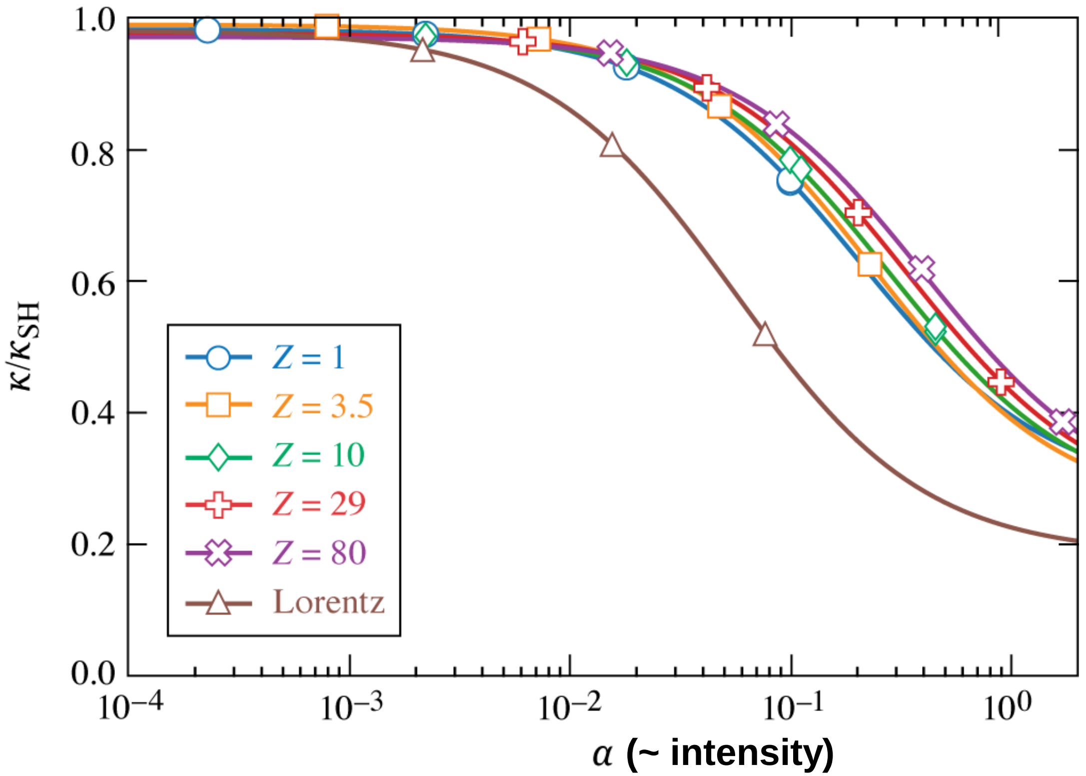
Thermal Conductivity of a Laser Plasma



Nathaniel R. Shaffer
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Laboratory for Laser Energetics

LLNL HEDS Seminar
14 Dec 2023

Summary

The presence of a laser field reduces the thermal conductivity of a plasma due to nonlinear absorption effects

- **Vlasov-Fokker-Planck simulations demonstrate that the thermal conductivity of a plasma depends on laser intensity, which is not accounted for in radiation-hydrodynamics simulations.**

- **Conductivity reduction happens because the laser depletes the population of high-energy conduction electrons, analogous to the “Langdon effect” for laser absorption.**

- **The effect can be cast as a correction factor on top of the standard Spitzer-Härm conductivity model, which is easy to fit and implement in radiation-hydrodynamics codes. The effect is predicted to be modest in typical direct-drive corona conditions, but could be substantial in hohlraums.**

- **Simulations of non-local conduction imply non-trivial modifications to standard non-local models may needed in absorbing regions.**

Collaborators

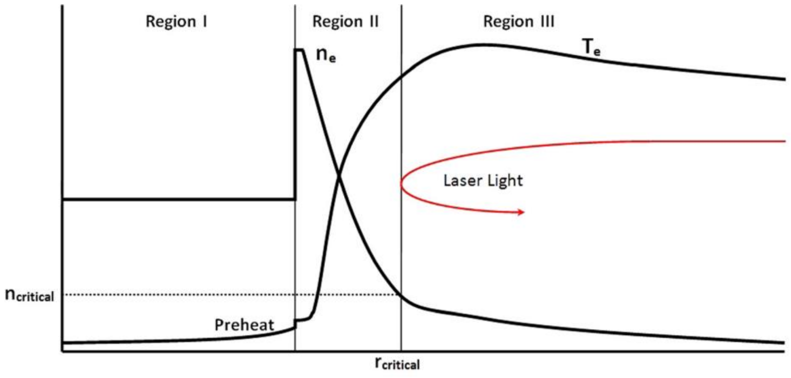
Andrei V. Maximov and Valeri N. Goncharov
Laboratory for Laser Energetics

Mark Sherlock
Lawrence Livermore National Laboratory

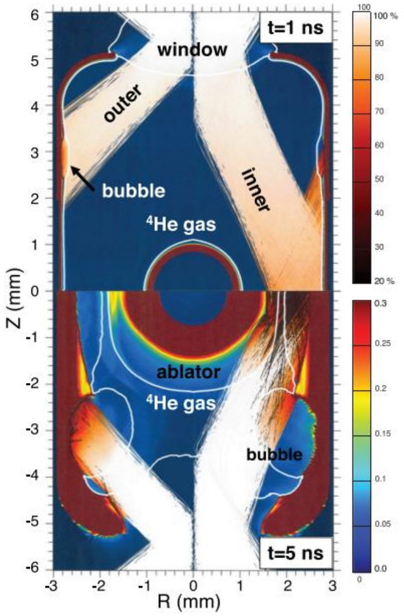
Accurate thermal conduction models are essential for predicting energy balance and transport in laser-produced plasmas

Indirect-Drive ICF**

Direct-Drive ICF*

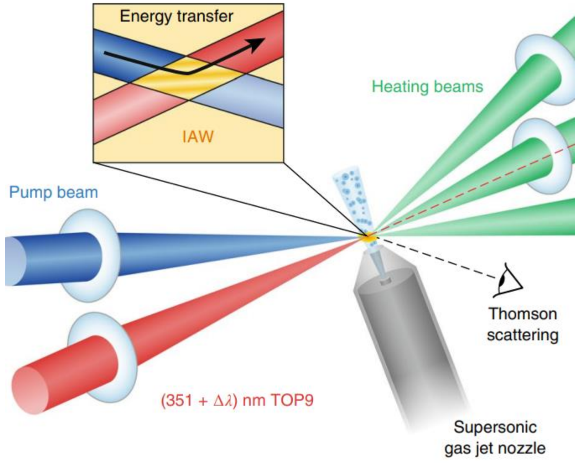


Coupling efficiency



Radiation transport

Gas-Jet Platforms†



Thermodynamics

* D. Cao, G. Moses, and J. Delettrez, *Phys. Plasmas* 22, 082308 (2015).
** N. B. Meezan *et al.*, *Phys. Plasmas* 27, 102704 (2020).
† D. P. Turnbull *et al.*, *Nat. Phys. Lett.* 16, 181 (2020).

The baseline thermal conduction model for ICF relies on fragile assumptions about the state of the plasma

Spitzer-Härm local conduction*

$$\vec{Q}_e = -\kappa_{\mathrm{SH}}\,\nabla T_e \qquad \kappa_{\mathrm{SH}} \propto \frac{T_e^{\frac{5}{2}}}{Z\ \ln\Lambda}$$

Assumption 1: weak temperature gradients

$$\lambda_{\mathrm{mfp}} \frac{\nabla T_e}{T_e} \ll 1$$

Violated? Need *non-local* conduction models.

Assumption 2: Maxwell-Boltzmann equilibrium

$$f_0(v) = n_e \left(\frac{m_e}{2\pi T_e}\right)^{\frac{3}{2}} e^{-\frac{m_e v^2}{2T_e}}$$

Violated? Need to revise *both* local and non-local theory.

This talk focuses on how lasers produce non-Maxwellian equilibria and how that impacts conduction.

* L. Spitzer, Jr. and R. Härm, *Physical Review* 89, 977 (1953).

Graphical Outline: A Matrix of Thermal Conduction Models

	No Laser	With Laser
Weak Gradients	Spitzer-Härm	This Work
Sharp Gradients	Current Non-local Models	Work in Progress

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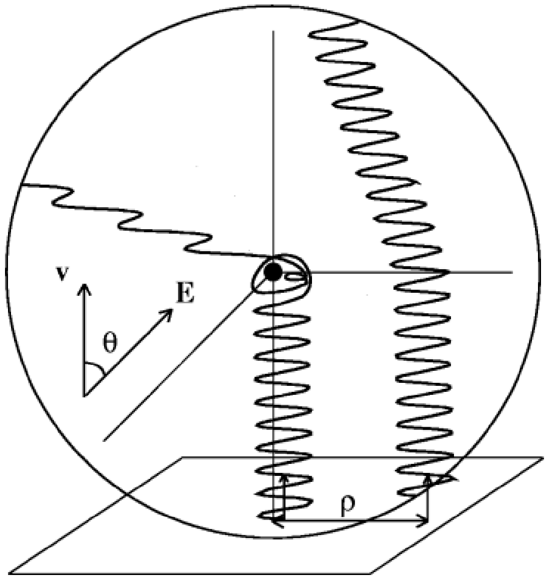
Inverse Bremsstrahlung Detour

A classical model of inverse bremsstrahlung (IB) absorption has all the necessary features to understand its impact on thermal conduction

Single-particle picture: collisional conversion of oscillatory energy to thermal energy*



Kinetic picture: heating due to interference between EM field and induced current**

$$\partial_t f - \frac{e}{m_e}\Re\{\vec{E}\, e^{-i\omega t}\}\cdot\partial_{\vec{v}} f = C_{ee}[f,f] + C_{ei}[f]$$

$$f = \underbrace{f_0}_{\text{dc}} + \Re\{\underbrace{f_1\, e^{-i\omega t}}_{\text{ac}}\}$$

Quiver speed

$v_E = e|\vec{E}|/(m_e\omega)$

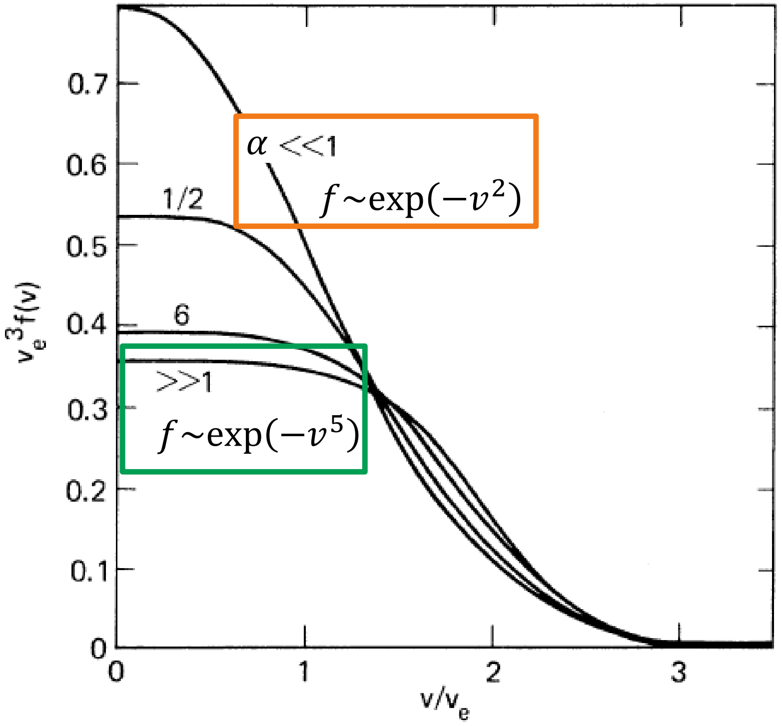
$$\partial_t f_0 \approx C_{ee}[f_0, f_0] + \underbrace{\partial_{\vec{v}}\cdot\left[\frac{v_E^2}{6\tau_{ei}(v)}\,\partial_{\vec{v}} f_0\right]}_{C_{IB}[f_0]}$$

IB absorption is a velocity-space diffusion process

* A. Brantov *et al.*, *Phys. Plasmas* 10, 3385 (2003).
** I. P. Shkarofsky, T. W. Johnston, and M. P. Bachynski, *The Particle Kinetics of Plasmas* (Addison-Wesley, 1966).

Inverse bremsstrahlung absorption warps the shape of the electron distribution function away from equilibrium

Langdon Effect*



"Langdon parameter"

$$\alpha = Z\frac{v_E^2}{v_T^2} \approx 0.4\, Z\, T_{\mathrm{keV}}^{-1}\, \lambda_{\mu\mathrm{m}}^2\, I_{\mathrm{PW/cm^2}}$$

$\alpha \ll 1$ **: e-e collisions dominate**

$\alpha \gg 1$ **: IB absorption dominates**

Thermal speed

$v_T = \sqrt{T_e/m_e}$

Quiver speed

$v_E = e|\vec{E}|/(m_e\omega)$

IB leads to an intensity-dependent "equilibrium" distribution function

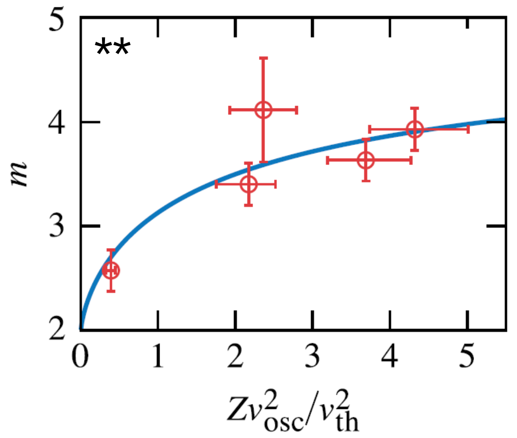
* A. B. Langdon, *Phys. Rev. Lett.* 44, 575 (1980).

Measurements and simulations of absorption support a super-Gaussian model for the electron distribution function and absorption rate

Super-Gaussian model*

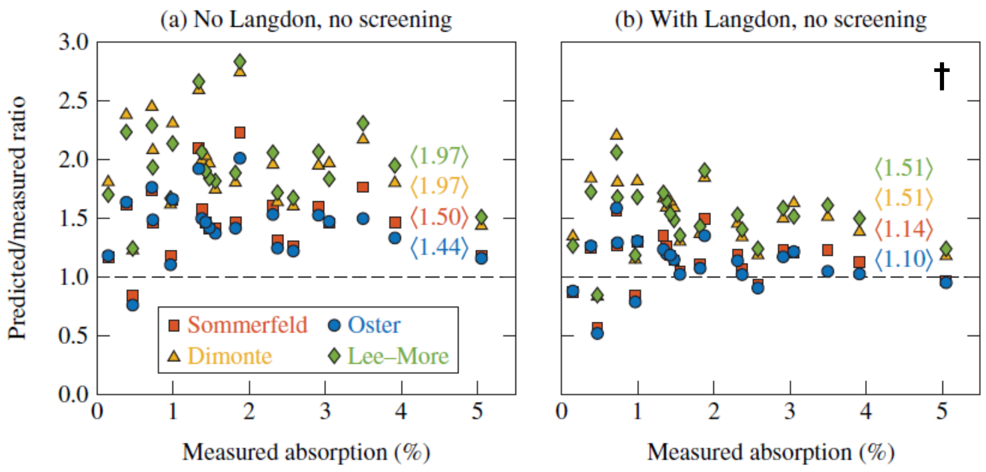
$$f_0(v) \sim \exp(-v^m)$$

$$m(\alpha) = 2 + \frac{3}{1 + 1.66/\alpha^{0.724}}$$



Intensity-dependent absorption rate

$$\nu_{IB}(\alpha) = \nu_{IB}(0) \times \frac{f_0(v=0)}{f_{MB}(v=0)}$$



High intensity → non-Maxwellian $f_0(v)$ → intensity-dependent absorption rate

* J. P. Matte *et al.*, *Plasma Phys. Control. Fusion* 30, 1665 (1988).
** A. L. Milder *et al.*, *Phys. Rev. Lett.* 127, 015001 (2021).
† D. P. Turnbull *et al.*, *Phys. Rev. Lett.* 130, 145103 (2023).

Graphical Outline: A Matrix of Thermal Conduction Models

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Sharp Gradients	Current Non-local Models	Work in Progress

Inverse Bremsstrahlung Detour

An intensity-dependent distribution function implies intensity-dependent transport coefficients

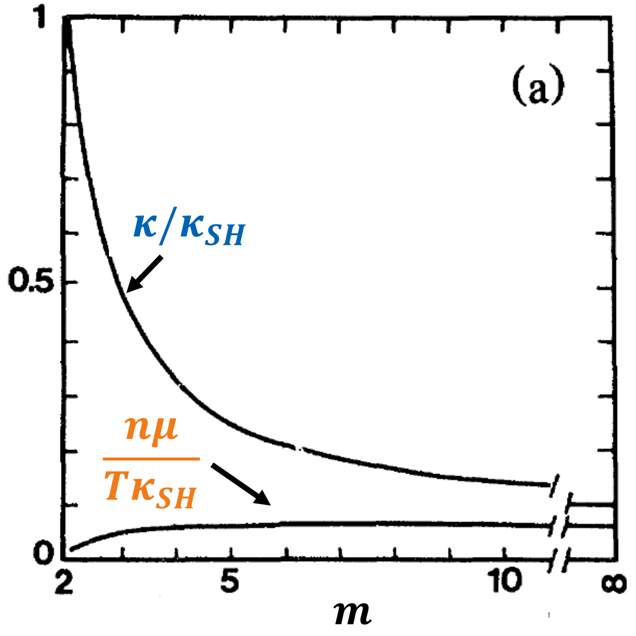
- Mora & Yahi (1982)*: Spiter-Härm-type heat flux calculation with super-Gaussian ansatz for f_0

$$\vec{Q} = -\kappa\nabla T + \mu\nabla n$$

m-dependent thermal conductivity

Novel (but small) density-gradient effect

- Two shortcomings:
  - Neglected e-e collisions (Lorentz limit, only valid as $Z \to \infty$)
  - Must specify the super-Gaussian *m*. Should we use the IB models for this? (Spoiler: NO)



We revisit this problem using accurate kinetic simulations

* P. Mora and H. Yahi, *Phys. Rev. A* 26, 2259 (1982).

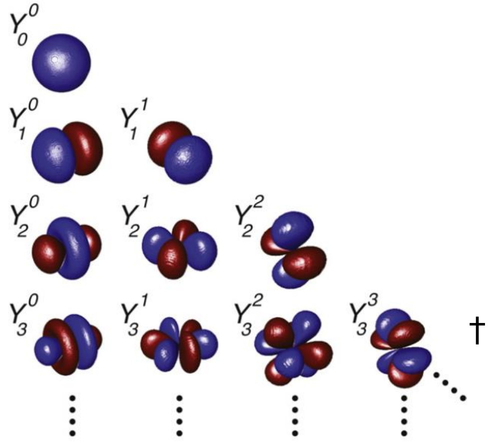
Vlasov-Fokker-Planck simulations allow for accurate kinetic modeling of absorption and conduction

- *K2*: a Fortran 2D-3V code for solving the Vlasov-Fokker-Planck (VFP) equation*

$$f(\vec{x},\vec{p},t)=\sum_{\ell=0}^{\ell_{\max}}\sum_{m=-\ell}^{\ell} f_\ell^m(x,y,p,t)\,Y_\ell^m(\hat{p})$$

- Continuum kinetics: no particle noise
- Tunable Maxwell solver (relativistic ↔ quasineutral)
- Fully implicit collision operators
- Two options for absorption
  - Langdon-style diffusion operator
  - Solve for coupled ac/dc distributions**

$$\partial_t f+\vec{v}\cdot\partial_{\vec{x}}f-e\left(\vec{E}+\vec{v}\times\vec{B}\right)\cdot\partial_{\vec{p}}f=C_{ee}[f,f]+C_{ei}[f]$$



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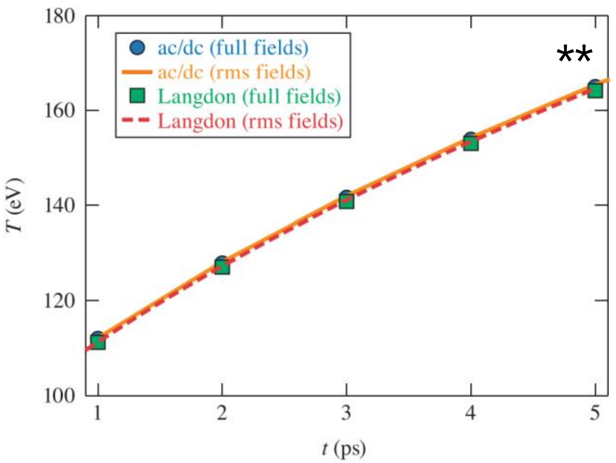


**

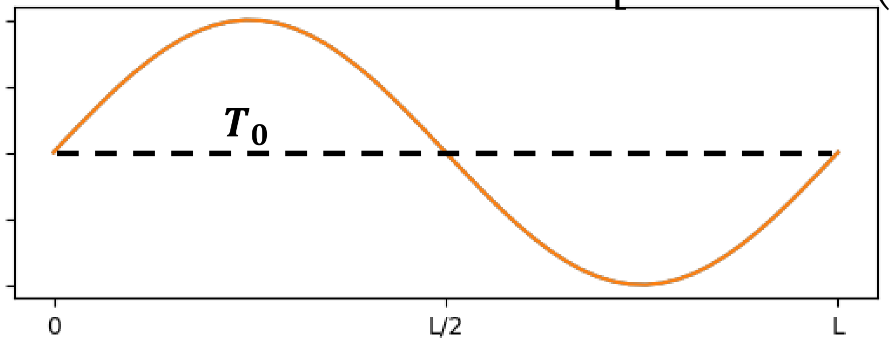
VFP simulations are well-suited for studying collision-dominated transport processes

* M. Sherlock *et al.*, *Phys. Plasmas* 24, 082706 (2017).
** N. R. Shaffer, M. Sherlock, A. V. Maximov, and V. N. Goncharov, *Phys. Plasmas* 30, 043906 (2023).
† M. Tzoufras, A. R. Bell, P. A. Norreys, and F. S. Tsung, *J. Comp. Phys.* 230, 6475 (2011).

The thermal conductivity is extracted from Fourier analysis of a homogeneously absorbing plasma with periodic heat flow

- **Long-wavelength temperature perturbation relaxation**

$$T(x, t = 0) = T_0\left[1 + 10^{-3}\sin\left(\frac{2\pi x}{L}\right)\right]$$



- **Constant laser intensity**

$$I = \{0, 10^{12}, 10^{13}, 10^{14}, 10^{15}\}\frac{\mathrm{W}}{\mathrm{cm}^2}$$

- **Extract conductivity from $k = 2\pi/L$ Fourier modes**

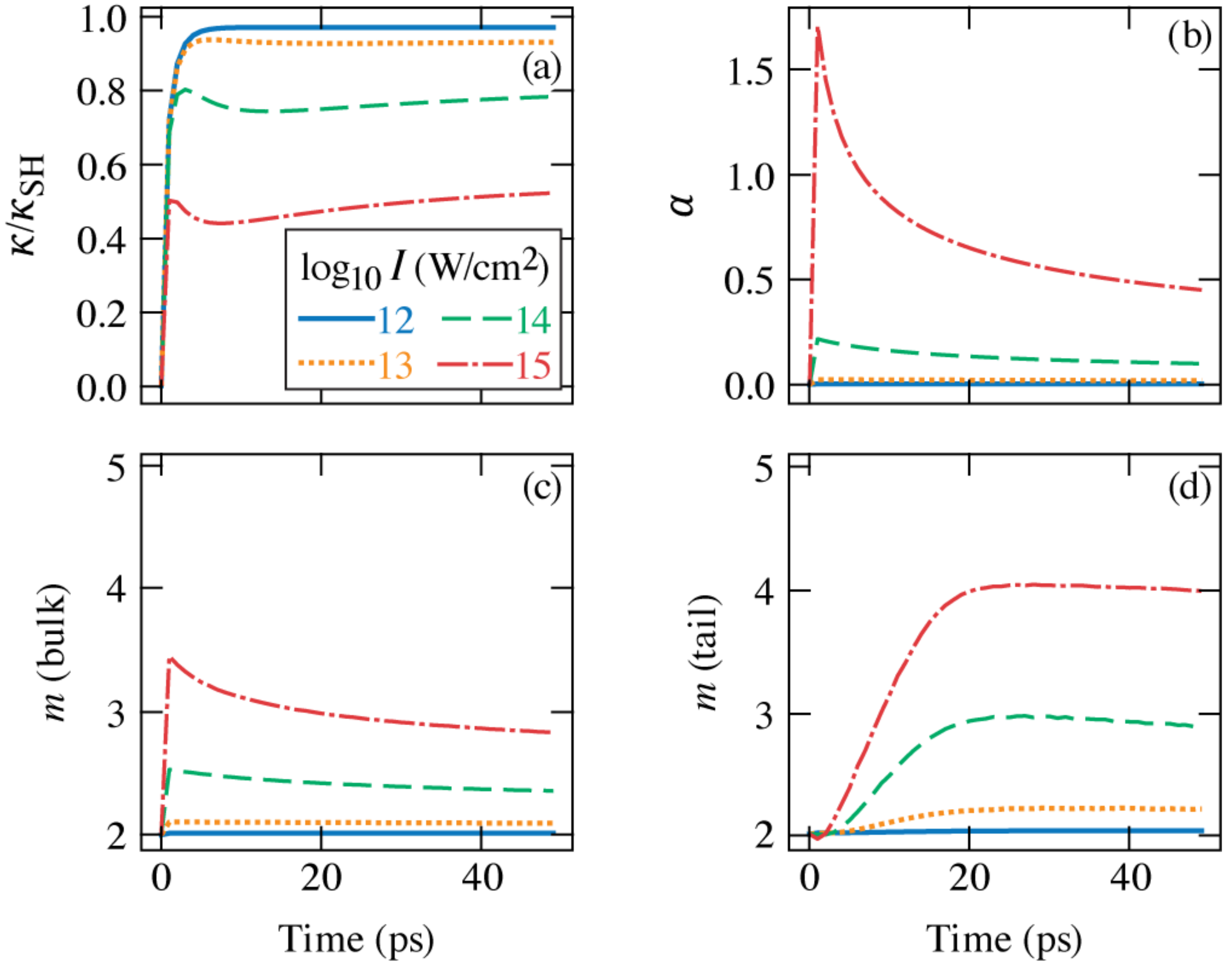
$$T(x, t) = T_0(t) + \mathrm{Re}\left[T_k(t)\, e^{ikx}\right]$$

$$Q(x, t) = \mathrm{Re}\left[Q_k(t)\, e^{ikx}\right]$$

$$\boxed{Q = -\kappa\nabla T \;\Rightarrow\; \kappa = \frac{Q_k}{ikT_k}}$$

By solving the kinetic equation numerically, no assumption is made on e-e collisions or shape of f_0

Due to absorption, the temperature, conductivity, and shape of $f_0(v)$ are all time-dependent, but a quasi-steady regime can be identified



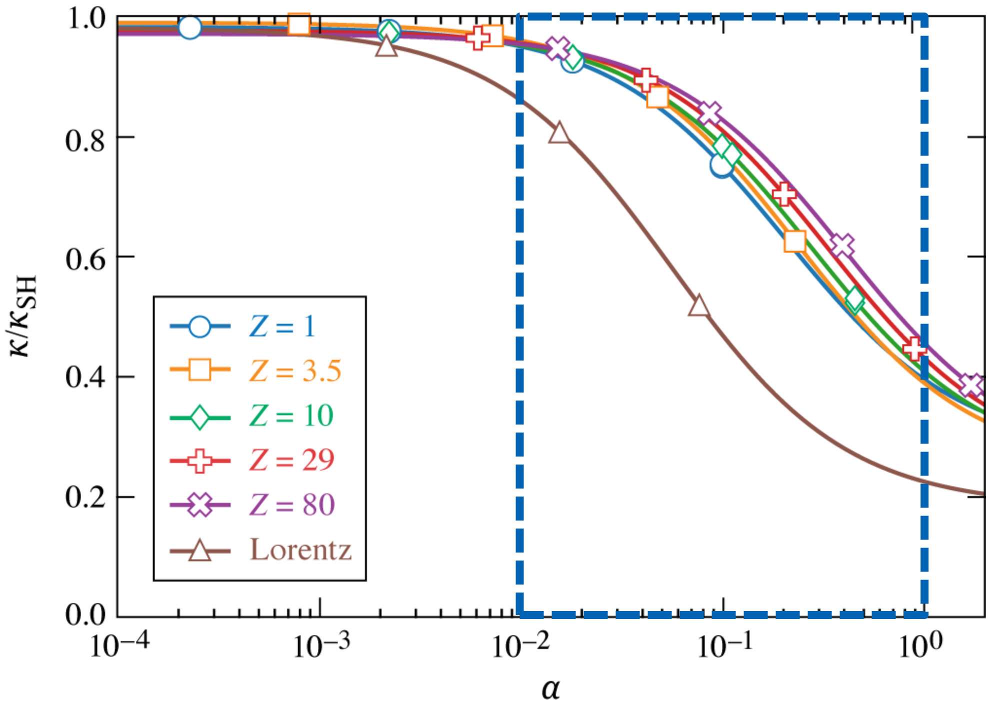
$Z = 10$

"Bulk": $v \leq 2.5 v_T$

"Tail": $v \geq 2.5 v_T$

* N. R. Shaffer, A. V. Maximov, and V. N. Goncharov, *Phys. Rev. E* 108, 04205 (2023).

Systematic scans over Z and α show a substantial reduction in conductivity



- **Up to ~50% reduction at ICF-relevant conditions**
  - **Less dramatic for direct-drive (low *Z*)**
  - **More dramatic in hohlraums (high *Z*)**
- **Easily fit to a simple functional form* for hydro implementation**

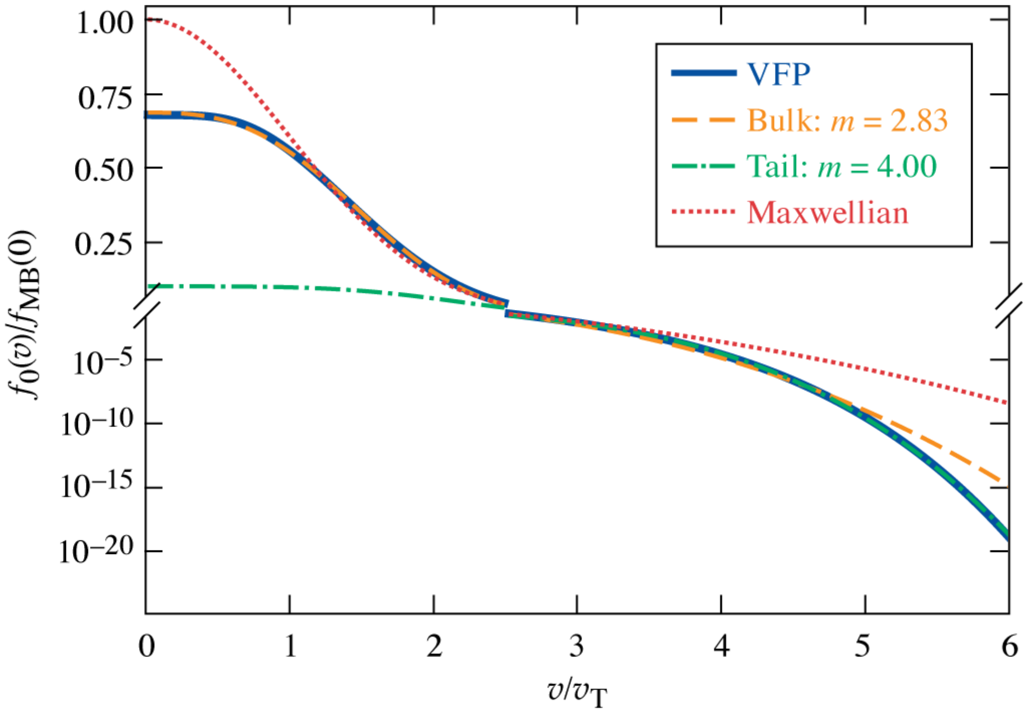
$$\frac{\kappa}{\kappa_{SH}} = \frac{c_0(Z) + c_1(Z)\alpha}{1 + c_2(Z)\alpha}$$

- **The Lorentz approximation over-estimates the conductivity reduction**

What is the underlying cause of conductivity reduction?

* N. R. Shaffer, A. V. Maximov, and V. N. Goncharov, *Phys. Rev. E* 108, 045204 (2023).

Lasers reduce the thermal conductivity by depleting the tail electrons responsible for conduction

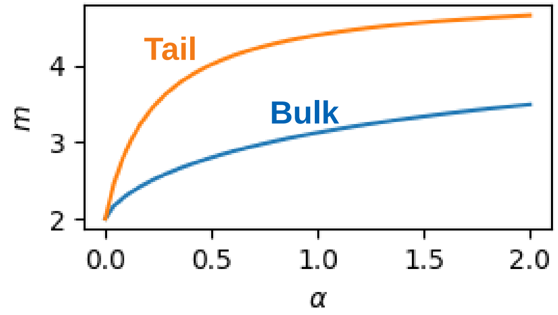


Bulk electrons (standard IB theory*)

$$m_{\mathrm{bulk}}(\alpha) = 2 + \frac{3}{1 + 1.66/\alpha^{0.724}}$$

Tail electrons (new theory)**

$$m_{\mathrm{tail}}(\alpha) = 2 + \frac{3}{1 + 0.247/\alpha^{0.972}}$$



"Super-Gaussian" models developed for IB must be revised to describe tail electron depletion

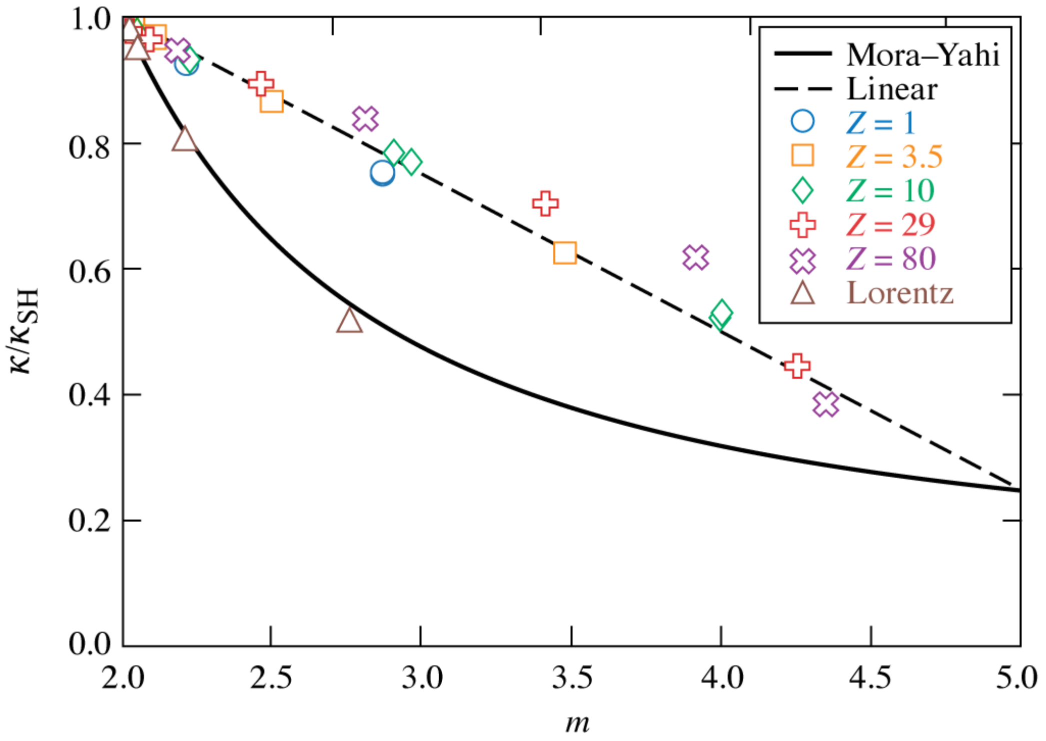
* J. P. Matte *et al.*, *Plasma Phys. Control. Fusion* 30, 1665 (1988).
** N.R. Shaffer, A. V. Maximov, and V. N. Goncharov, *Phys. Rev. E* 108, 045205 (2023).

Thermal conductivity reduction has a nearly universal form in terms of the tail exponent

- As a function of m_{tail}, all simulations with full e-e collisions collapse to a linear trend

$$\frac{\kappa}{\kappa_{SH}} = 1 - 0.251(m_{\text{tail}} - 2)$$

- Mora—Yahi evaluated with m_{tail} matches Lorentz simulations
- Lorentz results only agree with full simulations in the extreme limits
  - *m*=2 (trivial case)
  - *m*=5 (*all* e-e negligible)



A full account of e-e collisions is essential to accurately quantify thermal conductivity reduction by intense lasers

Graphical Outline: A Matrix of Thermal Conduction Models

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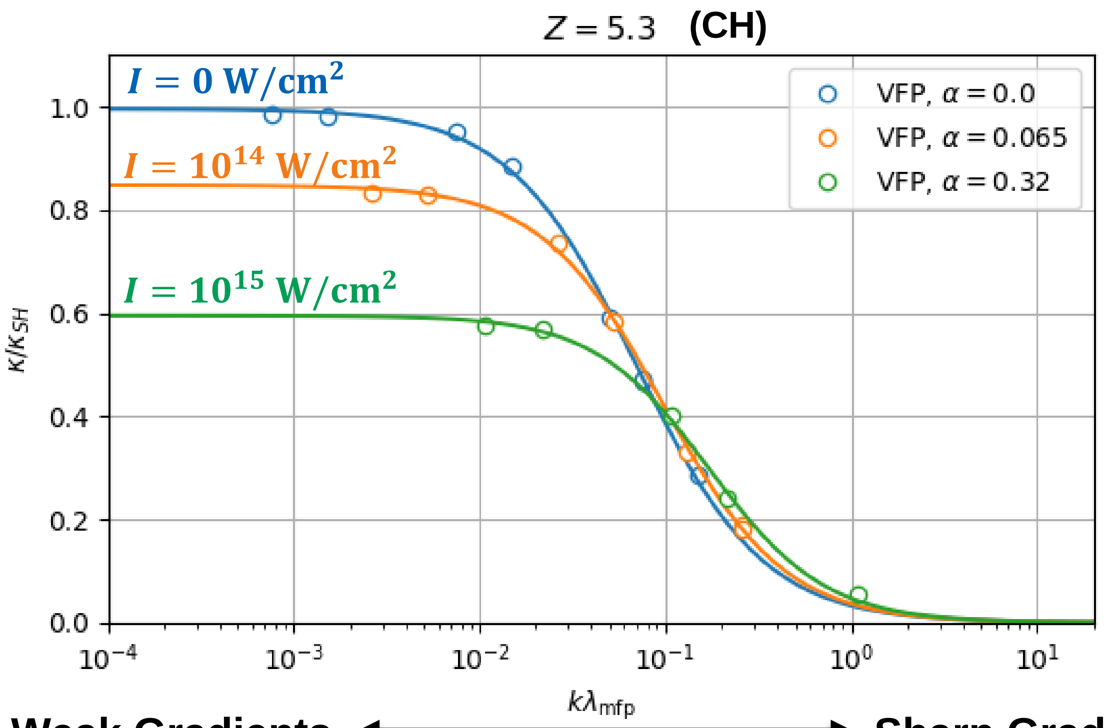
Weak Gradients	Spitzer-Härm	This Work
Sharp Gradients	Current Non-local Models	Work in Progress

Periodic simulations can access non-local transport by considering short-wavelength temperature perturbations

$$T(x,t) = T_0(t) + \mathrm{Re}\left[T_k(t)\, e^{ikx}\right]$$

$$\kappa \rightarrow \kappa(k)$$



Weak Gradients ⟷ **Sharp Gradients**

Non-locality implies scale-dependent conductivity

Wavenumber-dependent conductivity has historically been important in formulating non-local conductivity models

- **Convolution-type models**

$$Q(x) = \int W(x,x')\, Q_{SH}(x')\, dx' \longrightarrow W(k) \sim \frac{\kappa(k)}{\kappa_{SH}}$$

- **Examples**

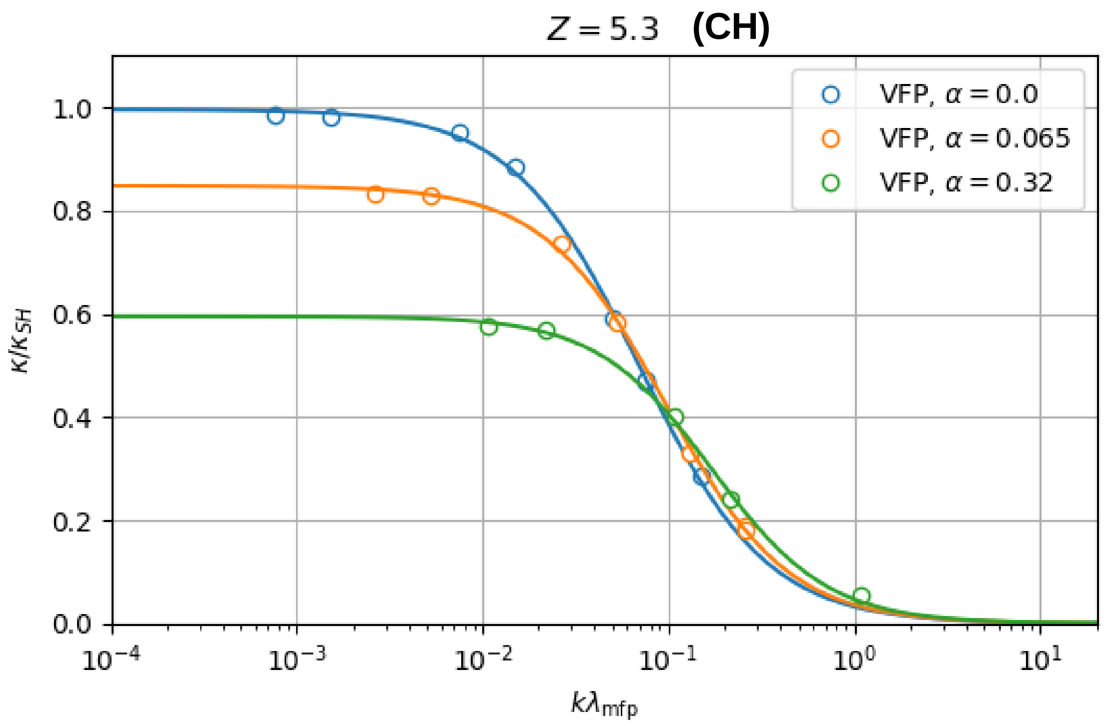
  - **LMV*/SNB†/iSNB‡** $\dfrac{\kappa(k)}{\kappa_{SH}} \sim \dfrac{1}{1+\left(k\lambda_{mfp}\right)^2} \longrightarrow W_{LMV}(x,x') \sim \dfrac{1}{\lambda_{mfp}} \exp\left(-\dfrac{|x-x'|}{\lambda_{mfp}}\right)$

  - **Epperlein-Short**** $\dfrac{\kappa(k)}{\kappa_{SH}} \sim \dfrac{1}{1+k\lambda_{mfp}} \longrightarrow W_{ES}(x,x') \sim \dfrac{1}{\pi\lambda_{mfp}} \left(\dfrac{|x-x'|}{\lambda_{mfp}}\right)^{-2}$

Intensity-dependent conductivity implies intensity-dependent delocalization physics

* J. F. Luciani, P. Mora, and J. Virmont, *Phys. Rev. Lett.* 51, 1664 (1983).
** E. M. Epperlein and R. W. Short, *Phys. Fluids B* 3, 3092 (1991).
† G. P. Schurtz, Ph. D. Nicolaï, and M. Busquet, *Phys. Plasmas* 23, 4238 (2000).
‡ D. Cao, G. Moses, and J. Delettrez, *Phys. Plasmas* 22, 082308 (2015).

Laser-induced tail electron depletion has three main effects on the non-local conductivity



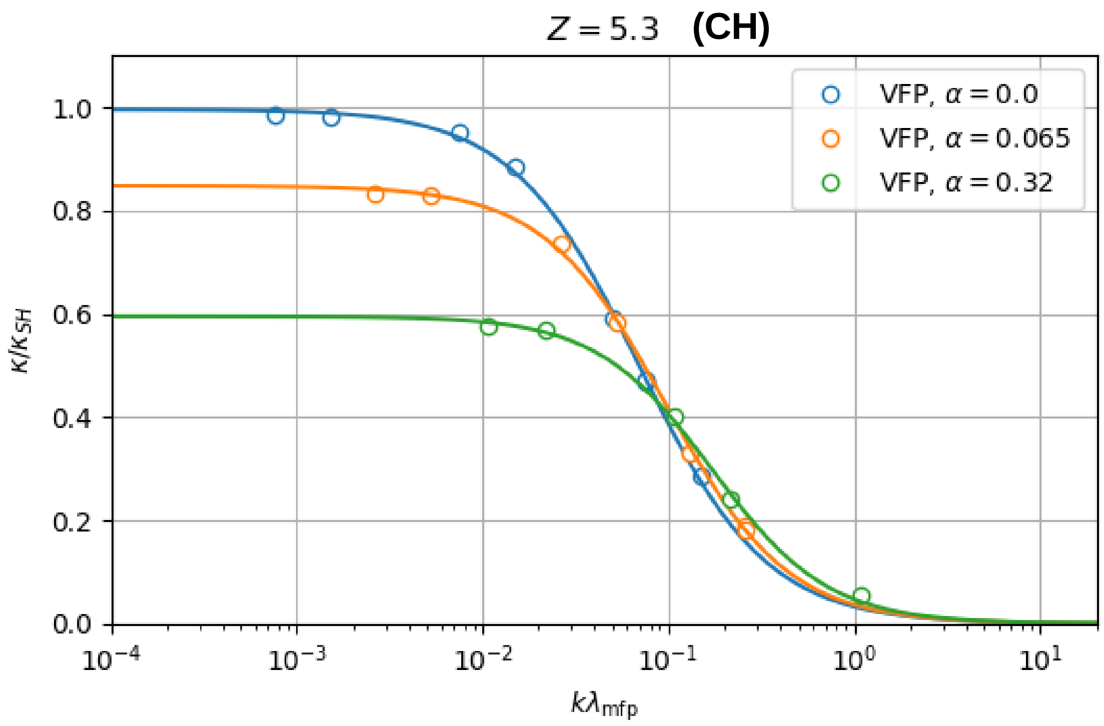
$$\frac{\kappa(k)}{\kappa_{\mathrm{SH}}} = \frac{a}{1 + \left(b\sqrt{Z}k\lambda_{\mathrm{mfp}}\right)^{c}}$$

Model parameters:

- ***a*** **characterizes the local (k → 0) limit**
- ***b*** **characterizes the** ***effective*** **mean-free path**
- ***c*** **characterizes the response to steep gradients**

Intensity dependence of model parameters informs how we might develop new intensity-dependent non-local kernels

Laser-induced tail electron depletion has three main effects on the non-local conductivity



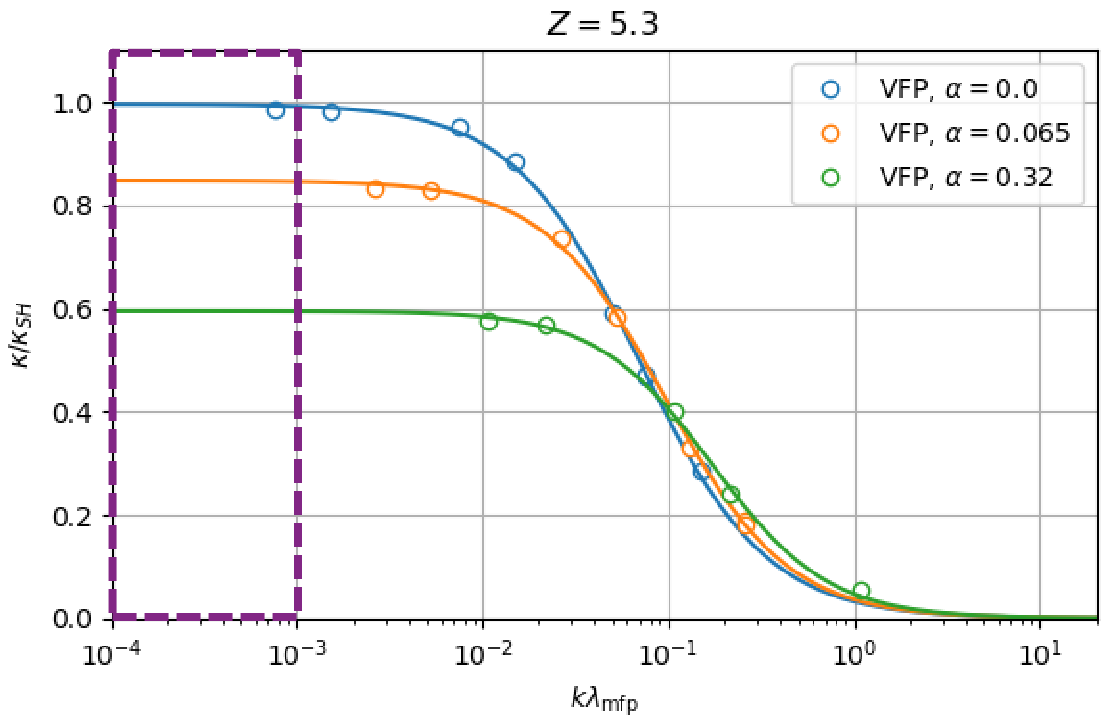
$$\frac{\kappa(k)}{\kappa_{\mathrm{SH}}} = \frac{a}{1 + \left(b\sqrt{Z}k\lambda_{\mathrm{mfp}}\right)^{c}}$$

α	a	b	c
0	1.00	6.20	1.28
0.065	0.85	4.47	1.33
0.32	0.60	2.51	1.40

3 Effects of increasing α:

Intensity dependence of model parameters informs how we might develop new intensity-dependent non-local kernels

Laser-induced tail electron depletion has three main effects on the non-local conductivity



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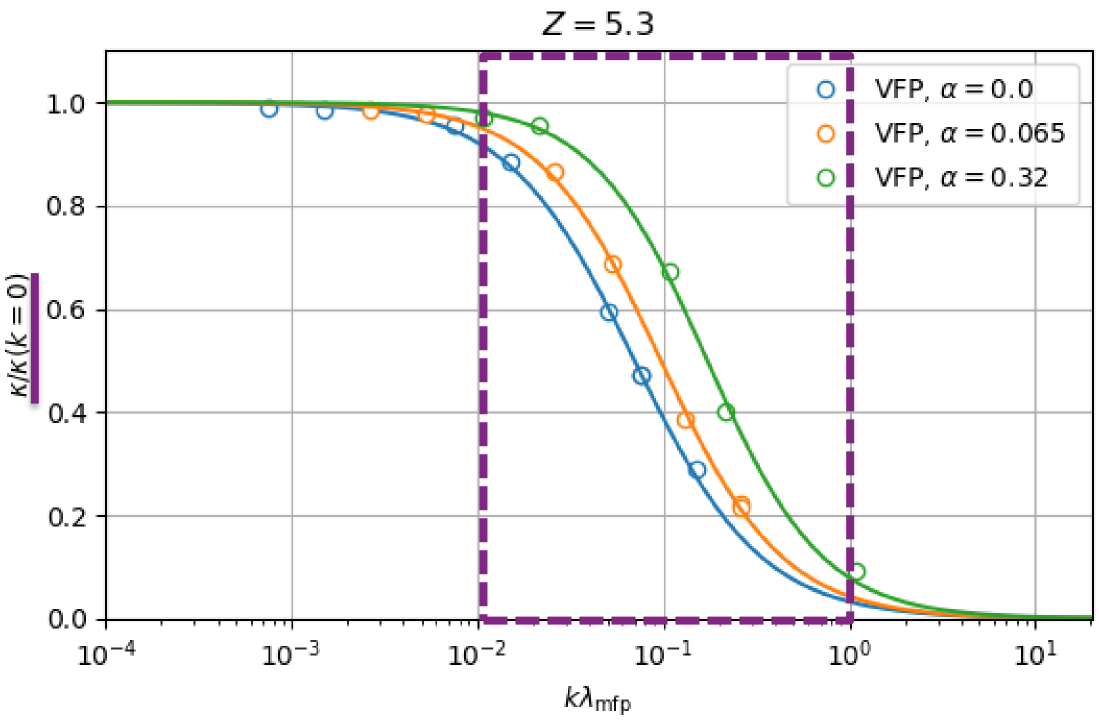

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2. Shortens the effective mean free path

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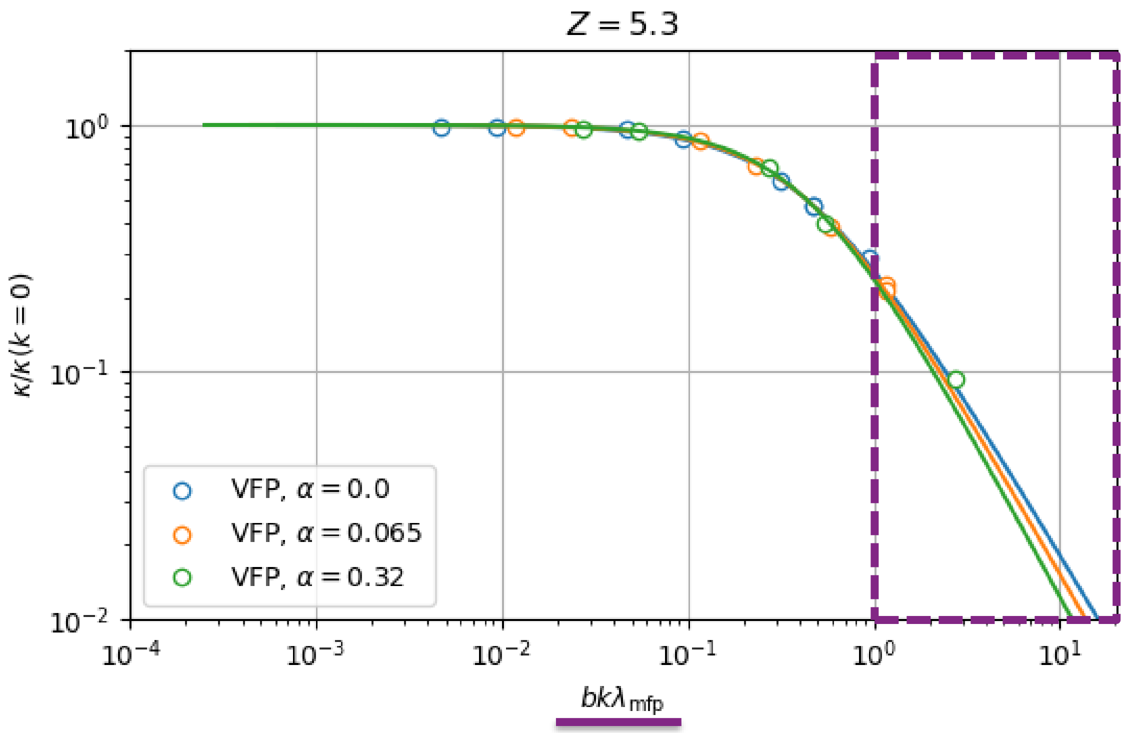
Laser-induced tail electron depletion has three main effects on the non-local conductivity



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3 Effects of increasing α:	1. Reduces the local thermal conductivity	2. Shortens the effective mean free path	3. Suppresses flow across very steep gradients

Intensity dependence of model parameters informs how we might develop new intensity-dependent non-local kernels

Future work will investigate the impact of conductivity reduction in ICF modeling applications

- *LILAC* implementation of intensity-dependent Spitzer-Härm correction factor
- Further *K2* VFP simulations in planar/spherical geometries (i.e., non-periodic conduction)
- Assess if non-local conduction models would benefit from intensity-dependent corrections

Interested? Let’s talk!

The presence of a laser field reduces the thermal conductivity of a plasma due to nonlinear absorption effects

- Vlasov-Fokker-Planck simulations demonstrate that the thermal conductivity of a plasma depends on laser intensity, which is not accounted for in radiation-hydrodynamics simulations.

- Conductivity reduction happens because the laser depletes the population of high-energy conduction electrons, analogous to the "Langdon effect" for laser absorption.

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- Simulations of non-local conduction imply non-trivial modifications to standard non-local models may needed in absorbing regions.