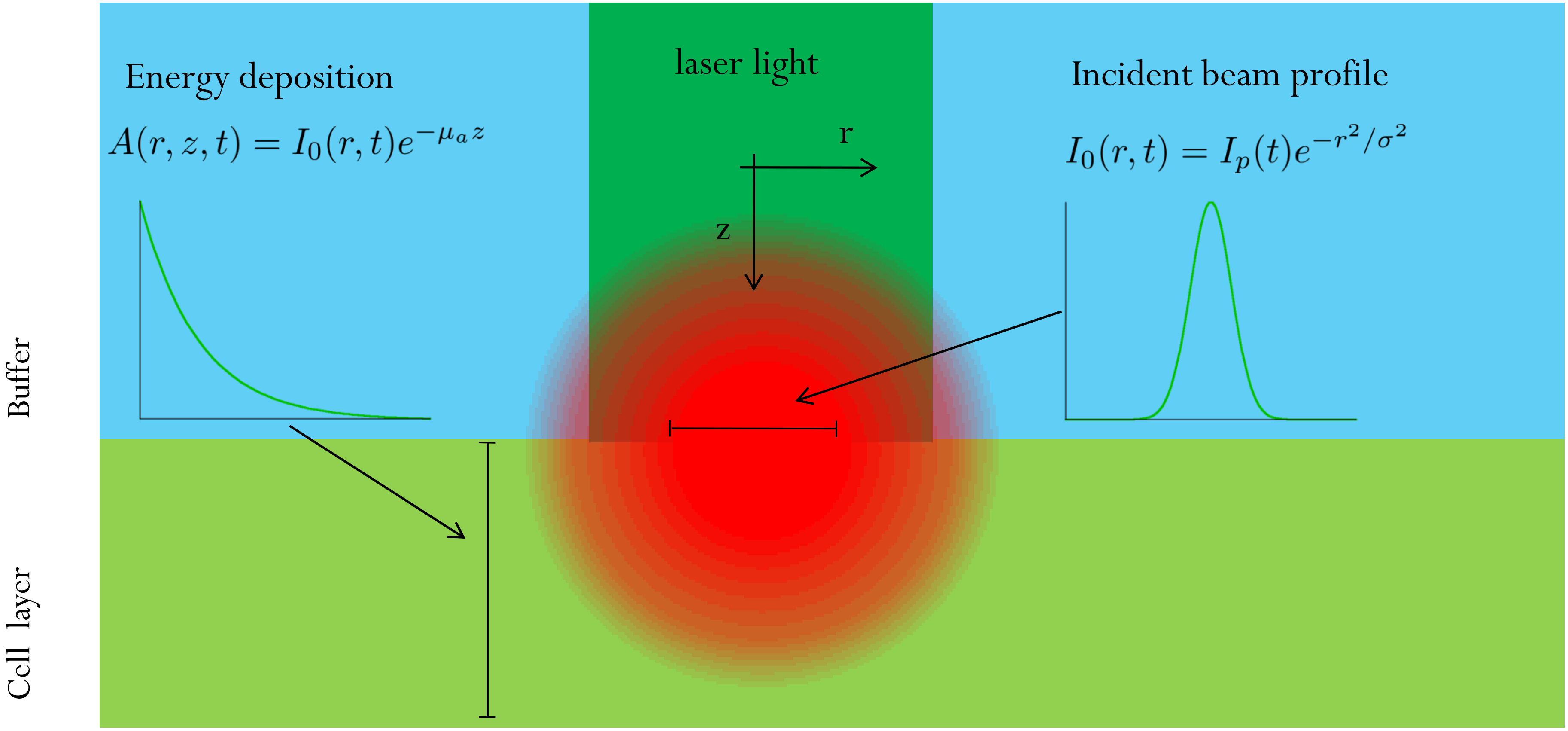
Cell Culture: Predicting Temperature



Laser interaction

$$\rho c \frac{\partial T(r,z,t)}{\partial t} - \nabla \cdot \kappa \nabla T(r,z,t) = \boxed{A(r,z,t)}$$

Cell Culture: Predicting Temperature



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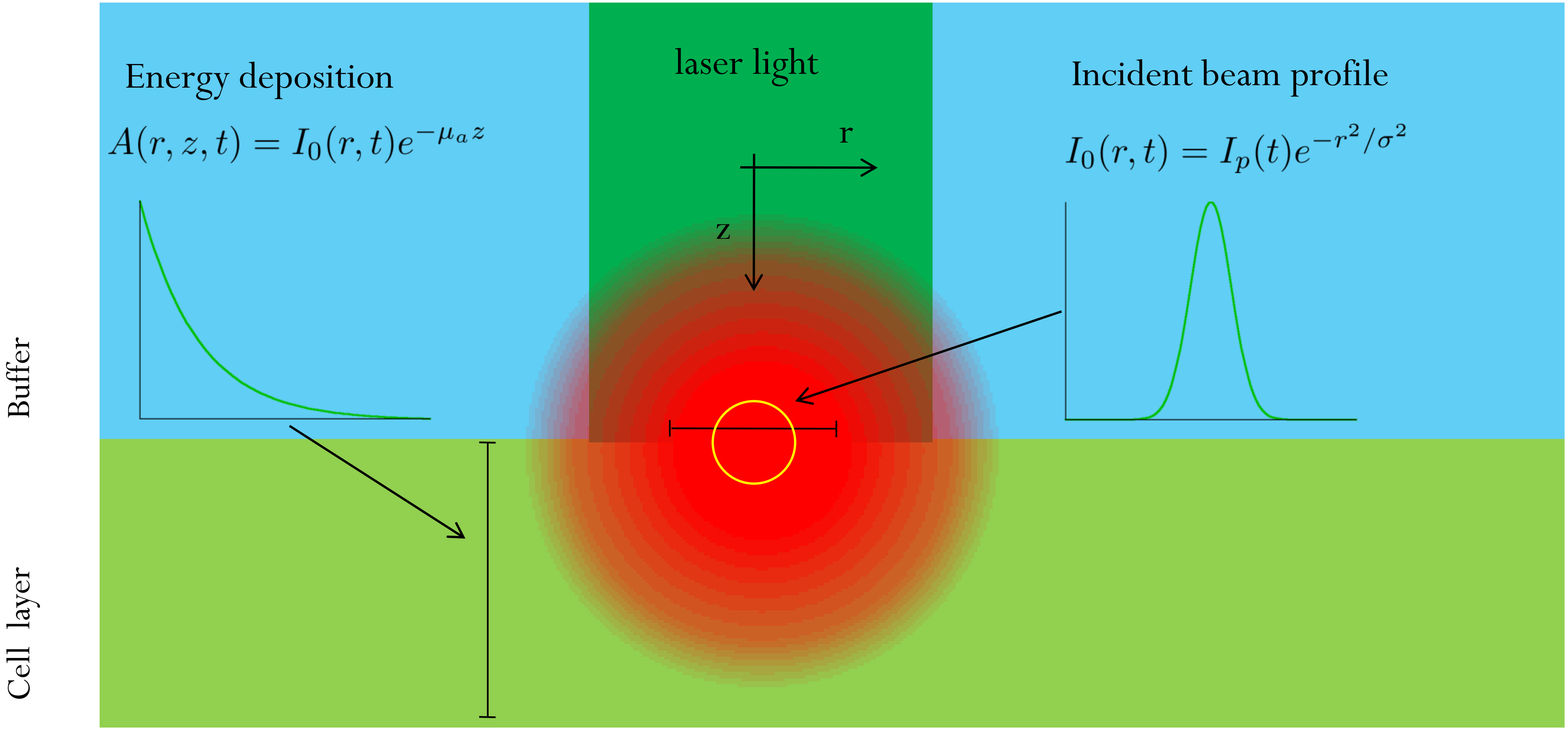

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Cell Culture: Predicting Temperature

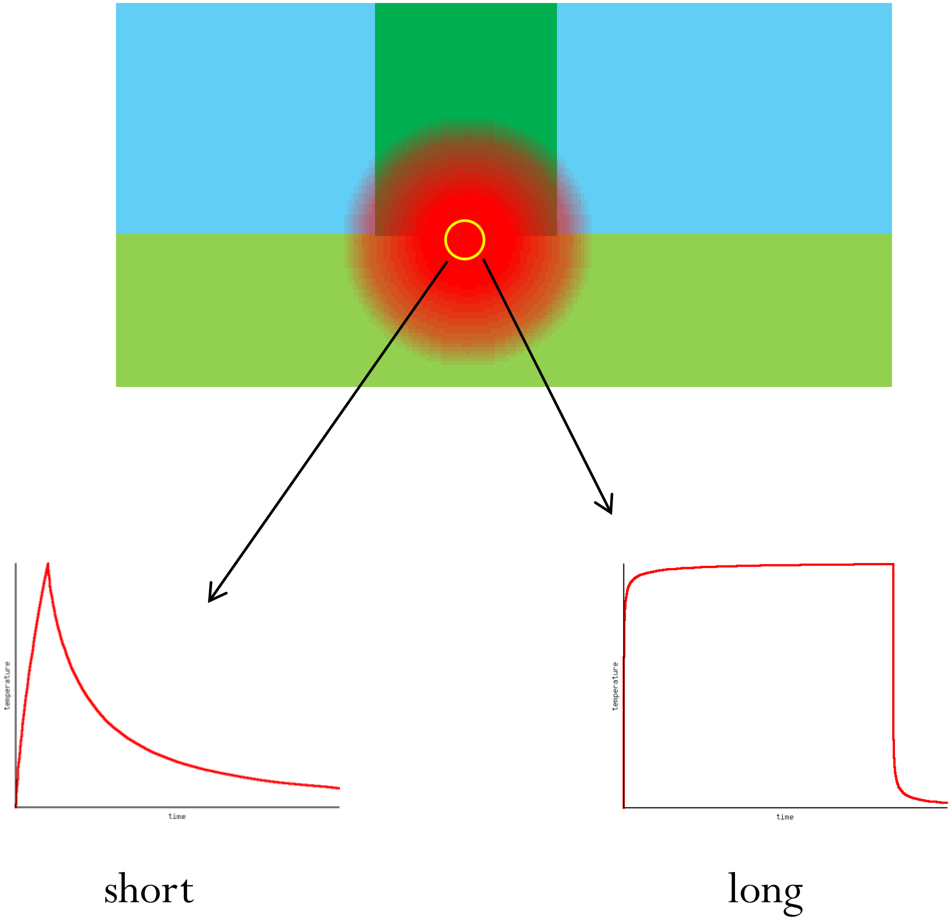
- Peak temperature rise is linearly dependent on incident laser power

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot \kappa \nabla T = I_0 e^{-\mu_a z}$$

$$\downarrow$$

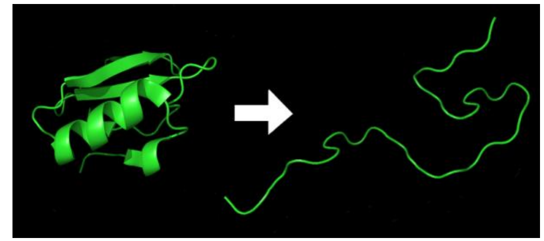
$$T = mI_0 + T_0$$

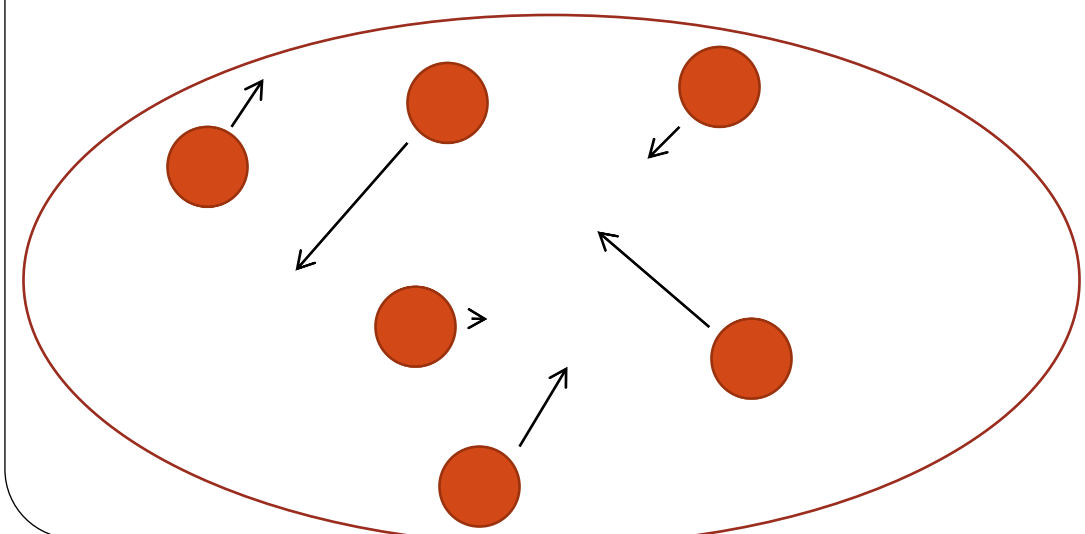
- For "long" exposures, the temperature can be considered constant



Damage Models: Thermal

- Proteins collide with each other and unfold
- Accumulation of unfolded protein is a chemical reaction
- Damage occurs if enough proteins are denatured





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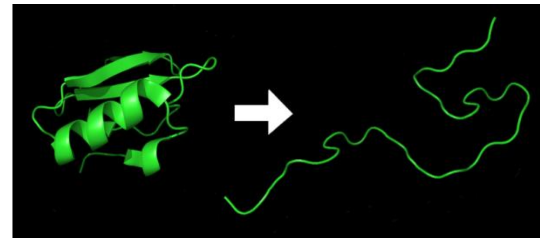
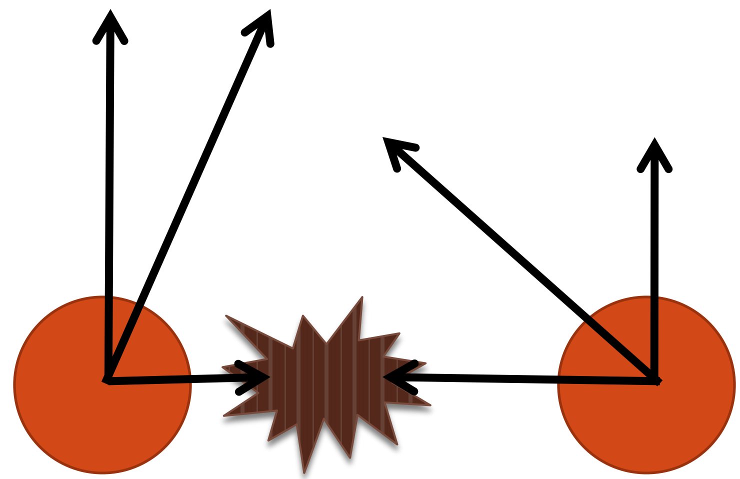
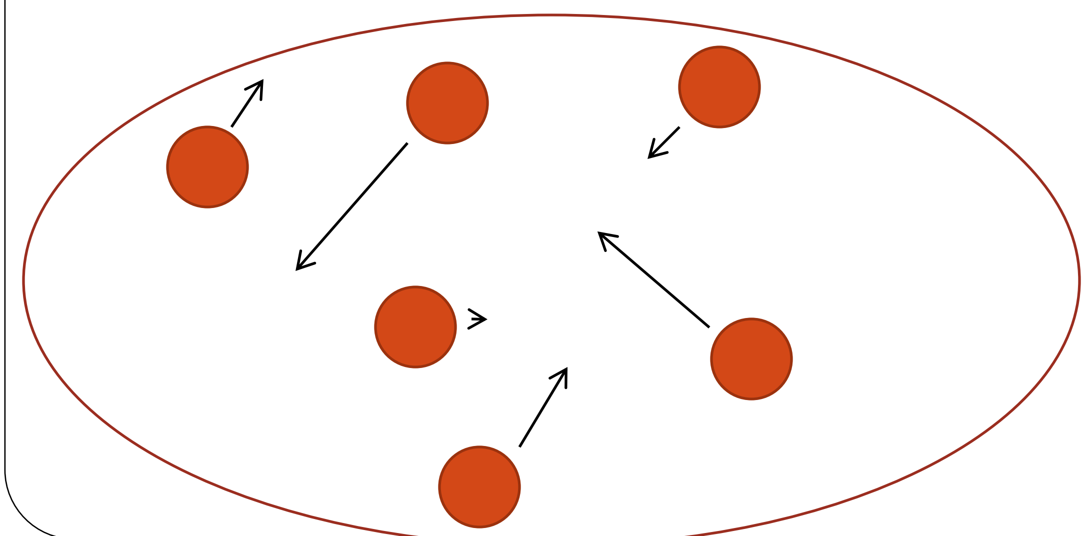






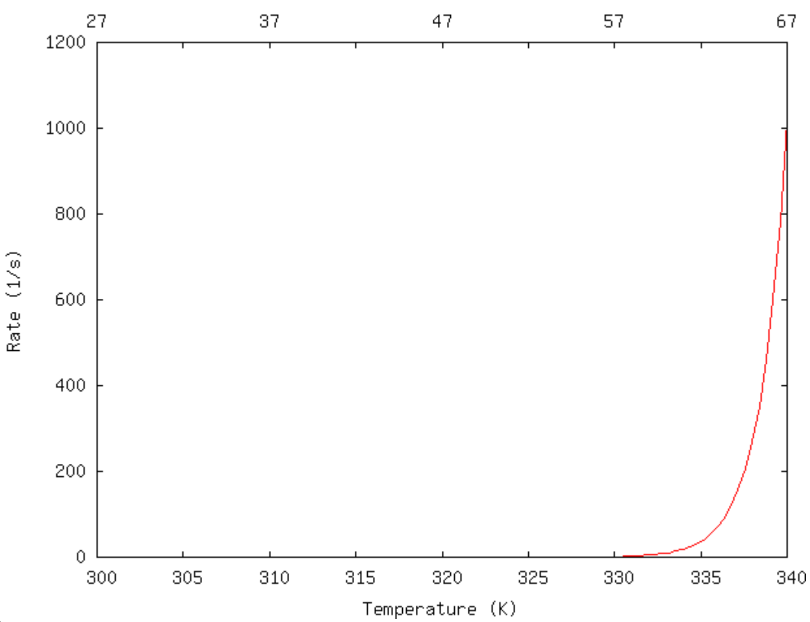
$$\frac{d\Omega}{dt} = Ae^{-\frac{E_a}{RT}}$$

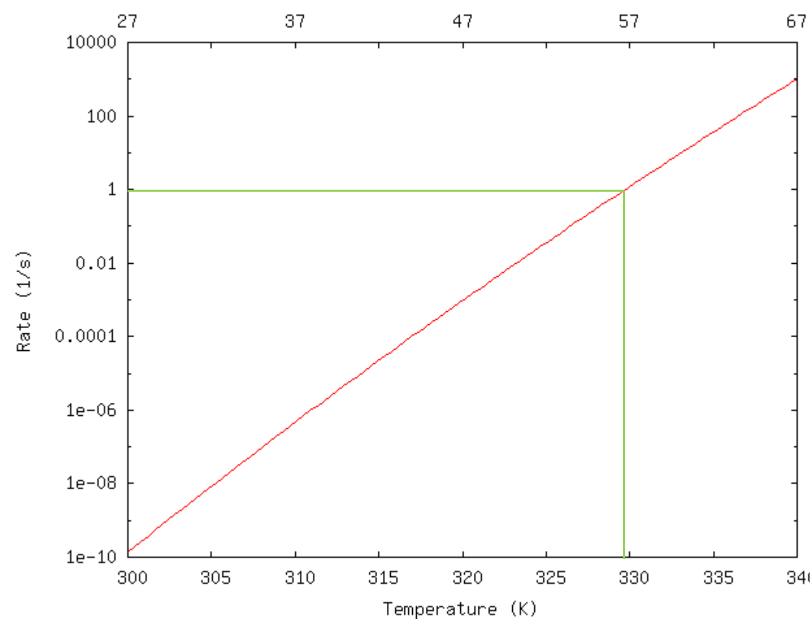
Arrhenius Rate

The Famous Arrhenius Rate

- The rate of a "zeroth-order" chemical reaction

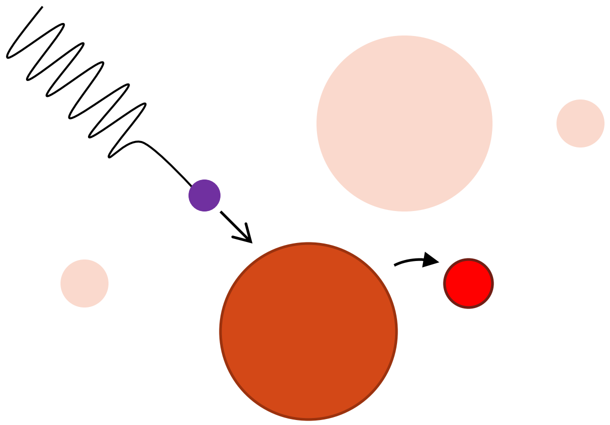
$$\frac{d\Omega}{dt} = Ae^{-\frac{E_a}{RT(t)}}$$





Damage Models: Photochemical

- Molecule absorbs photon of (sufficient energy) and creates a free radical
- Highly reactive product goes on to disrupt cell function
- Cell death occurs if enough free radicals are produced



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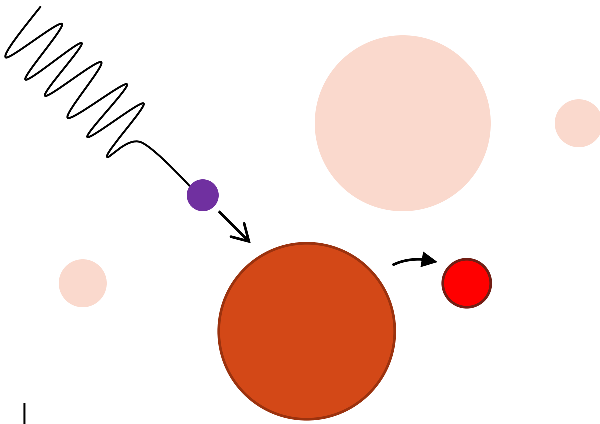
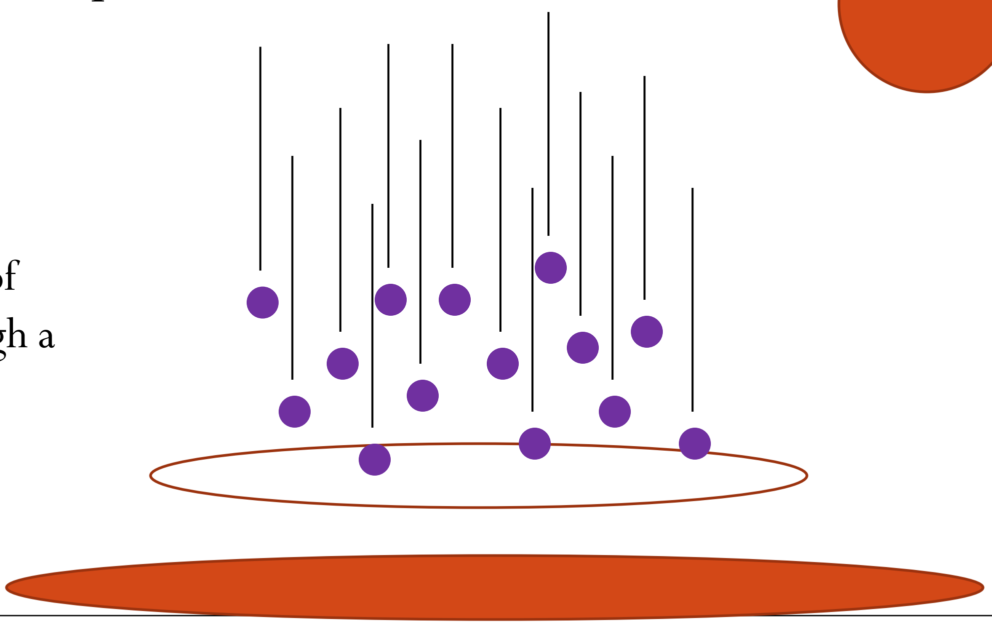


$$\frac{d\Omega_p}{dt} = \epsilon\phi$$

Photon flux: number of photons passing through a surface, per unit type



Thermal Damage Thresholds

- Peak temperature rise is linearly dependent on incident laser power

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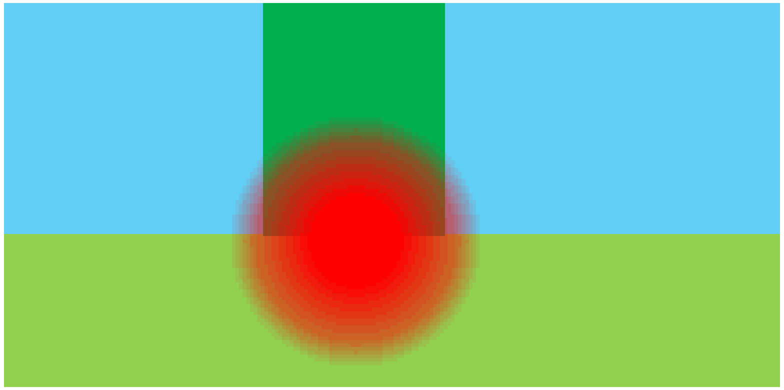
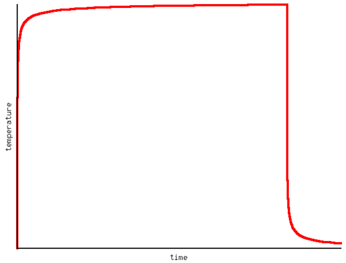


- For "long" exposures, the temperature can be considered constant
- Given the temperature, we can compute the accumulated damage

$$\frac{d\Omega}{dt} = Ae^{-\frac{E_a}{RT}}$$

$$\Omega(\tau) = \int_0^{\tau} Ae^{-\frac{E_a}{R(mI_0+T_0)}}\, dt \longleftarrow$$



Thermal Damage Thresholds

- We need the incident laser power as a function of damage
- Warning: possibly boring derivation to follow

Notes

$$mI_0 + T_0$$

$$\Omega(\tau) = Ae^{-\frac{E_a}{R(mI_0+T_0)}}\tau$$

$$\Omega(\tau) = 1$$

$$1 = Ae^{-\frac{E_a}{R(mI_0+T_0)}}\tau$$

$$0 = \ln(A\tau) - \frac{E_a}{R\,(mI_0 + T_0)}$$

$$(mI_0 + T_0) = \frac{E_a}{R\ln(A\tau)}$$

$$I_0 = \frac{1}{m}\left(\frac{E_a}{R\ln(A\tau)} - T_0\right)$$

Damage Threshold is defined as $\Omega = 1$

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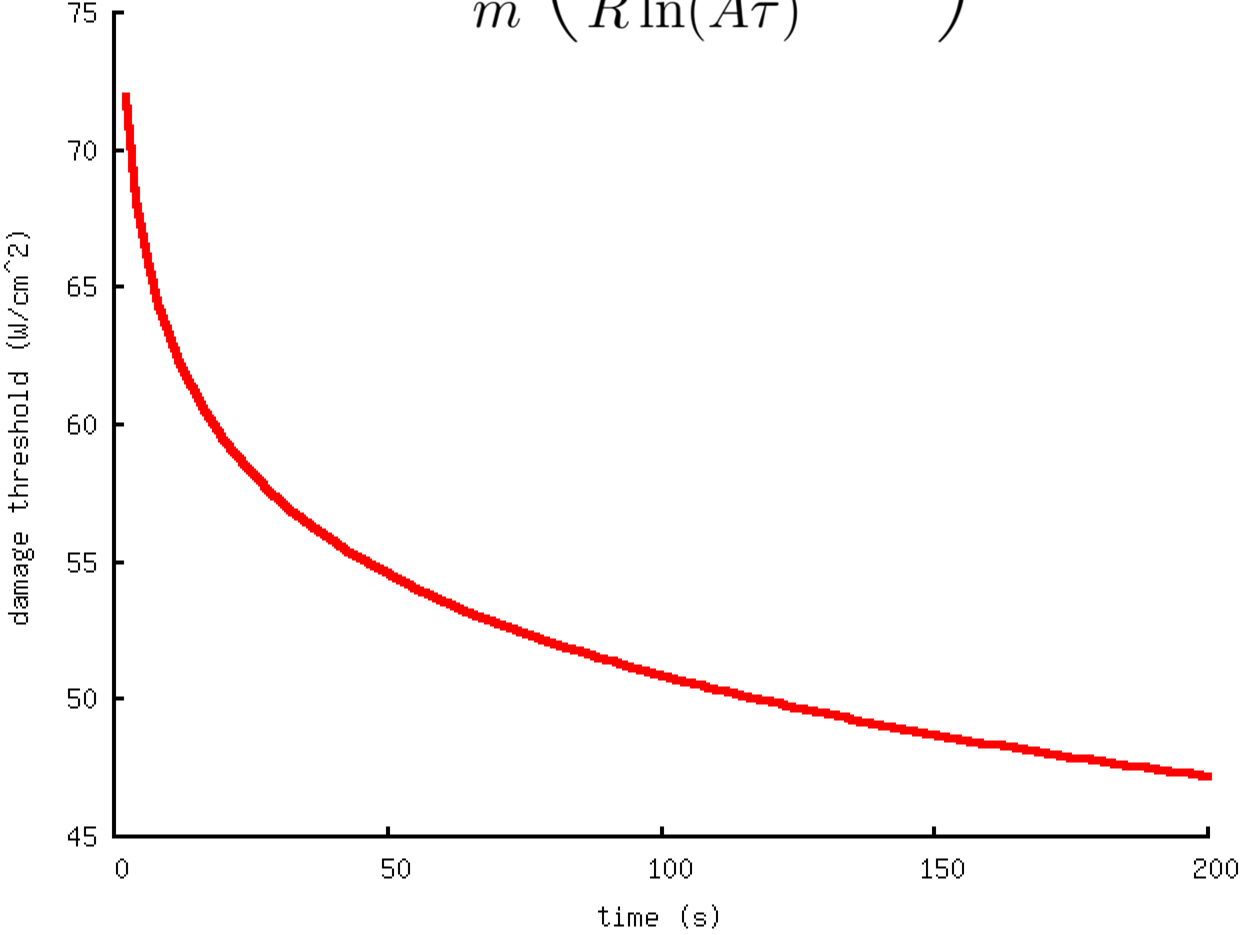
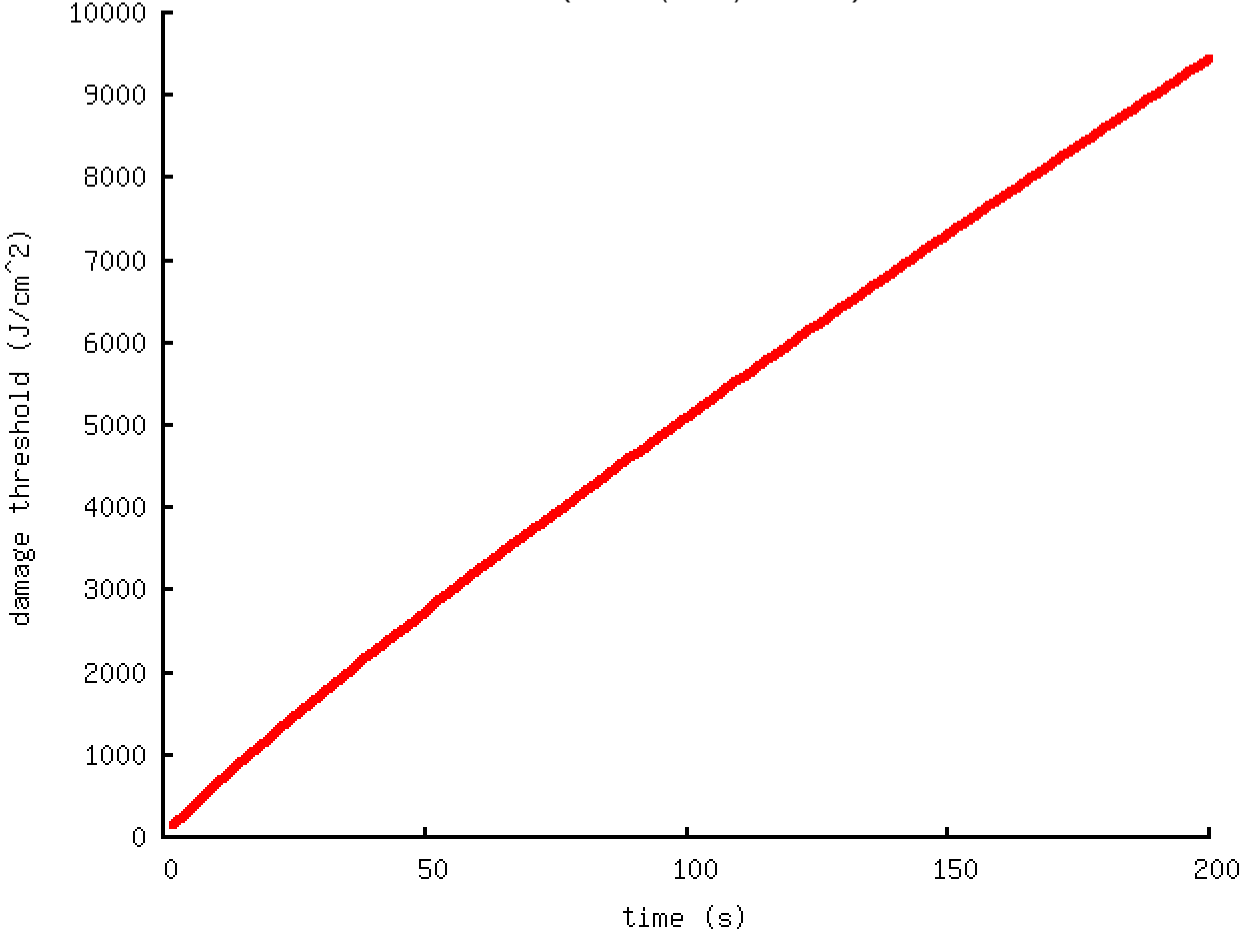
Thermal Damage Thresholds: Dependence on Exposure Duration

$$I_0 = \frac{1}{m}\left(\frac{E_a}{R\ln(A\tau)} - T_0\right)$$

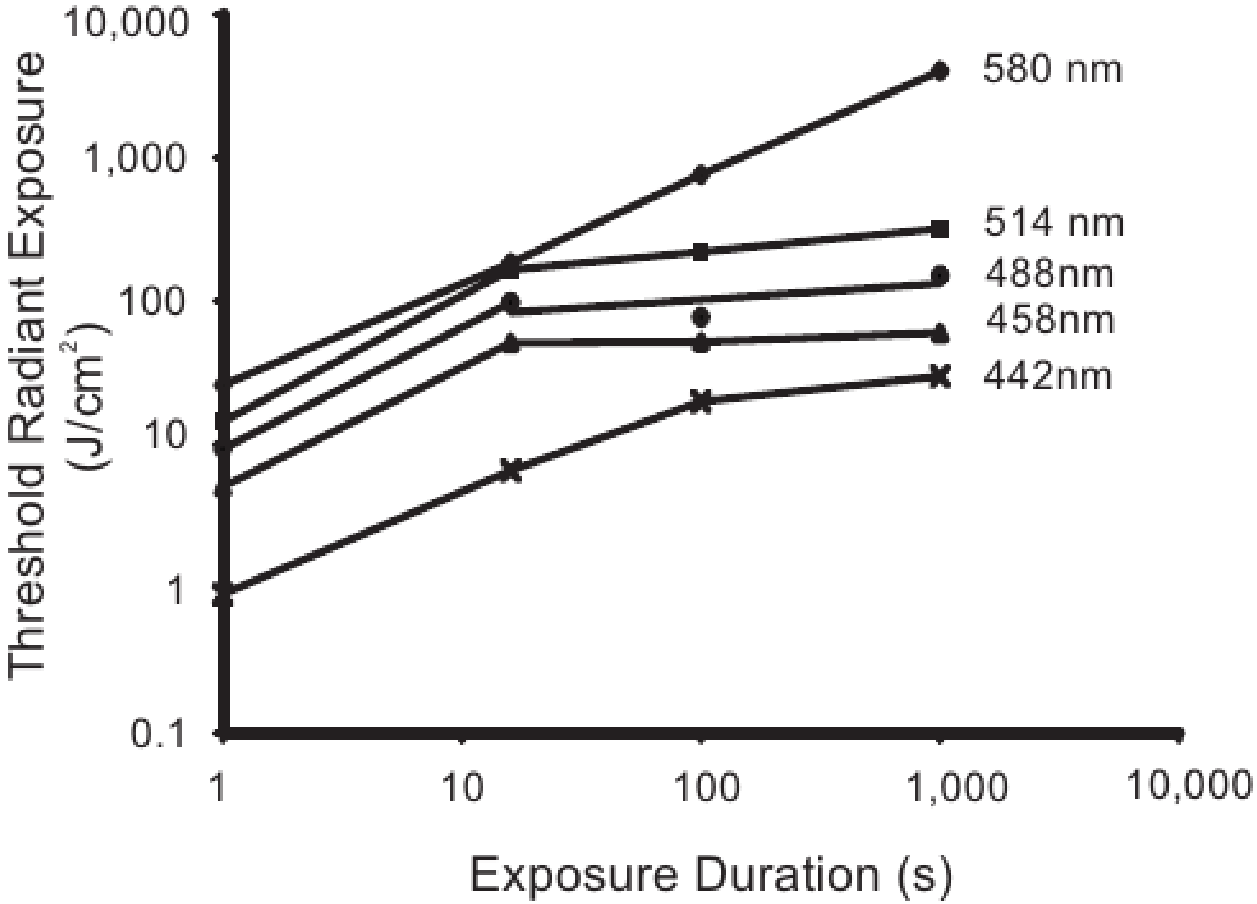


Thermal Damage Thresholds: Radiant Exposure (total number of photons)

$$E_0 = I_0 \tau = \frac{\tau}{m}\left(\frac{E_a}{R\ln(A\tau)} - T_0\right)$$

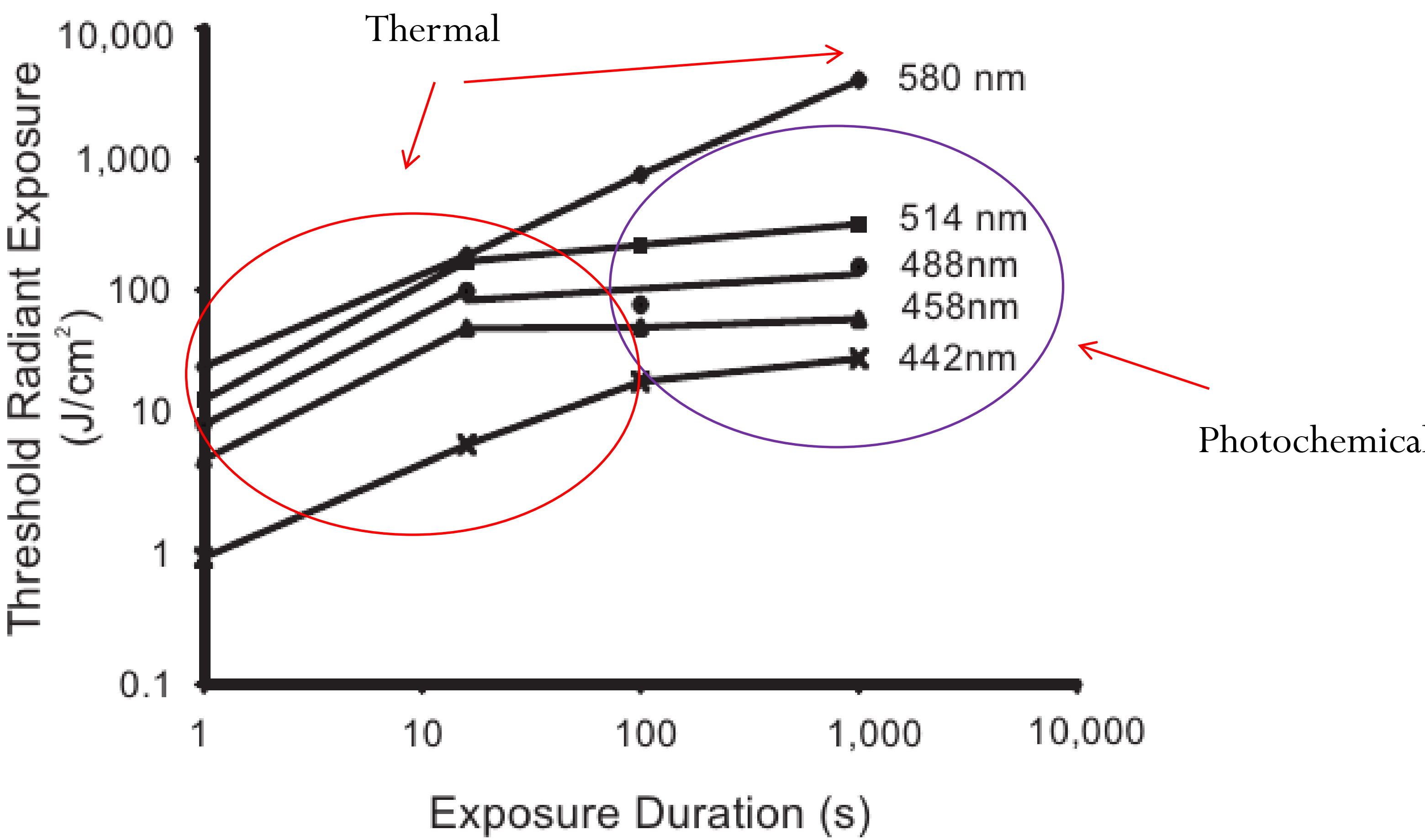


Experimental Data



Ham et al., "Sensitivity of the Retina to Radiation Damage as a Function of Wavelength", *Photochemistry and Photobiology*, 1979

So we're done



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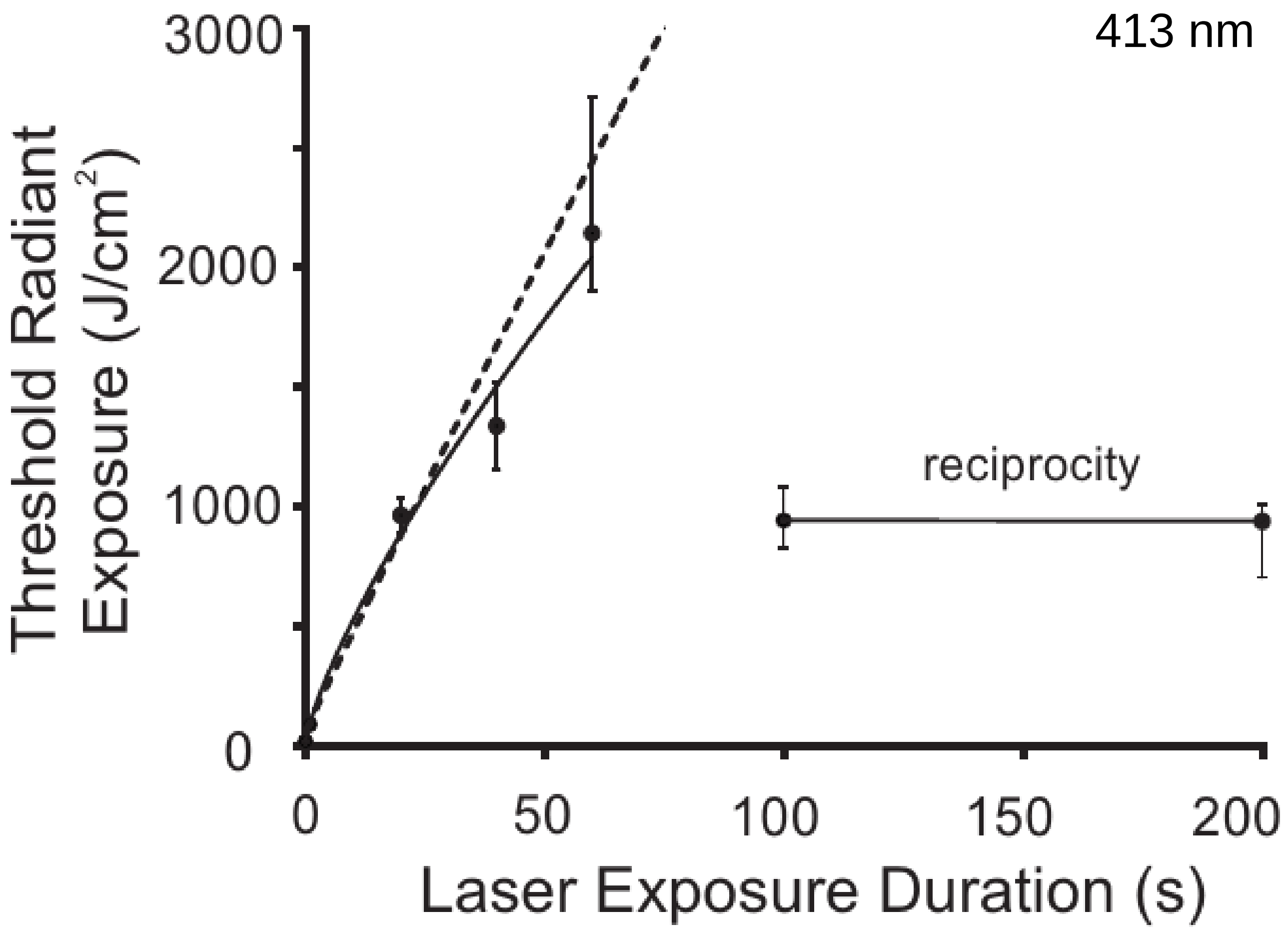
But wait…



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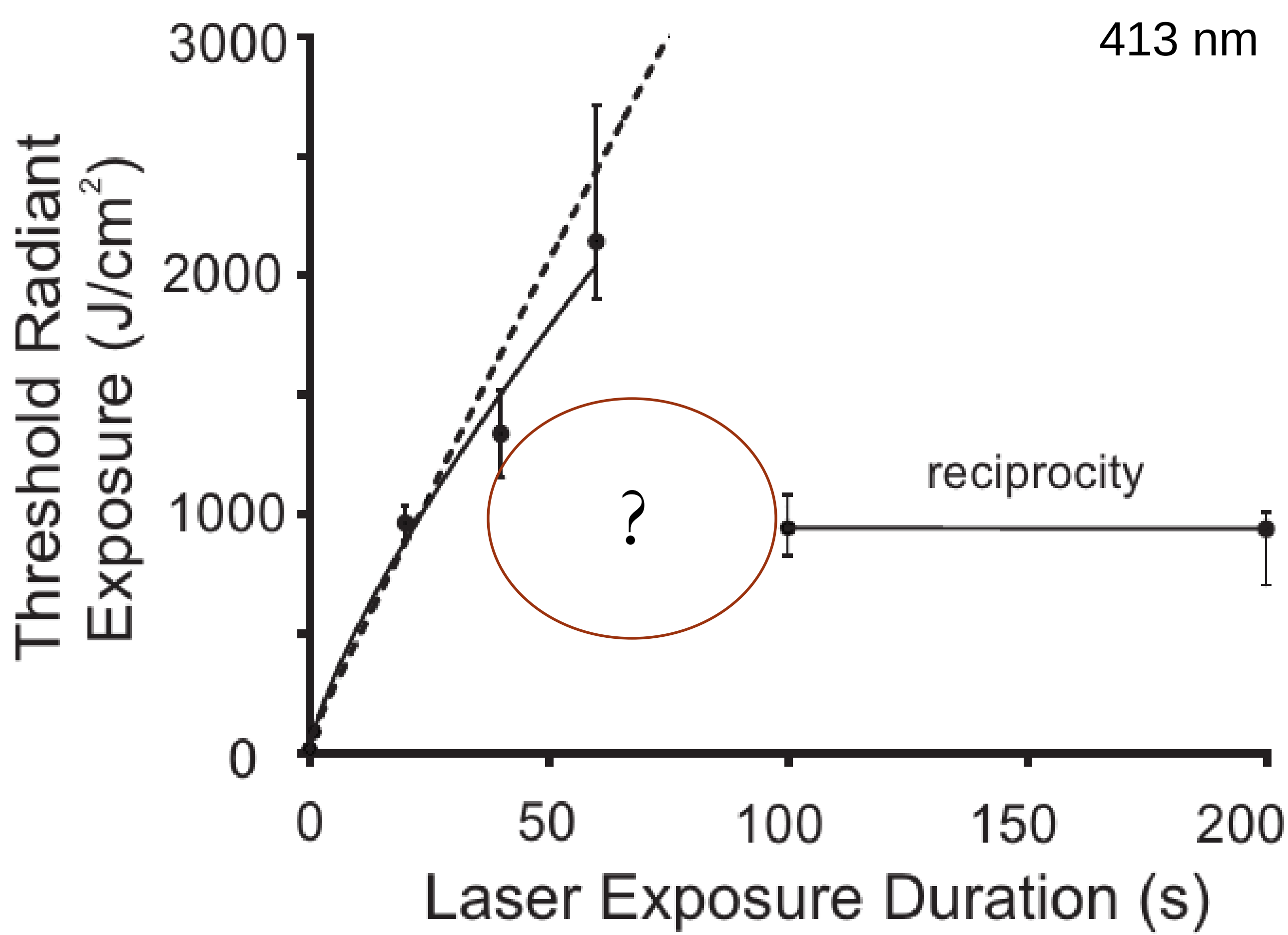

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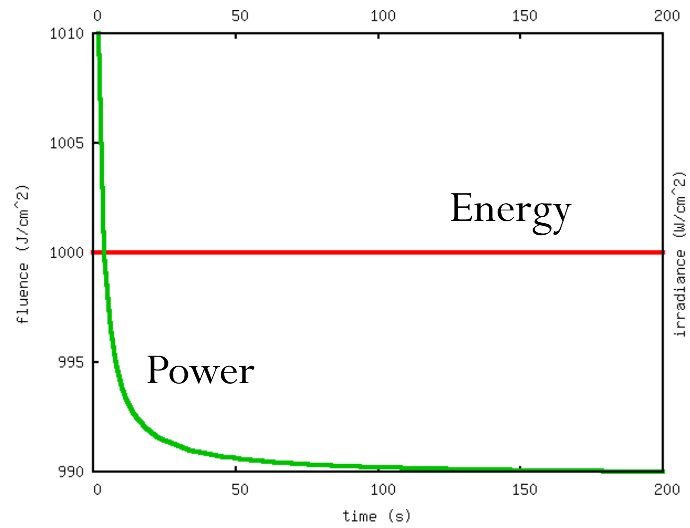
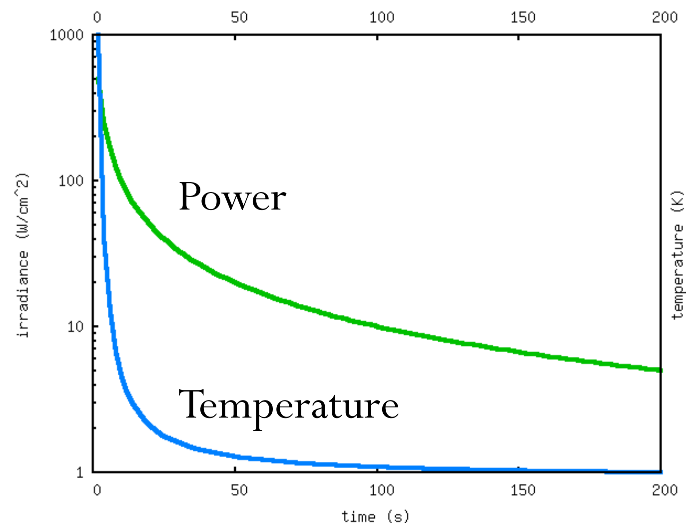
Recall

$$I_0 = \frac{E_0}{\tau}$$

$$T = mI_0 + T_0$$

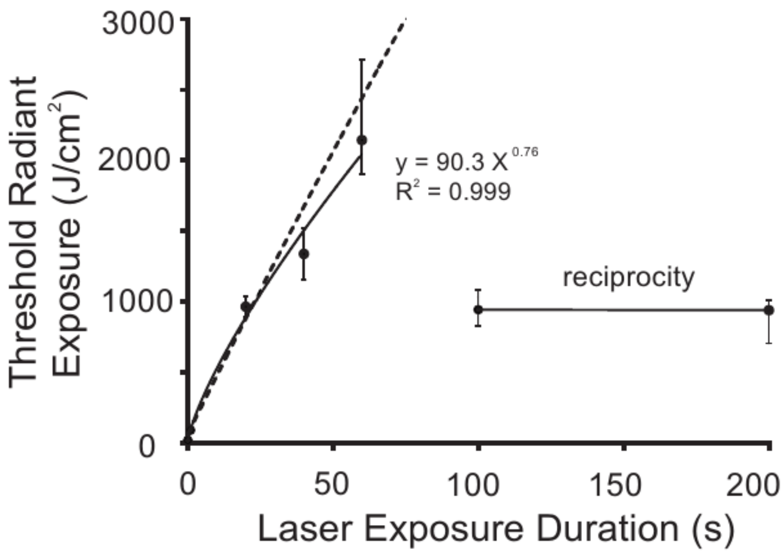
- Constant energy -> lower temperature for longer exposure
- Chemical reaction rates decrease with temperature





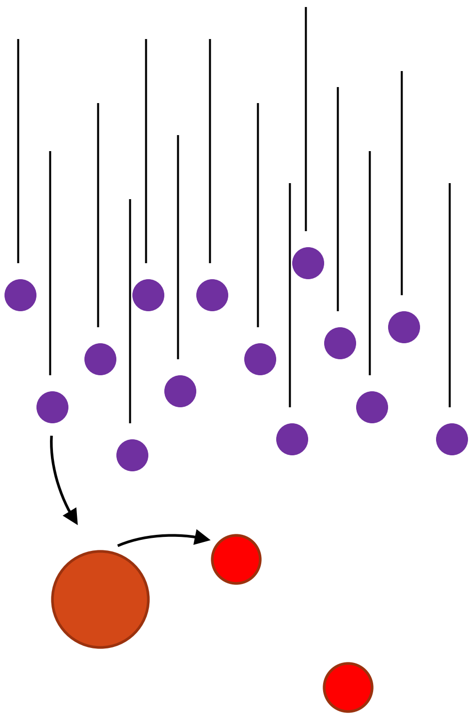
Our Hypothesis

- This trend could be explained if the photochemical damage mechanism could be "shut off" for exposures less than 100 seconds
- Exposures less than 100 seconds lead to higher temperature rises
- So, if the photochemical damage mechanism could be shut off for high temperatures, we would expect this effect



A New Model

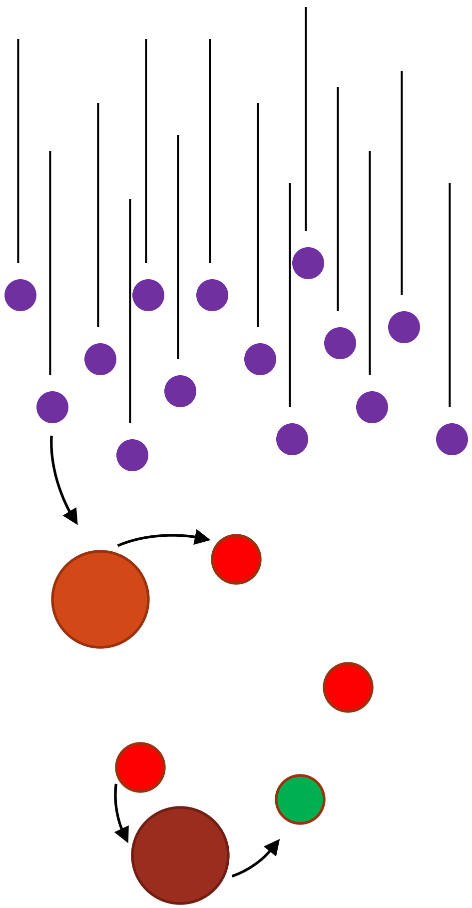
- Molecule (blue) absorbs a photon (green) and creates a toxic product (red)



$$\frac{d\Omega_p}{dt} = \epsilon\phi$$

A New Model

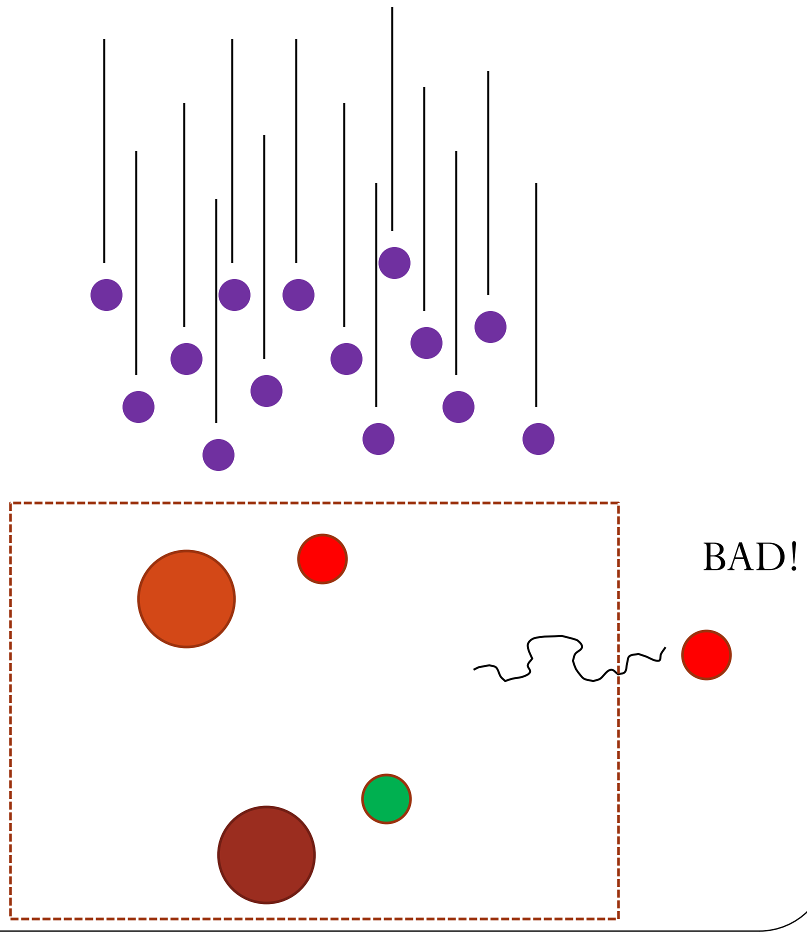
- Add quenching rate
  - Toxic product reacts with some other molecule (orange) to produce a non-toxic product



$$\frac{d\Omega_p}{dt} = \epsilon\phi - \Omega_p A_p e^{-E_{ap}/RT(t)}$$

A New Model

- Add quenching rate
  - Damage is caused if toxic product is allowed to migrate around the cell.
  - Threshold will correspond to some dangerous level of buildup



$$\frac{d\Omega_p}{dt} = \epsilon\phi - \Omega_p A_p e^{-E_{ap}/RT(t)}$$

Turning off photochemical damage

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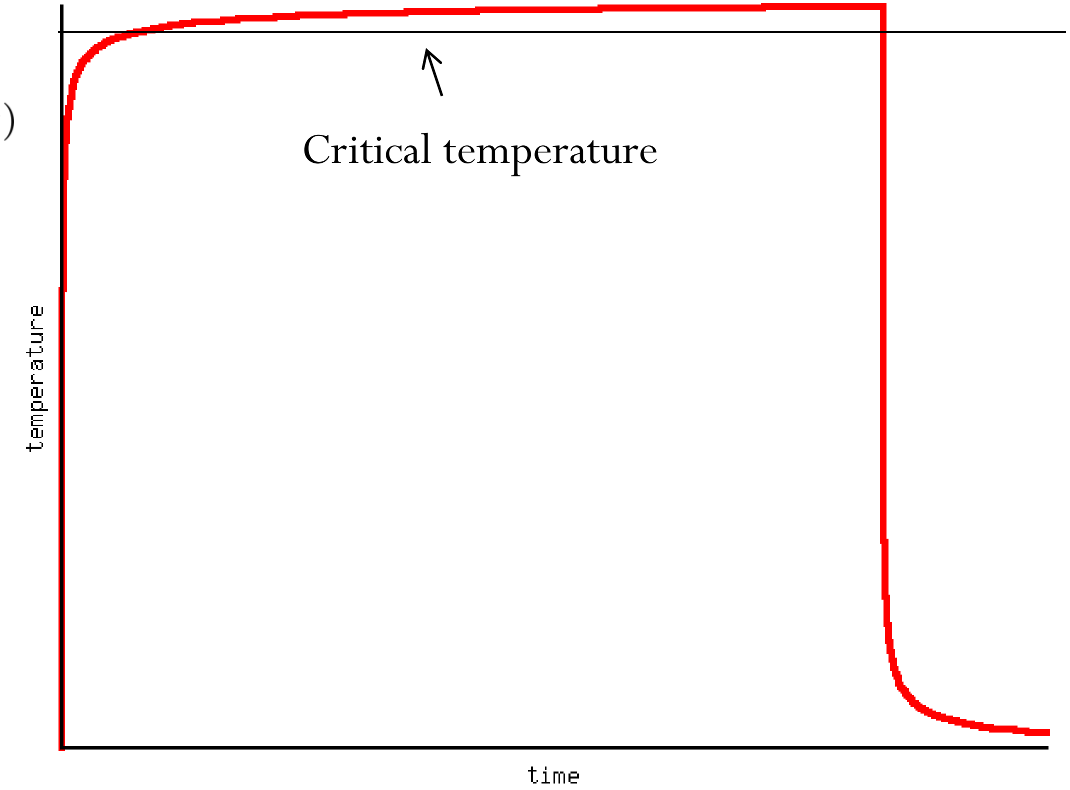

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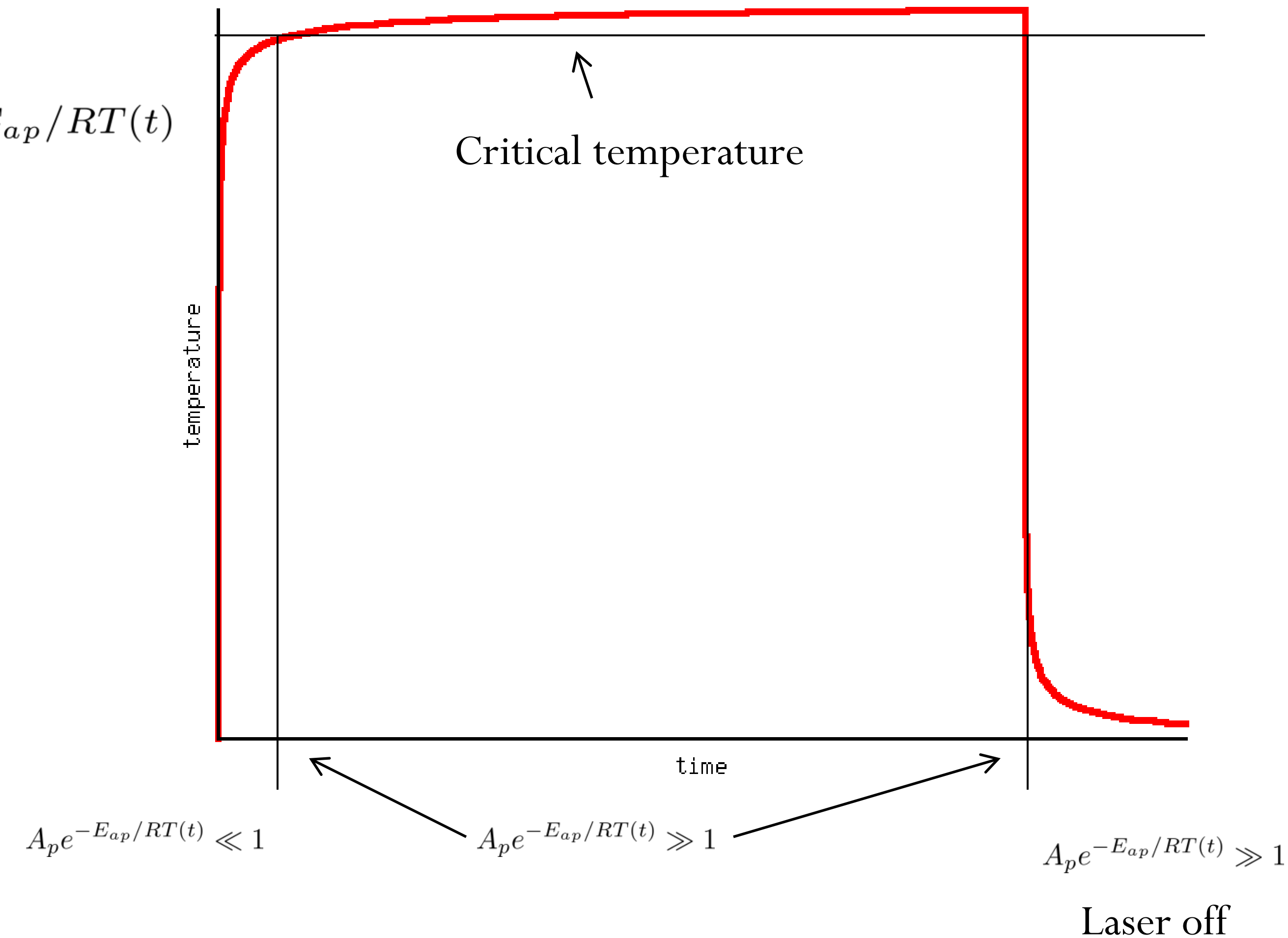
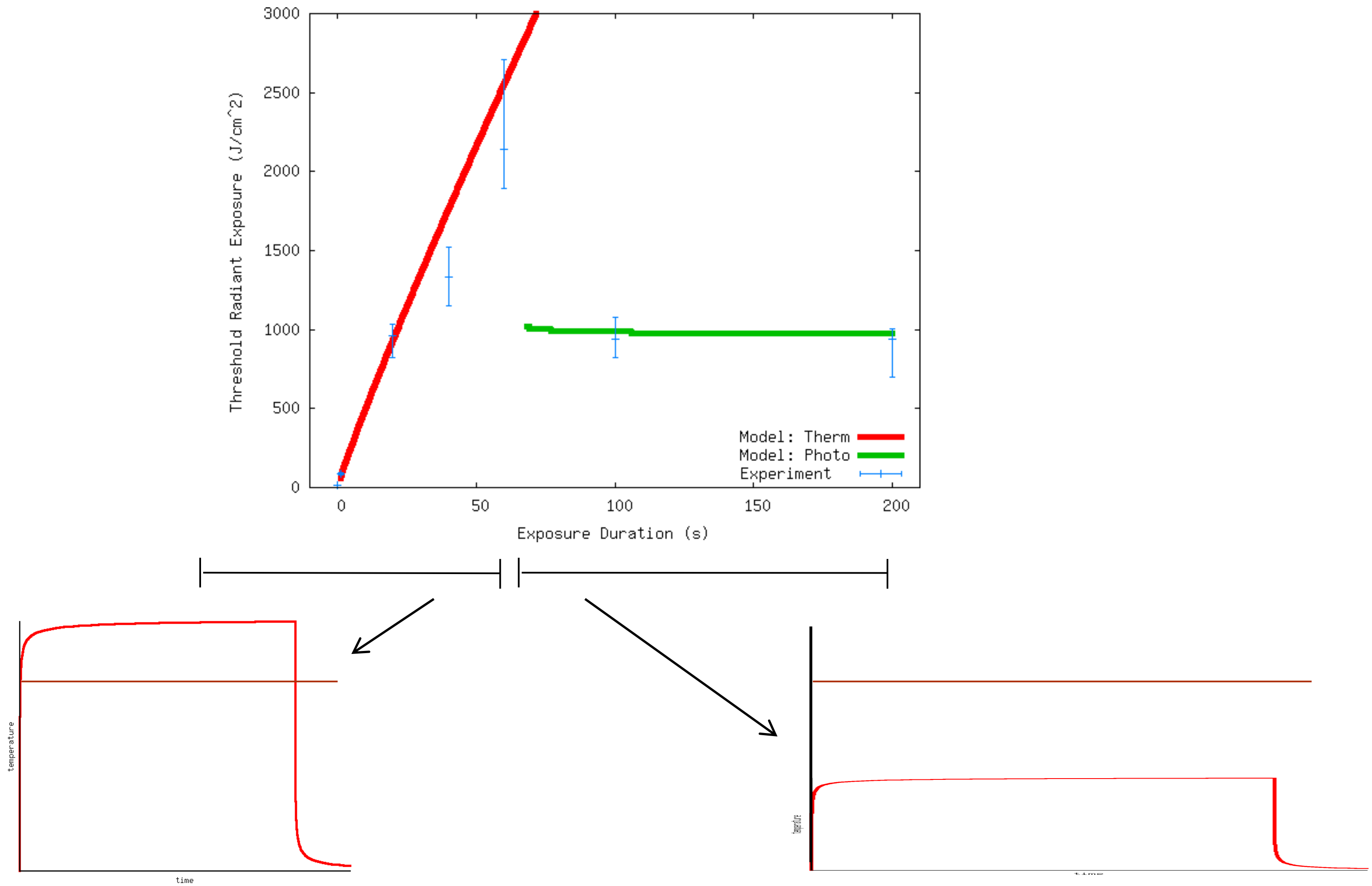
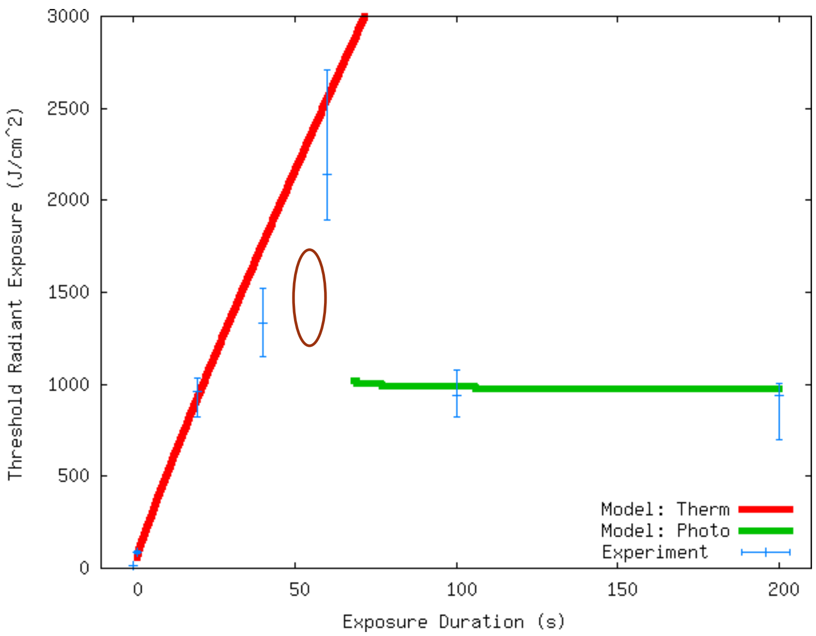


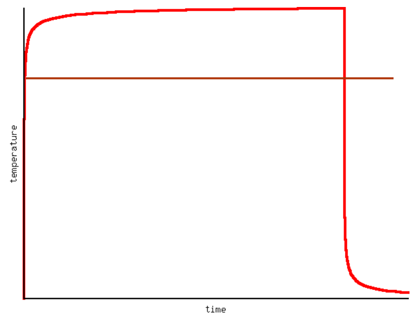
Predicted Damage Thresholds



Future Experiments

- The thermal-photochemical transition could be explained by a simple "minimum time to cause damage" model
- A multiple-pulse experiment could help validate our hypothesis.
- Photochemical damage additivity is greatly reduced under our model





Conclusions

- The disconnect between thermal damage thresholds and photochemical damage thresholds can be explained by considering a temperature dependent photochemical damage rate
- The model we have proposed requires two coefficients, which would need to be determined experimentally, just as the Arrhenius thermal damage model does
- We have neglected the details of the "efficiency" for creating photochemical damage. In reality, this will likely depend on the wavelength and possibly the temperature as well

Acknowlegements

- Air Force Research Lab – Optical Radiation Branch
  - Dr. Robert Thomas
  - Dr. Michael Denton
  - Mr. Larry Estlack
  - Dr. Ben Rockwell

Questions