Plasma and Warm Dense Matter Studies

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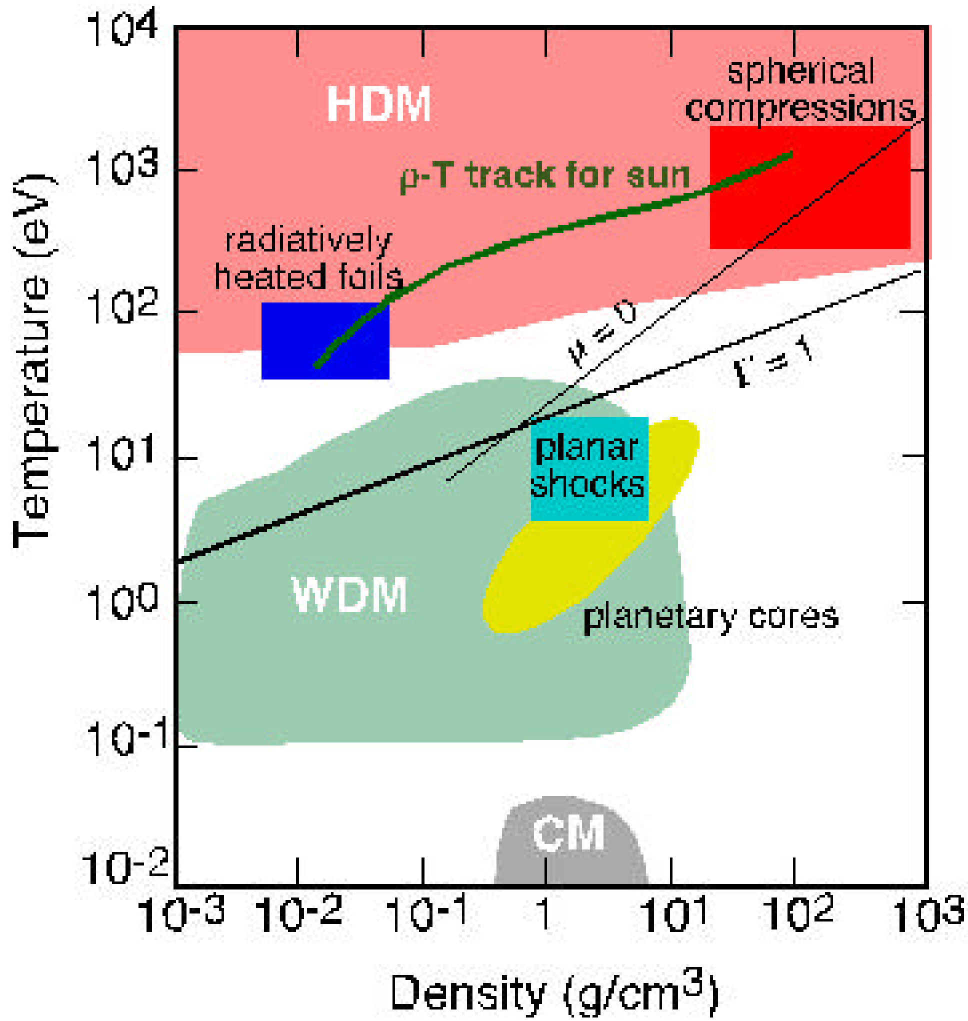
The Importance of these States of Matter Derives from their Wide Occurrence

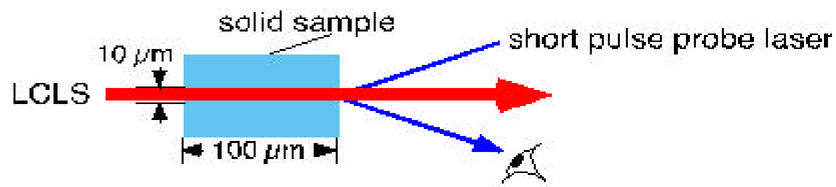
- **Hot Dense Matter (HDM) occurs in:**
  - **Supernova, stellar interiors, accretion disks**
  - **Plasma devices: laser produced plasmas, Z-pinches**
  - **Directly driven inertial fusion plasma**
- **Warm Dense Matter (WDM) occurs in:**
  - **Cores of large planets**
  - **Systems that start solid and end as a plasma**
  - **X-ray driven inertial fusion implosion**



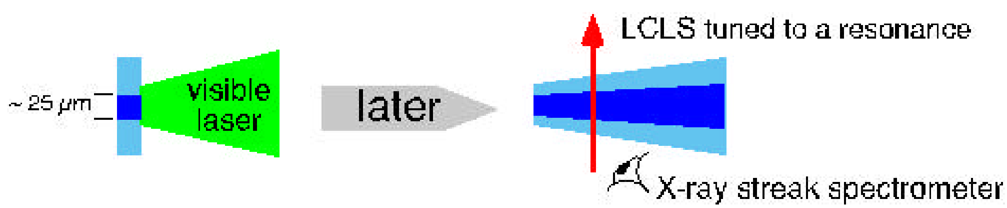
Highlight of Three Experimental Areas in the High-Density Finite-temperature Regime

LCLS

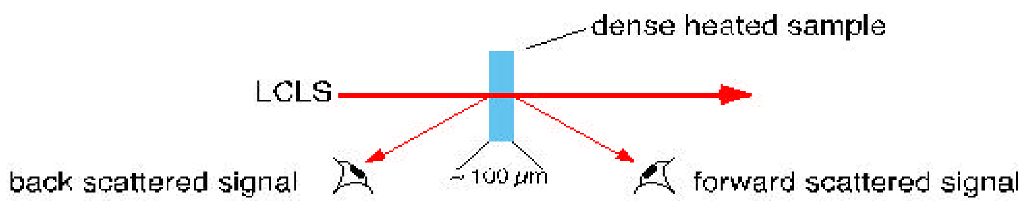
- **Creating WDM**
  - **Generate 10 eV solid density matter**
  - **Measure the fundamental nature of the matter via equation of state**



- **Probing resonances in HDM**
  - **Measure kinetics process, redistribution rates, kinetic models**



- **Probing dense matter**
  - **Perform, *e.g*., scattering from solid density matter**
  - **Measure n_e, T_e, <Z>, *f*(v), and damping rates**



LCLS, Uniquely, Can Both Create and Probe High-density Finite-temperature Matter

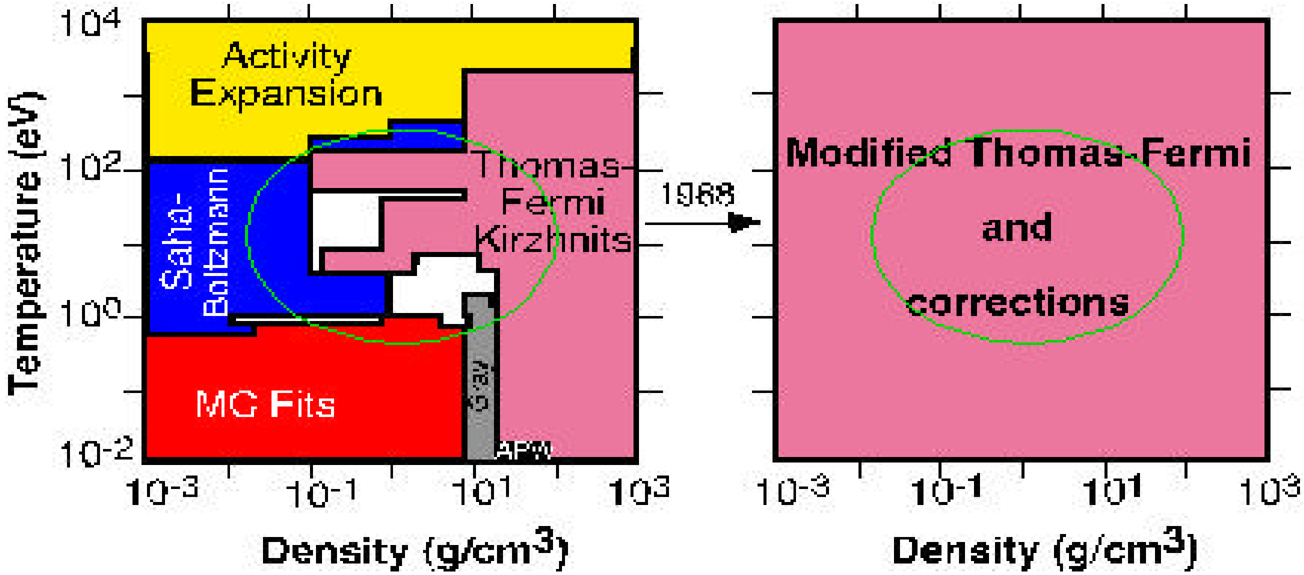
- **To create WDM requires rapid uniform bulk heating**
  - **High photon numbers, high photon energy, and short pulse length => high peak brightness**
- **To pump/probe HDM requires an impulsive source of high energy photons**
  - **Pump rate must be larger than competing rates**
  - **No laser source has flux (laboratory x-ray lasers or otherwise)**
- **To measure plasma-like properties requires short pulses with signal > plasma emission**
  - **No existing source can probe HDM or create WDM to probe**

- ***10^{10} increase in peak brightness allows access to novel regimes***

Theoretically the Difficulty with WDM is There are No Small Parameters

LCLS

- **WDM is the regime where neither condensed matter (T = 0) methods nor plasma theoretical methods are valid**
- **The equation of state (EOS) of Cu indicates the problems**

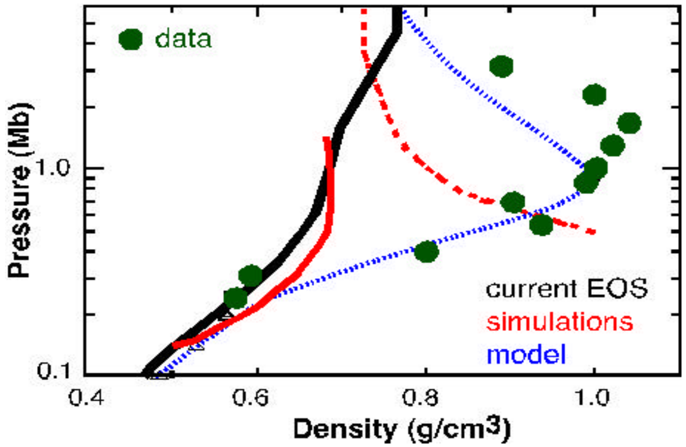


- **Thermodynamically consistent EOS based on numerous schemes has proved impossible (attempted from 70's)**
- **A single incomplete description is now employed (from 1988)**

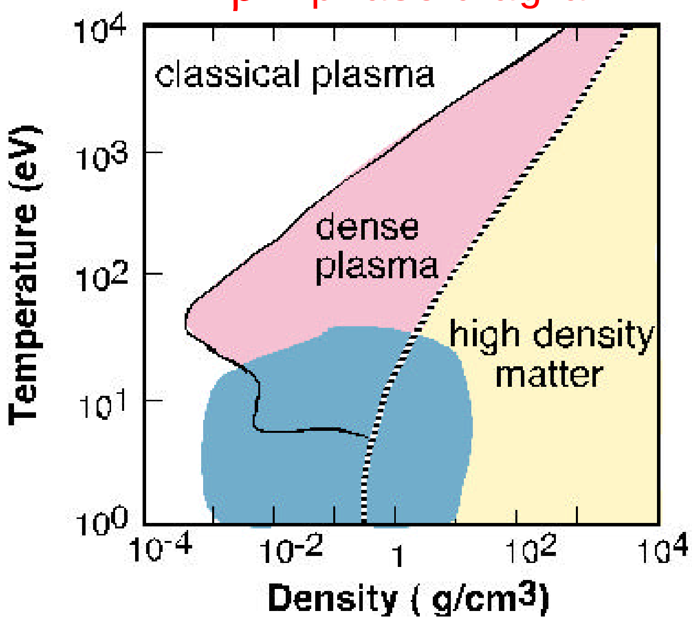
In the WDM Regime Information Leads to New Results – LCLS Will Be Unique Source of Data

LCLS

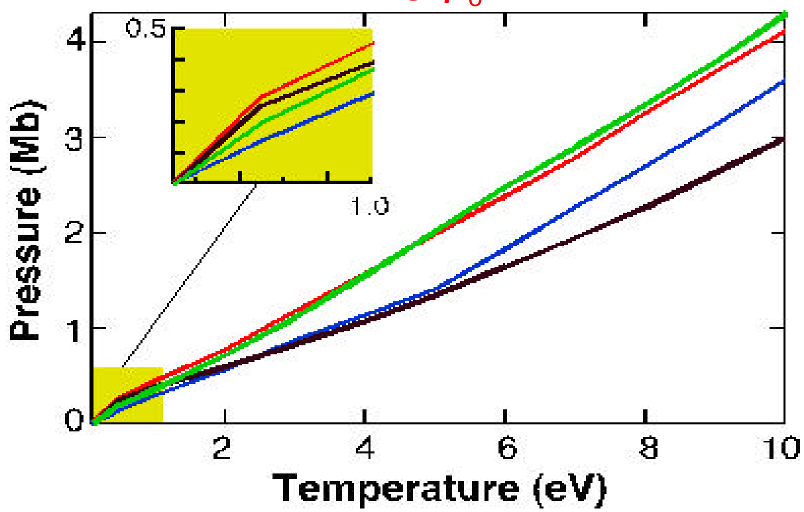
- **Experimental data on D_2 along the Hugoniot shows theories were and are deficient**
- **LCLS can heat matter rapidly and uniformly to generate isochores**

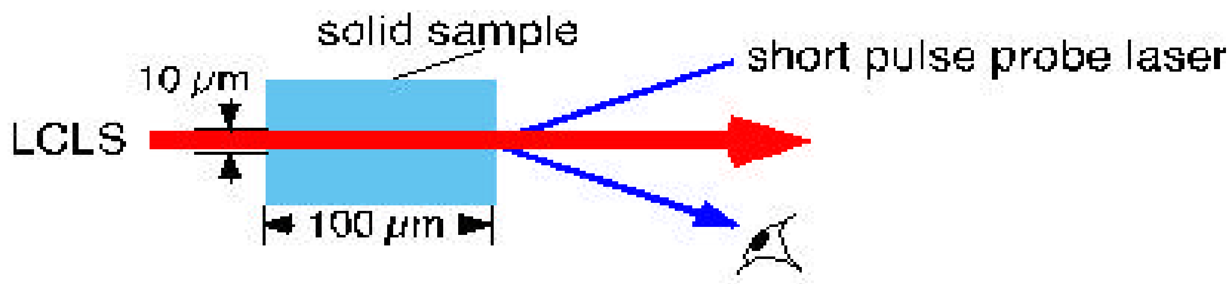


Al ρ-T phase diagram



EOS's along ρ_o Al isochore





- For a 10x10x100 μm sample of Al
  - Ensure the sample uniformly heated use 33% of beam energy
  - Equating absorbed energy to total kinetic and ionization energy

$$\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_p^i \quad \text{where} \quad I_p^i = \text{ionization potential of stage } i-1$$

- Generate a 10 eV solid density with $n_e = 2\text{x}10^{22}$ cm^{-3} and <Z> ~0.3
- State of material on release can be measured with a short pulse laser
  - Estimated to be $C_s \sim 1.6\text{x}10^6$ cm/s with pressure 4 Mb
  - For 500 fs get surface movement by 80 Å
- Material rapidly and uniformly heated releases isentropically

Experiment 2: LCLS Can Excite a Line Transition in HDM and Provide Observable Results

LCLS

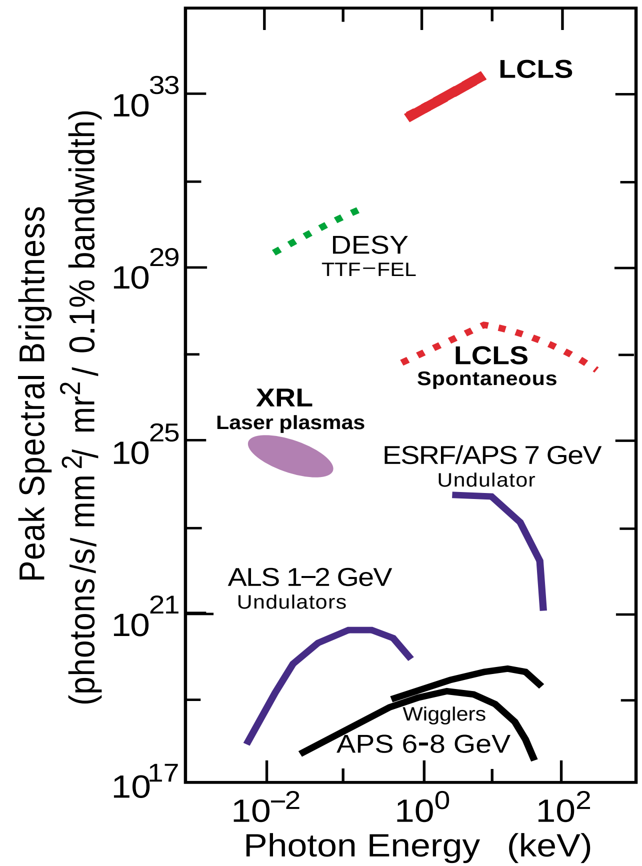
- **For HDM the plasma collision rates and spontaneous decay rates are large**

- **To effectively move population, pump rate, R, must be > decay rate, A => R $\geq$ A**

- **For I = 10^{14} W/cm² R/A ~ $10^{-4} g_U / g_L \lambda^4$**
  - **For LCLS**

    λ ~ 10 Å ⇨ R/A ~ 1
  - **For laboratory x-ray lasers**

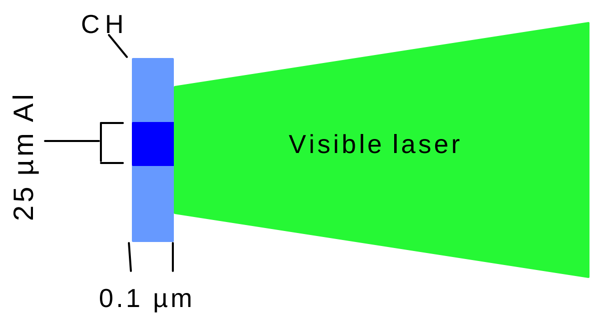
    λ > 100 Å ⇨ R/A << 1



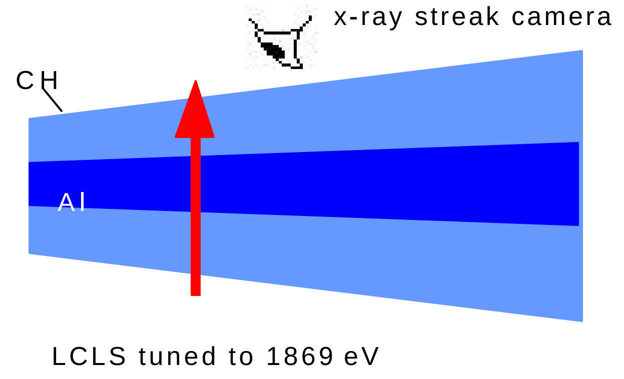
LCLS Will Create Excitation Levels That Are Observable in Emission

LCLS

- **Schematic experiment**

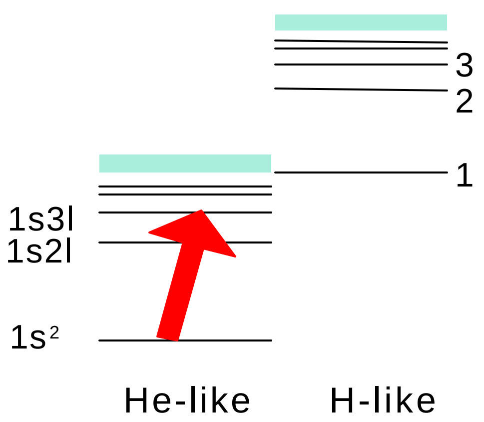


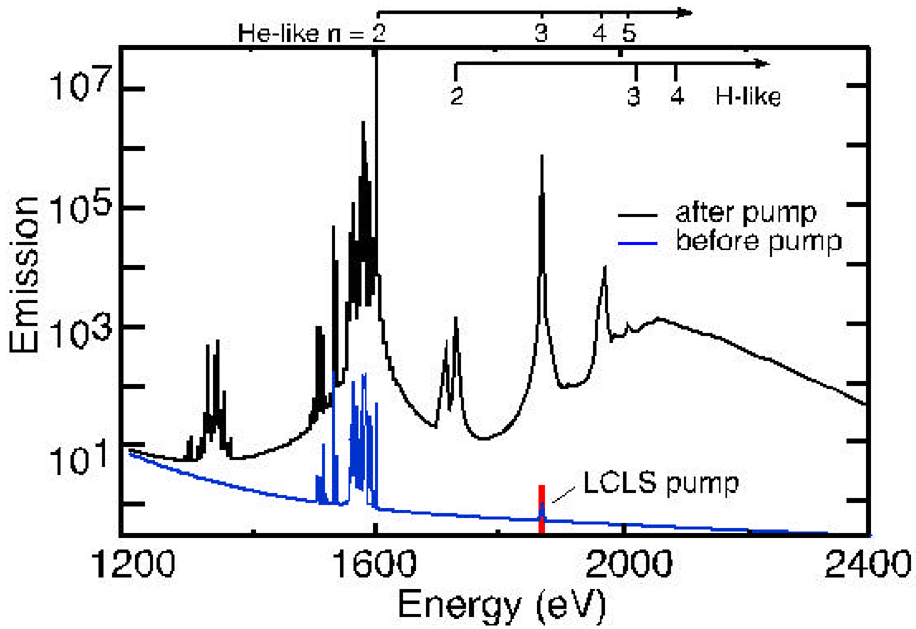
• **t = 0 laser irradiates Al dot**



• **t = 100 ps LCLS irradiates plasma**

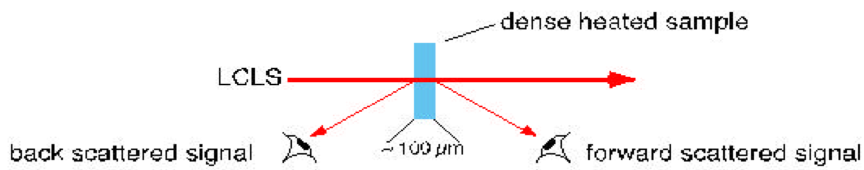
- **Simulations**



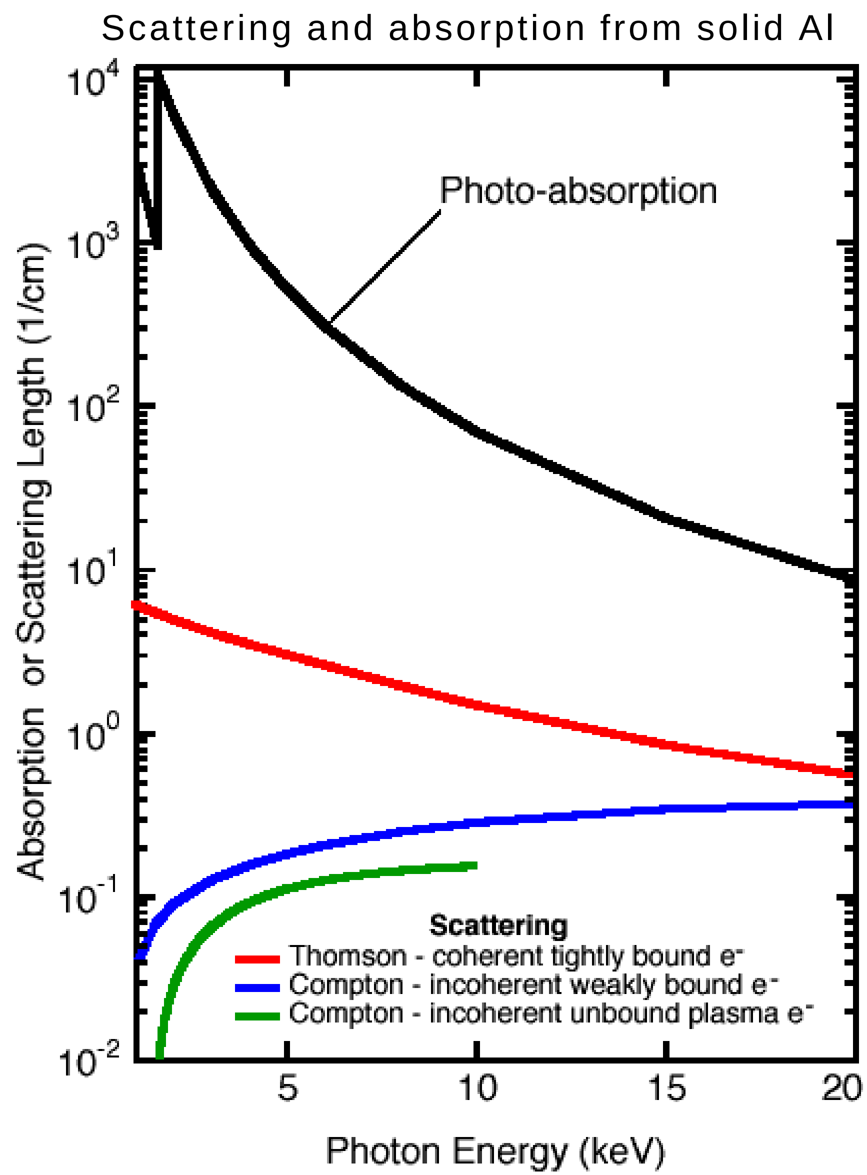


Experiment 3: LCLS Will Measure Properties of Solid Density Finite Temperature Matter

LCLS

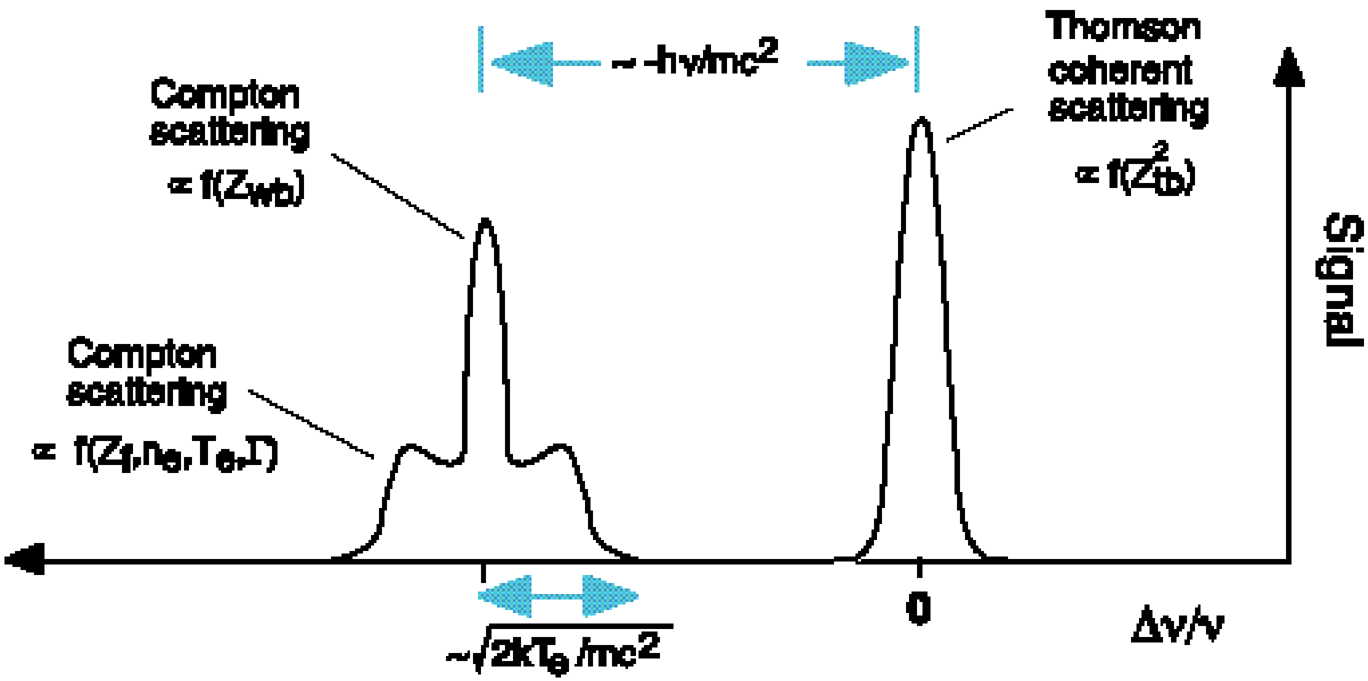


- **Scattering from free electrons provides a measure of the T_e, n_e, f(v), and plasma damping**
  - **structure alone not sufficient for plasma-like matter**
- **Due to absorption, refraction and reflection visible lasers can not probe high density**
  - **no high density data**
- **LCLS scattering signals will be well above noise for both WDM and HDM**



Scattering of LCLS Will Provide Data on Free, Tightly-, and Weakly-bound Electrons

- **Weakly-bound and tightly-bound electrons depend on their binding energy relative to the Compton energy shift**
  - **Those with binding energies less than the Compton shift are categorized weakly bound.**



- **For a 25 eV, 4x10^{23} cm^{-3} plasma the LCLS produces10^{4} photons from the free electron scattering**

Goal for WDM Experiments at the LCLS: Measure EOS and Plasma-like Properties

- **EOS measurements illuminate the microscopic understanding of matter**
  - **The state of ionization is extremely complex when the plasma is correlated with the ionic structure**

- **Other properties of the system depend on the same theoretical formulations**
  - **For example, conductivity and opacity**

Goal for HDM Experiments at the LCLS: Study Kinetics, Line Shapes, and Plasma Formation

- **Since the advent of HDM laboratory plasma quantitative data has been scarce**
  - **The rapid evolution of high T_e and n_e matter requires a short duration, high intensity, and high energy probe => LCLS**
- **The LCLS will permit measurements of:**
  - **Kinetics behavior – rates, model construction**
  - **Plasma coupling – direct measurement of S(k, I)**
  - **Line transition formation – line shapes, shifts, ionization depression**
  - **HED plasma formation – measure matter in the densest regions**