

# Creating & Probing Extreme States of Matter With an X-Ray FEL

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# The importance of these states of matter derives from their wide occurrence

- Hot Dense Matter

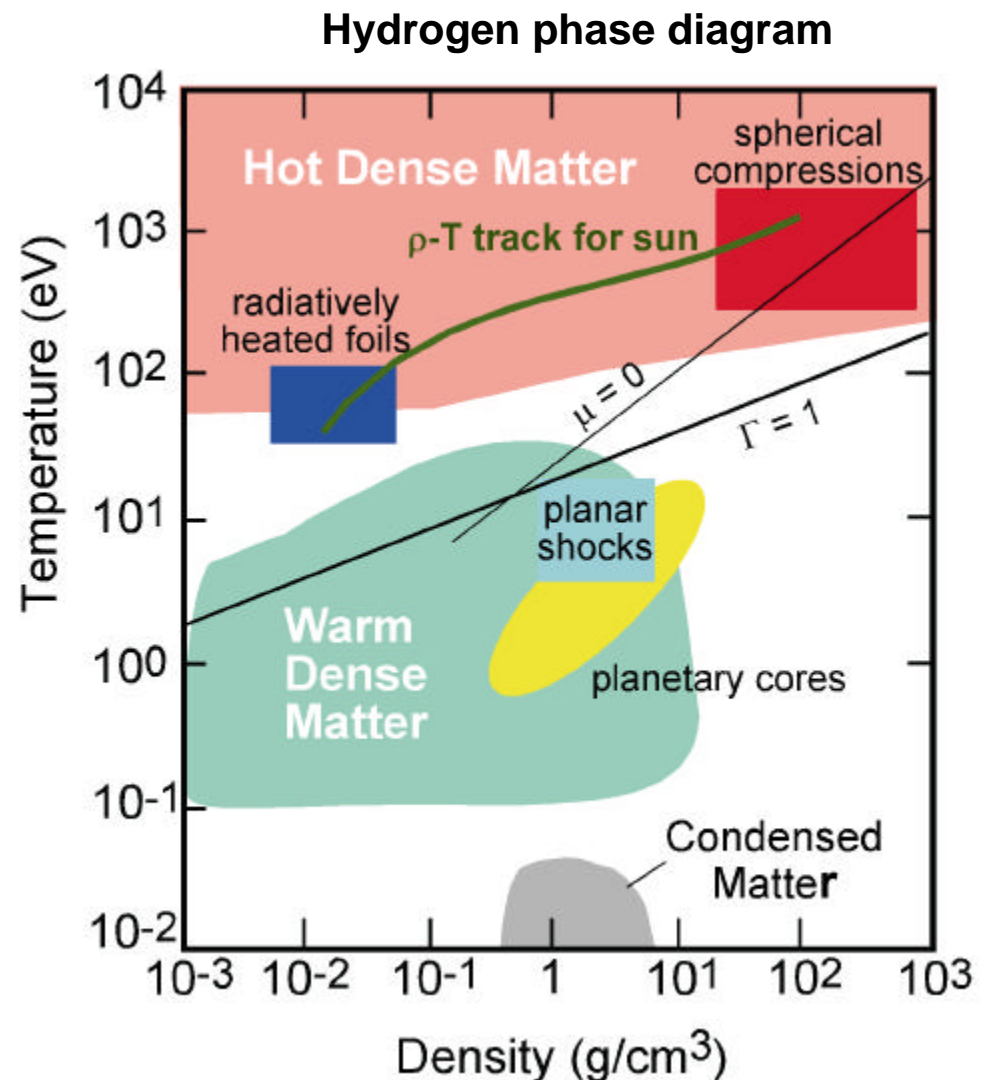
occurs in:

- Supernova, stellar interiors, accretion disks
- Plasma devices: laser produced plasmas, Z-pinch
- Directly driven inertial fusion plasma

- Warm Dense Matter

occurs in:

- Cores of large planets
- Systems that start solid and end as a plasma
- X-ray driven inertial fusion implosion

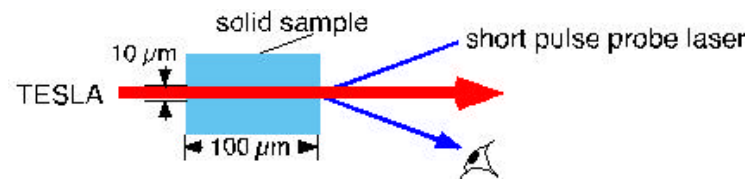


# Highlight three experimental areas in the high-density finite-temperature regime

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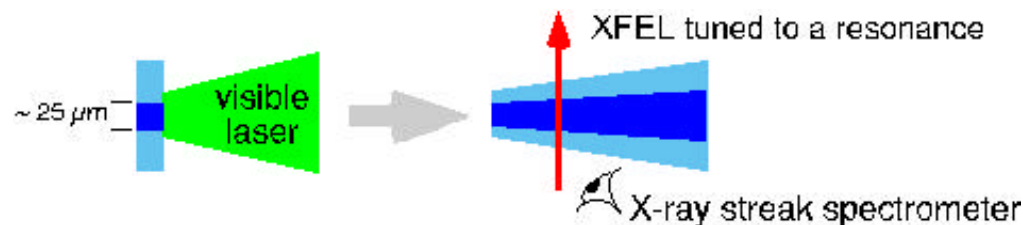
- Creating Warm Dense Matter

- Generate  $\leq 10$  eV solid density matter
- Measure the fundamental nature of the matter via equation of state



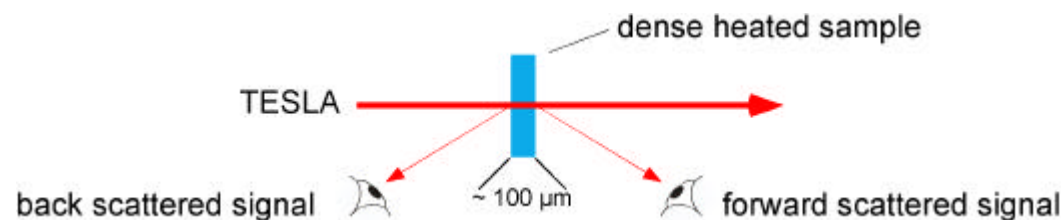
- Probing bound-bound transitions in Hot Dense Matter

- Measure kinetics process, redistribution rates, kinetic models



- Probing dense matter

- Perform, e.g., scattering from solid density matter
- Measure  $n_e$ ,  $T_e$ ,  $\langle Z \rangle$ ,  $f(v)$ , and damping rates



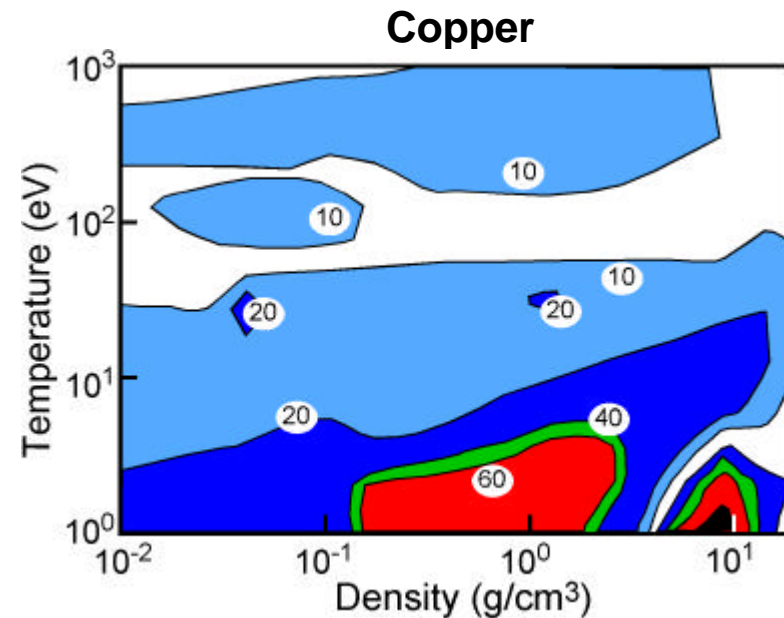
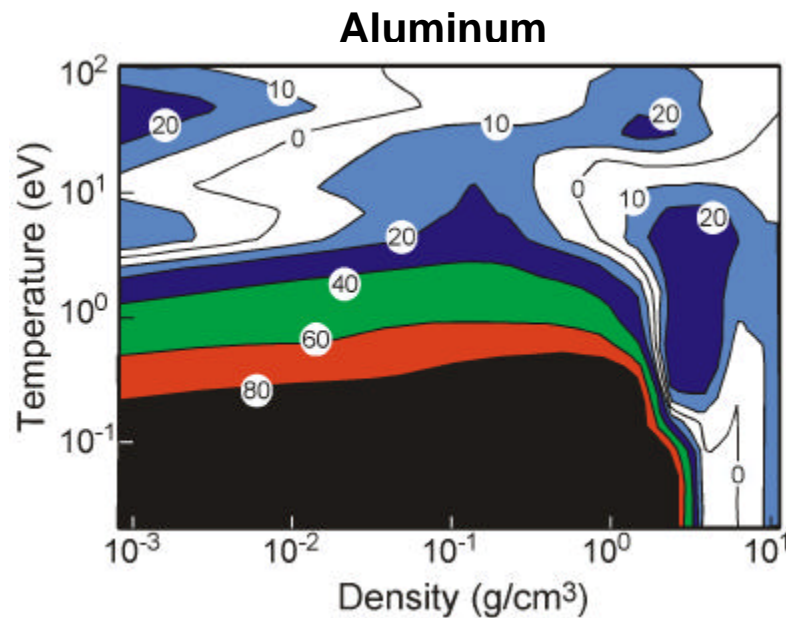
# Short pulse XFELs, uniquely, can both create and probe high-density finite-temperature matter

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- To create Warm Dense Matter requires *rapid* uniform bulk heating
    - High photon numbers, high photon energy, and short pulse length => high peak brilliance
  - To pump/probe Hot Dense Matter requires a fast-rising short-duration 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 Hot Dense Matter
    - No existing source can create Warm Dense Matter to probe
- > ***10<sup>10</sup> increase in peak brilliance allows access to novel regimes***

# In Warm Dense Matter regime large errors exist even for most studied materials

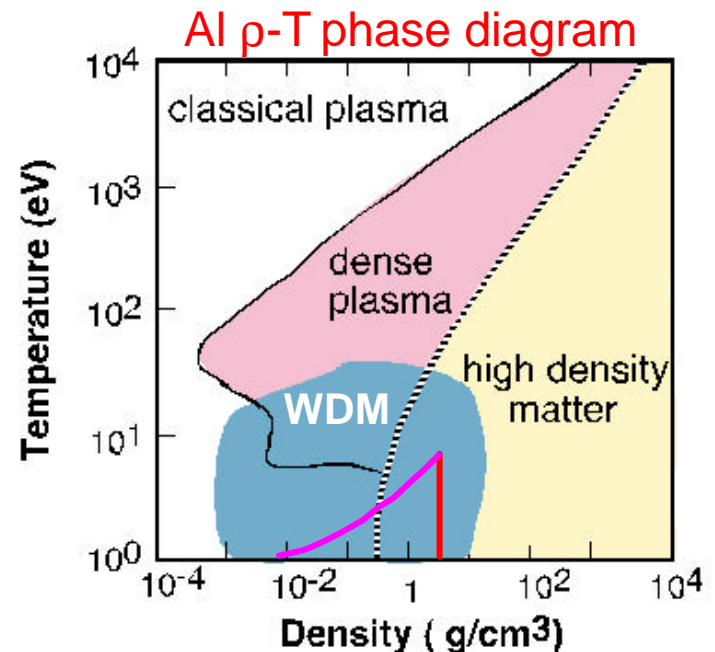
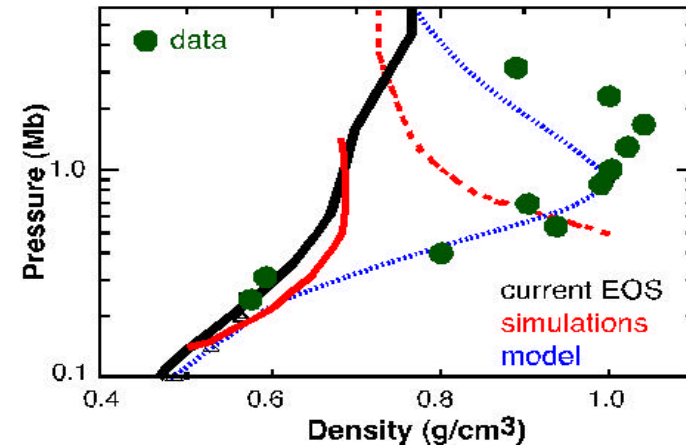
Contours of % differences in pressure



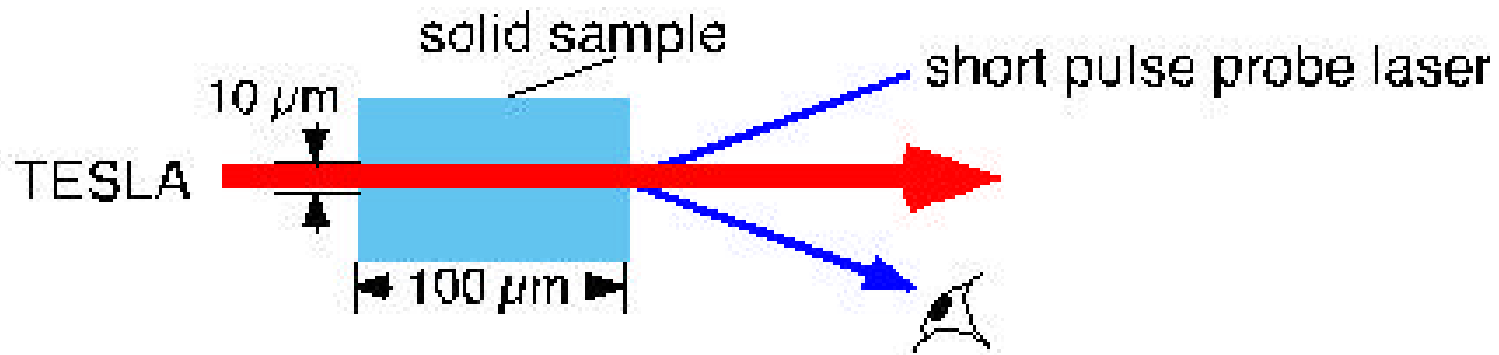
- Differences > 80% in the Equation of State are common
- Measurements are essential for guidance
- Where data exist, along the principal Hugoniot, the models agree!!
- Principal Hugoniot:  $\rho$ -T-P response curve defined by single shocks of varying pressure

# In Warm Dense Matter regime *data* leads to new results - TESLA is a unique resource

- Experimental data for  $D_2$  along the Hugoniot shows theories are deficient
- An XFEL can heat matter rapidly and uniformly to create **isochores** ( $\rho$  is constant) and release isentropes (entropy is constant)



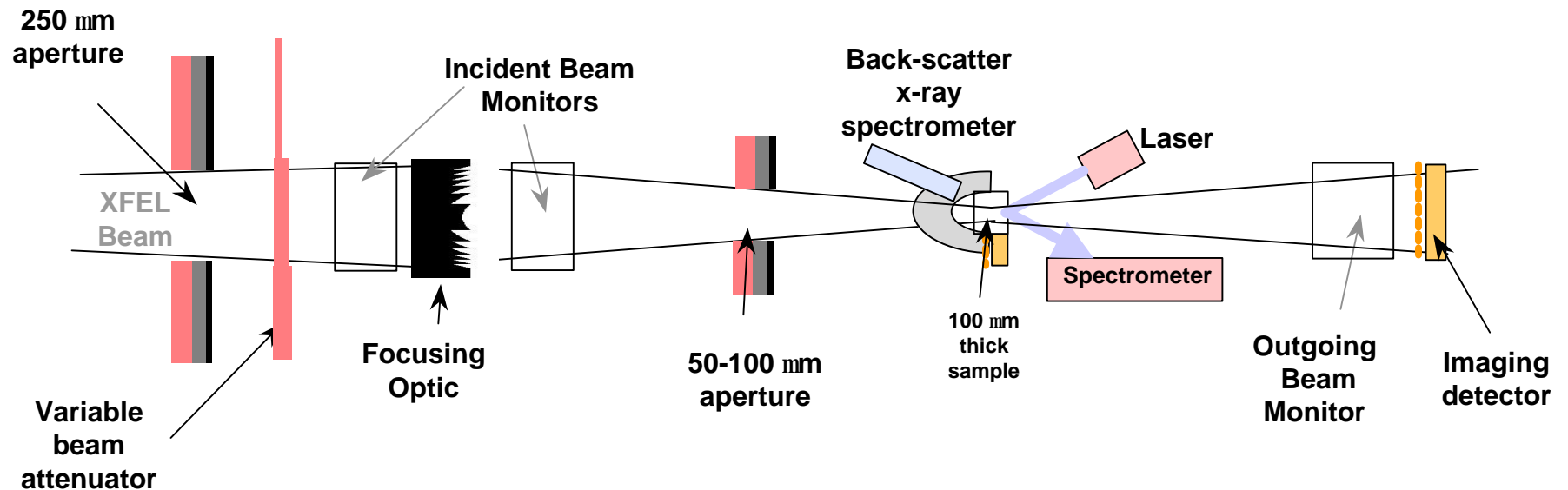
# TESLA will create Warm Dense Matter in a straightforward experimental setup



- Focus TESLA to a  $10 \times 10\ \mu\text{m}$  spot on aluminum
- Creates 10 eV solid density matter with  $n_e = 2 \times 10^{22}\ \text{cm}^{-3}$  and  $\langle Z \rangle \sim 0.3$
- State of material on release can be measured with a short pulse laser
- Material rapidly and uniformly heated releases isentropically

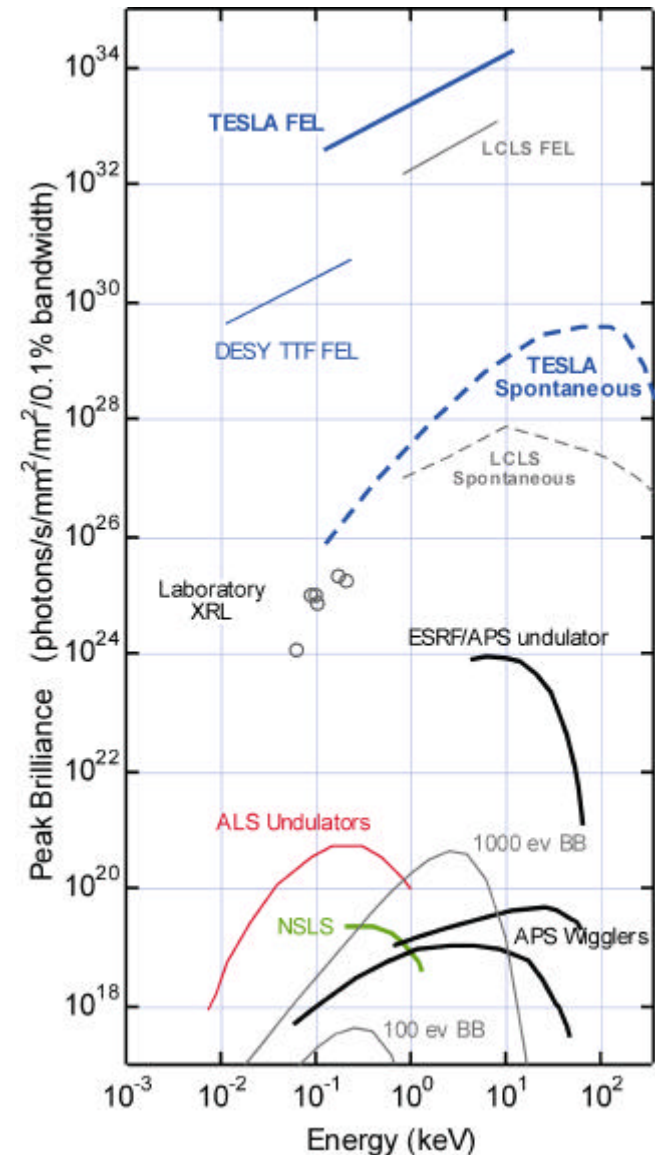
# Warm Dense Matter requires straightforward experimental design

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# For **Hot Dense Matter** TESLA can excite a line transition and generate unique results

- For Hot Dense Matter the plasma collision rates and spontaneous decay rates are large
- To effectively move population, pump rate,  $R$ , must be  $>$  decay rate,  $A$   
 $\Rightarrow R > A$
- For  $I = 10^{14} \text{ W/cm}^2$   $R/A \sim 10^{-4} g_U/g_L \lambda^4$ 
  - TESLA attains needed excitation strength  
 $\lambda \sim 10 \text{ \AA} \rightarrow R/A > 1$
  - All Laboratory x-ray lasers are *insufficient*  
 $\lambda > 100 \text{ \AA} \rightarrow R/A \ll 1$

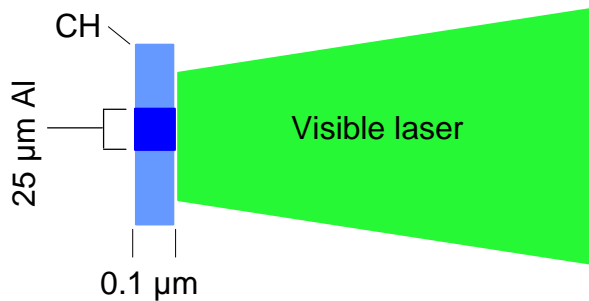


# TESLA can photopump a transition:

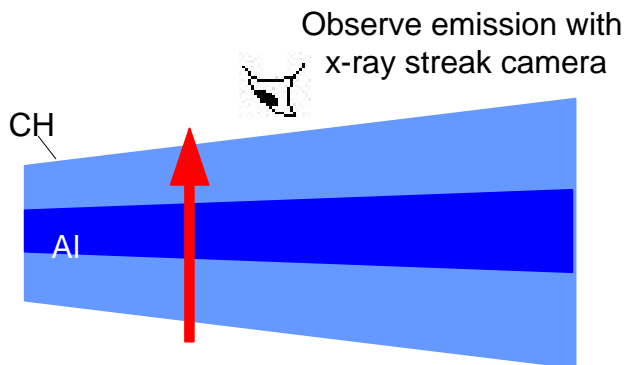
## The emission provides critical tests of plasma processes

- Experiment

- $t = 0$  laser irradiates Al dot

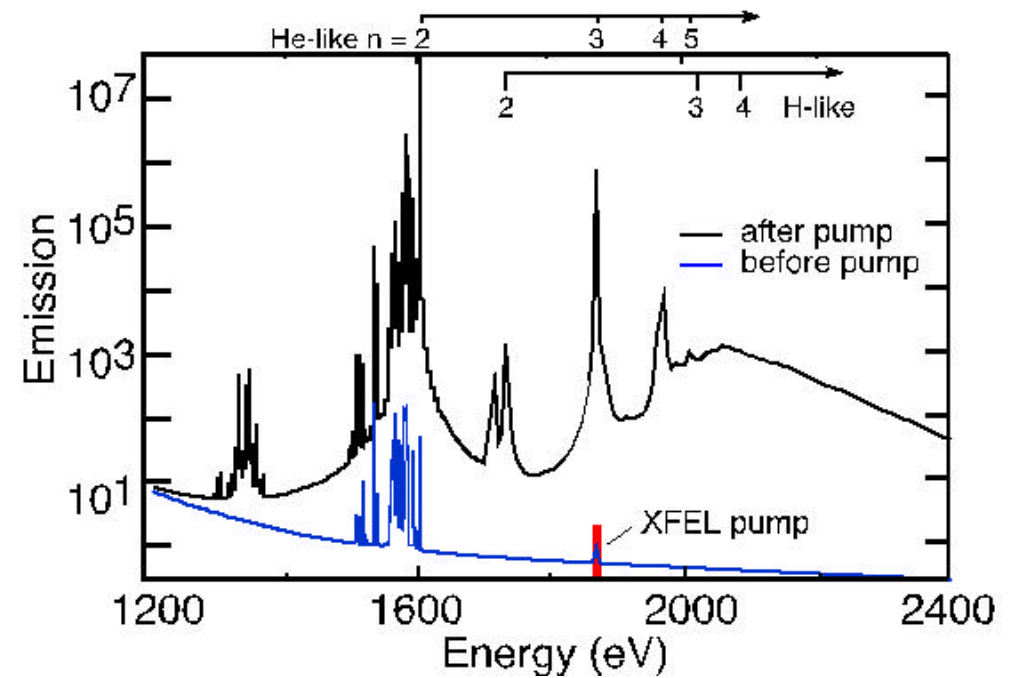


- $t = 100$  ps XFEL irradiates plasma



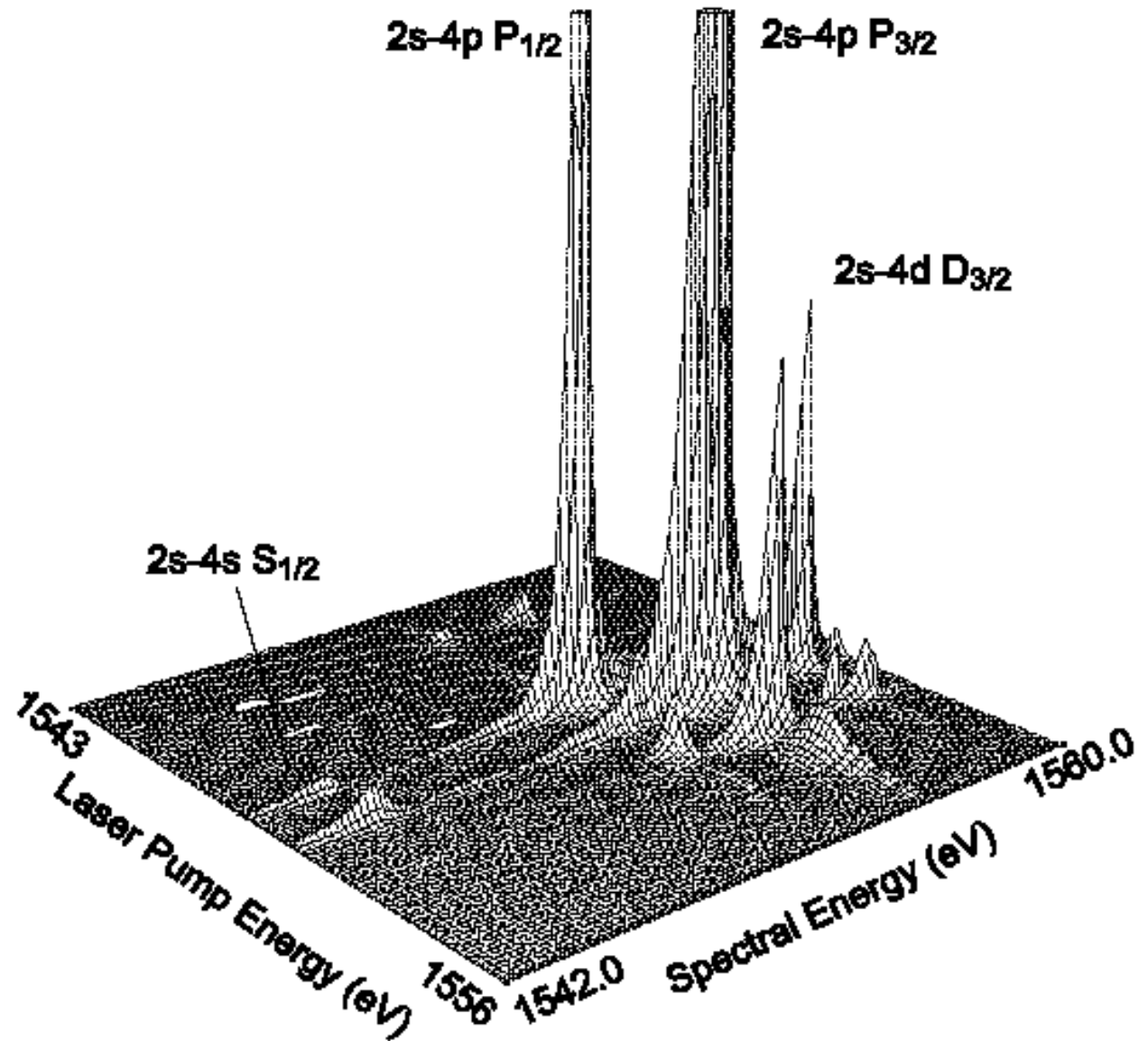
XFEL tuned to 1869 eV

- Simulation

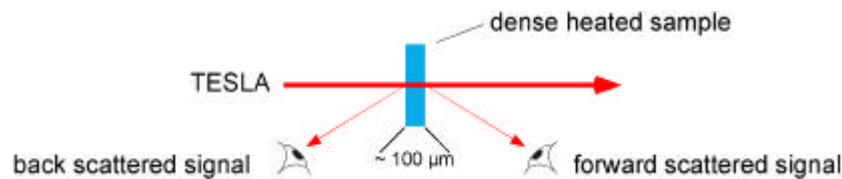


# TESLA with reduced bandwidth can tune through a line to provide plasma rate data

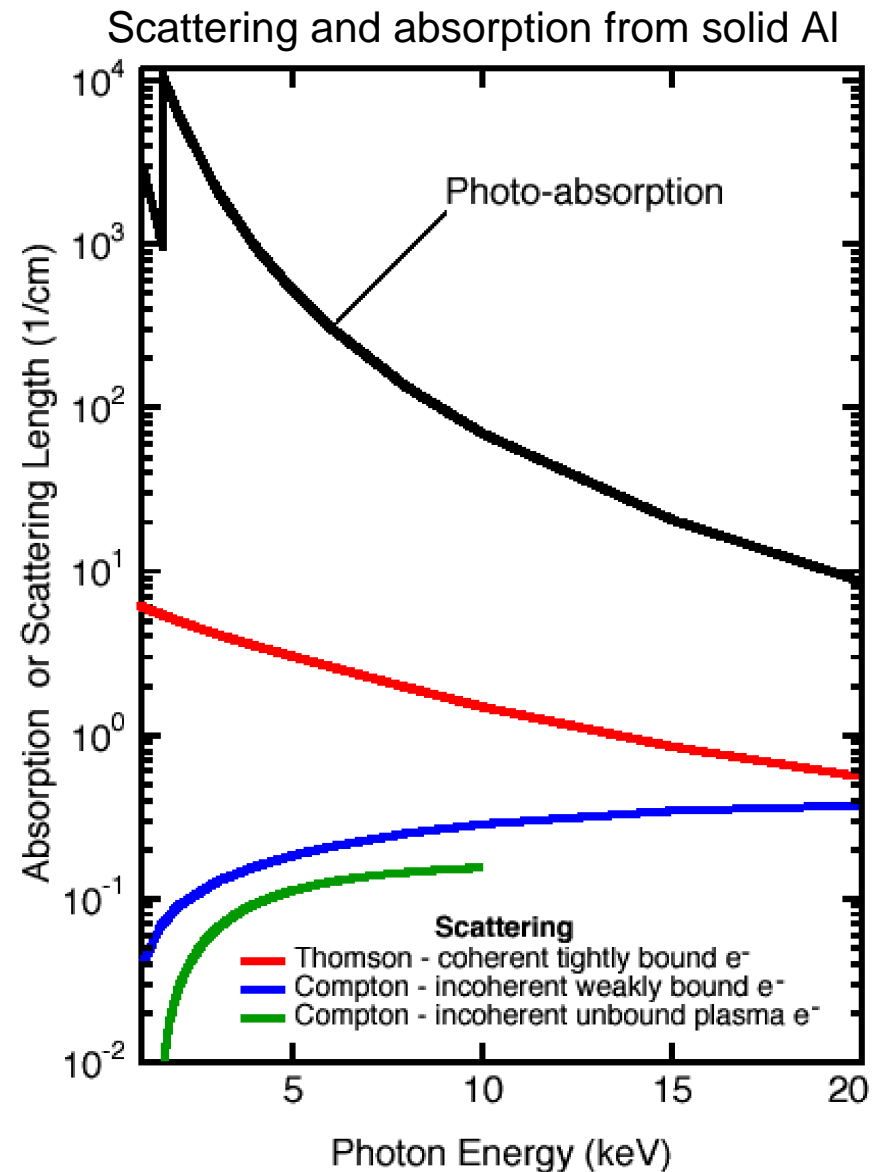
- Example:  
pumping Li-like  
Iron  $1s^22l - 1s^24l$
- Collision rates  
and plasma field  
fluctuations can  
be measured
- Bandwidth of  $\sim 10^{-4}$   
is easily  
obtained by use  
of a crystal



# TESLA can be used to **probe** solid density *finite* temperature matter

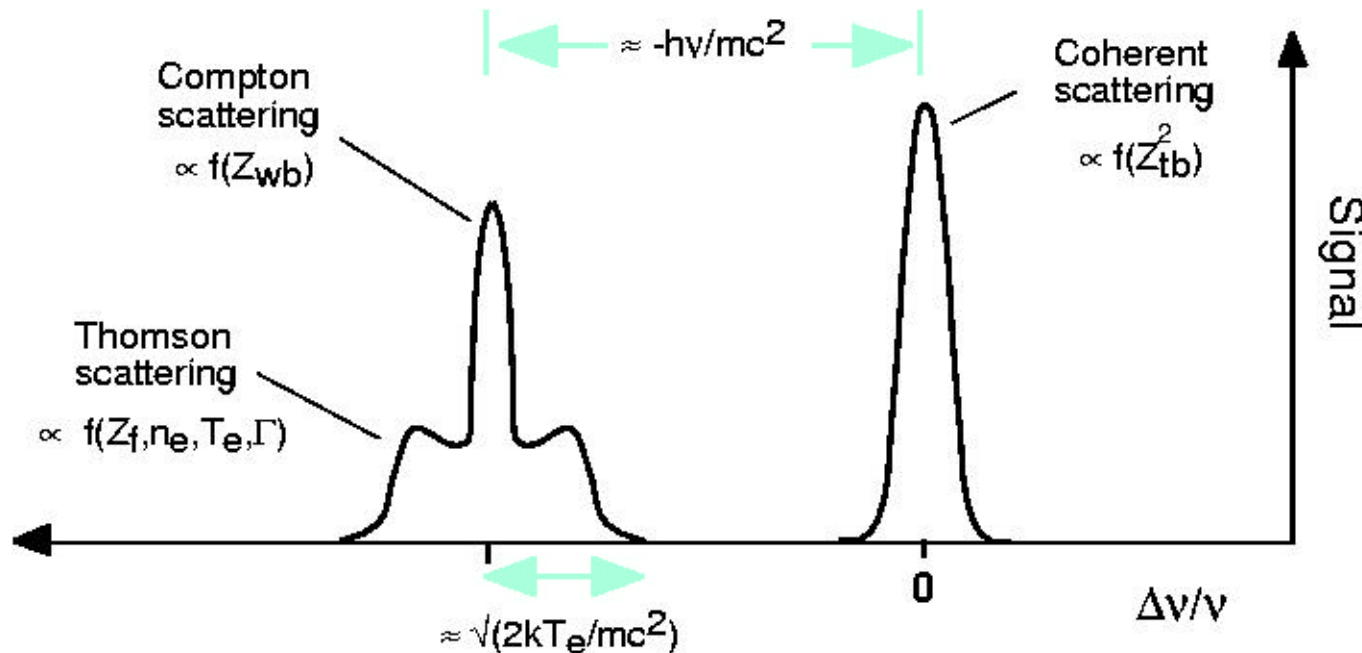


- Scattering from free electrons provides a measure of the  $T_e$ ,  $n_e$ ,  $f(v)$ , and plasma damping  
=> structure alone not sufficient for plasma-like matter
- Due to absorption, refraction and reflection neither visible nor laboratory x-ray lasers can probe high density  
=> no high density data
- TESLA scattering signals will be well above noise for both Warm and Hot Dense Matter



# Scattering of the XFEL will provide data on free, tightly-, and weakly-bound electrons

- Weakly-bound (wb) and tightly-bound (tb) electrons depend on their binding energy relative to the Compton energy shift



- For a 25 eV,  $4 \times 10^{23} \text{ cm}^{-3}$  plasma the TESLA produces  $10^4$  photons from the free electron scattering
- Can obtain temperatures, densities, mean ionization, velocity distribution from the scattering signal

# **Goal for TESLA Warm Dense Matter experiments: Measure Equation of State and plasma properties**

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- Equation of State 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 Hot Dense Matter experiments at TESLA: study kinetics, line shapes, and plasma formation**

- Since the advent of Hot Dense Matter laboratory plasmas quantitative data has been very scarce
  - The rapid evolution of high  $T_e$  and  $n_e$  matter requires a short-duration, high-intensity, and high-energy probe => TESLA
- TESLA will permit measurements of:
  - Kinetics behavior - rates, model construction
  - Plasma coupling - direct measurement of  $S(k,\omega)$ , the dynamic structure factor
  - Line transition formation - line shapes, shifts, ionization depression
  - High energy density plasma formation - measure matter in the densest regions