Extremely difficult, hard to validate, painful to analyze (but exciting): Experiments studying radiation and heat transport of laboratory plasmas at near astrophysical conditions

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Lawrence Livermore National Laboratory

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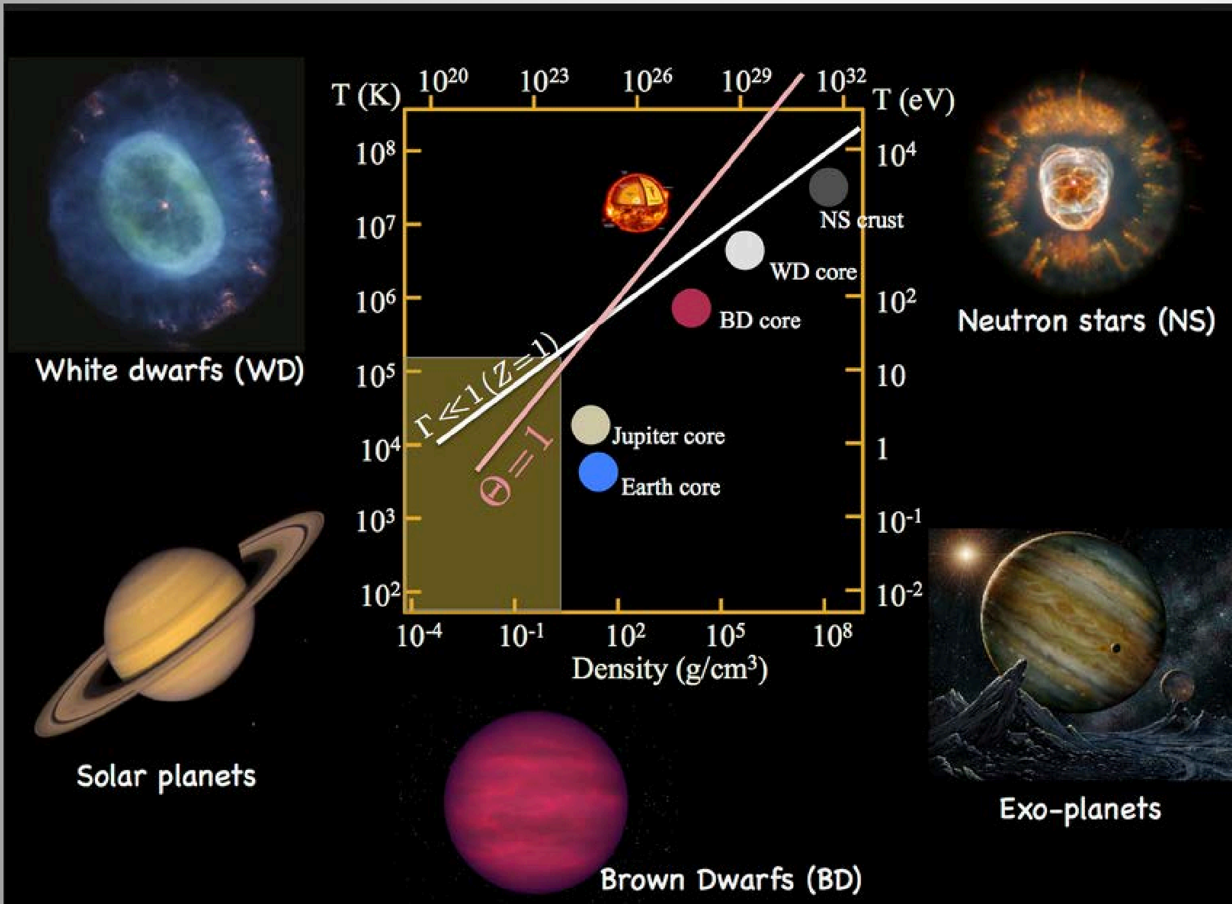
Outline

- Motivation-why pursue Extreme Difficult, …

- Opacity-The focus of this presentation
  - The emission campaign-a different method to determine opacity
  - Ionization depression-what happens to bound states as plasma density increases
- Even more difficult-Thermal conductivity
  - An idea in the works
- Summary

Extremely difficult

Stellar interiors can cover a wide range of plasma conditions



$$\Gamma_{ab} = \frac{Z_a Z_b e^2}{kT}\left(\frac{4\pi\ n}{3}\right)^{1/3}$$

Plasma coupling

$$\lambda_a = \sqrt{\frac{2\pi\ \hbar^2}{m_a kT}}$$

Thermal deBroglie wavelength

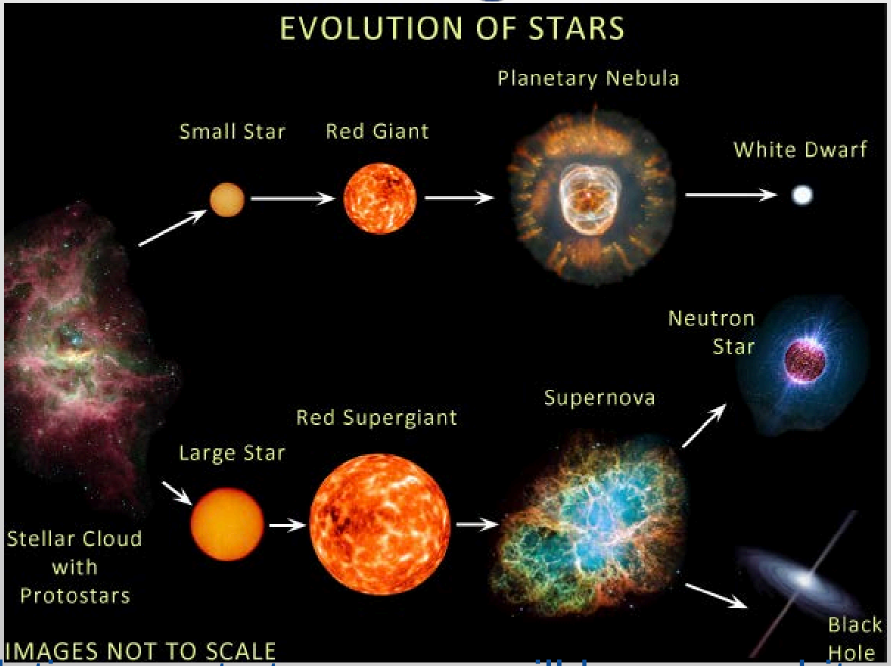
$$\frac{1}{\lambda_D^2} = \frac{4\pi\, e^2 n_e}{kT_e} + \sum_i \frac{4\pi\, Z_i^2 e^2 n_i}{kT_i}$$

Debye length

n	T	λ_D	R_{ion}	ω_P
10^{24}	1keV	7.4×10^{-8}	2.4×10^{-9}	9.0×10^{15}
10^{14}	10eV	1.5×10^{-4}	1.4×10^{-5}	6.0×10^{11}

Extremely difficult

Understanding transport in stellar interiors can impact our understanding of the Universe



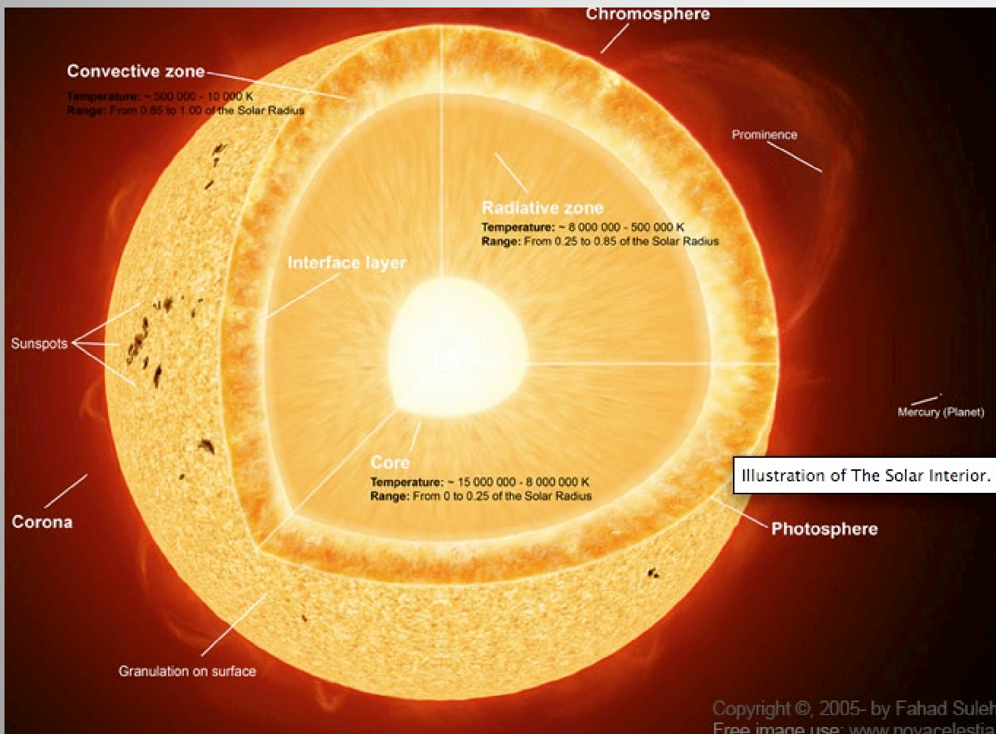
- General star population-most stars are or will become white dwarfs
- Age-luminosity curve is used to “date” the galactic disk (and star clusters in general)
- Age models have a strong dependence on radiation cooling rate
- Estimates suggest as much as a 30% error due to uncertainty in opacity (Wood, *White Dwarfs*, pg. 41-45-1994)

Stellar evolution is could play a role in interpreting the age of the Universe

Let's look at a typical M-class star

Our star (the Sun) is such a star.

In general, a star's cooling rate is dictated by the loss of radiation at the surface.



Location in Sun	Temperature (K°)	Density (g/cm^3)	Γ_{ii}
Core	13,600,000	150	0.08
Radiative	7000000-2000000	0.2	0.09-0.07
Convection	5700	0.2	23
Corona	~2000000	1e-11	1e-5

The metallicity of the Sun is 0.0122. Moderate and high Z elements diffuse toward the surface from radiation pressure and convection cooling. The opacity of the moderate and high Z elements dictates the cooling of a typical (M-class) star.

Physics data is required to understand the evolution of stellar material

- Energy escapes stars in the form of charged particles, neutrinos, (but mostly) by radiation

- Energy transport through the star is described by*,

$$\frac{dT_{TC}}{dr} = -\frac{1}{\mu}\frac{l}{4\pi r^2}$$ → Energy transport from conduction

$$\frac{dT_R}{dr} = \frac{3\kappa\rho l}{64\pi r^2 \sigma T^3}$$ → Energy transport from radiation

$$\frac{dT_C}{dr} = \left(1 - \frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr}$$ → Energy transport from convection

$$r = radius,\ \mu = thermal\ conductivity,\ \rho = density$$

$$\gamma = {}^{c_p}/_{c_v}\ (adiabatic\ index),\ P = pressure$$

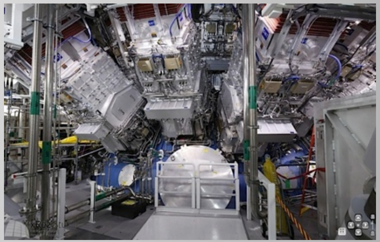
*C. Hansen, et al, *Stellar Interiors* (2004)

Opacity and thermal conductivity are needed to solve the equations for stellar structure

Painful to analyze

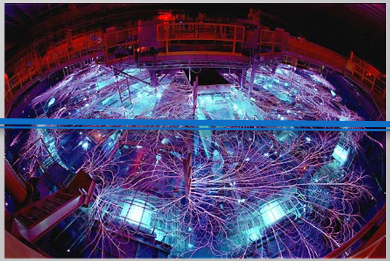
Recent laboratory experiments could provide a path to generating physics data in near astrophysical conditions

- Experiments currently being performed at large laser facilities, pulse power facilities, and XFELs are providing data in these difficult plasma physics regimes.
  - Large scale laser facilities (e.g., ~~NIF~~, ~~Omega~~, Orion, etc)



  - XFELs (e.g., LCLS)

  - ~~Pulse power facilities (e.g., Z Sandia)~~



Experiments from Orion and the LCLS will be discussed

How are opacities are calculated ?

1. **<u>Need plasma conditions</u>**!!
2. Need a theory of atomic structure:
   a. Determine all the energy levels, ionization potentials (and wave functions for each energy level)-Hartree-Fock

3. Calculate all the oscillator strengths of all possible transitions

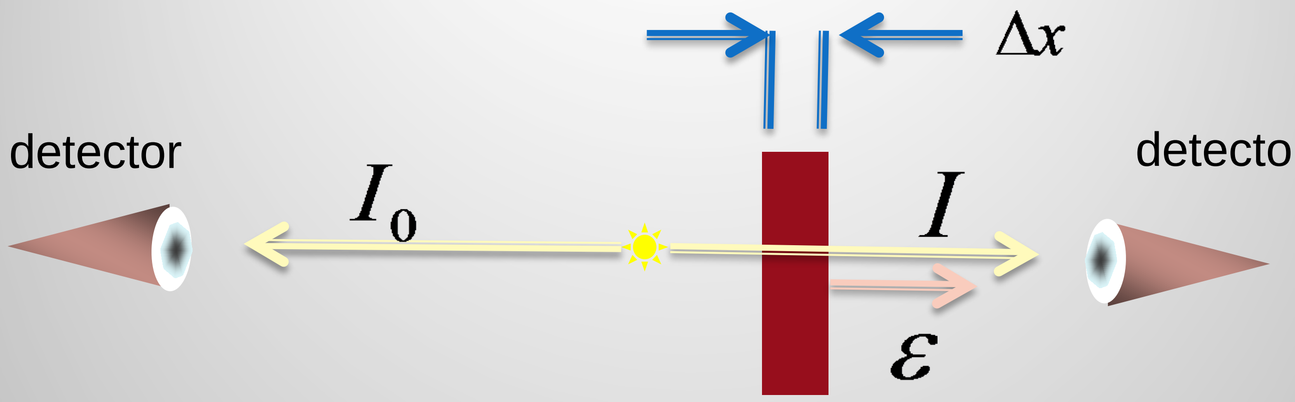
1. Calculate all photoionization cross sections

1. Calculate all free-free cross sections

2. Calculate the line-broadening of each transition

These calculations can be challenging and need to be bench-marked with good experiments

What's needed to measure opacities?



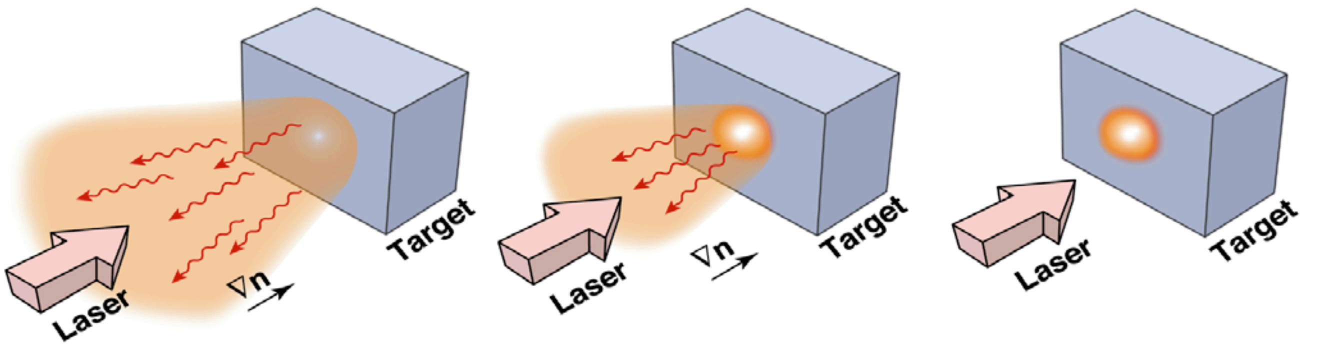
$$I = I_0 e^{-k_\nu \Delta x} + \varepsilon$$

1. Must know plasma density and temperature!
2. Plasma emissivity
3. MINIMAL SPATIAL AND TEMPORAL GRADIENTS!

Gradients in the plasma conditions can lead to large uncertainty in the measured opacity

Painful to analyze

Short pulse laser heated solids use the target's inertial mass to maintain high density during heating



Long pulse (~1 ns)

- Long gradient scale lengths
- Heating during expansion leads to high temperature Coronal plasma

Short pulse (~100 ps)

- Shorter gradient scale length
- High temperature during expansion leads to high temperature Corona and high temperature critical surface

Very short pulse (<1 ps)

- Short gradient scale lengths
- Heating with little or no expansion

Measure high temperature opacity using emission spectroscopy

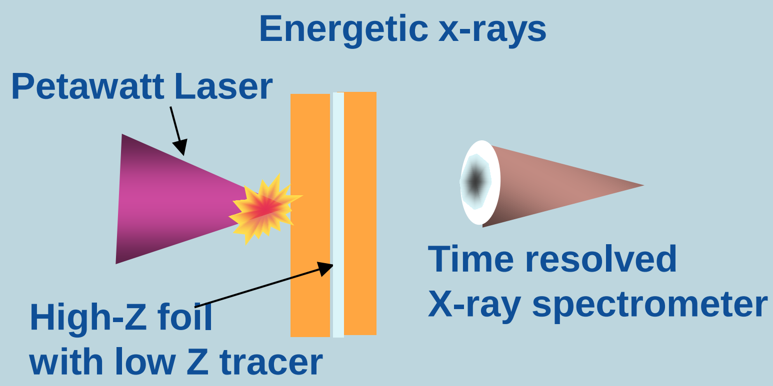
It is inherently difficult to measure opacities at large T and ρ

- Difficult to create uniform plasmas (i.e., small spatial gradients)
- The back-lighter must be fairly featureless and brighter than the source
- Measurements must consider the temporal evolution of the source and back-lighter
- To understand the physics, detailed spectral features must be resolved

Improving code opacities will require "new" approaches

In equilibrium, Kirchhoff's law states,

$$\frac{\varepsilon_\nu}{\kappa_\nu} = \frac{2h\nu^3}{c^2} e^{-h\nu/kT} \text{ or } \kappa_\nu = \frac{\varepsilon_\nu c^2}{2h\nu^3} e^{-h\nu/kT}$$

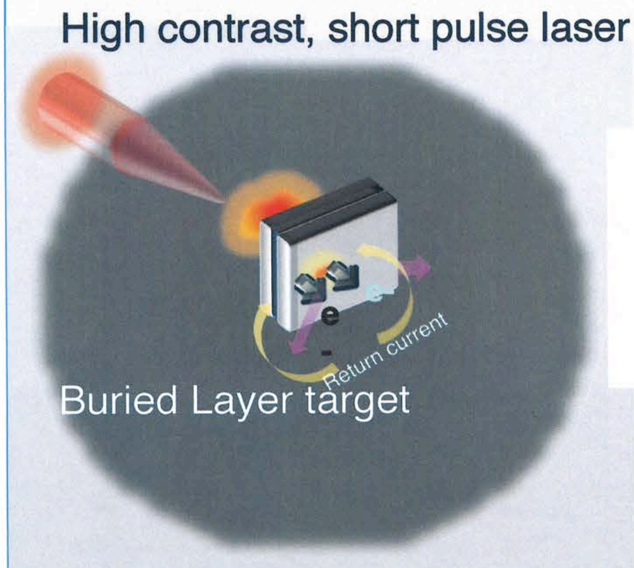


Short pulse laser heated buried layers can be used to create conditions for near LTE opacity measurements

Our initial task is to evaluate the viability of producing usable opacity data using short pulse laser heated buried layers

Technique

Short-pulse buried layers generate non-thermal electrons that lead to high temperature, high density plasmas



$$J_C = -J_h = \sigma.E$$

$$\frac{\delta B}{\delta t} = -\nabla \times E = \nabla \times \left(\frac{J_h}{\sigma} \right)$$

Basic Idea

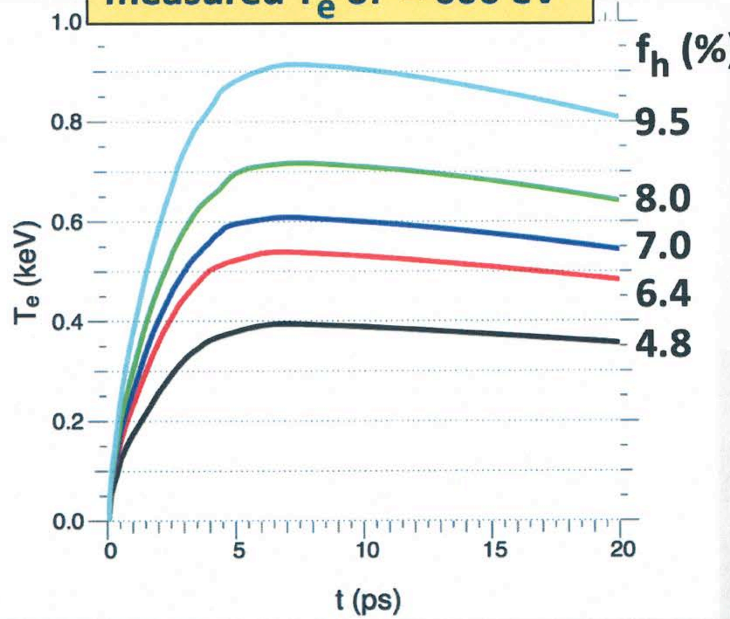
- High intensity, laser-solid interaction generates non-thermal electrons
- Streaming electrons and return current heats buried layer
- Tamp keeps layer dense

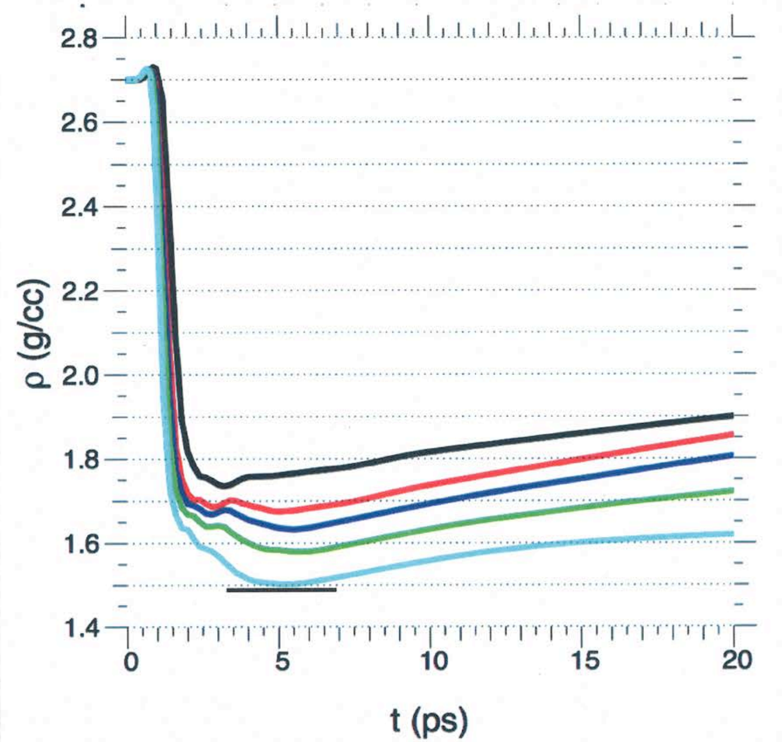
Proof of principle experiments were performed on HELEN-Brown et al,PRL 106, 185003 (2011)

Technique

Layer temperature vs. time for various values of the hot electron fraction

f_h of 7% matches the measured T_e of = 600 eV



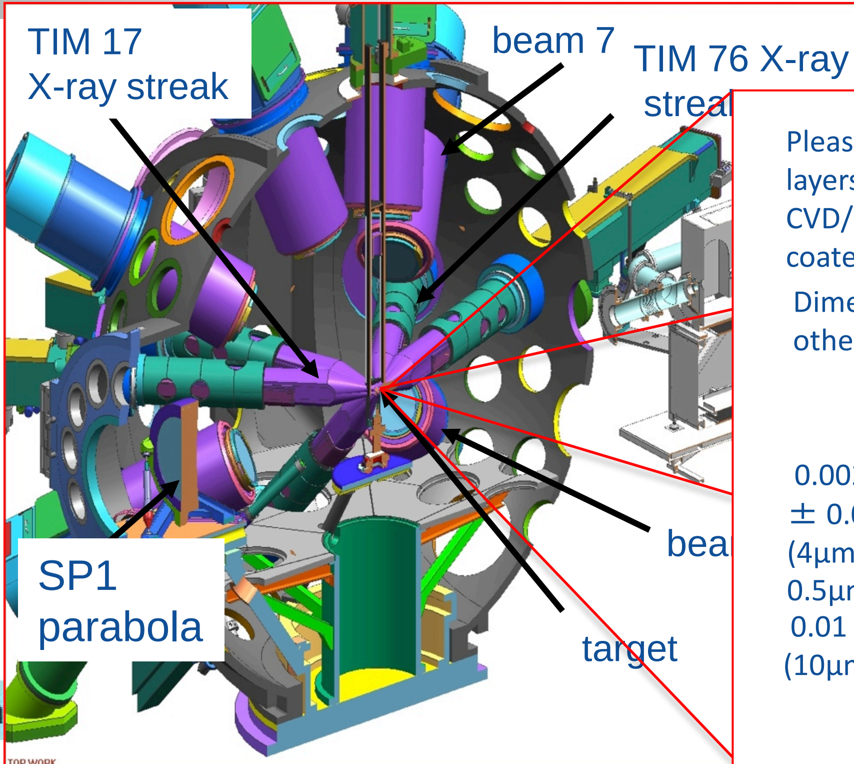


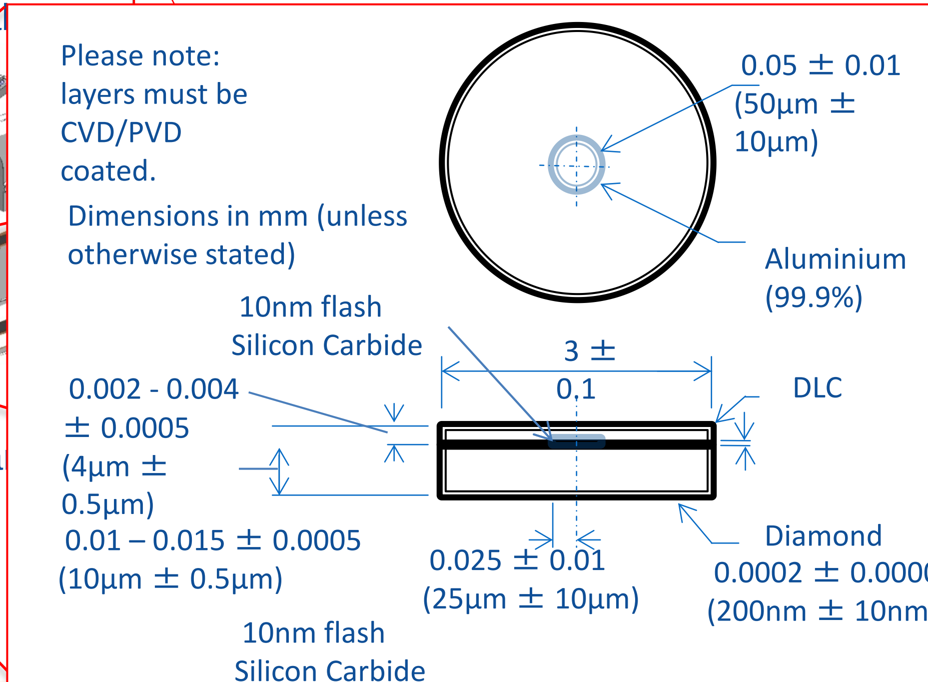
1D Lasnex calculations by Rich London

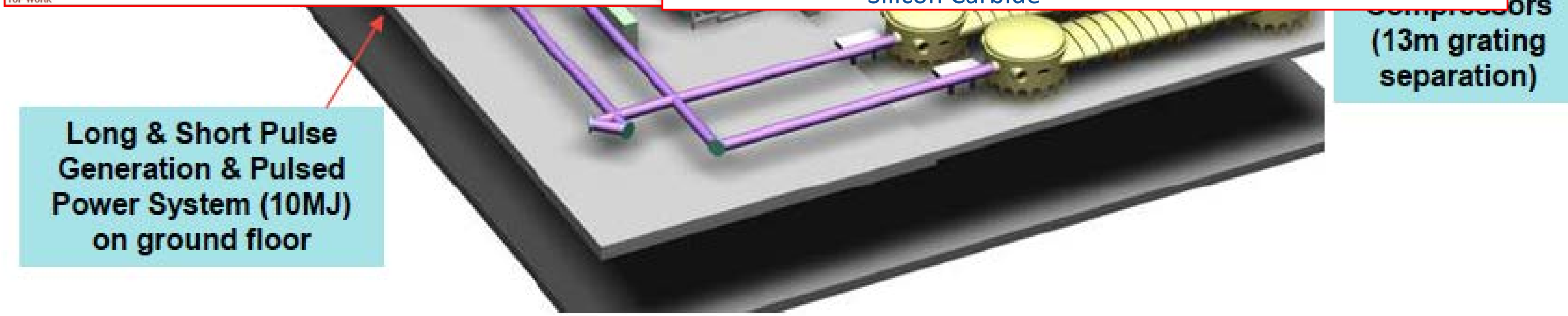
measured ρ = 1.5 ±0.5 g/cc

Painful to analyze

Orion allows for higher short pulse laser heating and ...n than HELEN or TITAN

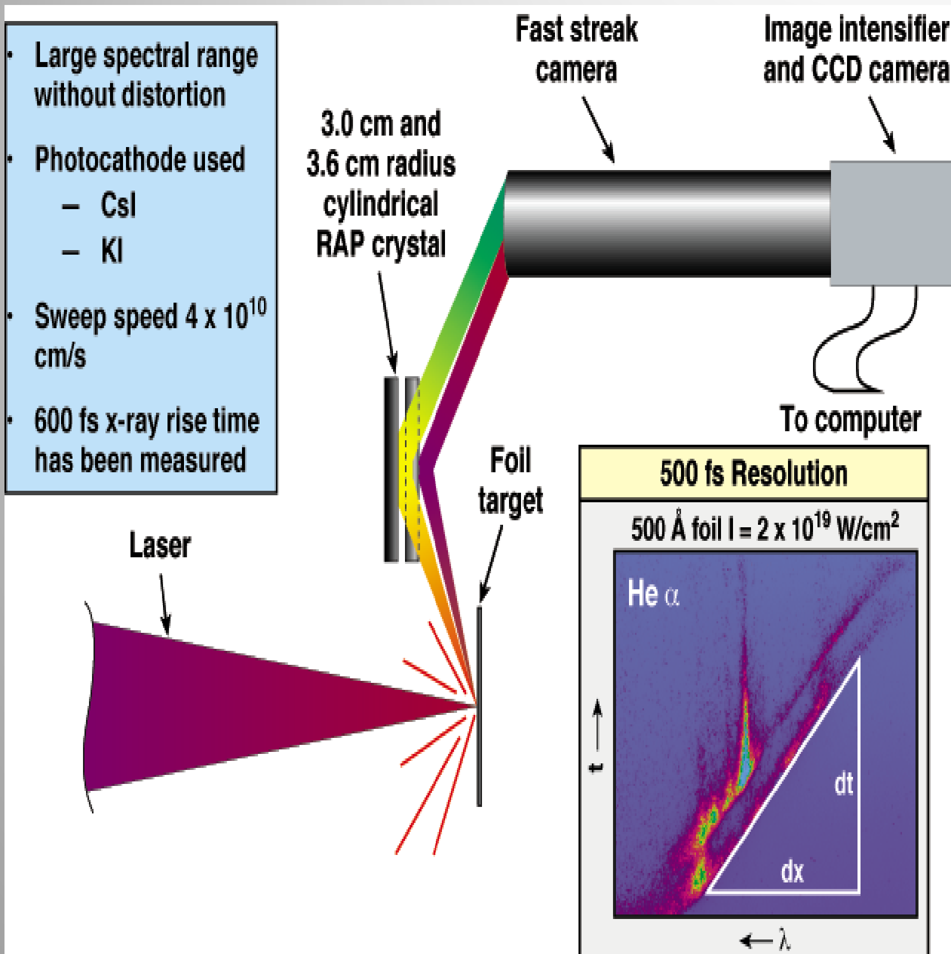




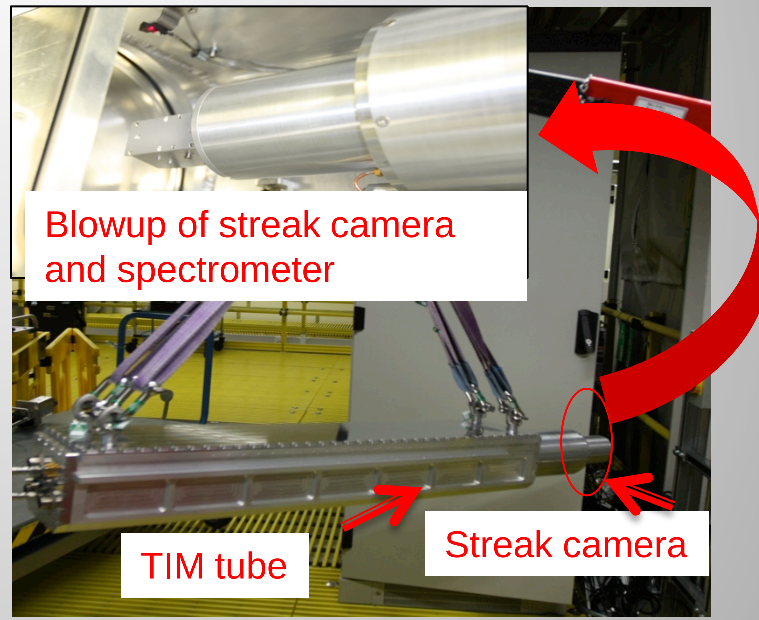


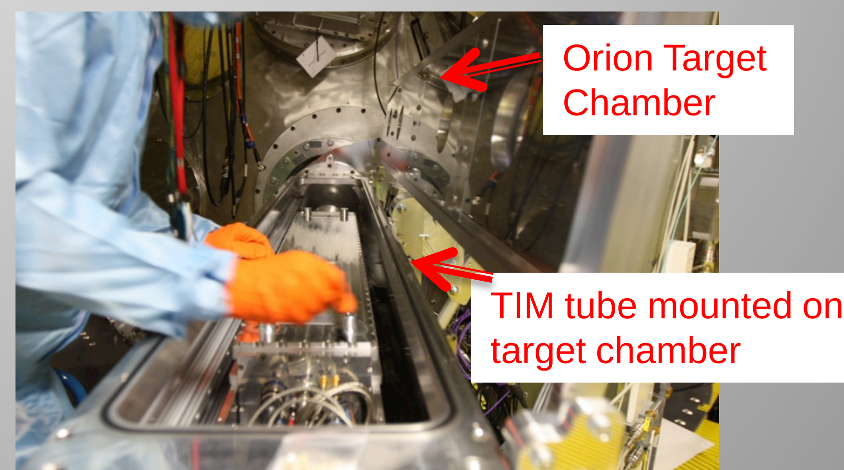
Painful to analyze

The transient nature of short pulse laser heated targets requires picosecond time resolution



Sample aluminum data taken at LLNL with the LLNL TREX x-ray streak camera





Painful to analyze

How are plasma properties extracted from x-ray spectroscopy?

In 1-D $\rightarrow$ $\frac{d}{dx} I(\omega,x) = \varepsilon(\omega,x) - \kappa(\omega,x) I(\omega,x), \quad \varepsilon(x,\omega) = \frac{\hbar\omega}{4\pi} L(\omega,x) A_{nm}^{Z-1,a} N_m^{Z-1,a}$

In general (NLTE), the rate equations are solved to determine *N*. But consider LTE:

For T_e in LTE we ignore opacity,

$$I(\omega,x) = \left(\hbar\omega^2 r_0 / 2\pi c\right) f_{mn} N_m L(\omega,x)$$

- Saha Equilibrium suggests

$$N_m = \frac{n_n g_m \exp(-E_m/kT)}{g_n \exp(-E_n/kT)} = N_n \frac{g_m}{g_n} \exp[-(E_n - E_m)/kT]$$

- The ratio of line intensities is

$$\frac{I_a}{I_b} = \frac{\lambda_a^3}{\lambda_b^3} \frac{g_a}{g_b} \frac{f_a}{f_b} \frac{\exp[-E_a/kT]}{\exp[-E_b/kT]} = \frac{g_a}{g_b} \frac{f_a}{f_b} \frac{\lambda_a^3}{\lambda_b^3} \exp[-(E_b - E_a)/kT]$$

or

$$\boxed{kT = \frac{E_b - E_a}{\ln(I_a \lambda_a^3 g_b f_b / I_b \lambda_b g_a f_a)}}$$

For N_e line shape is calculated

$$I(\omega,x) \propto L(\omega,x) = \int L_{Stark} L_{Doppler} \, d\omega dx$$

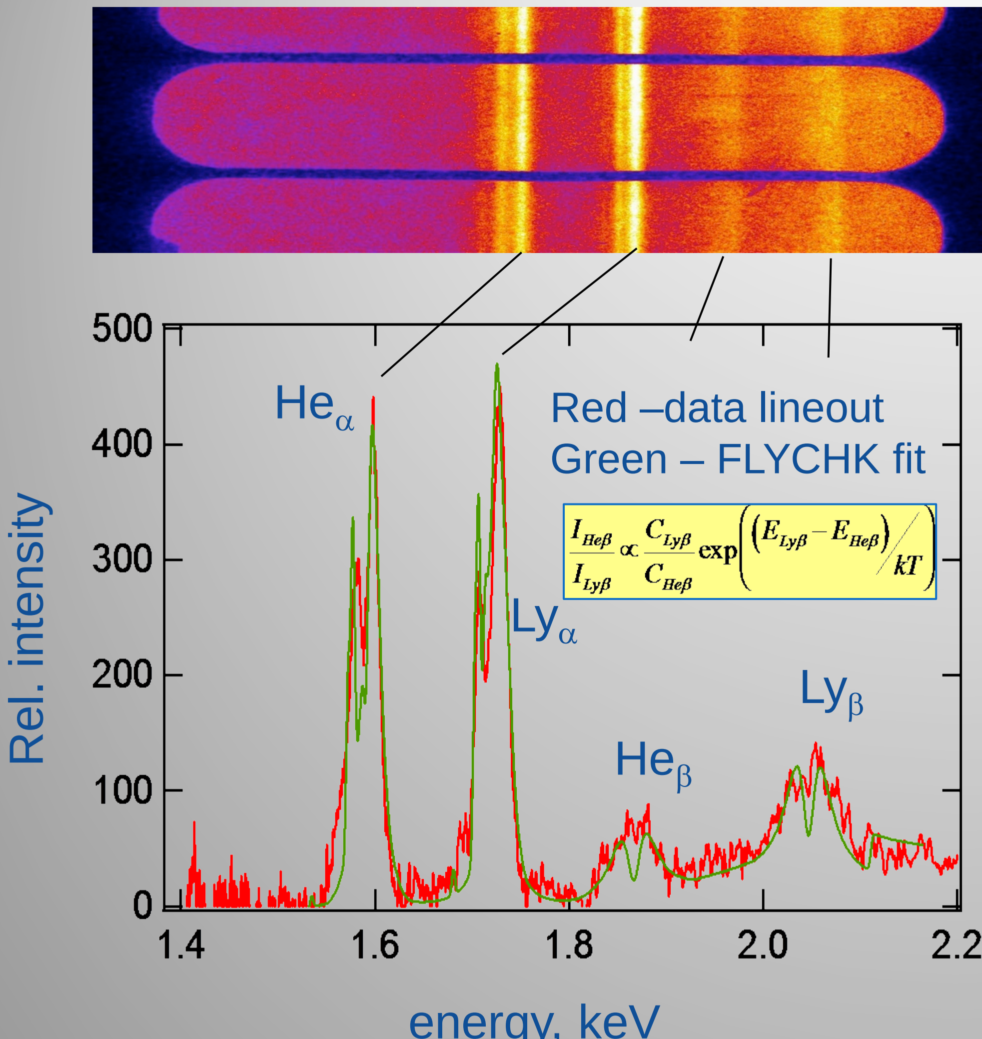
- Stark width is used to determine N_e

$$L_{Stark}(\omega,x) = \int \underbrace{W_{mf}(\varepsilon,x)}_{\downarrow\, T_i} \bullet \underbrace{I_{impact}(\varepsilon,\omega,x)}_{\downarrow\, N_e} d\varepsilon dx$$

- Lines intensities and widths are fitted using a CR code. Density and temperatures are adjusted until a “good” fit is achieved

Exciting (??)

ORION commissioning experiments have been used to gather preliminary data



Time integrated data collected using short pulse heating/long pulse compression

Target:
12µm CH/0.2µm Al/10µm CH

Shock compression by two Orion 0.5ns beams.
Short pulse heating 100J,
2ω, 0.6ps.

Compressed plastic data – FLYCHK fit indicates **6g/cc, 550eV**

Error propagation suggests a 50% error in the intensity ratio leads to 10% error in the temperature

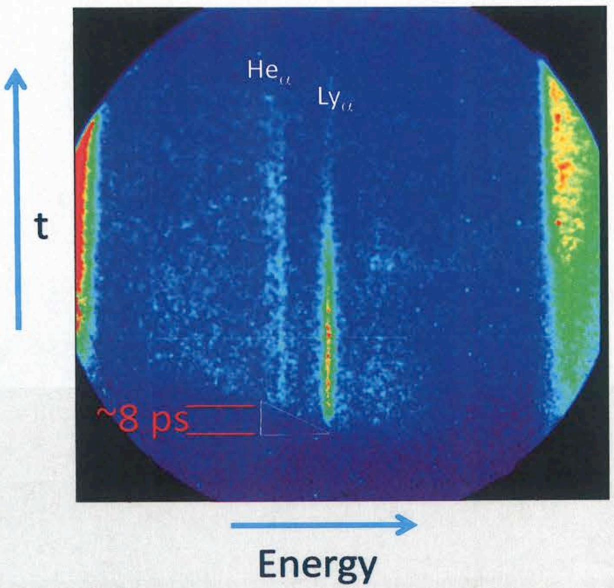
Long pulse compression/short pulse heating has been successfully demonstrated

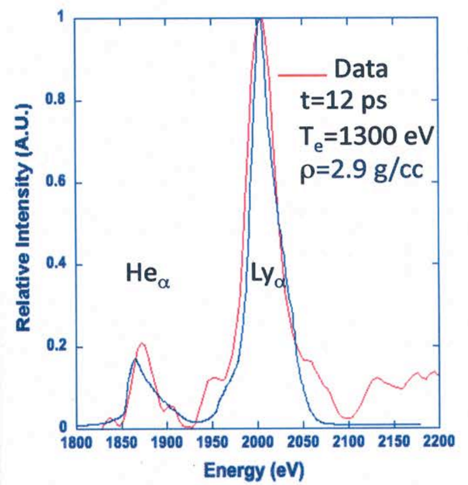
The plasma conditions(ρ, T_e) are the **highest** we've achieved for an opacity platform

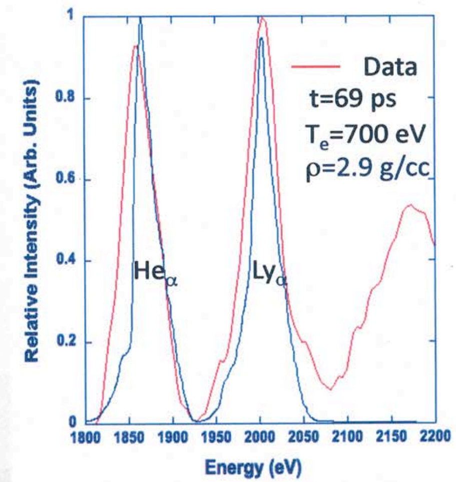
Si

Time resolved temperature results illustrate a more detailed picture of the temperature evolution

- The LLNL-TREX streak camera was used to document the temporal evolution of the plasma characteristics







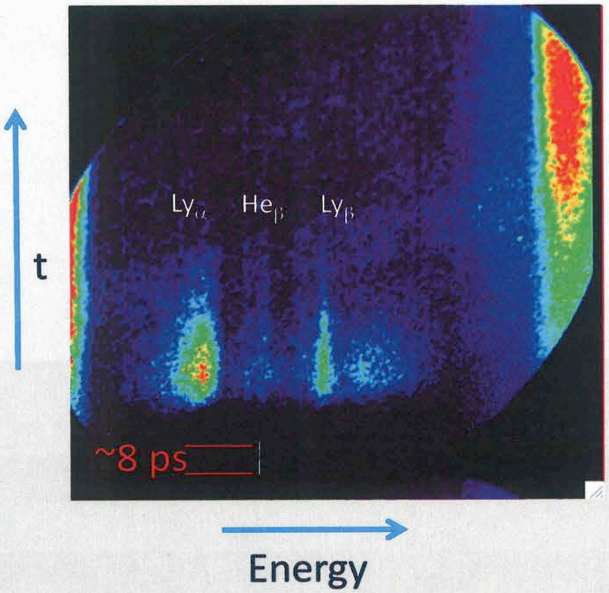
Target: 8µm Pary N/0.1 µm Al/ 11µm Pary

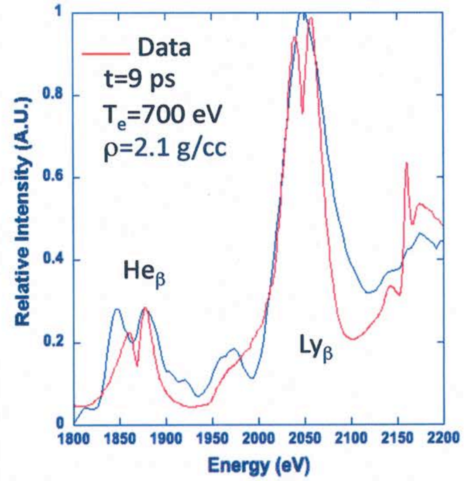
Laser conditions: 5 x 10^{19} W/cm^2

The time-resolved data suggest the plasmas reach a higher peak temperature than the time integrated data suggest

Time resolved data collected at a lower laser intensity to acquire data at a lower peak temperature

Target: 5µm CH/0.2µm Al/2µm CH



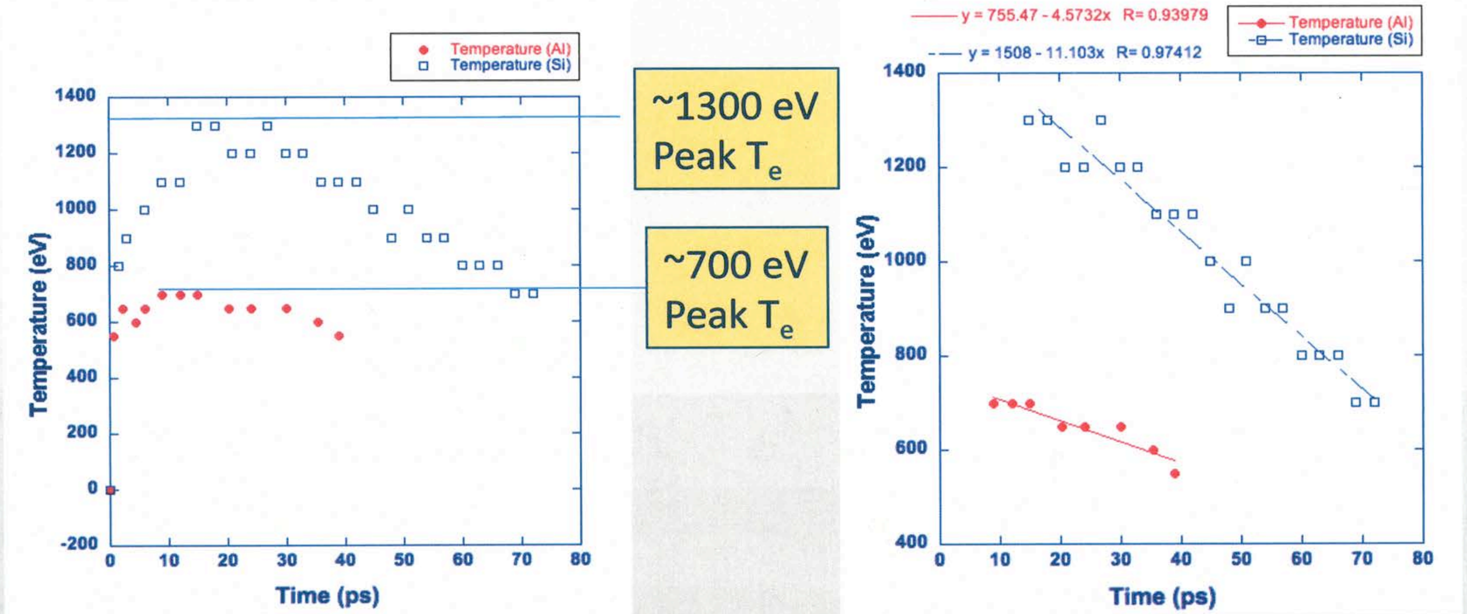


Laser conditions: 7 x 10^{18} W/cm^2

At lower focused laser intensity, the data shows a lower peak temperature

Using FLYCHK fits for a high intensity and moderate intensity shot, we have tracked the temporal evolution of the target

- The peak temperature is changed by varying the laser intensity



- Lower peak T_e results in slower cooling time

Simulations are still in process but what are the general scaling laws?

- Radiation- No simple scaling law, but for high T we expect

$$T_R = T_{ff} + T_{fb} + T_{bb}$$
$$\propto \frac{Z^2}{t^2} + \frac{Z^2 N_a}{t^{2/3}} + \frac{N_a}{t^{2/3}}$$

Griem, Plasma Spectroscopy, pg 193-198

- Hydrodynamic-

$$T \propto \frac{1}{t^{2/3}}$$

Shepherd, et al, J.Q.S.R.T., vol. 58, no 4-6, 1997, pg 911-916

- Thermal Conduction-

$$\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\chi\frac{\partial T}{\partial x}, \qquad \Rightarrow T \propto \frac{1}{t}$$

Zeldovich and Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, pg 657-668

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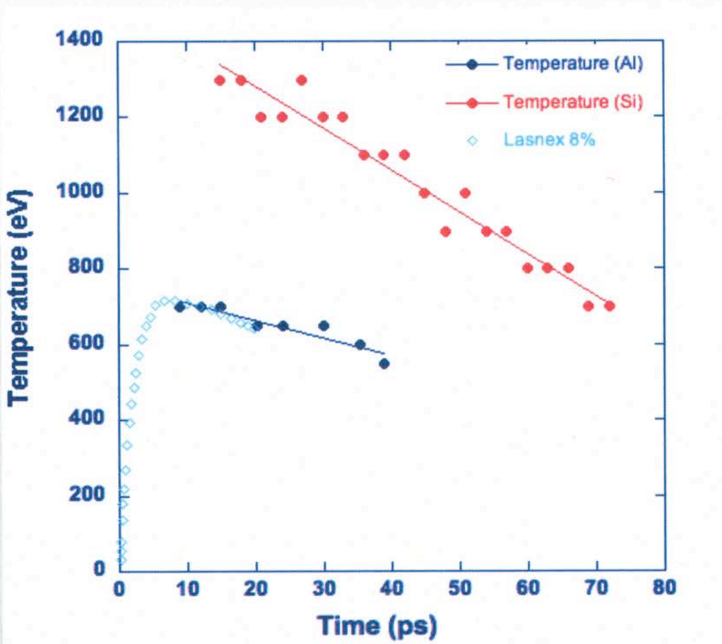
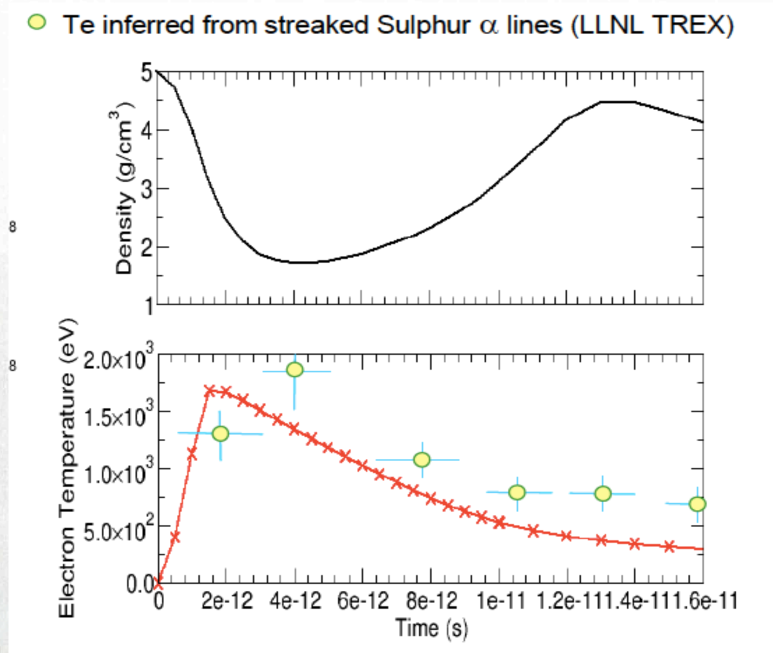
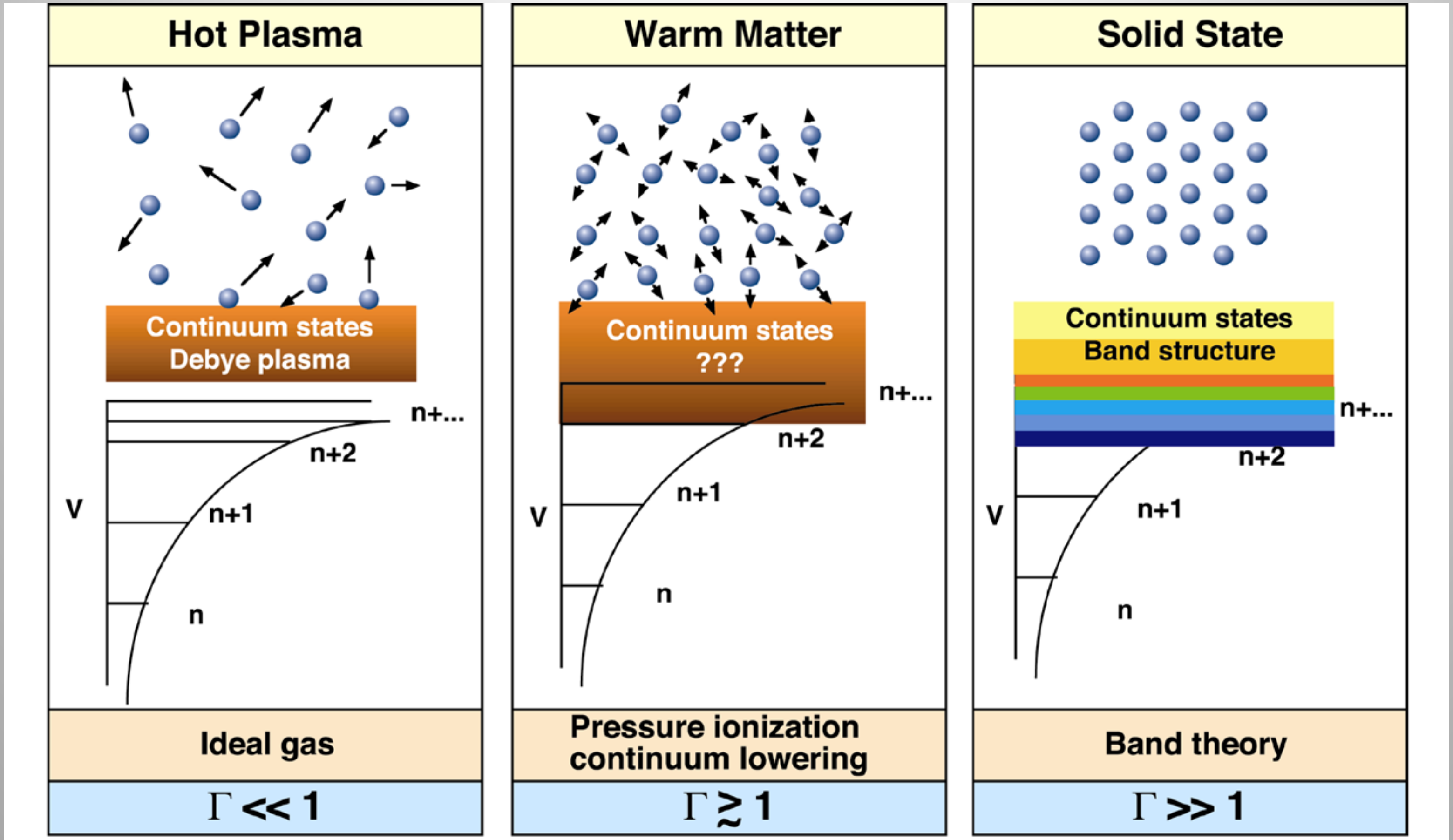
Rad-Hydro codes suggest a slightly faster cooling rate

- Preliminary results show reasonable agreement, but there are a couple of observations:
  - Lasnex with 8% fast electrons does a reasonable job out to 20 ps
    - Simulations were not for the exact conditions
    - Electrons are released at the tamp boundary at t=0
    - Disagreement seems to increase later in time
    - Currently working on detailed simulations





How does density affect bound states in plasmas??



Although there are several theories to predict the effects of correlations on bound states, little experimental data exist in this regime

Two models were compared at systematically increasing plasma density

The expression for continuum lowering (hydrogenic system)*

$$\Delta E_{SP} = \left[\left(\frac{6e^2}{r_D kT}+1\right)^{2/3} - 1\right]\frac{kT}{4},$$

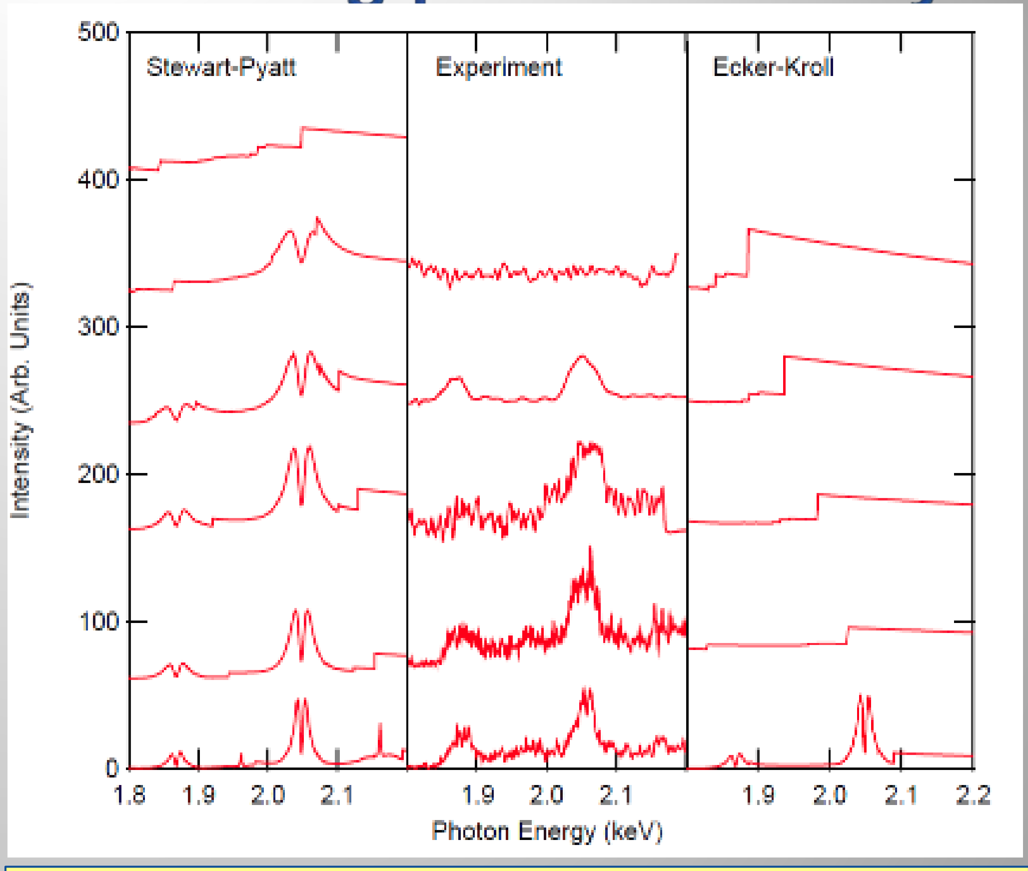
$$\Delta E_{EK} = \begin{cases} e^2/r_D & \text{when } N \le N_{CR} \\ G_K e^2/r_W & \text{when } N > N_{CR} \end{cases}, \text{ where}$$

$$r_W = \left(\frac{3}{4\pi N}\right)^{1/3}, \; r_D = \left(\frac{kT}{4\pi e^2 N}\right)$$

$$G_K = \frac{2.2\left(N_{CR}e^2\right)^{1/2}}{N_{CR}^{1/3}\left(kT\right)^{1/2}}$$

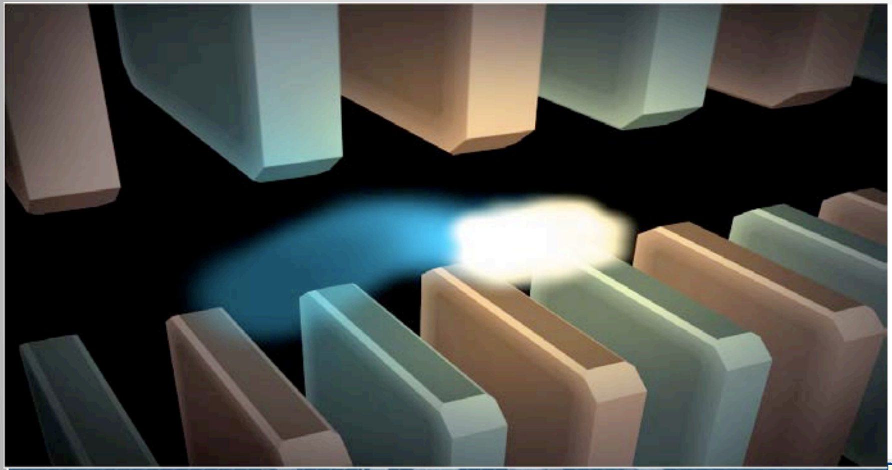
$$N_{CR} = \frac{3}{4\pi}\left(\frac{kT}{e^2}\right)^3$$

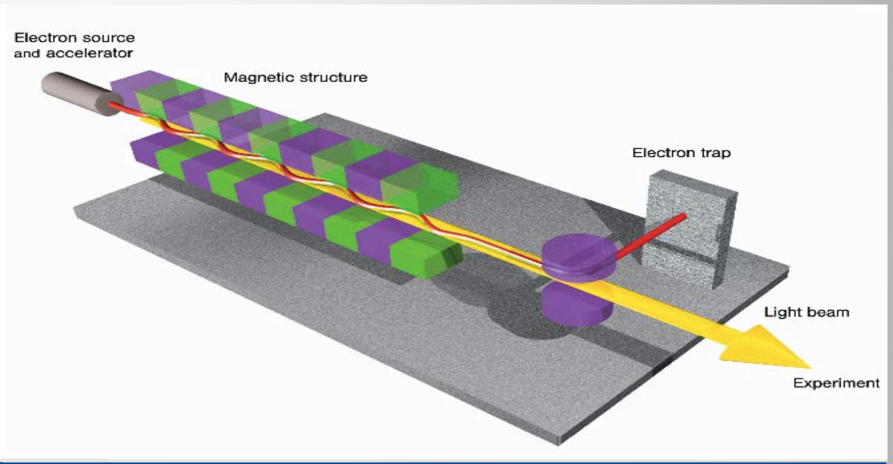
* J. A. Kunc, et al, Astro. Journal **396**, 364-368 (1992)

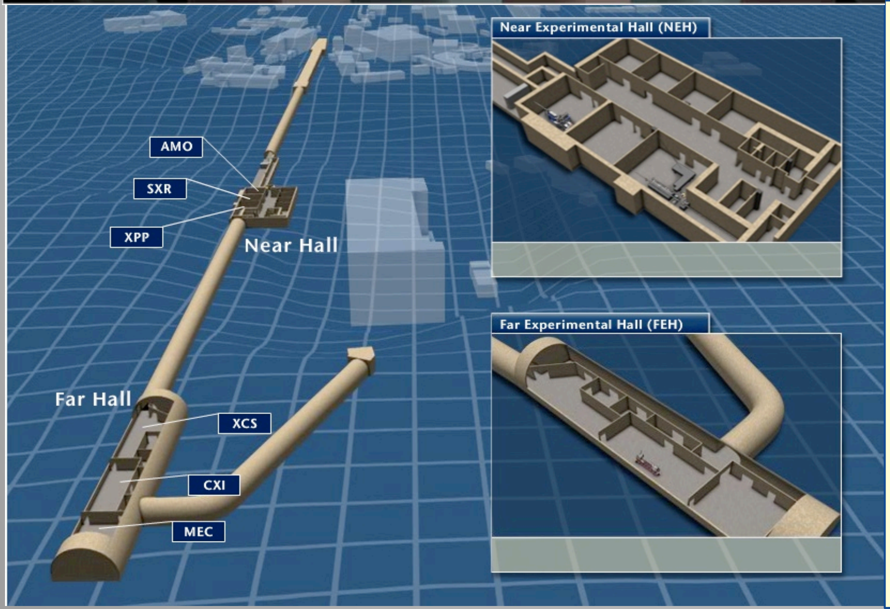


There are other models (e.g., Debye-Huckell) but most have “hard cutoff”. In general, wave functions slowly become non-discrete approaching the continuum. Proper calculation would use a code like “Purgatorio”.

The Linear Coherent Light Source (LCLS) offers great possibilities to explore plasmas in a unique way







- Free electron laser
- Photon energy-480 eV-10 keV !
- Bandwidth- 0.2-0.5%
- Energy per pulse-2-3 mJ (as high as 4 mJ)
- Pulse length- 60-80 fs!
- Repetition rate- 120 Hz.

Experiments at LCLS suggest the most commonly used continuum lowering model SP is incorrect

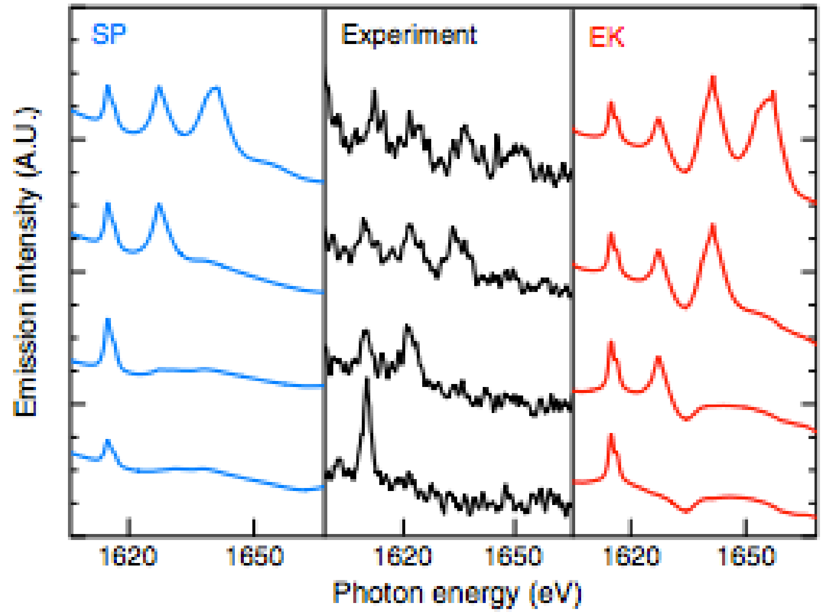
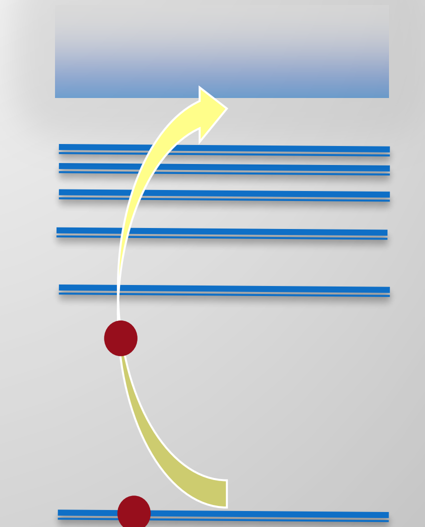


FIG. 3 (color online). Observation of the *K*-shell fluorescence corresponding to initial states with double core holes, along with SCFLY simulations using the SP and EK models. From the bottom, the spectra correspond to 1720, 1750, 1780, 1805 eV pump photon energies.



1. XFEL heats thin solid

1. Tune XFEL to photo-pump electrons from ground state to upper states

The future …

1. Data from materials important for radiation transport in stellar interiors (e.g., Fe).

2. Can we resolve the differences in the two ionization potential experiments.

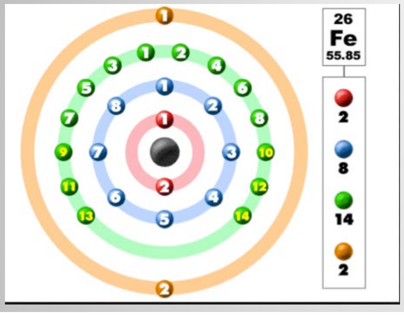
3. Measure of thermal conductivity ??

Can we use ramp compression to study CL or pressure ionization in dense plasma??

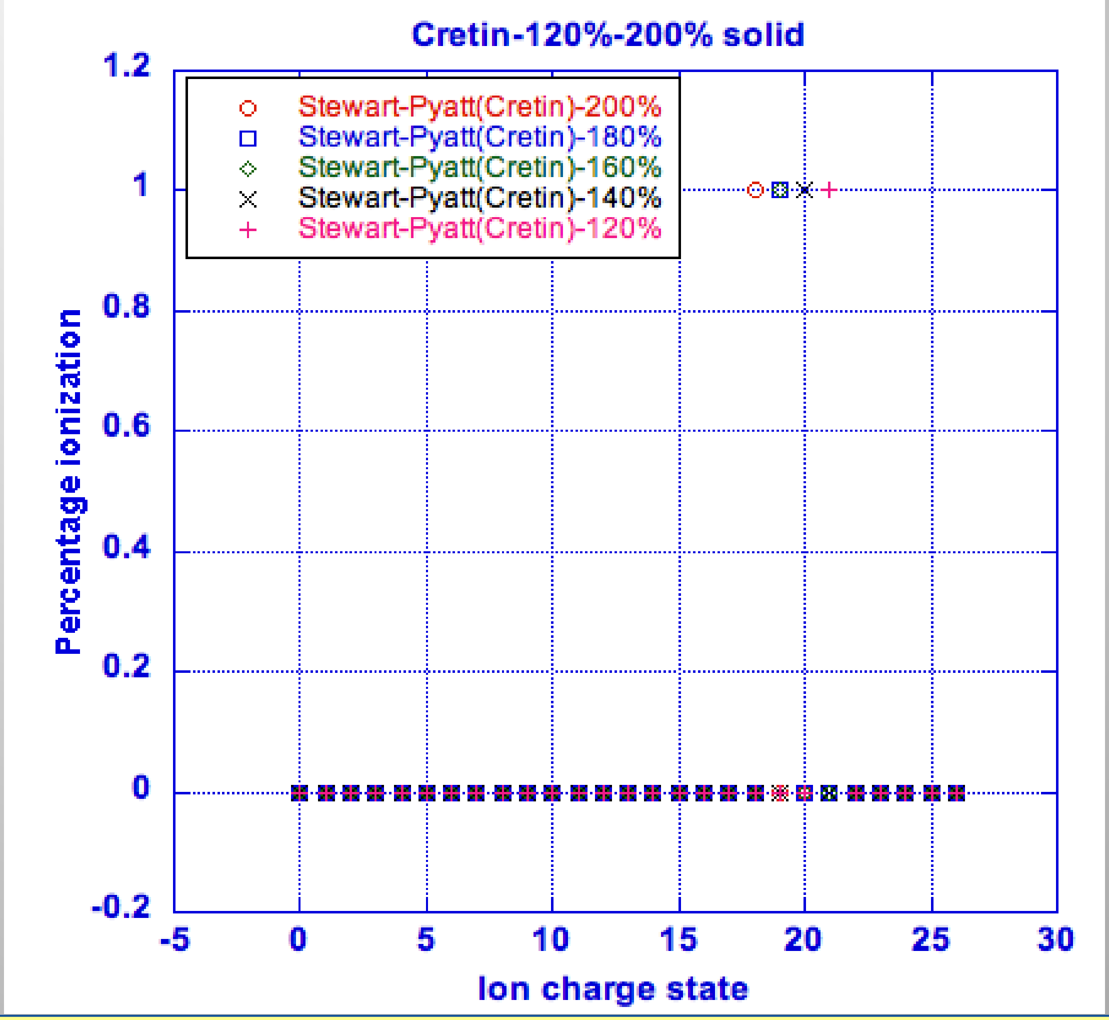
- Idea was to see it there is an ionization effect due to increased pressure.
- Does Stewart-Pyatt predict a different ionization balance than Eckart-Krol?
- Pressure increase was simulated in material by increasing the mass density
- Simulations done on Fe (planetary science and astrophysically relevant) with FLYCHK and Cretin
- Assumptions: Te=Ti= 2 eV background electron and ion temperature , Tr=0,(low background temperature eliminates ionization due to electron collisions), calculations performed non-LTE in both cases and the DCA atomic physics model for Cretin.
- 0-d so no radiation transport (probably not important)

First- Compare Stewart-Pyatt from FLYCHK and Cretin

Fe



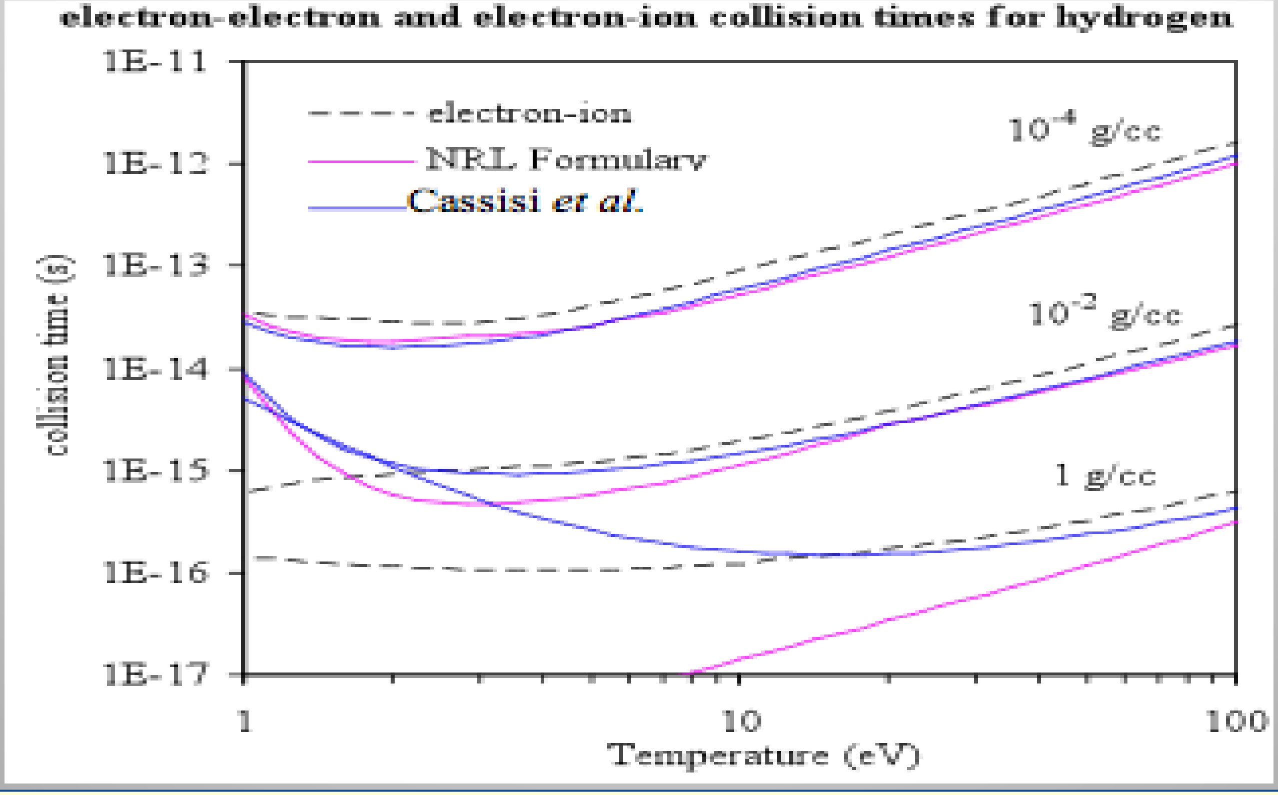
$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^6$



Model suggest ionization balance changes as pressure increases in solid (with no temperature ionization)

Theory comparisons suggest large variations in thermal conductivity in the WDM regime

$$\kappa = \frac{\pi^2}{3} k_B^2 T \frac{Z_i}{\Omega} \left\langle \frac{1}{\tau_\kappa} \right\rangle^{-1}, \quad \tau_\kappa = \left[1/\tau_\kappa^{ei} + 1/\tau_\kappa^{ee} \right]^{-1}$$

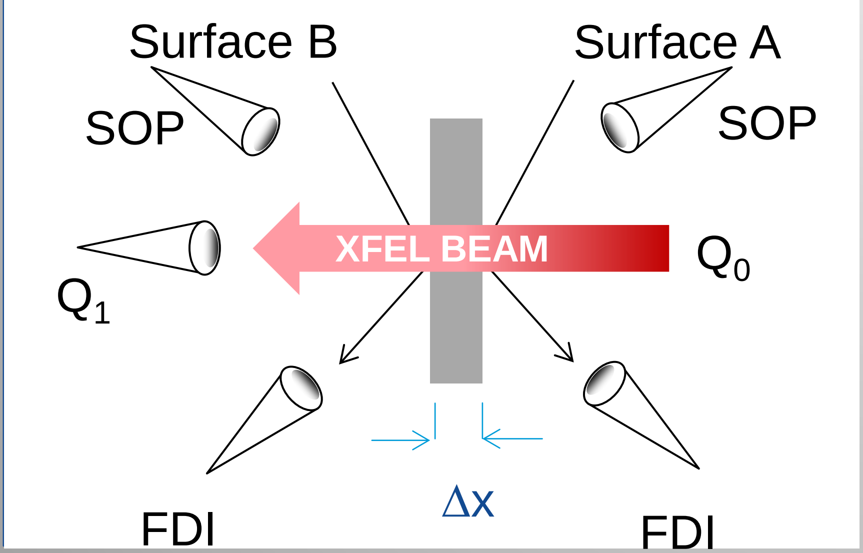


Differences in thermal conductivities determine by different theories vary greatly in the WDM regime

Technique: Thermal conductivity will be determined by imprinting a known temperature gradient in a sample

The XFEL beam is used to heat the sample

•**The attenuation of the XFEL or JLF beam deposits energy as $e^{-\mu\Delta x}$, resulting in a longitudinal temperature gradient.**



We will compare two methods of determining thermal conductivity

1. **Heat conduction equation**

$$\rho\, c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\kappa \frac{\partial T}{\partial x}\right],$$

$$assume\ T(x,t) \sim T(x)T(t)$$

$$\boxed{(Q_1 - Q_0)\bullet \frac{1}{T_{b1}} \frac{T_{b0} - T_{b1}}{t_1 - t_0} = \kappa \frac{T_b - T_a}{\Delta x}}$$

2. **Wiedemann-Franz law**

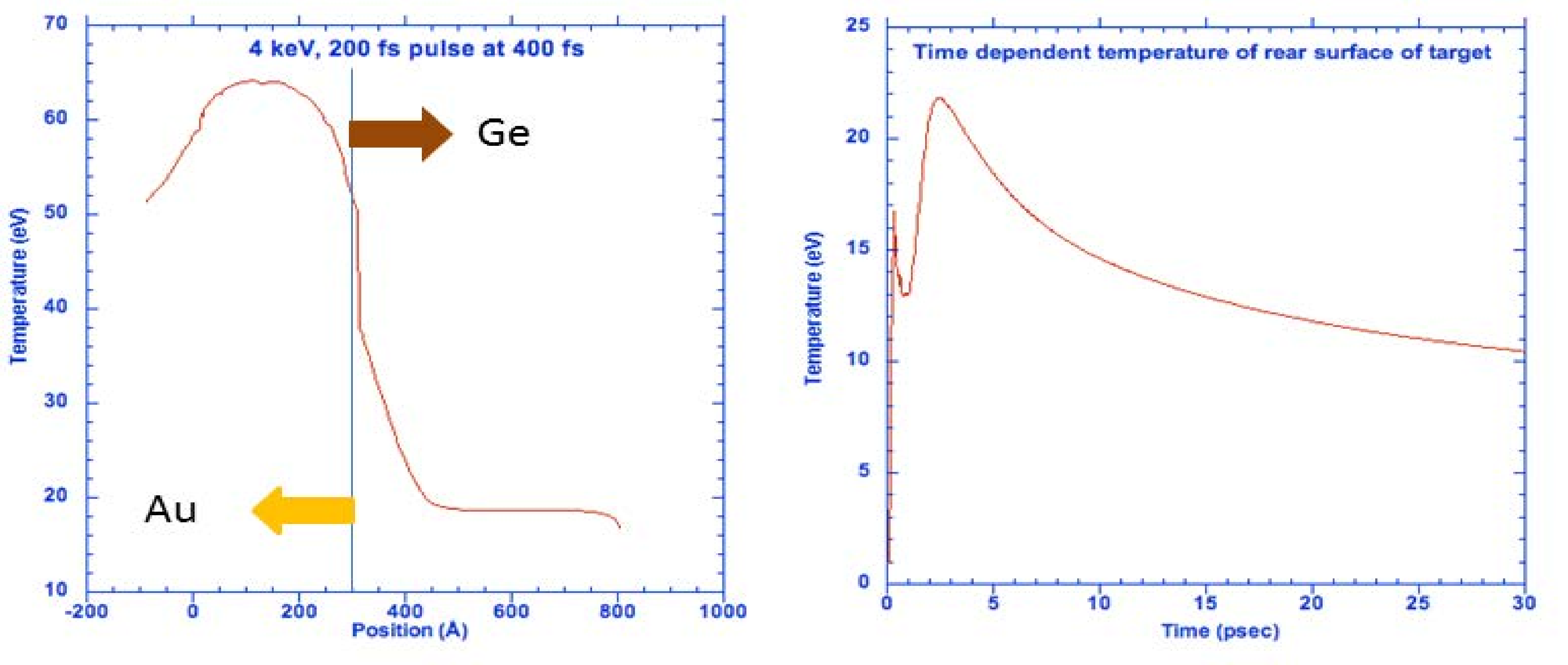
$$R_F = \frac{4\pi\sigma/\omega + 1 - 2(2\pi\sigma/\omega)^{1/2}}{4\pi\sigma/\omega + 1 + 2(2\pi\sigma/\omega)^{1/2}}$$

$$\boxed{\frac{\kappa}{\sigma} = LT,}$$

This project will provide the first data set for benchmarking models and codes in the unexplored regime.

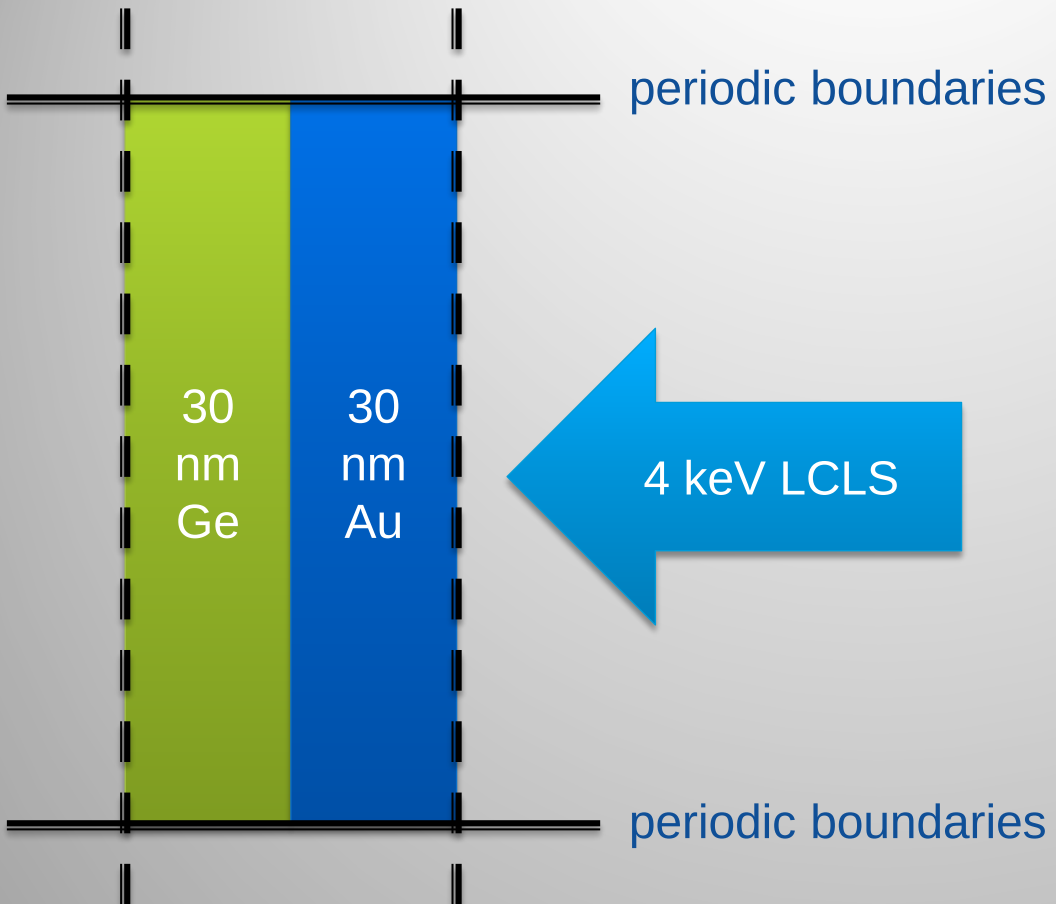
1-D simulation suggests measurable thermal transport between layers

- Simulation performed using HYADES
- Does not include Auger electrons



Rapid x-ray heating of a bi-layer sample provides a platform for measuring thermal conductivity

The effects of Auger electrons can be observed using a Monte-Carlo simulation



reflecting boundaries
(emulates Coulomb trapping)

Technique:

- Monte-Carlo model for x-ray absorption
- Monte-Carlo model for photo- and Auger-electron propagation (scattering and stopping)

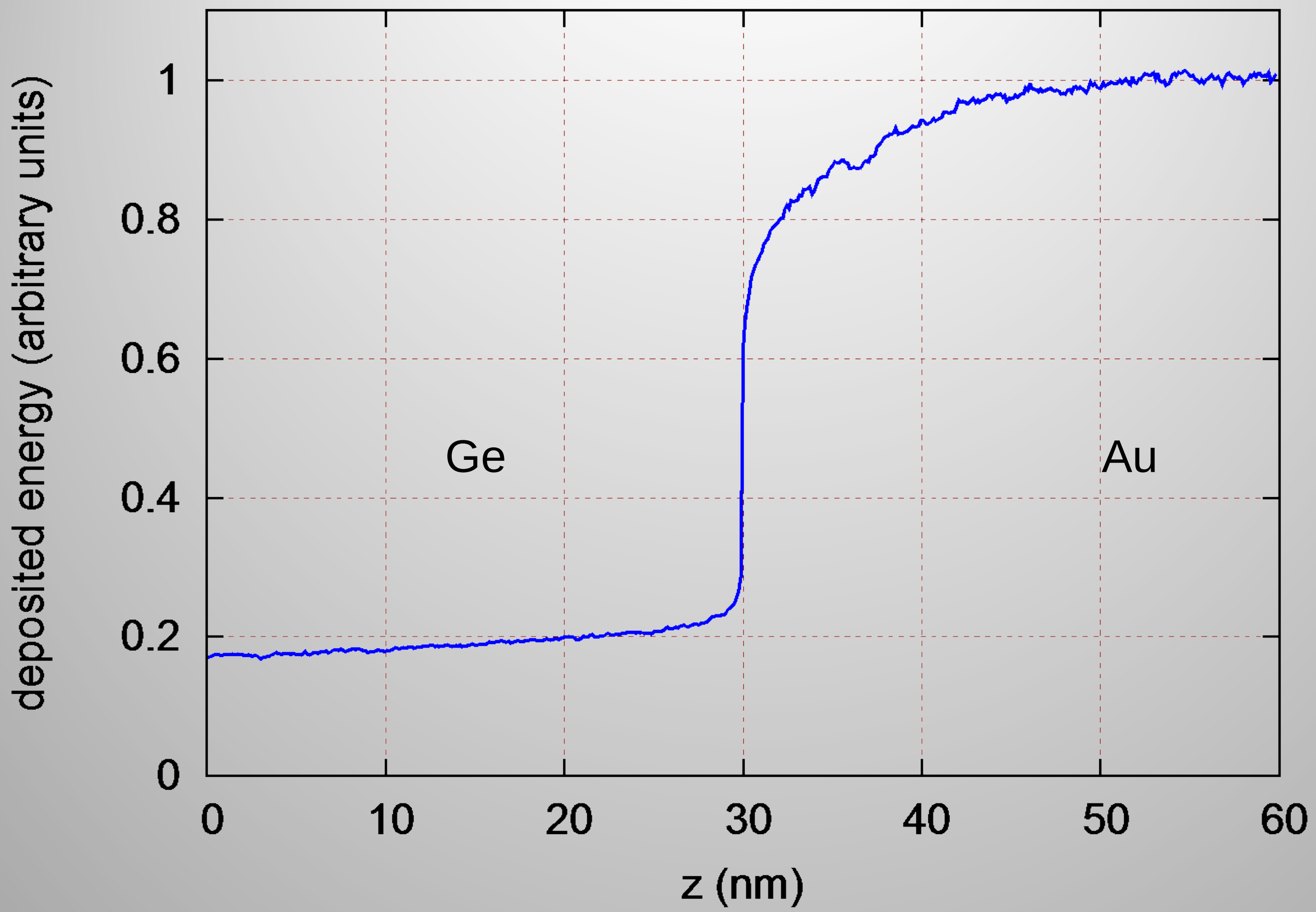
Assumptions:

- Emission direction of photo electrons is dipole
- Emission direction of Auger electron is uniform
- Cold material properties
- Charge trapping emulated by electron-reflecting surfaces
- Beam infinitely large

Some neglected effects:

- Charge trapping:
  - Finite size effect of the beam
  - Reflecting boundaries simplistic (a fraction of the electrons might even escape!)
- Heating of material during the pulse

Energy distribution in bilayers irradiated by LCLS pulses



Auger electrons have a minimal effect on the initial temperature gradient

Summary

1. Physics data (in **difficult** regimes) relevant to astrophysical conditions can be reached with new laboratory plasma experiments. In particular, opacity measurements and radiative cooling results are providing data for model comparisons in these difficult regimes

2. The experiments can be **painful** to perform and analyze. They require difficult, dynamic measurements.

3. The data is **exciting** because it could provide data that may answer long standing questions about the Universe.