University Scale Experiment for Modeling Energy Transport in Strongly Coupled Plasmas

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HEDS Seminar Series- July 27, 2023

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MSU and UCLA Team

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Overview

- Motivation
- Experimental Setup
- Modeling Experiment
- Results

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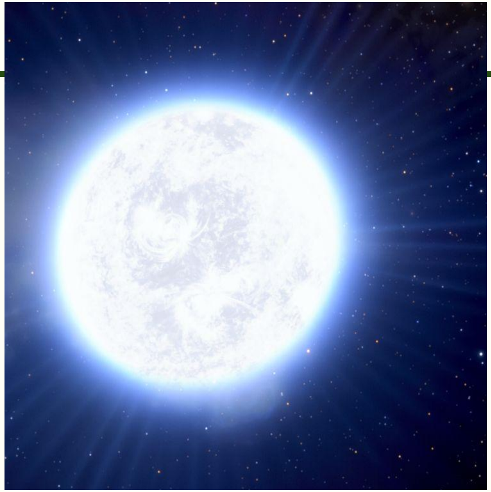
Fusion, Astrophysics and more



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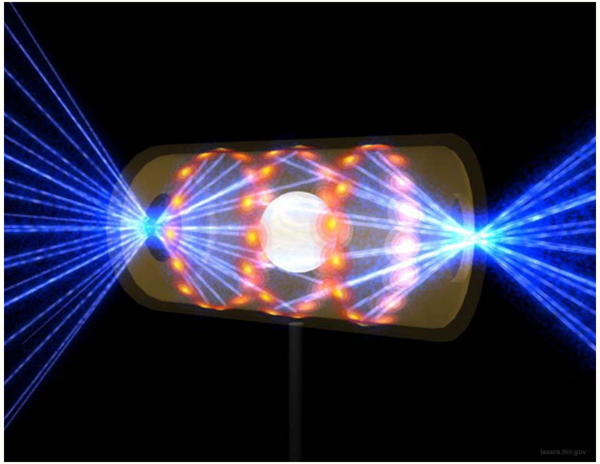

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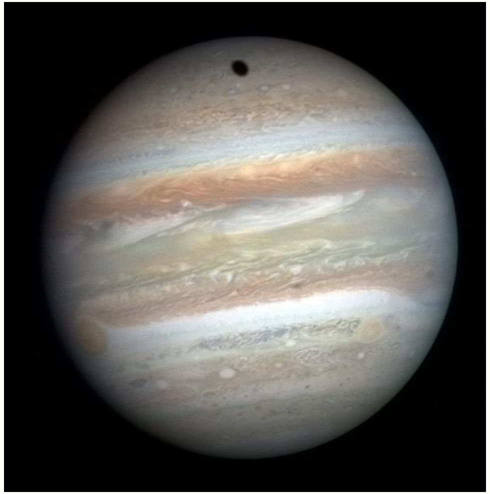

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Strongly Coupled and High Energy Density Plasmas

OMEGA

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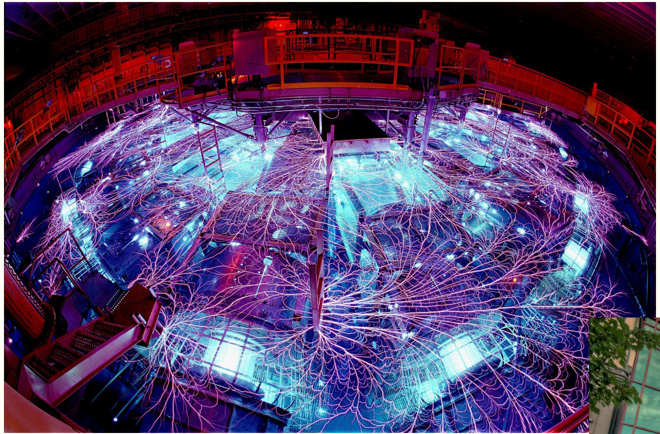
Z Machine



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NIF

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Application to Inertial Confinement Fusion (ICF)

- In ICF:
  - Many non-equilibrium processes occurring
  - Difficult to tease out individual parameters
  - Sometimes difficult to get time on the experiment
- Energy transport equations

$$\frac{\partial E_e}{\partial t} = -\nabla \cdot [vE_e - k_e \nabla T_e] - \mathbf{P_e} : \nabla \mathbf{u} - G(T_e - T_i) + S_\gamma,$$
$$\frac{\partial E_i}{\partial t} = -\nabla \cdot [vE_i - k_i \nabla T_i] - \mathbf{P_i} : \nabla \mathbf{u} + G(T_e - T_i) + S_\gamma,$$
$$\frac{\partial E_\gamma}{\partial t} = -\frac{4}{3}\nabla \cdot (\mathbf{u}E_r) + \nabla \cdot (\kappa_r \nabla E_r) - c\sigma_a(E_r - \sigma T_e^4) + \frac{1}{3}\mathbf{u} \cdot \nabla E_r$$

- Need validated models for transport coefficients, EOS

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EOS

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Application to Inertial Confinement Fusion (ICF)

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EOS

Transport Coefficients

$$\frac{\partial E_e}{\partial t} = -\nabla \cdot [vE_e - k_e \nabla T_e] - \mathbf{P_e} : \nabla \mathbf{u} - G(T_e - T_i) + S_\gamma,$$

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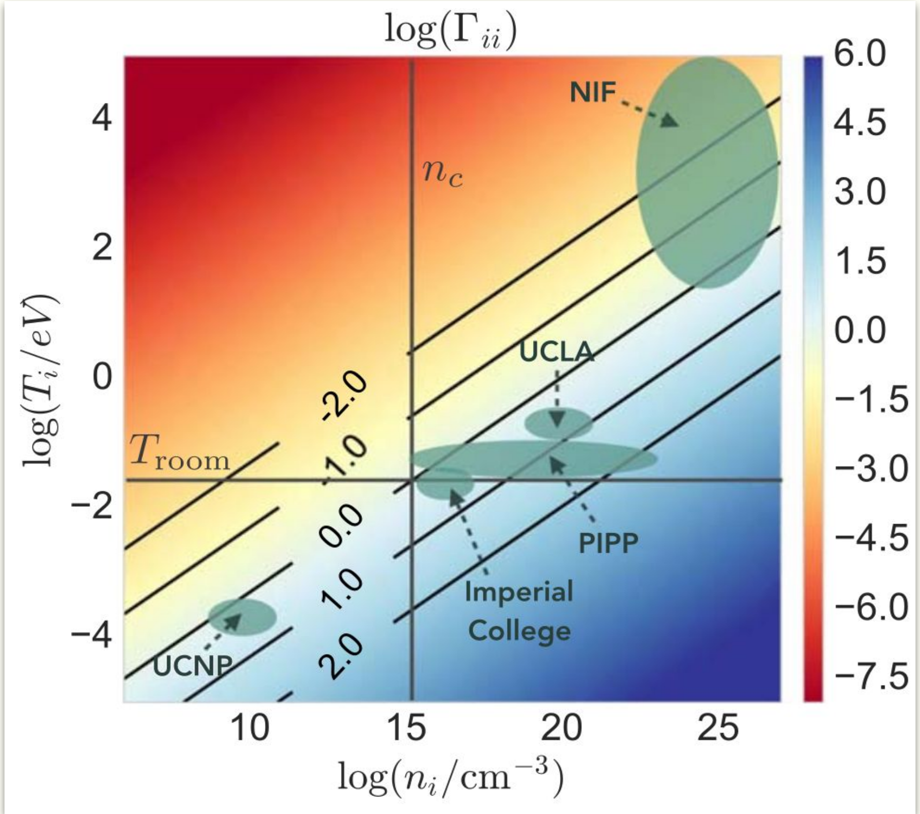
- Need validated models for transport coefficients, EOS

Regimes of Strongly Coupled Plasmas

Many regimes with similar physics:

- Ultracold Neutral Plasmas (UCNP)
- Pressure Induced Precorrelated Plasmas (PIPP)



G. Dharuman Liam G. Stanton and M. S. Murillo New J. Phys. 20 (2018) 103010

Literature Review

- Complexity of ICF motivates clean testing environments
- Recent example: Ultracold Neutral Plasmas (UCNP)
  - Successes include

Exploring the crossover between high-energy-density plasma and ultracold neutral plasma physics EP

Cite as: Phys. Plasmas **26**, 100501 (2019); doi: 10.1063/1.5119144
Submitted: 9 July 2019 · Accepted: 22 September 2019 ·
Published Online: 24 October 2019

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Scott D. Bergeson,[1,a] Scott D. Baalrud,[2,b] C. Leland Ellison,[3,c] Edward Grant,[4,d] Frank R. Graziani,[3,e] Thomas C. Killian,[5,f] Michael S. Murillo,[6,g] Jacob L. Roberts,[7,h] and Liam G. Stanton[8,i]

Relaxation of strongly coupled binary ionic mixtures in the coupled mode regime

Cite as: Phys. Plasmas **28**, 062302 (2021); doi: 10.1063/5.0048030
Submitted: 18 February 2021 · Accepted: 4 May 2021 ·
Published Online: 3 June 2021

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Luciano G. Silvestri,[1,a] R. Tucker Sprenkle,[2] Scott D. Bergeson,[2] and Michael S. Murillo[1]

PHYSICAL REVIEW X **6**, 021021 (2016)

Experimental Measurement of Self-Diffusion in a Strongly Coupled Plasma

T. S. Strickler,[1] T. K. Langin,[1] P. McQuillen,[1] J. Daligault,[2] and T. C. Killian[1]
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(Received 7 December 2015; revised manuscript received 24 March 2016; published 17 May 2016)

Overview

- Motivation
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Laser Breakdown Gases

- UCNPs offers important model validation and strongly coupled physics insight
- Density is incredibly small, $n_i \sim 10^{10}\ \mathrm{cm}^{-3}$
- Desire for an intermediate case with
  - Clean insight into dynamical processes
  - Densities closer to ICF, other applications
- Promising possibility is a high-pressure gases ionized by a laser

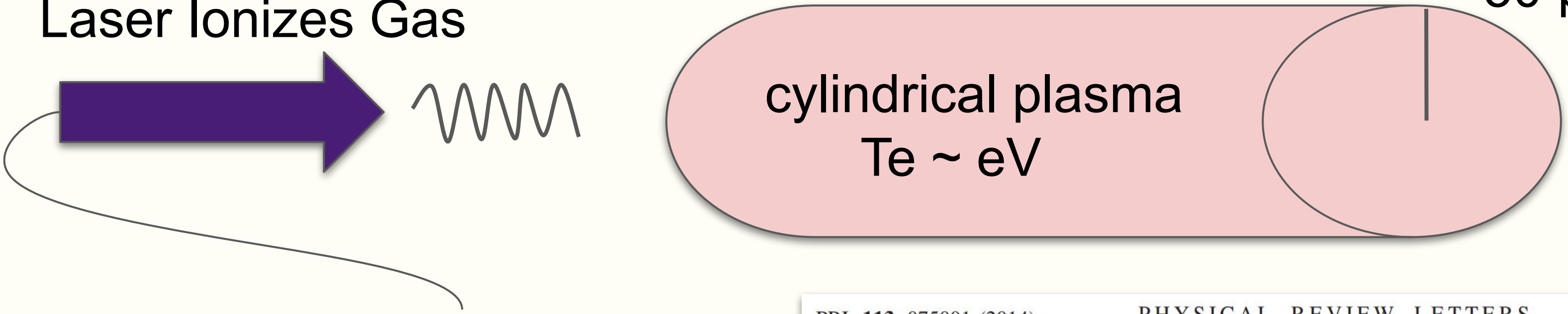
Laser Breakdown Experimental Setup

Xe, Ar, He, or H gas

Cold gas at ~ 300 K

50 μm FWHM

Laser Ionizes Gas



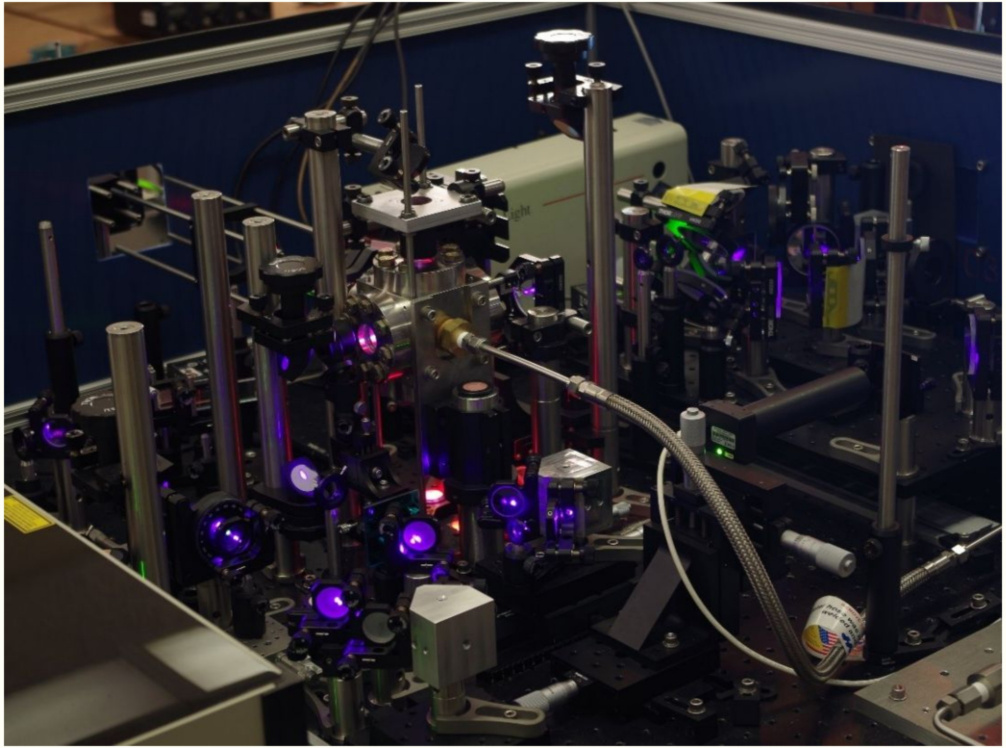
800 nm (65-250) fs ~0.5 mJ

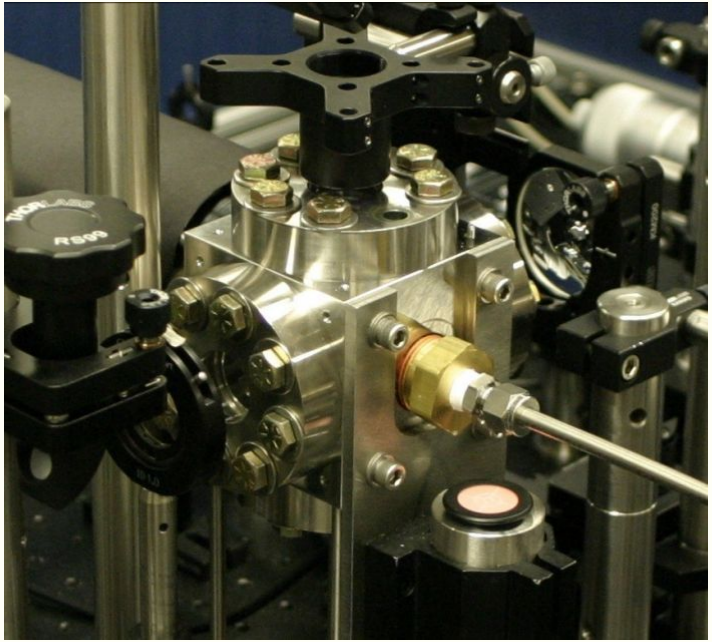
PRL **113,** 075001 (2014) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2014

Blackbody Emission from Laser Breakdown in High-Pressure Gases

A. Bataller,* G. R. Plateau, B. Kappus, and S. Putterman
Department of Physics and Astronomy, University of California, Los Angeles, Los Angeles, California 90095, USA
(Received 14 April 2014; published 15 August 2014)

Setup: Optics and Chamber at UCLA





Review of Laser Induced Breakdown

Spectroscopy Applications

Focal Point Review

Laser-Induced Breakdown Spectroscopy (LIBS), Part II: Review of Instrumental and Methodological Approaches to Material Analysis and Applications to Different Fields

David W. Hahn and Nicoló Omenetto

Laser-induced breakdown spectroscopy (LIBS) – an emerging field-portable sensor technology for real-time, *in-situ* geochemical and environmental analysis

Russell. S. Harmon[1], Frank C. De Lucia[2], Andrzej W. Miziolek[2], Kevin L. McNesby[2], Roy A. Walters[3] & Patrick D. French[4]
[1] *US Army Research Office, PO Box 12211, Research Triangle Park, NC 27709, USA*
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[4] *ADA Technologies, Inc., 8100 Schaffer Parkway, Suite 130, Littleton, CO 80127, USA*

A review of the use of laser-induced breakdown spectroscopy for bacterial classification, quantification, and identification

Check for updates

Steven J. Rehse*
University of Windsor, Department of Physics, Windsor, Ontario N9B 3P4, Canada

'Fundamental' Plasma Physics

PRL **113,** 075001 (2014) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2014

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(Received 14 April 2014; published 15 August 2014)

Strong Coulomb coupling influences ion and neutral temperatures in atmospheric pressure plasmas

M D Acciarri[1], C Moore[2] and S D Baalrud[1,*]
[1] Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109, United States of America
[2] Sandia National Laboratories, Albuquerque, NM 87185, United States of America

New Journal of Physics
The open access journal at the forefront of physics
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IOP Institute of Physics
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PAPER

Controllable non-ideal plasmas from photoionized compressed gases

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[1] Department of Computational Mathematics, Science and Engineering, Michigan State University, East Lansing, MI 48824, United States of America
[2] Department of Mathematics & Statistics, San José State University, San José, CA 95192, United States of America
[3] Author to whom any correspondence should be addressed.

Our Goals

- Nice experimental data on a new platform for strongly coupled plasmas
- Lower density, and simpler plasma is a good testbed
- Need to supplement efforts in the ICF community in validating transport and EOS

Goals for this project

- Understand all relevant physical processes
- Build model for this experiment
- Fit model parameters to data
    - Extract insight into transport for HED plasmas

Overview

- Motivation
- Experimental Setup
- **Modeling Experiment**
- Results

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Separating Initial Conditions from Simulation

Initial conditions:

- Laser pulse $\sim 100 \text{ fs}$
- Electron thermalization $\sim 1/\omega_{pe} \sim 10 \text{ fs}$
- Ion thermalization $\sim 1/\omega_{pi} \sim \text{ ps}$

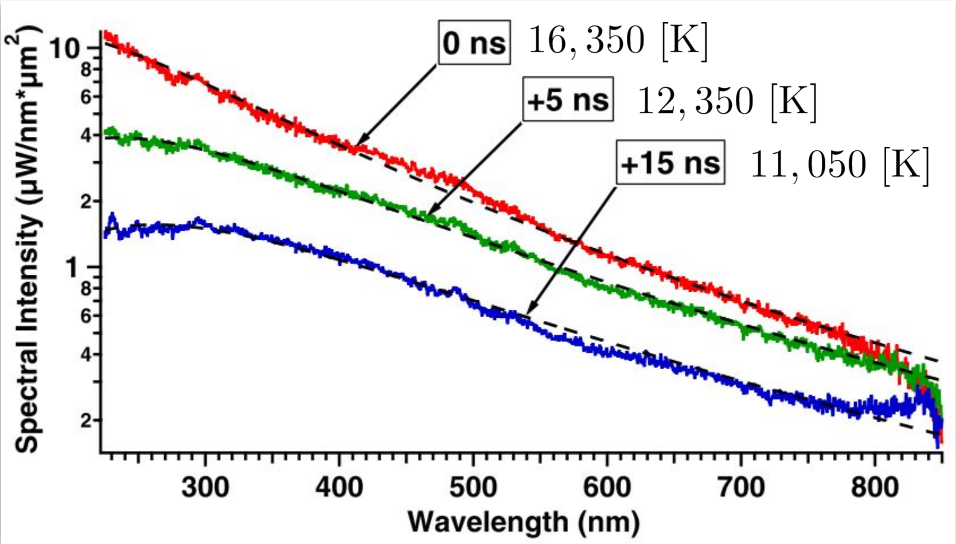
Simulate:

- e-i equilibration $\sim \tau_{ei} \sim \text{ns}$
- Thermal diffusion $\sim \frac{c_e R^2_{\text{FWHM}}}{k_e} \sim 100\mu\text{s}$
- expansion $\sim \frac{R_{\text{FWHM}}}{c_s} \sim 50 \text{ ns}$

Measuring Visible Light

- Measurements in approximately visible wavelengths
- Show near blackbody behaviour

Xe 5 bar



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Initial Conditions: Optical Absorption

- We measure light intensity
- Where are the photons coming from?

Absorption dominated by free-free inverse bremsstrahlung

$$1/\bar{l}_\gamma = \kappa = \frac{\nu_{ei}}{c}\left(\frac{\omega_{pe}}{\omega}\right)^2 \frac{1}{\sqrt{1-(\omega_{pe}/\omega)^2}} f_L f_{sc}$$

PHYSICAL REVIEW LETTERS **130,** 145103 (2023)

Inverse Bremsstrahlung Absorption

D. Turnbull,[1,*] J. Katz,[1] M. Sherlock,[2] L. Divol,[2] N. R. Shaffer,[1] D. J. Strozzi,[2] A. Colaïtis,[3] D. H. Edgell,[1] R. K. Follett,[1] K. R. McMillen,[1] P. Michel,[2] A. L. Milder,[4] and D. H. Froula[1]
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[2]*Lawrence Livermore National Laboratory, Livermore 94550, California, USA*
[3]*Centre Lasers Intenses et Applications, Talence 33400, France*
[4]*University of Alberta, Edmonton, Alberta T6G 2R3, Canada*

(Received 10 January 2023; accepted 20 March 2023; published 4 April 2023)

- Set $f_{sc} = f_L = 1$ since
  - Since $\hbar\omega \sim k_B T_e$ (thermal equilbrium)
  - Electrons assumed thermalized by $\sim 1/\omega_{pe} \sim 10$ fs

Initial Conditions: Matching Spectrum

Integrate line of sight to get measured Intensity

$$I_{\text{exp}} \propto \int_{l.o.s.} dz B_\lambda(r,\lambda) e^{-\int_{-\infty}^{z} dz \kappa(r,\lambda)}$$

For $B_\lambda(r,\lambda)$ the spectral radiance over wavelength

- Assuming blackbody equilibrium at every point in space
- Exact absorption depends on ionization

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Initial Conditions: Ionization

How ionized are the ions?

- Estimate three body recombination (TBR) as (Pohl et al. 2008)

$$\tau_{TBR} = 0.36 \times 10^9 \frac{T_e[K]^{9/2}}{n_e^2}$$

- We refer instead to (Hahn 1997) which includes density effects

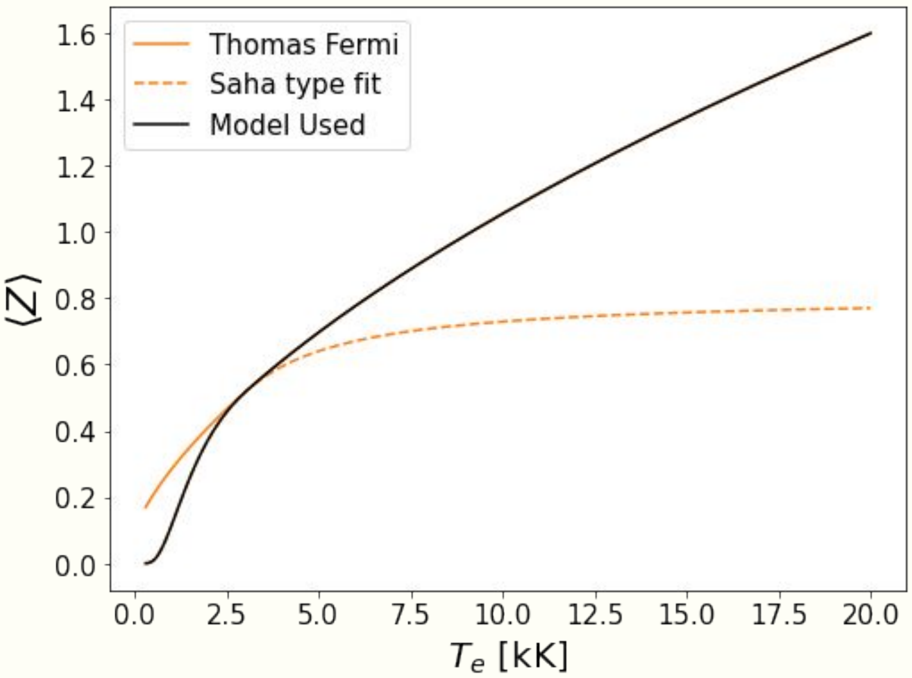
$$\tau_{TBR} = 2.77 \times 10^3 \frac{T_e[Ry]Z^4}{n_e^{5/6}}$$

- Both give, $\tau_{TBR} \lesssim \mathrm{ps}$, i.e. we assume *equilibrium ionization*

How to Model the Equilibrium Ionization

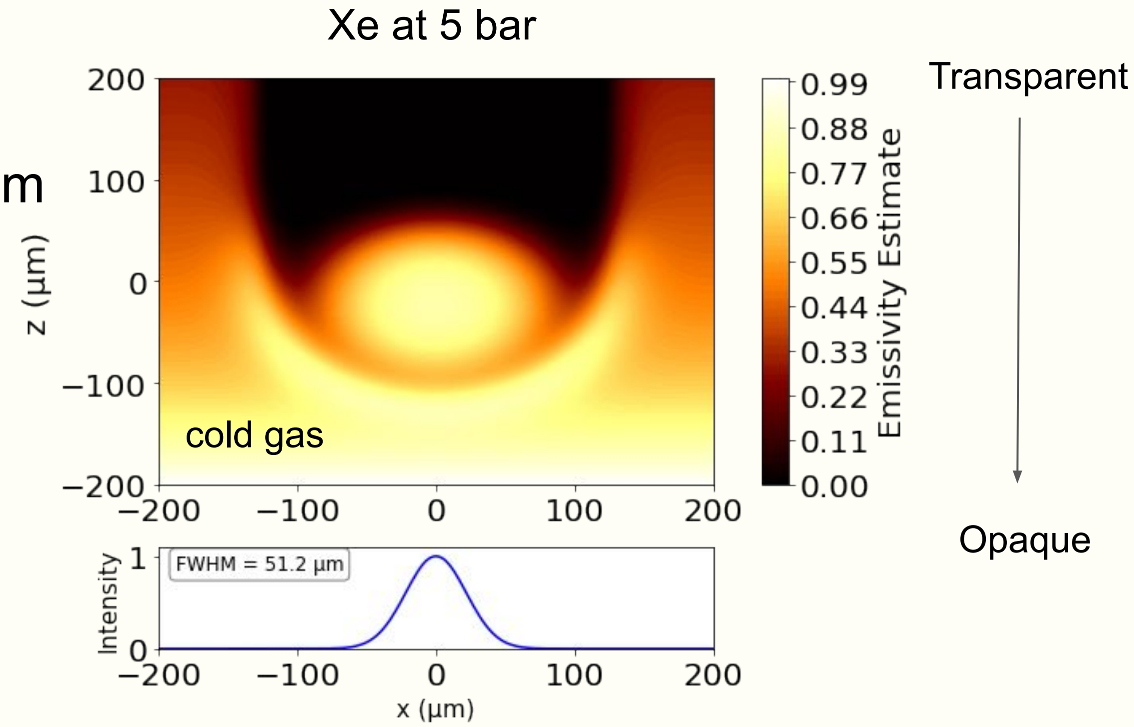
- Average Atom Model
  - Use Thomas-Fermi More
  - Issue at T=0
- Saha
  - Need ionization potential depression (ipd)

What is Z?



The Parts of the Plasma we can 'See'

- Total intensity observed vs. expected in vacuum



Initial Condition for Ions: Disorder Induced Heating

- Cause of ion heating in ultracold neutral plasmas
  - Similar idea to ‘bond softening’ in solid systems
- Sudden ionization over ~ 100 fs rapidly changes equilibrium

Leads to a temperature rise of

$$T_f = T_0 + \frac{4}{3}\pi n_i \int dr\ r^2 u_{ii}(r)(g_{ii}^f - g_{ii}^0)(r)$$

Over $\sim 1/\omega_{pi} \sim$ ps

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Initial Condition for Ions: Disorder Induced Heating

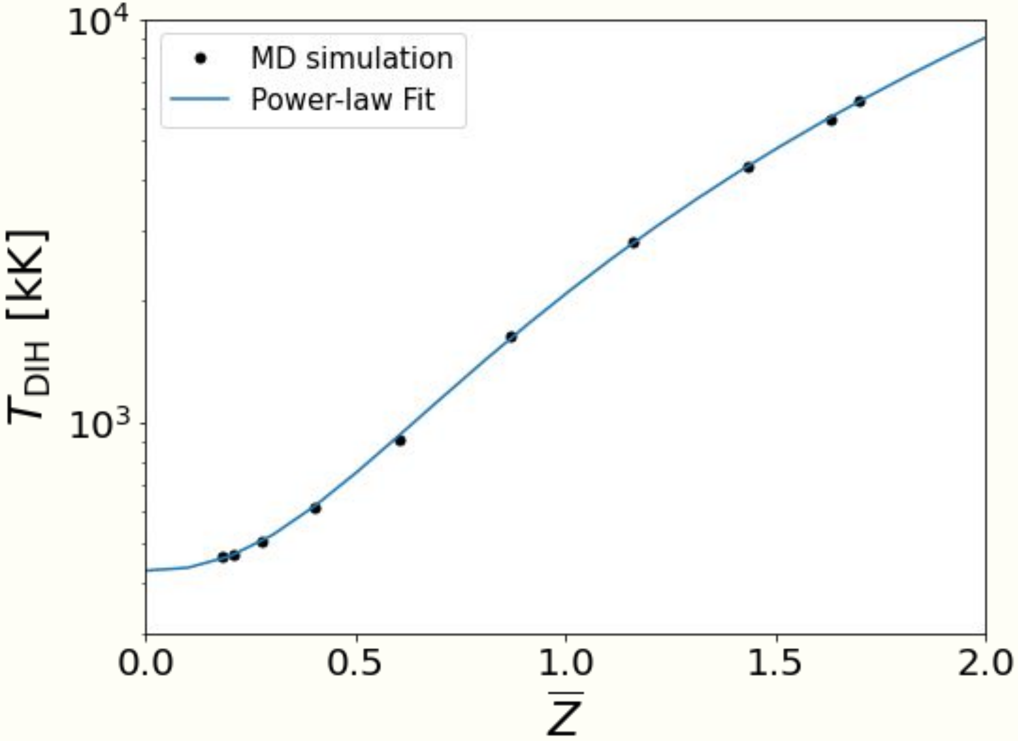
- Ran Yukawa classical MD with in-house Sarkas
- Inputs of: $Z, \bar{Z}, n_i$

SARKAS

Python MD code for plasma physics

Initial Condition for Ions: Disorder Induced Heating

Disorder Induced heating is a function of



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- expansion $\sim \dfrac{R_{\mathrm{FWHM}}}{c_s} \sim 50\ \mathrm{ns}$

Hydrodynamic Implementation

1-D cylindrical, two-temperature hydrodynamic model

- Continuity: $$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rvn) = 0$$
- Momentum: $$\left(\frac{\partial}{\partial t} + v\frac{\partial}{\partial r}\right)v = -\frac{1}{\rho}\frac{\partial P}{\partial r}$$
- Energy: $$\frac{\partial E_e}{\partial t} = -P_e\frac{1}{r}\frac{\partial}{\partial r}(rv) - \frac{1}{r}\frac{\partial}{\partial r}(rvE_e) - G(T_e - T_i),$$ $$\frac{\partial E_i}{\partial t} = -P_i\frac{1}{r}\frac{\partial}{\partial r}(rv) - \frac{1}{r}\frac{\partial}{\partial r}(rvE_i) + G(T_e - T_i)$$

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Physical Parameters Needed

The physical properties of the plasma are captured by:

1. energy densities, E_e, E_i (or specific heat $c_e, \; c_i$)
2. Pressures, $P_i, \; P_e$
3. e-i temperature relaxation rate, G
4. Ionization level $\bar{Z}$
5. electron thermal conductivity k_e
6. Radiation transport S_γ

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Specific Heats and Equation of State

We want the EOS separately for each species

- Need P_i, P_e
- Moderate coupling: $\Gamma_{ii} \sim \Gamma_{ee} \sim 1$

Simple picture:

Debye-Huckel (DH) one component plasma (OCP) with cutoff

$$g_{ii}(r) = Max\left[0, 1 - \frac{\bar{Z}^2}{rT_i}e^{-r/\lambda_D}\right]$$

For DH screening length λ_D

Specific Heats and Equation of State

- Cutoff leads to standard result, plus exponential

$$U_i = \frac{3}{2} n_i T_i - 2\pi \frac{n_i^2 Z^4}{T_i} e^{-W_0(\Gamma_i \kappa_i)}$$

For Lambert W Function W_0 from g cutoff, and $\kappa_i = a_i / \lambda_D$

$$P_i = n_i T_i - \frac{2\pi}{3} \frac{n_i^2 Z^4}{T_i} e^{-W_0(\Gamma_i \kappa_i)}$$

Issue is in some cases U goes negative! Use ideal gas U

- Repeat for electrons (jellium)

$$i \to e, Z \to 1$$

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Electron Ion Equilibration Rates

- Stanton-Murillo Transport, with $G = c_e \tau_{ei}$
- Where the electron to ion equilibration time is

$$\tau_{ei} = \frac{3(m_e + m_i)T_{ei}^{3/2}}{32\sqrt{2\pi\mu_{ei}}n_i\bar{Z}^2e^4K_{11}(g_{ei})}$$

‘Best’ modeling job you can do in binary collision approach

Efficient model for electronic transport in high energy-density matter

Cite as: Phys. Plasmas **28**, 082301 (2021); doi: 10.1063/5.0048162
Submitted: 24 February 2021 · Accepted: 6 July 2021 ·
Published Online: 2 August 2021

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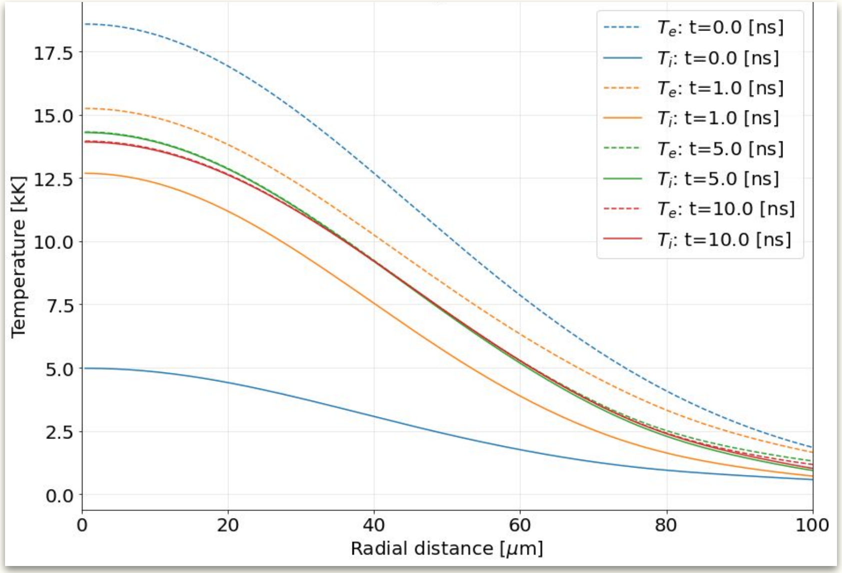
Liam G. Stanton[1,a] and Michael S. Murillo[2,b]

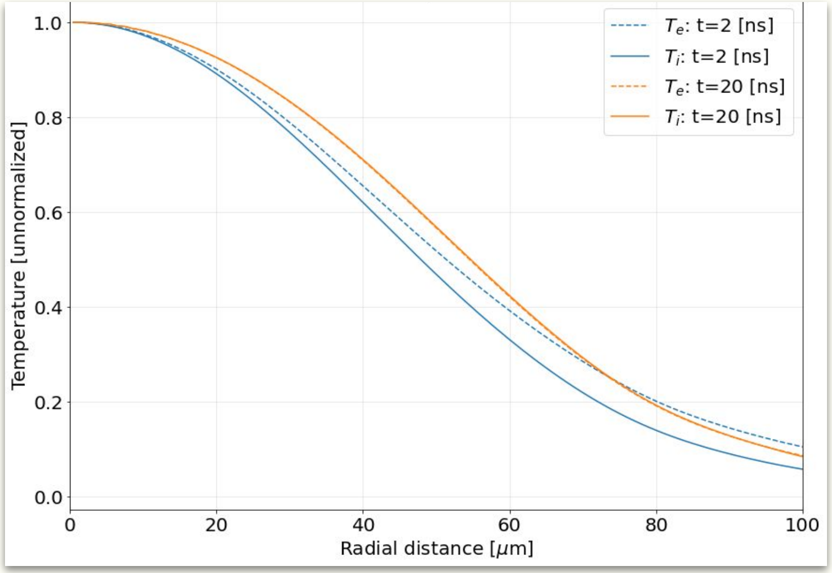
Results: Thermal Diffusion Profiles

We see the temperatures diffusing, and relaxing.

Actual Temperature



Normalized to max



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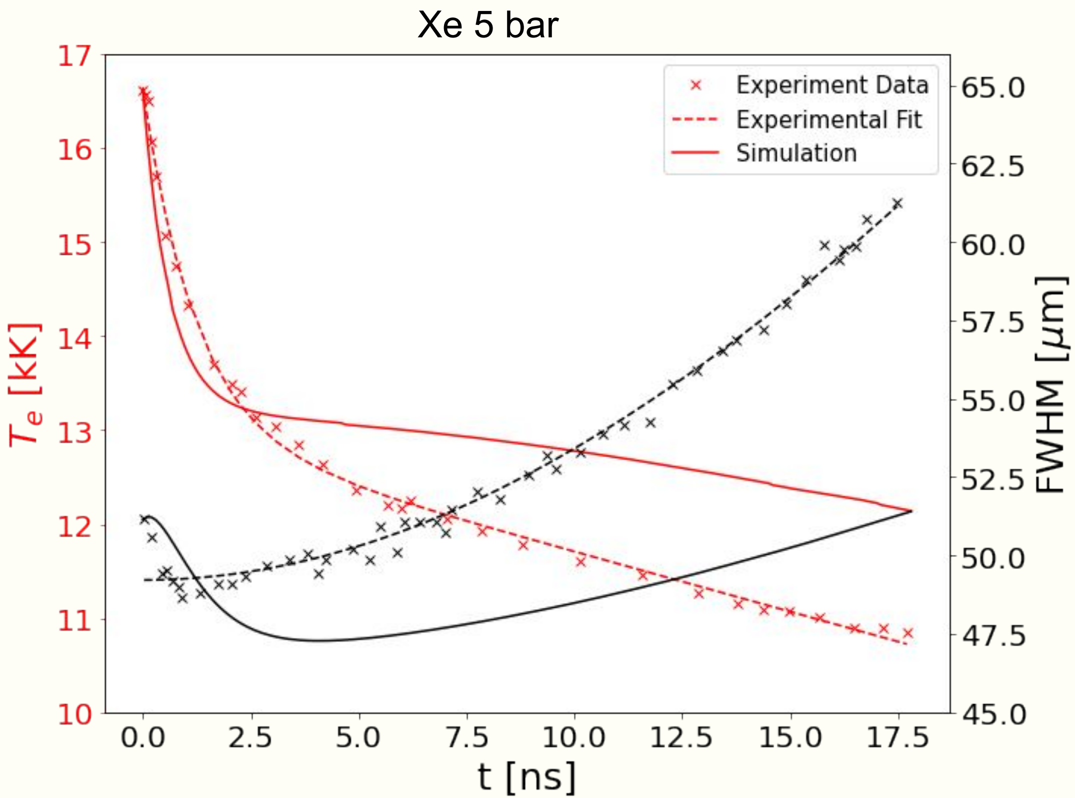
Numerical Results: Comparison to Experiment

Qualitative agreement

-Electron-ion equilibration too fast

-Simulated plasma expansion takes too slow



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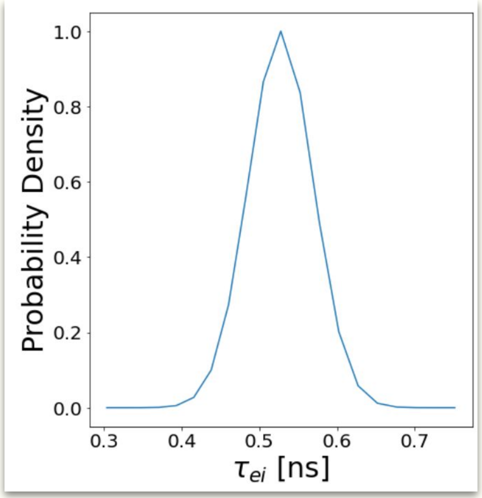
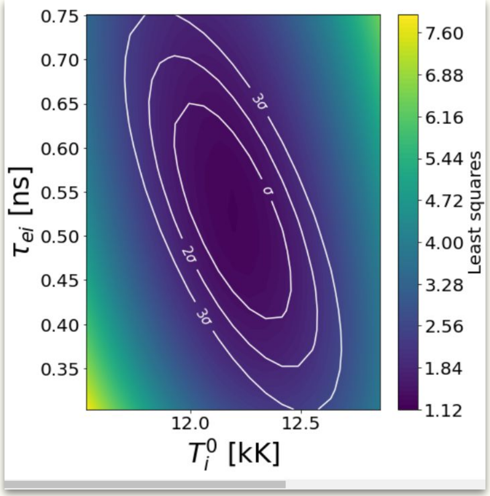
Parameter Fitting and Uncertainty Quantification

Fit to simple model (T_e^0, T_i^0, d, τ)

$$\dot{T}_e = -\tau(T_e - T_i) - d$$
$$\dot{T}_i = +\tau(T_e - T_i) - d$$

Without ion Temperature, cannot separate τ_{ei}, τ_{ie}





Statistical Uncertainty

Fit to simple model (T_e^0, T_i^0, d, τ)

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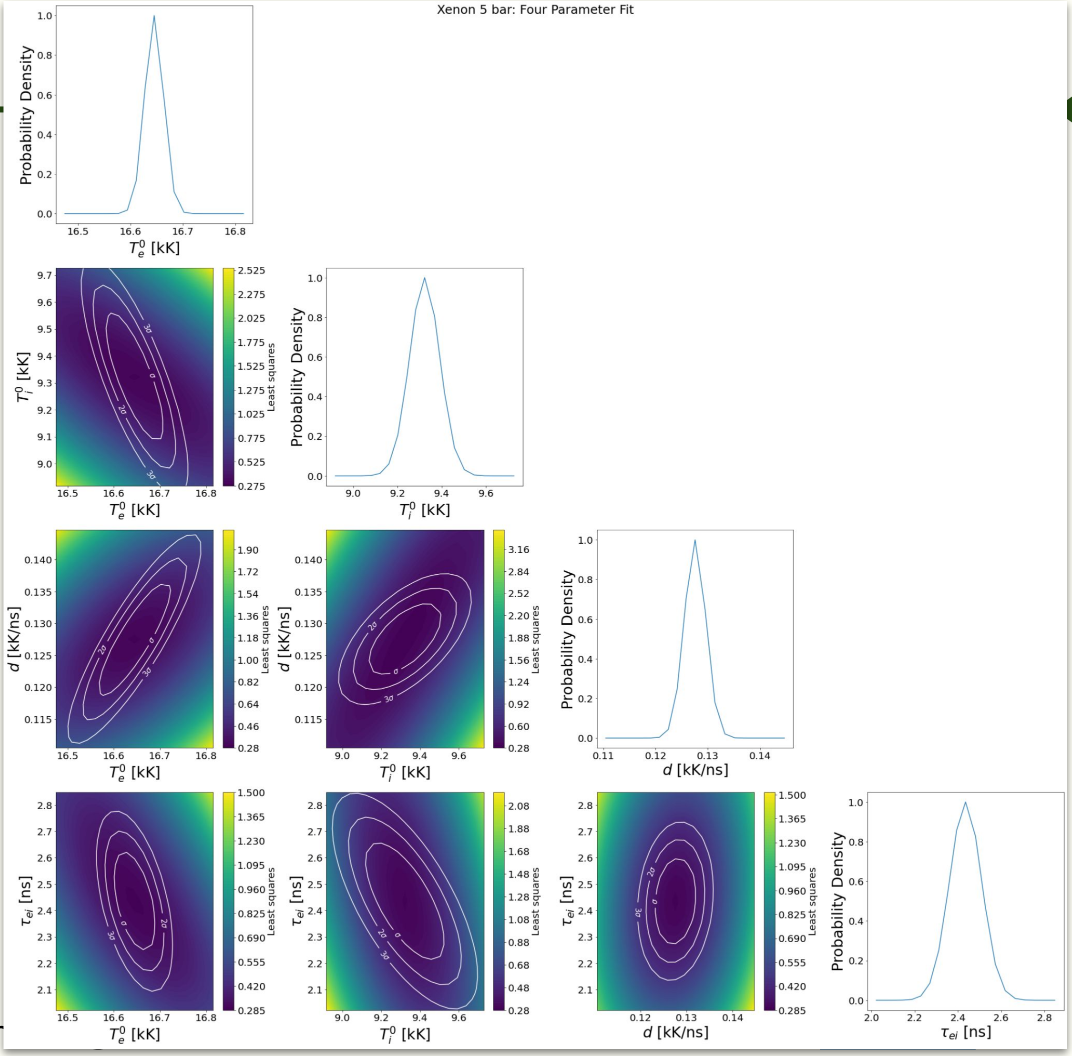


Conclusion

New platform for investigating energy transport in dense plasmas

Modeling Success:

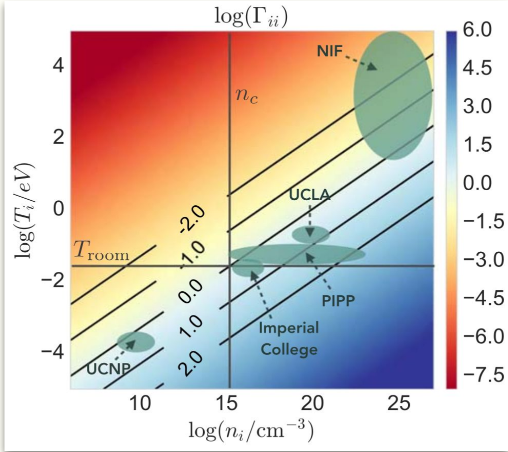
- Preliminary testing of transport coefficient validity
- Which physical processes are relevant is understood

Work in Progress:

- Plasma expansion appears to start faster than expected
- Initial ionization least understood process (by us)

Exciting Future Directions:

- More experimental measurements (Thomson scattering)
- ‘Arbitrary’ gas mixtures
- Wang group at Caltech has promising new data/techniques here



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