High Energy Density Science (HEDS) on X-ray FELs

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Interest in HEDS is growing rapidly and XFELs have a unique role to play

- Two recent National Academy of Science reports have highlighted HEDS:
  - *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, 2003)
  - *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003)
- National Taskforce on HEDS was convened to set priorities and develop coordinated plans
  - Report is now in the final editing stage
- HEDS case ***is*** the exactly the “plasma-related” science case already proposed for LCLS, TESLA, and VUV-FEL

Diverse HEDS experiments emphasizing the laser-like aspects of VUV-FEL are scheduled

- Participation is proposal process included > 100 participants from Europe and North America

	Experiment	Brief Description
Condensed Matter	Warm Dense Matter Creation	Using the FEL to uniformly warm solid density samples
	EOS Measurements	Use an optical laser to heat a sample and the FEL to provide a diagnostic of the bulk
	Near Edge Absorption	Use an optical laser to heat a solid and the FEL to probe the structural changes
	Femtosecond Ablation	Probe the nature of the ablation process on the sub-ps time scale
Plasma	Trapped, High Γ Plasmas	Use EBIT/laser-cooled trap and probe highly-charged strongly-coupled Coulomb systems
	Diagnostic Development	Develop the FEL for Thomson scattering, interferometry, and radiographic imaging
	FEL /Gas-Jet Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas
	FEL / Solid Interactions	Use the FEL directly to create extreme states of matter at high T and ρ
	Plasma-Spectroscopic Studies	Use the FEL as a pump to move bound state populations and study radiation redistribution
Bio-irelated	Coulomb Explosion	Study Coulomb Explosion process with emphasis on biological imaging problems
	Optics Damage	Study structural changes & disintegration processes of solids under FEL irradiation

LCLS starts experiments in 2009 and the proposal process has started

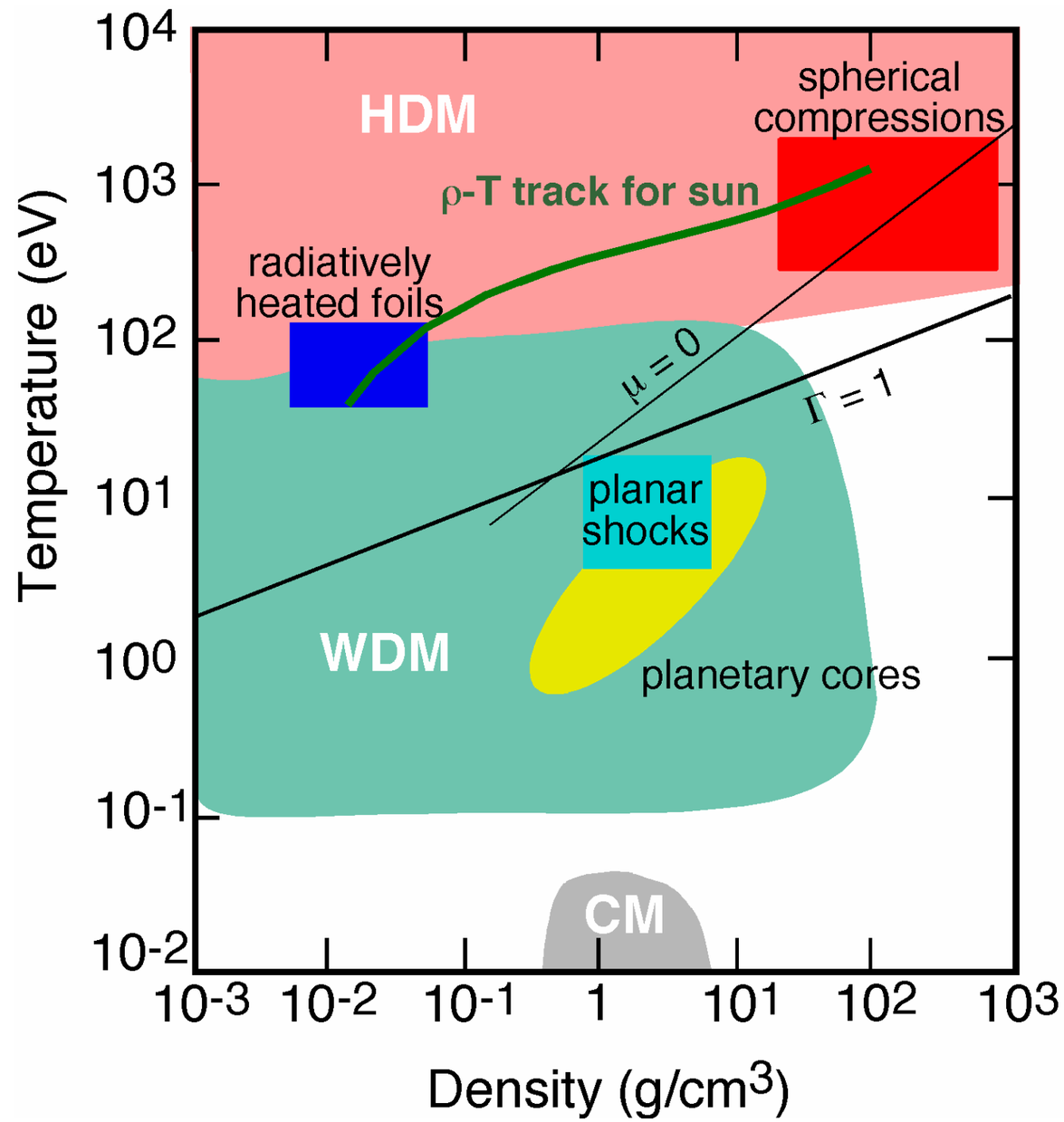
- *Letter of Intent* **for an HEDS experimental station submitted 21 June**
- **HEDS submission separates into Warm Dense Matter (WDM), Hot Dense Matter (HDM), and Diagnostic Development**

Experiment	Description
Warm Dense Matter Creation	Using the XFEL to uniformly warm solid density samples
Equation of State Measurements	Heat and probe a solid with an XFEL to provide a diagnostic of material properties
Absorption Spectroscopy	Heat a solid with an optical laser or XFEL and XFEL to probe
Shock Phenomena	Create shocks with a high-energy lasers and probe with the FEL
Surface Studies	Probe ablation/damage process to study structural changes and disintegration
FEL / Gas Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas
FEL / Solid Interaction	Use XFEL directly to create extreme states of matter at high temperature and density
Plasma Spectroscopy	Use XFEL as a pump to excite bound state populations
Diagnostic Development	Develop Thomson scattering, interferometry, and radiographic imaging

The importance of HED states derives from their wide occurrence

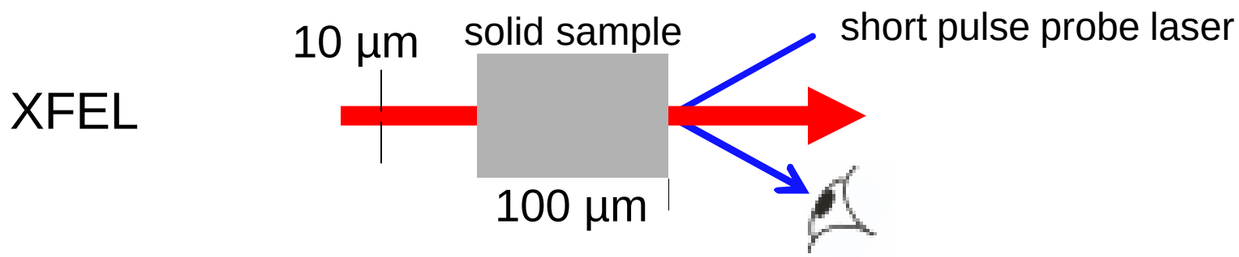
- Hot Dense Matter occurs in:
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly driven inertial fusion plasma
- Warm Dense Matter occurs in:
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven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

Hydrogen phase diagram

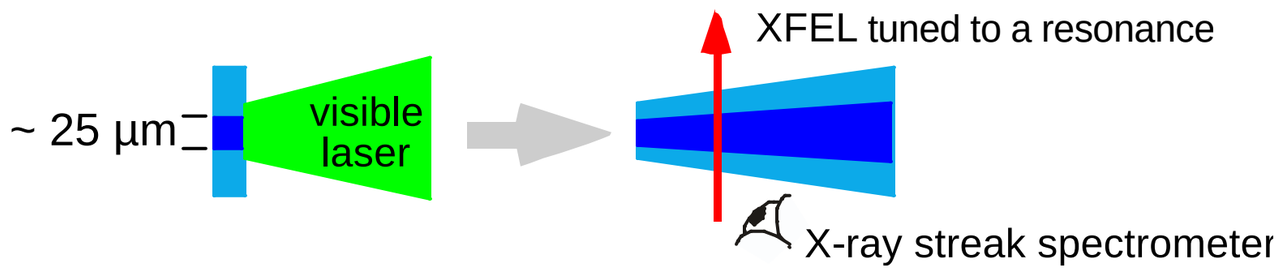


Three experiments in the high-energy density regime provide examples

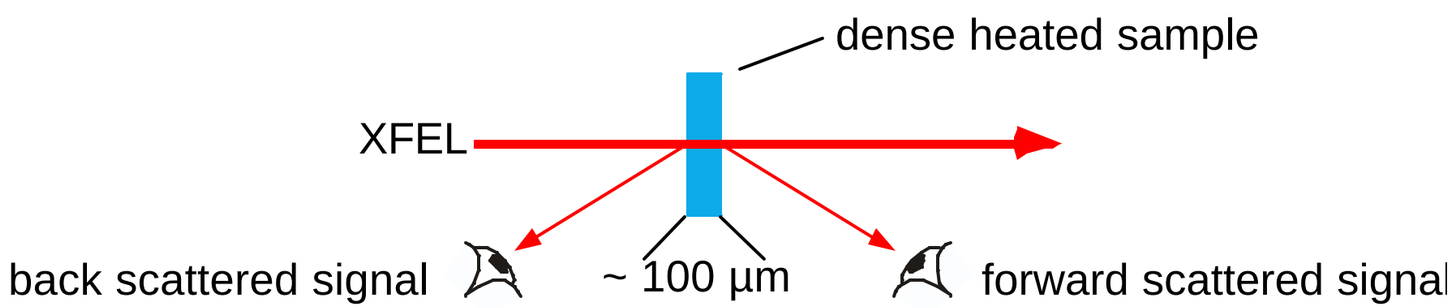
- **Creating Warm Dense Matter**
  - Generate ≤10 eV solid density matter and measure the equation of state



- **Probing bound-bound transitions in Hot Dense Matter**
  - Measure kinetics process, redistribution rates, kinetic models



- **Probing dense matter**
  - Thomson scattering to measure n_e, T_e, <Z>, f(v)



XFEL will be *unique* as it can both create and probe high-energy density matter

- To create Warm Dense Matter requires *rapid* uniform bulk heating
  - High photon numbers, high photon energy, and short pulse length => high peak brilliance

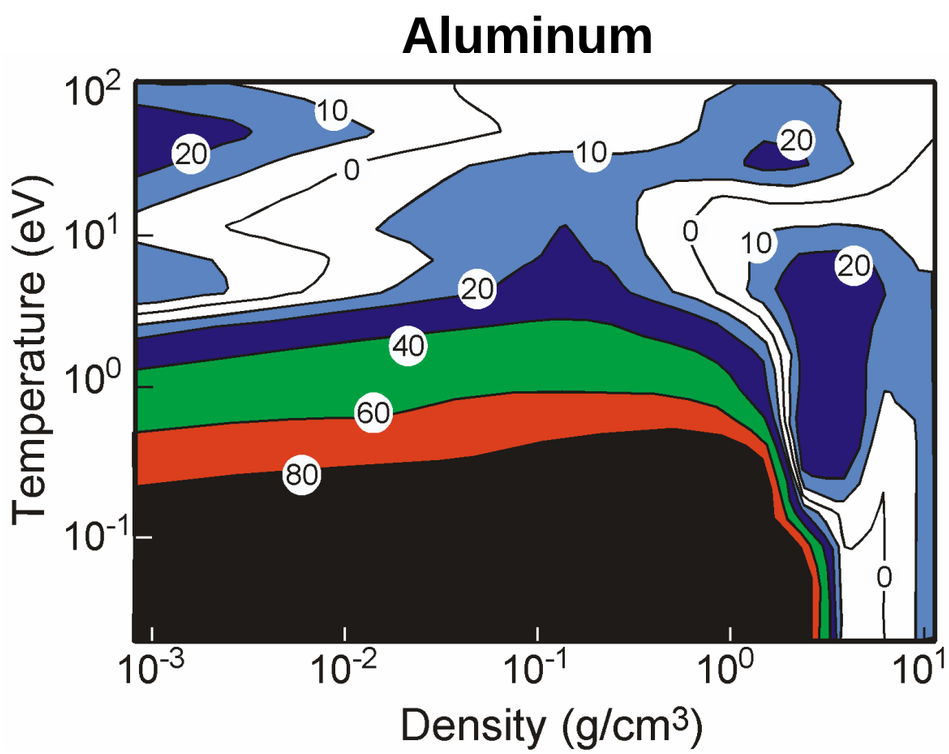
- To pump/probe Hot Dense Matter requires a fast-rising short-duration source of high energy photons
  - Pump rate must be larger than competing rates
  - No other laser source has flux

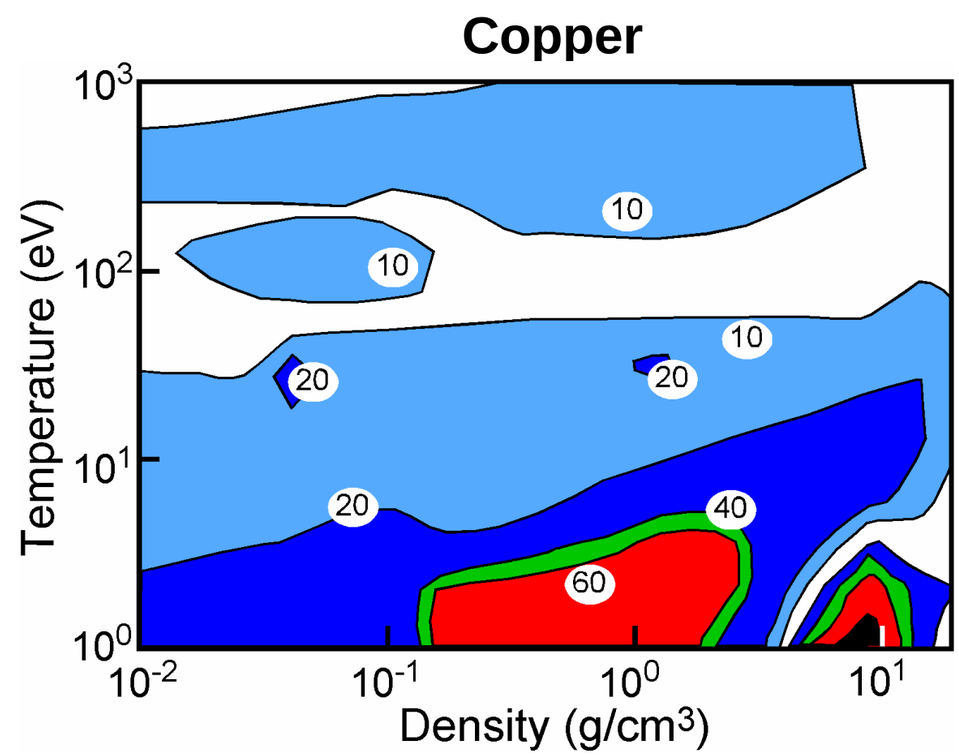
- To measure plasma-like properties requires short pulses with signal > plasma emission
  - No existing source can probe Hot Dense Matter on relevant time scales
  - No existing source can create Warm Dense Matter to probe

- ***10^{10} 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

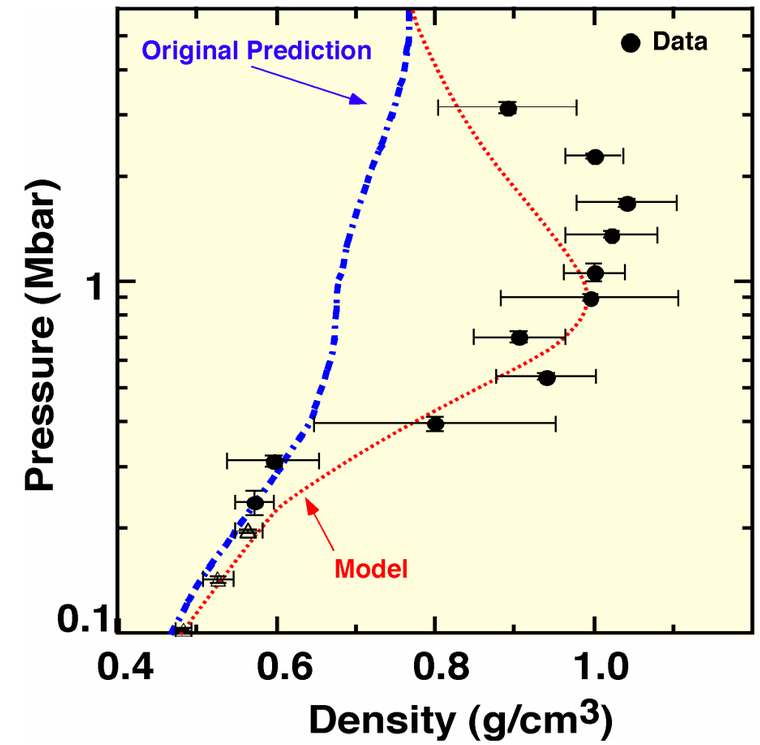




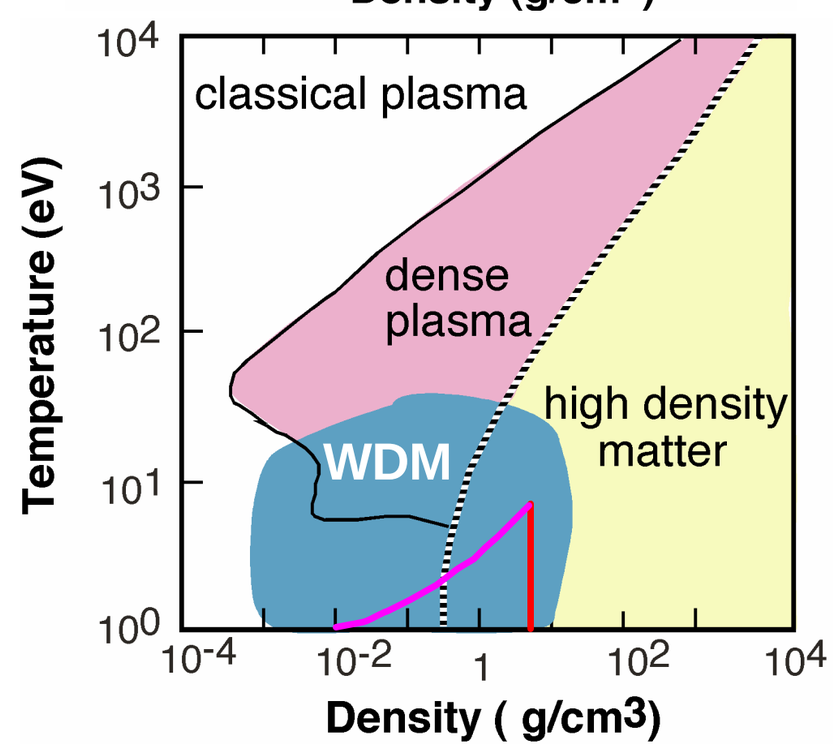
- Differences > 80% in the Equation of State are common
- Measurements are essential for guidance
- Where data exist, along the principal Hugoniot, the models agree!!
  - Principal Hugoniot: ρ-T-P response curve defined by single shocks of varying pressure

In Warm Dense Matter regime *data* leads to new results - XFEL will be unique resource

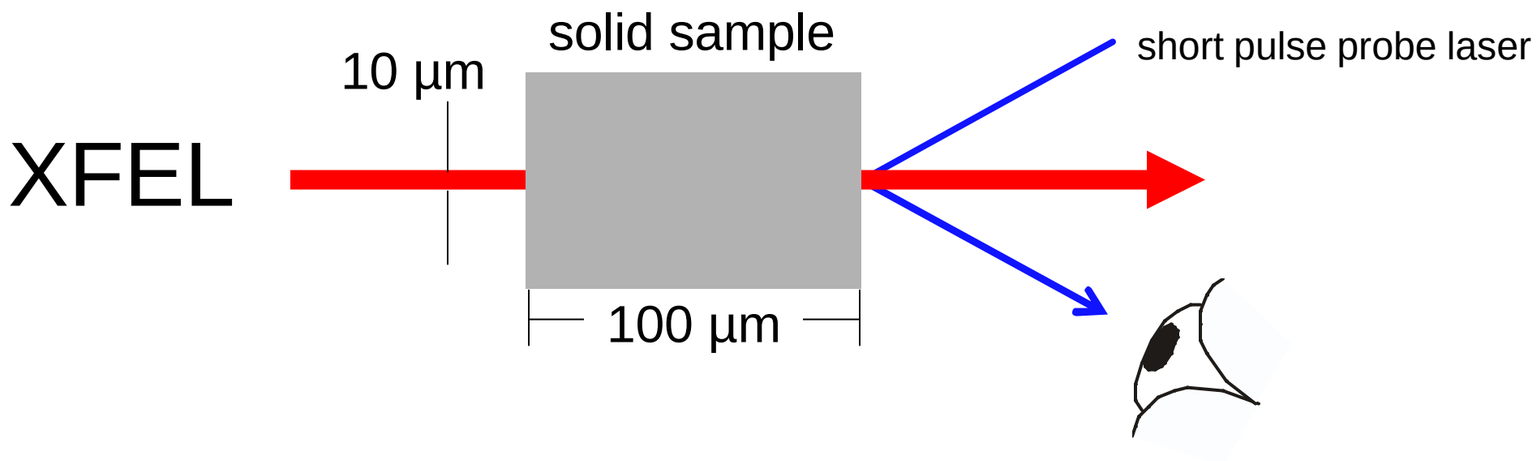
- Experimental data for D_2 along the Hugoniot shows theories are deficient



- An XFEL can heat matter rapidly and uniformly to create
  - isochores (ρ is constant) and release
  - isentropes (entropy is constant)



TESLA will create Warm Dense Matter in a straightforward experimental setup



- For a 10x10x100 µm thick sample of Al
  - Ensure sample uniformity by using only 66% of beam energy
  - Equating absorbed energy to total kinetic and ionization energy

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

  - Find 10 eV at solid density with $n_e = 2\times10^{22}$ cm^{-3} and <Z> ~0.3

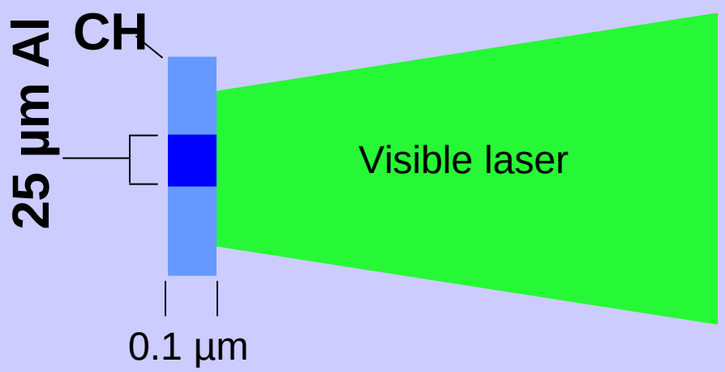
- State of material on release can be measured with a short pulse laser

- Material rapidly and uniformly heated releases isentropically

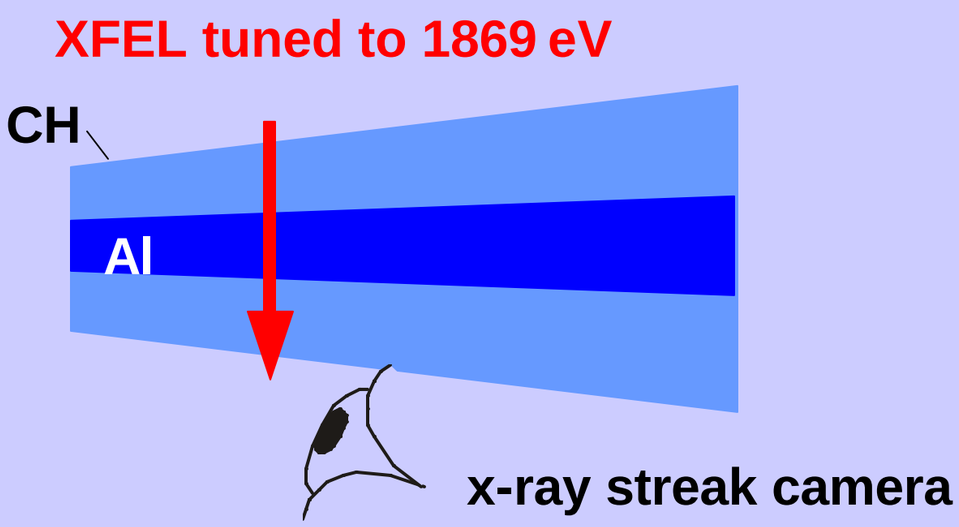
For Hot Dense Matter XFEL can excite a transition and generateunique results

Experiment

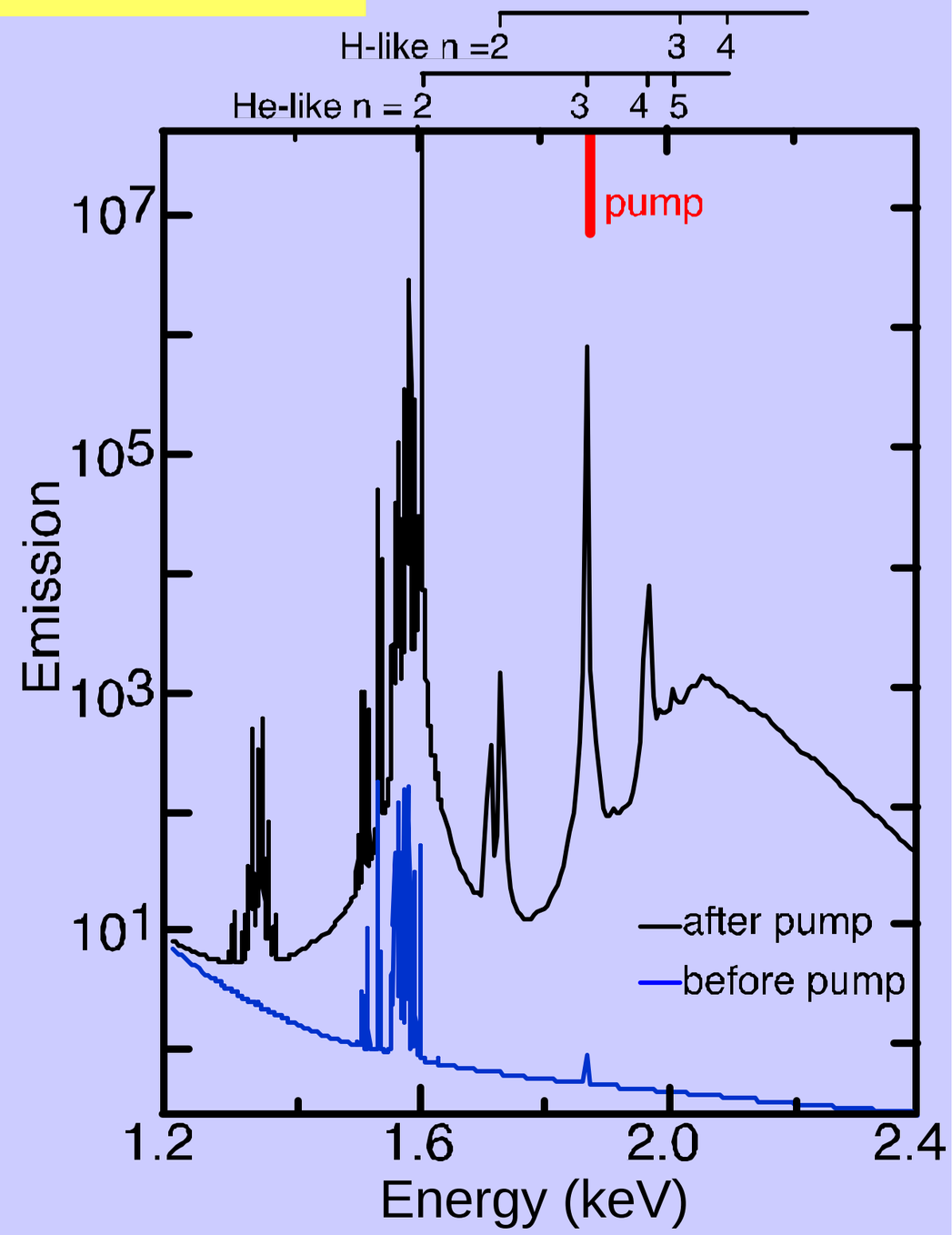
- **t = 0 laser irradiates Al dot**



- **t = 100 ps XFEL irradiates plasma**



Simulation

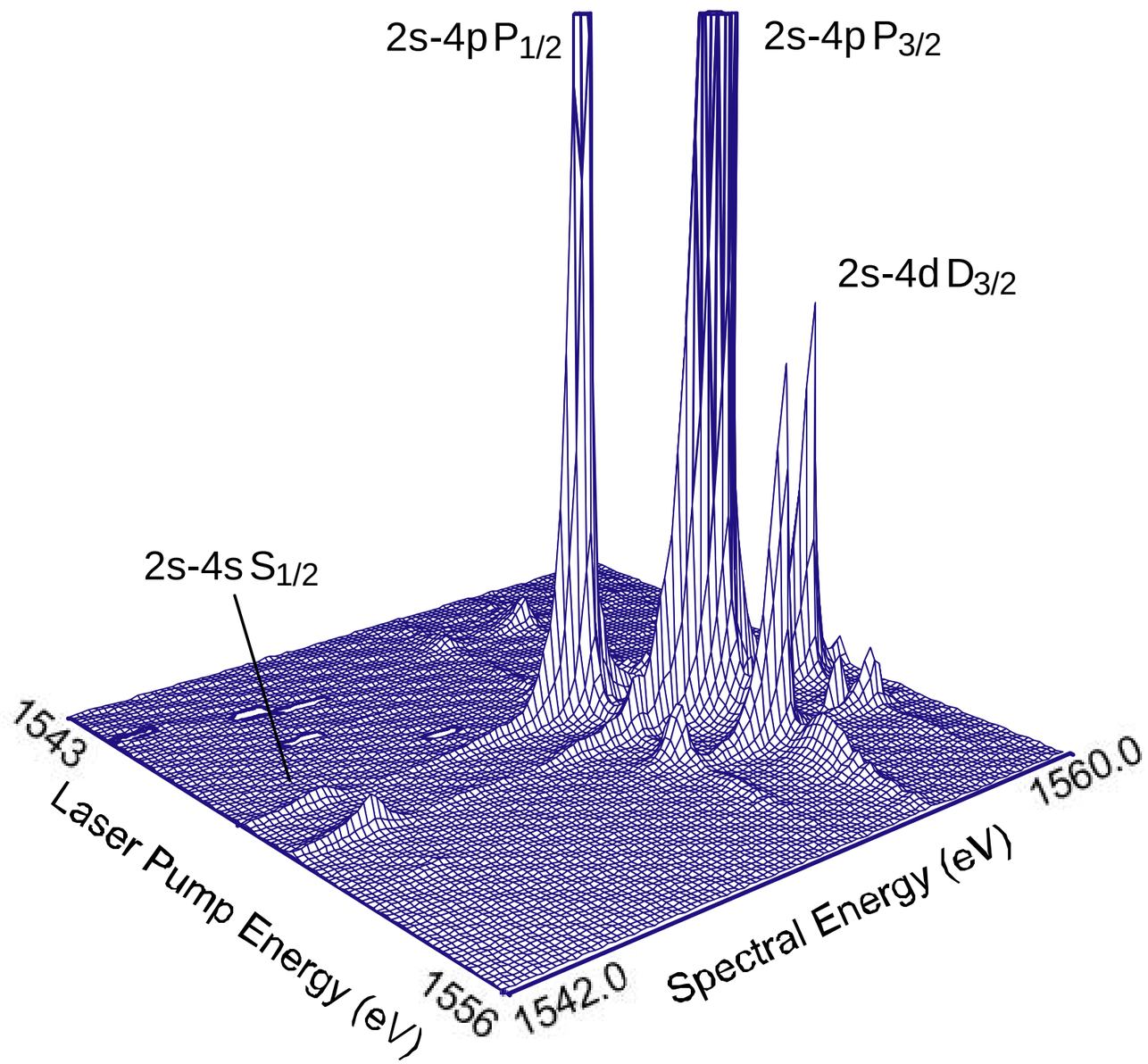


XFEL coupled to monochromator will tune through a line to provide plasma rates

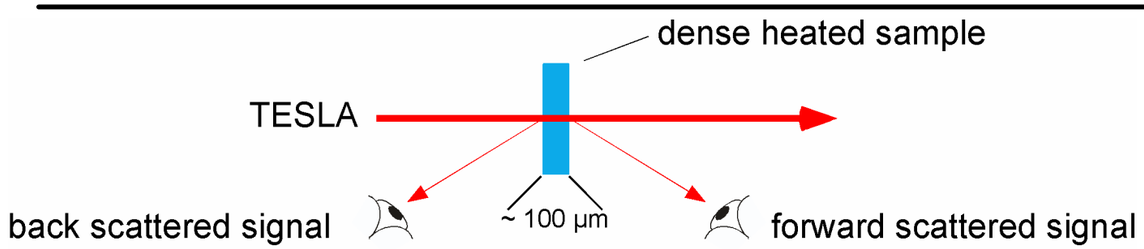
- Example: pumping Li-like Iron $1s^2 2l$ - $1s^2 4l$

- Collision rates and plasma field fluctuations can be measured

- Bandwidth of ~10^{-4} can be obtained by use of a crystal



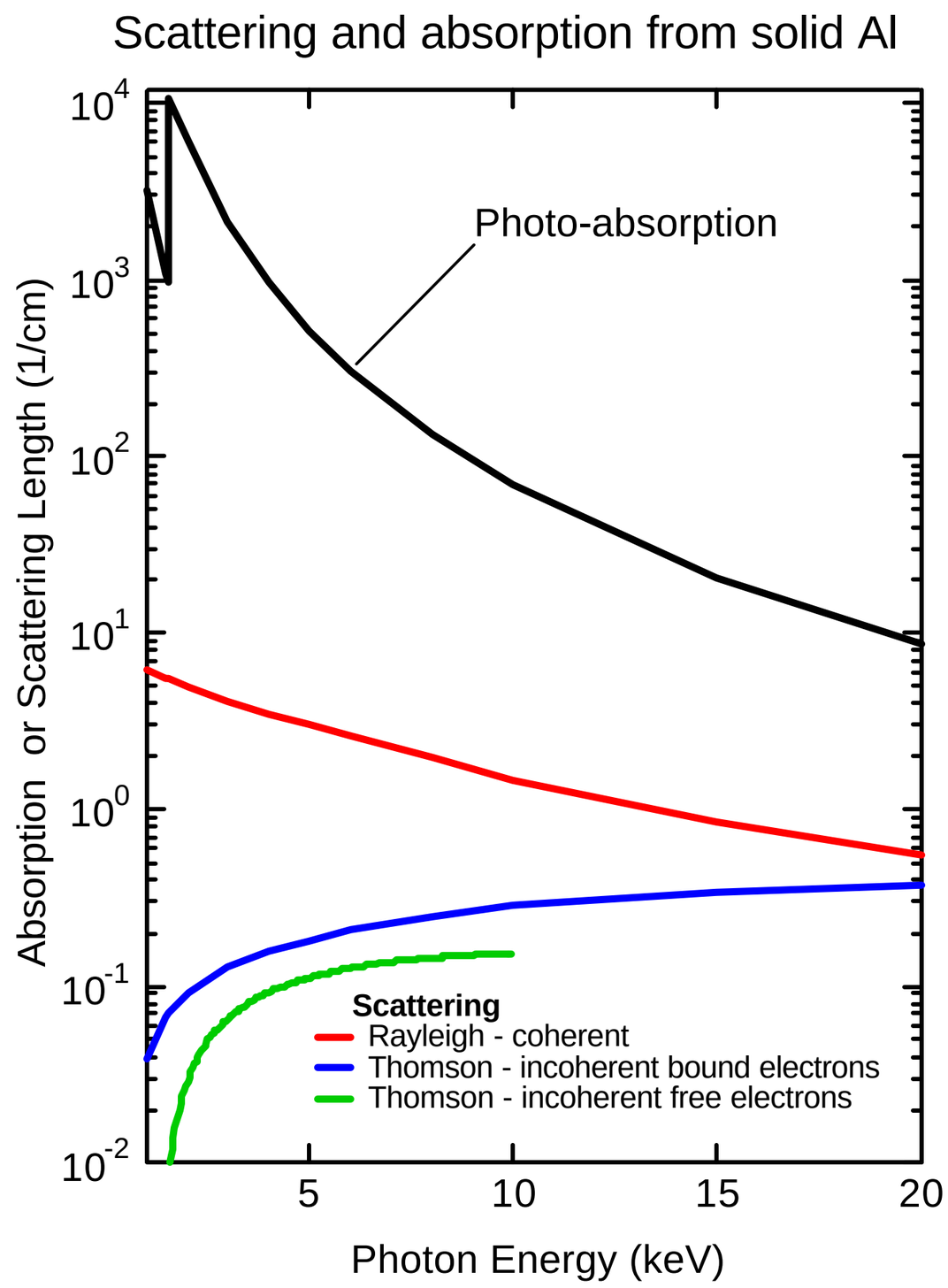
XFEL will be used to *probe* HED matter



- 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

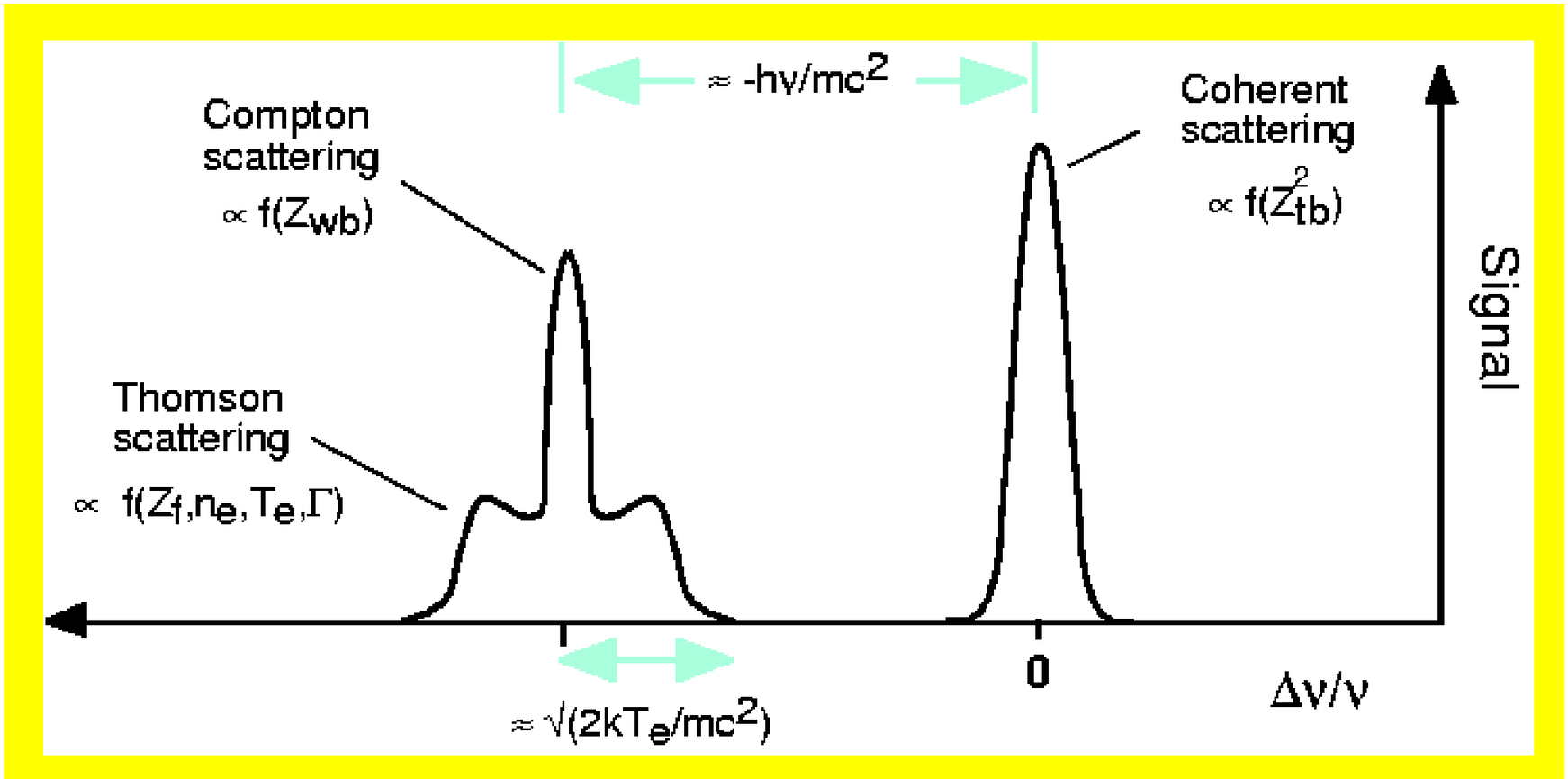
- XFEL scattering signals will be well above noise for all HED matter



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

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

schematic



- For a 25 eV, 4×10^{23} cm^{-3} plasma the XFEL produces 10^4 photons from the free electron scattering

- Can obtain temperatures, densities, mean ionization, velocity distribution from the scattering signal

Goal for TESLA WDM experiments: Measure equation of state, material properties, shocks

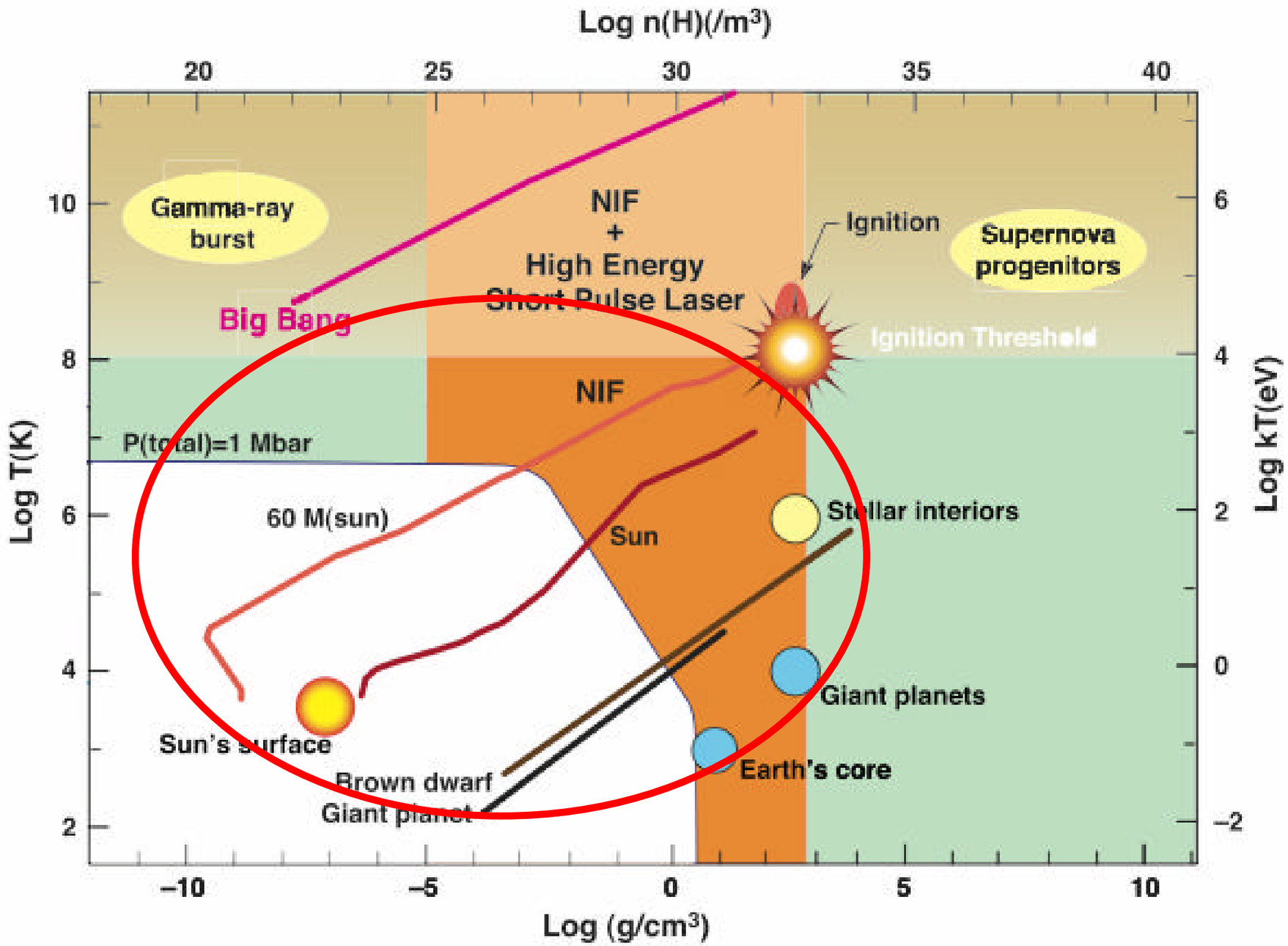
- Equation of State measurements illuminate the microscopic understanding of matter
  - The state of ionization is extremely complex when the plasma is correlated with the ionic structure
- Material properties of the system depend on the same theoretical formulations
  - Conductivity, opacity, transport properties
- Shock generated WDM probed with XFEL

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 => XFEL
- XFEL will permit measurements of:
  - Kinetics behavior - rates, model construction
  - Measurement of $S(k,\omega)$, the dynamic structure factor, to directly measure the *in situ* plasma properties
  - Spectral Line formation - line shapes, shifts, ionization depression
  - High energy density plasma formation - measure matter in the densest regions

Summary: HEDS regime defined by the NAS will be covered by XFEL experiments

Definition of High Energy Density: $\frac{E}{V} \geq 10^{12} \frac{\text{ergs}}{\text{cm}^3}$



Issues related to the HEDS case for the XFEL

- Optimum machine time structure and time resolution?
  - Bunch length and bunch pattern? 1 fs for HEDS
  - Is a duty cycle higher than 10 Hz necessary? No
- Optimum wavelength and/or wavelength tunability?
  - To perform pumping, heating and probing need maximum tunability and wide range of wavelengths.
- Role of coherence and coherence parameters?
  - None
- Specific experiment on the beamline lay-out?
  - To cover entire phase space requires two optical lasers (50 fs, 1 J) (~1 ns, >200 J)
- Use of spontaneous emission?
  - Important for broadband absorption studies