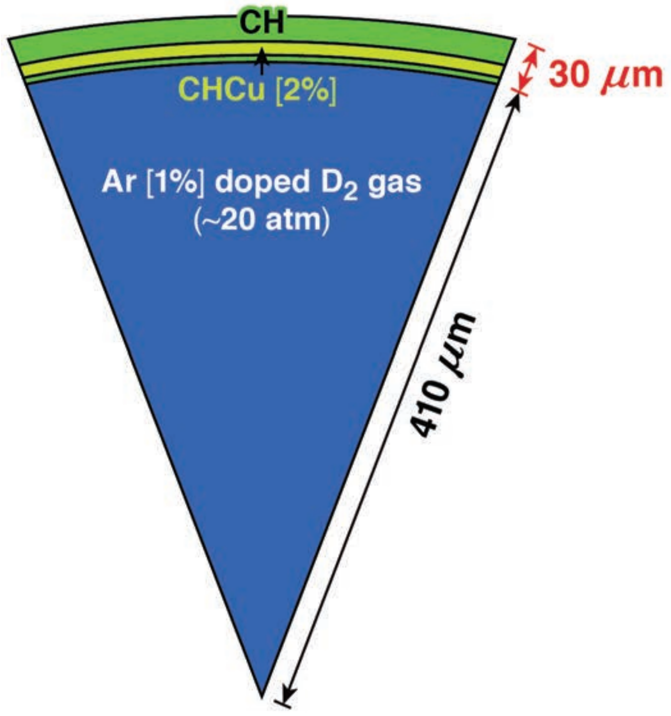
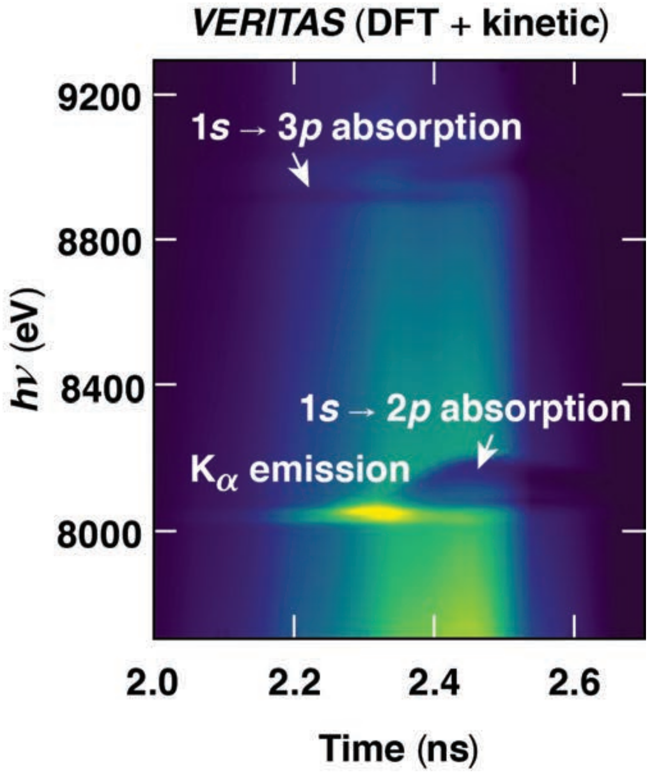
Probing Extreme Atomic Physics at Petapascal Pressures





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Division of Plasma Physics
Pittsburgh, PA
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Collaborators

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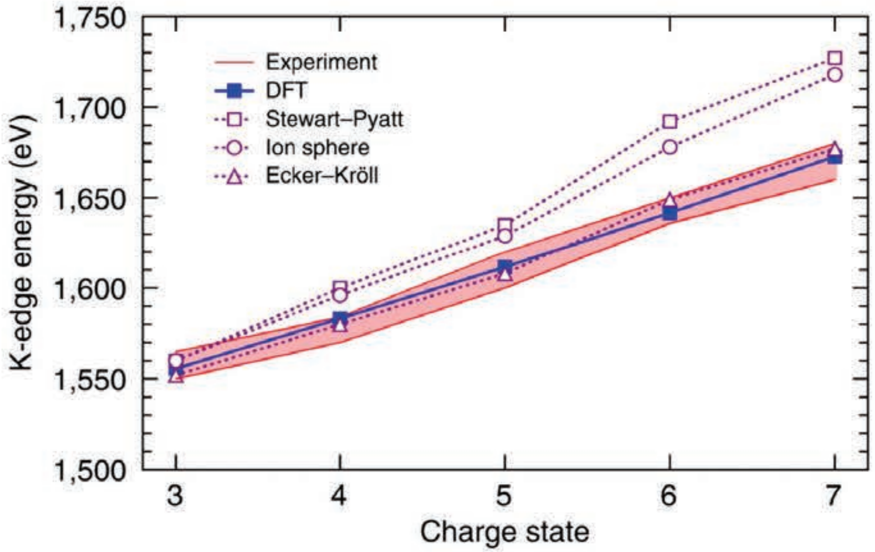
S. B. Hansen
Sandia National Laboratories

Atomic physics in warm/hot-dense plasmas at high pressures is far from being completely understood by the plasma physics community

Ionization potential depression (IPD) problem in dense plasmas*



The iron opacity "mystery"**

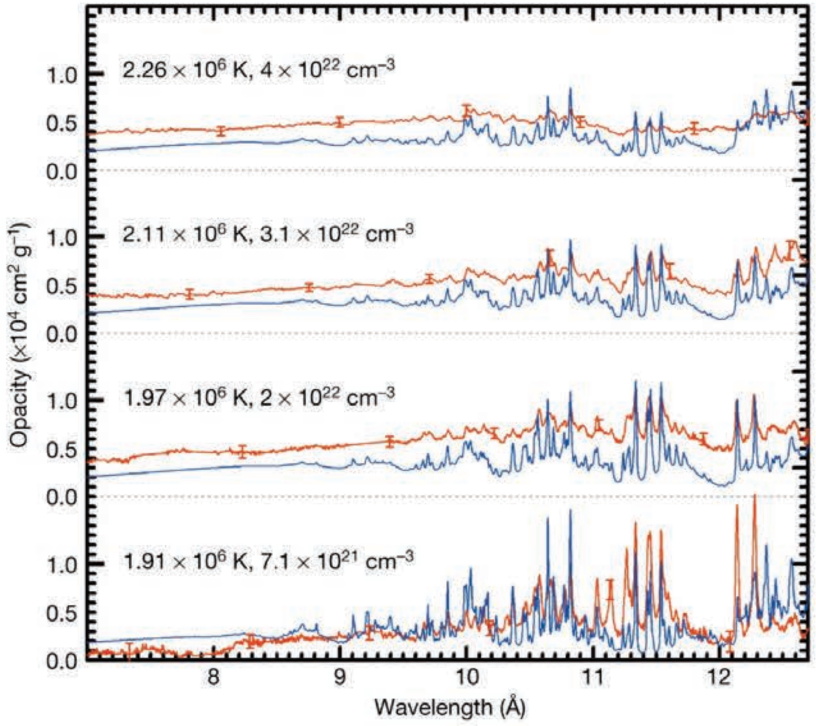


Figure 2: Measured iron opacity spectra at four T_e/n_e values compared with calculations.

>10 Mbar

~9 Mbar

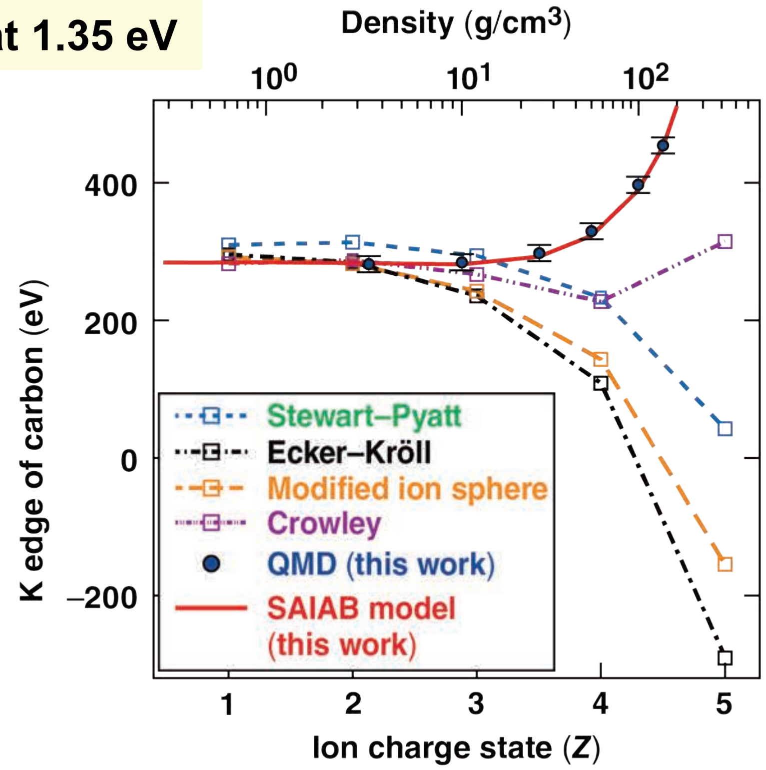
<1 Mbar

* O. Ciricosta *et al.*, Phys. Rev. Lett. 109, 065002 (2012);
S. M. Vinko *et al.*, Nature 482, 59 (2012);
D. J. Hoarty *et al.*, Phys. Rev. Lett. 110, 265003 (2013);
S. M. Vinko, O. Ciricosta, J. S. Wark, Nat. Commun. 5, 3533 (2014).

**J. E. Bailey, Nature 517, 56 (2015).

Thermal-DFT calculations have predicted new HED phenomena, such as *unusual K-edge movement* and interspecies radiative transitions,*** to occur in warm/hot and superdense plasmas

C at 1.35 eV



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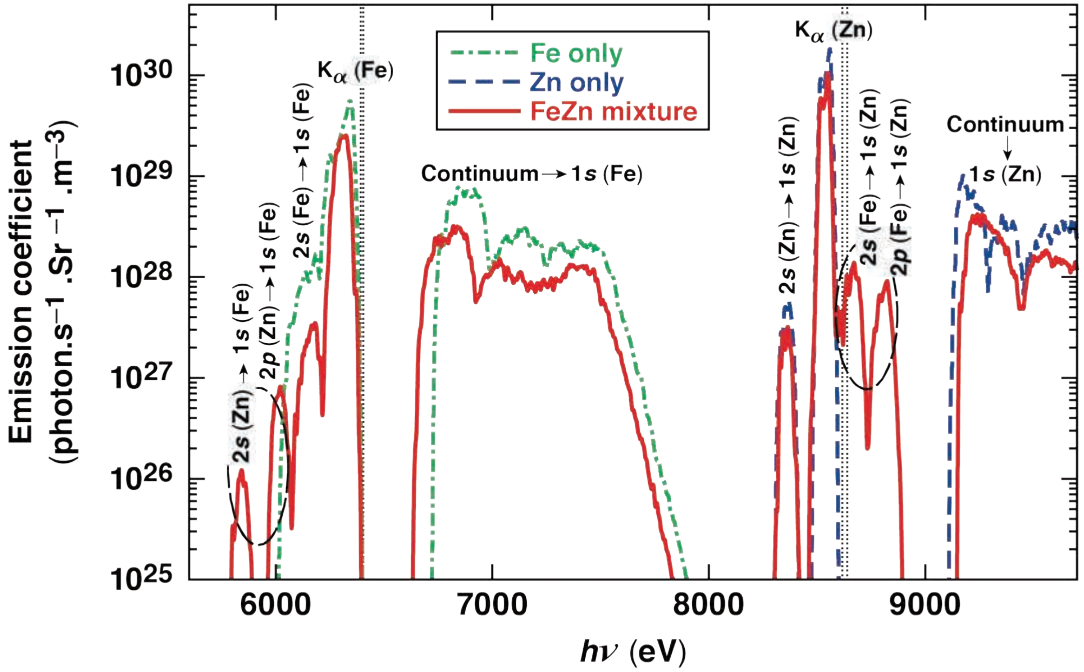
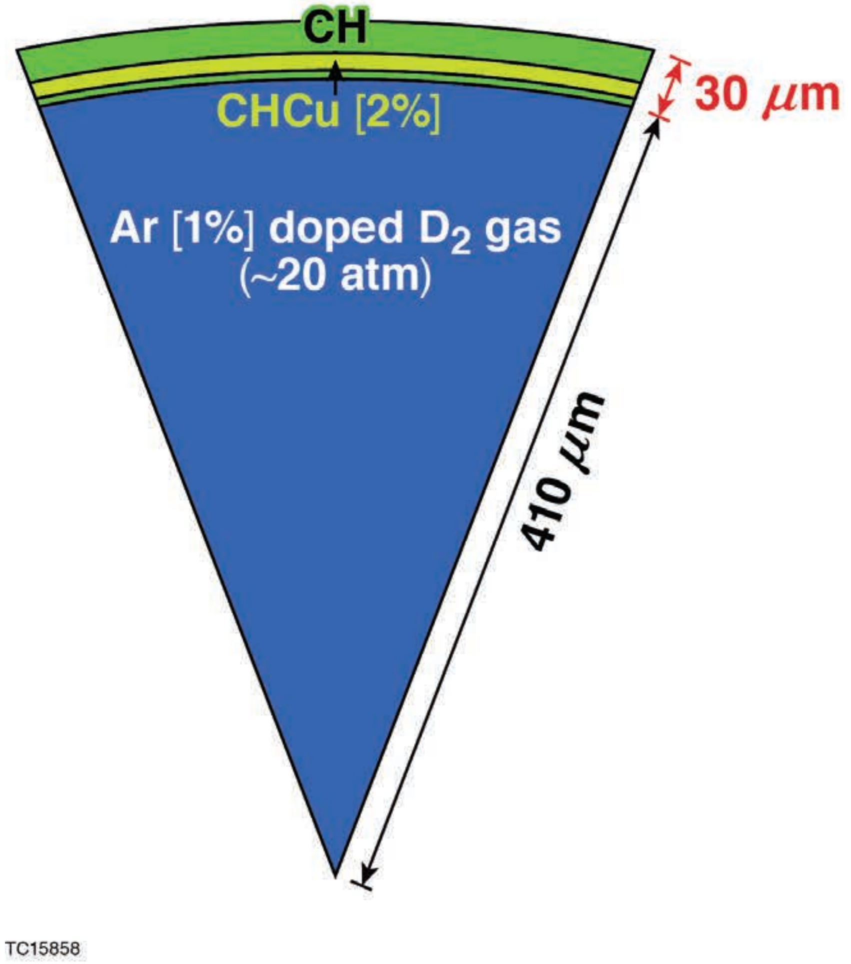
Fe + Zn at 1000 g/cm³ & 50 eV

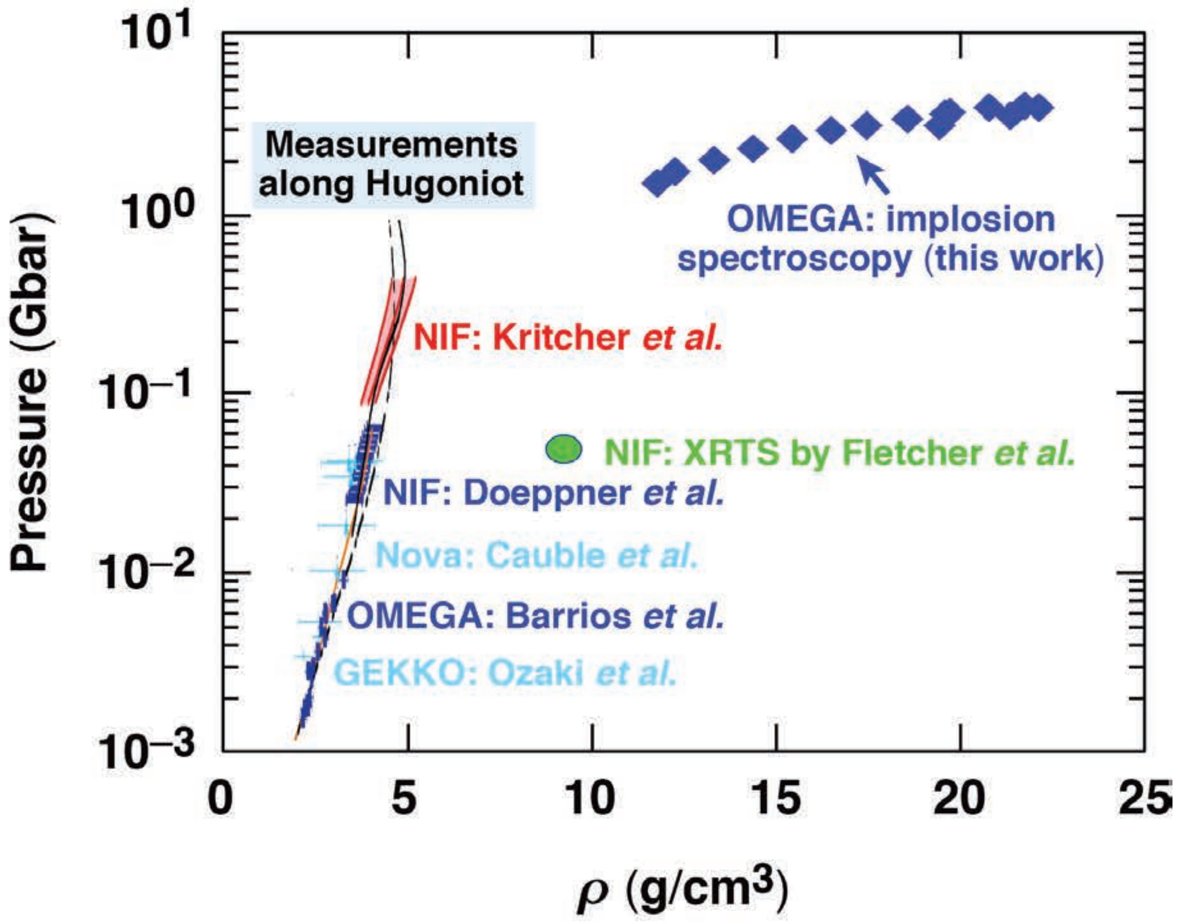


These DFT predictions, together with the existing controversies in the current understanding of dense plasmas, motivate our experiments on OMEGA.

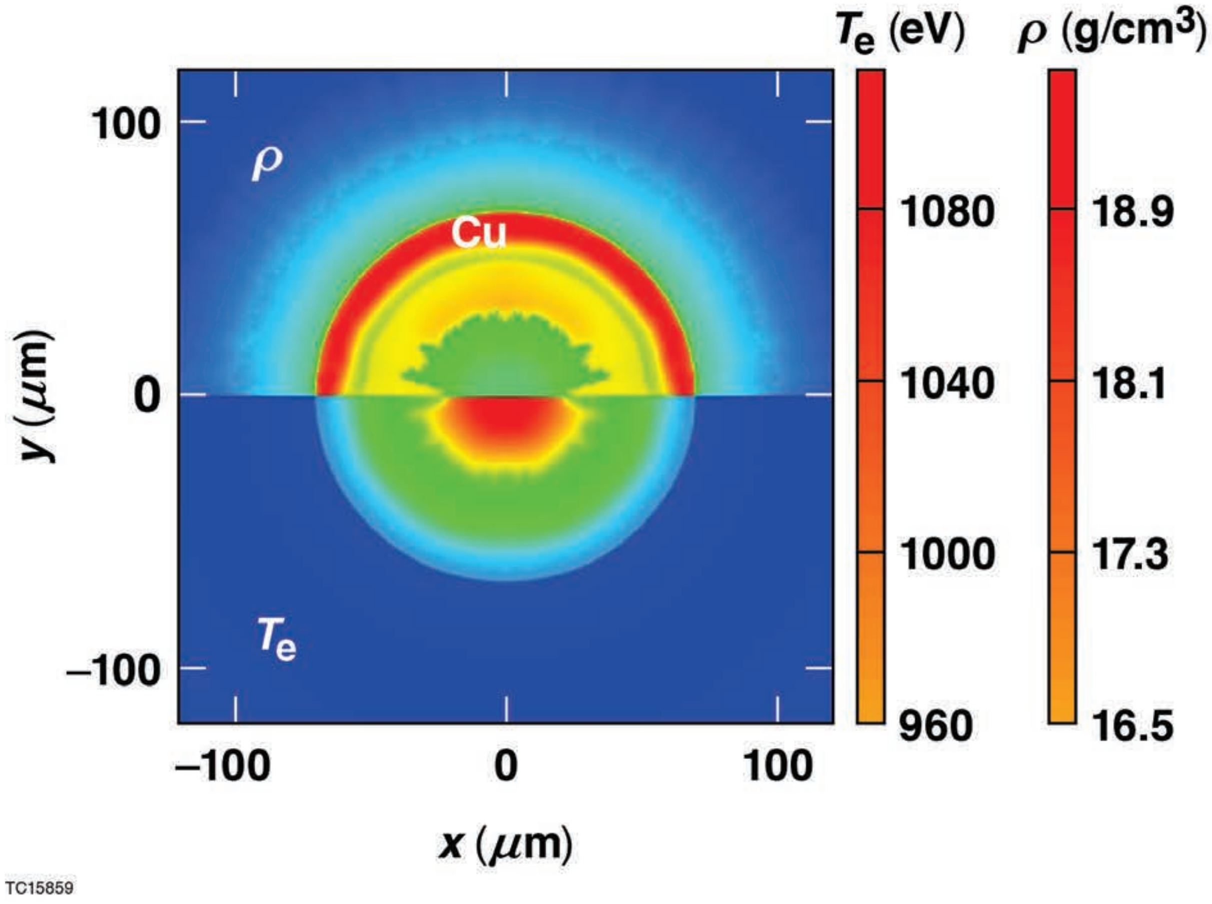
* S. X. Hu, Phys. Rev. Lett. 119, 065001 (2017).
** S. X. Hu *et al.*, Nat. Commun. 11, 1989 (2020).

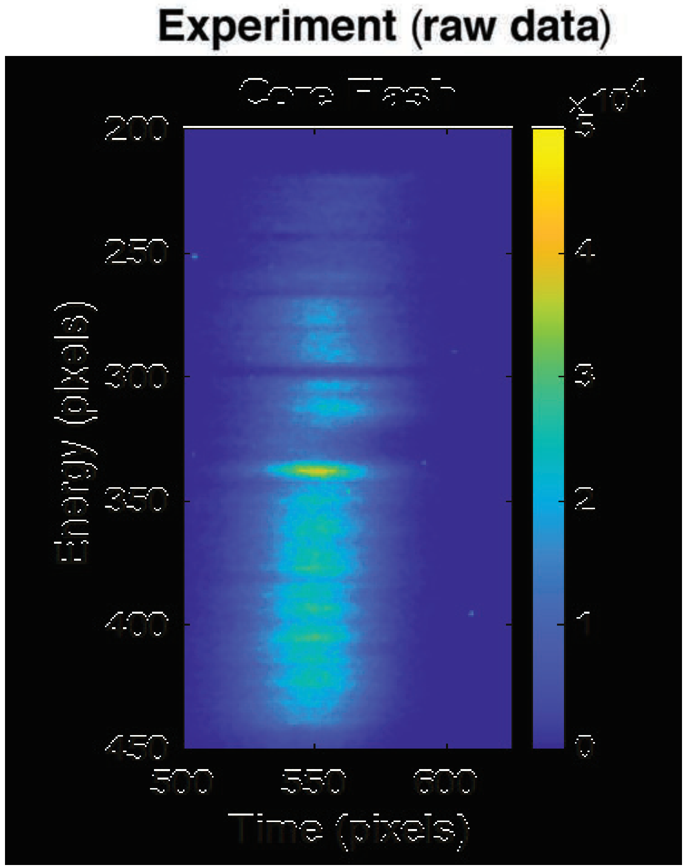
Using spherical implosions one can create and probe how HED matter behaves at petapascal pressures



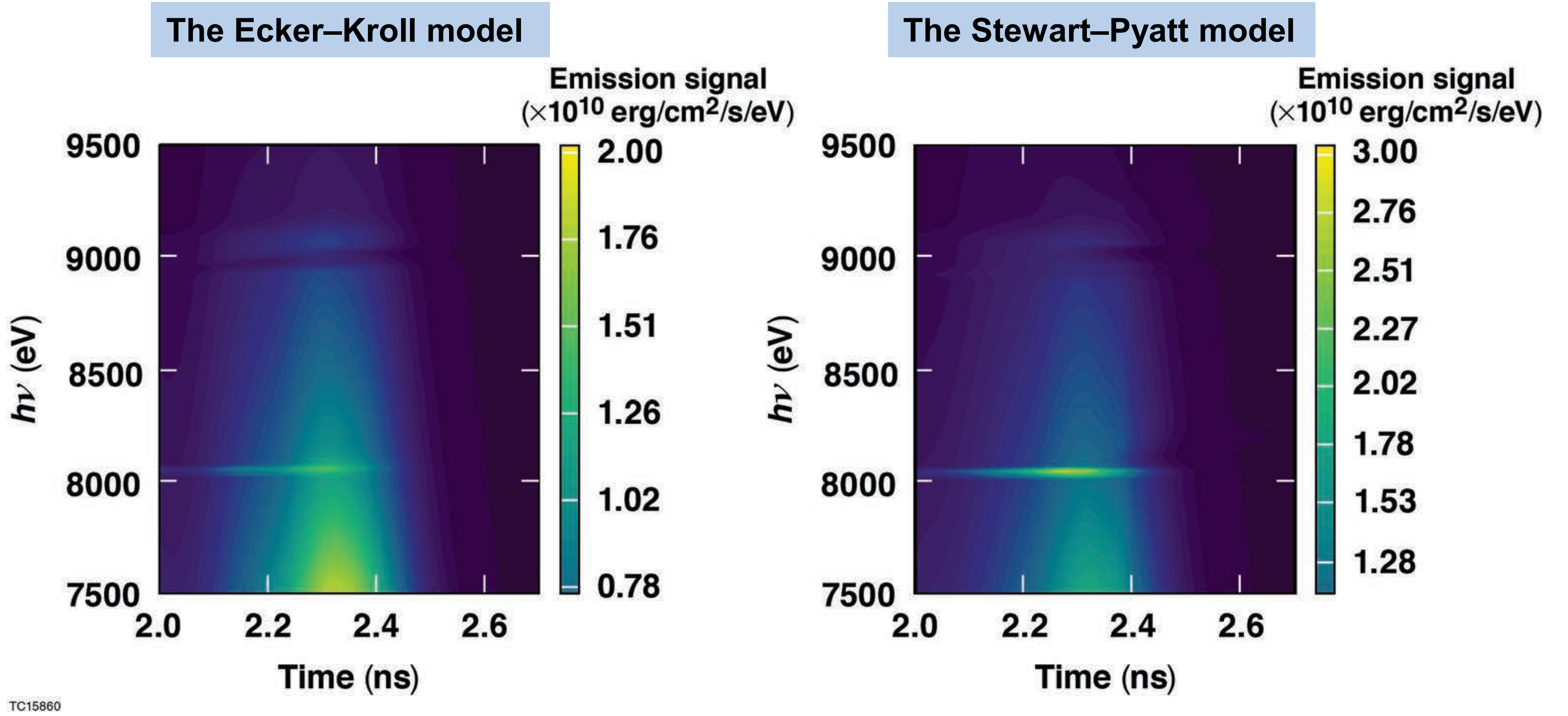


DRACO simulations show that this implosion platform can provide the dynamic plasma conditions to study extreme atomic physics in an uncharted territory





We have applied *Spect3D* to post-process hydro-simulations with different CRE (atomic-physics + continuum-lowering) models to compare with experiments



No single model gives all of the K_α/K_β emission and absorption features observed in experiments!

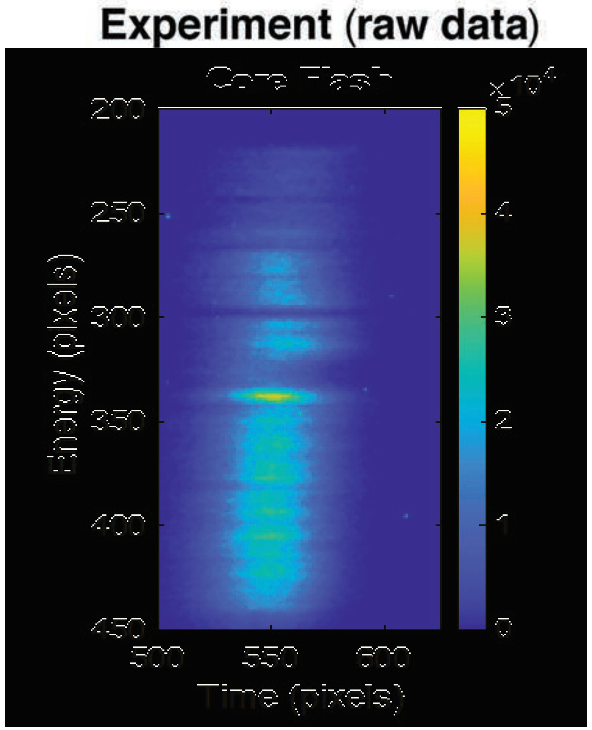
A DFT-based multiband non-LTE modeling code* (*VERITAS*) has been developed at LLE for a self-consistent understanding of extreme atomic physics at HED conditions

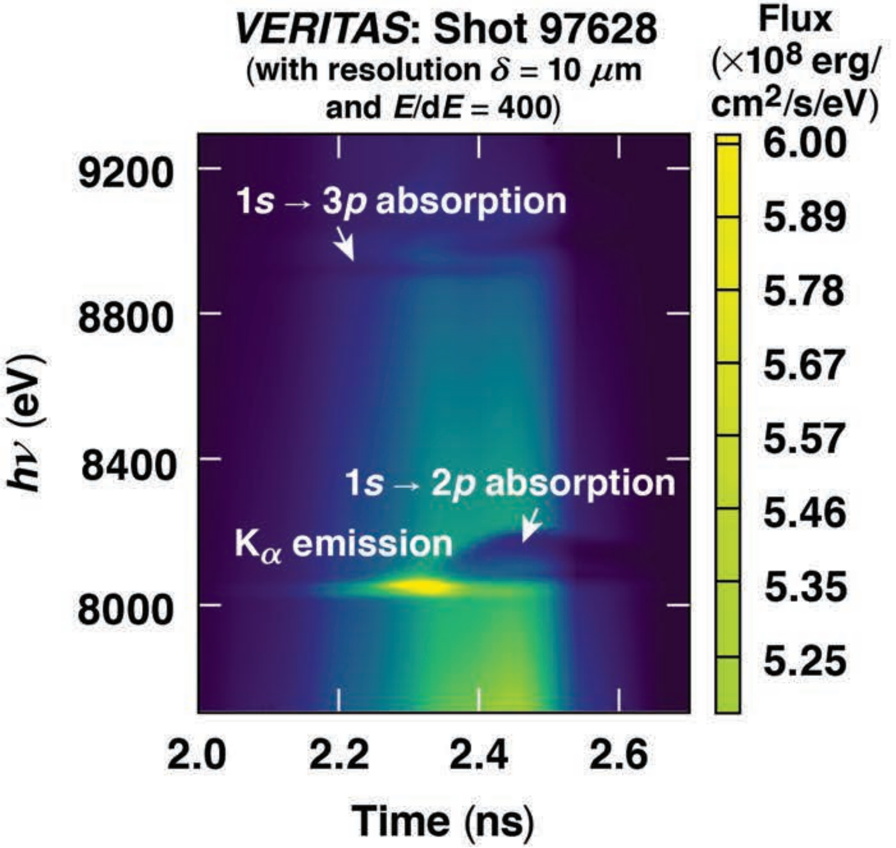
$$\begin{cases} -n_i \sum_{j \neq i}^{N_L} W_{ij} + \sum_{j \neq i}^{N_L} n_j W_{ji} = 0, \text{ (steady state)} \\ \mu \frac{\mathrm{d}I(r,n,v)}{\mathrm{d}z} = \eta(r,n,v) - \chi(r,n,v) I(r,n,v) \end{cases}$$

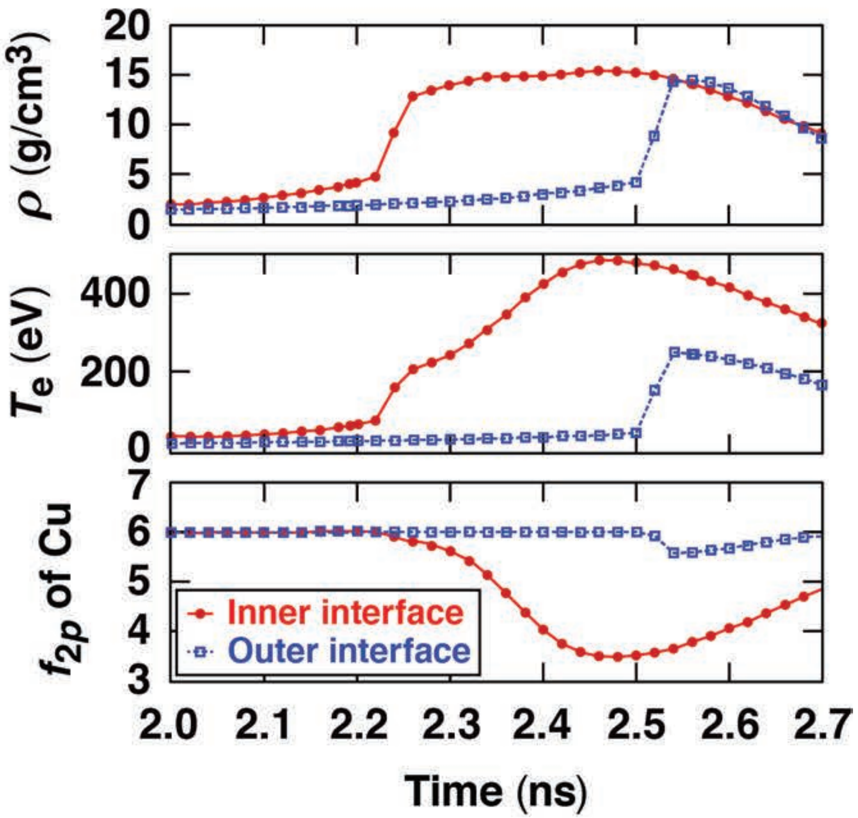
- The above coupled NLTE kinetic modeling can be solved for the self-consistent radiation field and state populations
- Instead of using a traditional atomic-physics model to calculate the Einstein coefficients (rates W_{ij}) for bound–bound and bound–free transitions, we extract them (oscillator strength) from DFT simulations!

* S. X. Hu *et al.*, "*VERITAS: A Density-Functional Theory Based Kinetic Modeling Code for X-Ray Spectroscopy of Warm-/Hot-Dense Plasmas*," to be submitted.
LTE: local thermodynamic equilibrium

The DFT-based *VERITAS* modeling predicts the expected spectral feature changes due to return shock and heat-wave propagation during stagnation







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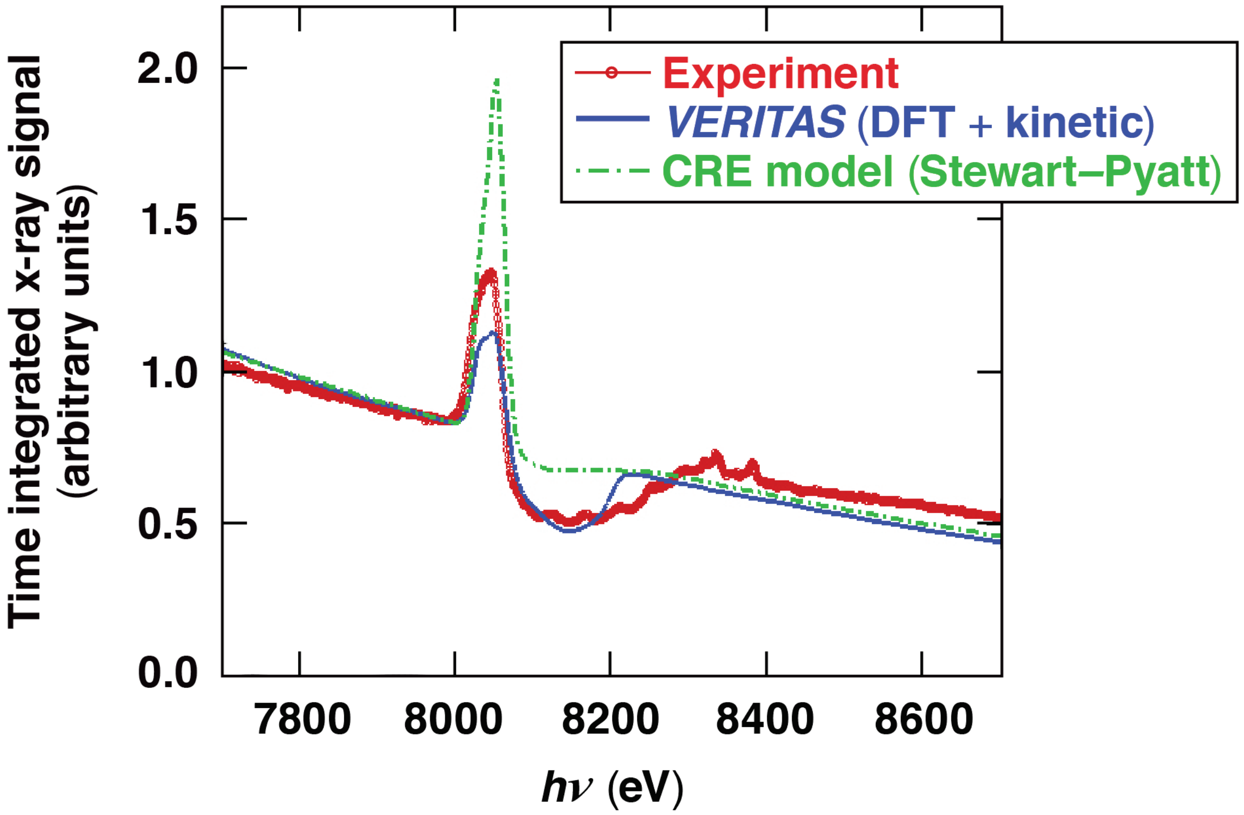
The DFT-based *VERITAS* modeling gives overall good agreement with experimental results for time-integrated spectra*



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Analysis of time-resolved spectrum and its comparisons with *VERITAS* and CRE models are underway.

*S. X. Hu *et al.*, "Probing Extreme Atomic Physics at Petapascal Pressures," in preparation.

Summary/Conclusions

Testing thermal density-functional theory (DFT) with precision experiments has been performed in an uncharted territory of extreme environments

- How atomic physics changes at petapascal pressures has been investigated with thermal-DFT calculations and precision K_α-/K_β-spectroscopy experiments on OMEGA*
- Traditional collision-radiative-equilibrium (CRE) models, using an atomic database with various continuum lowering models, are found to be unable to reproduce the dynamic 1*s*-2*p* absorptions observed in experiments
- A DFT-based multiband kinetic modeling code (*VERITAS)*, recently developed by us, gives self-consistent accounts for the ionization balance observed in warm/hot dense plasma experiments at petapascal pressures

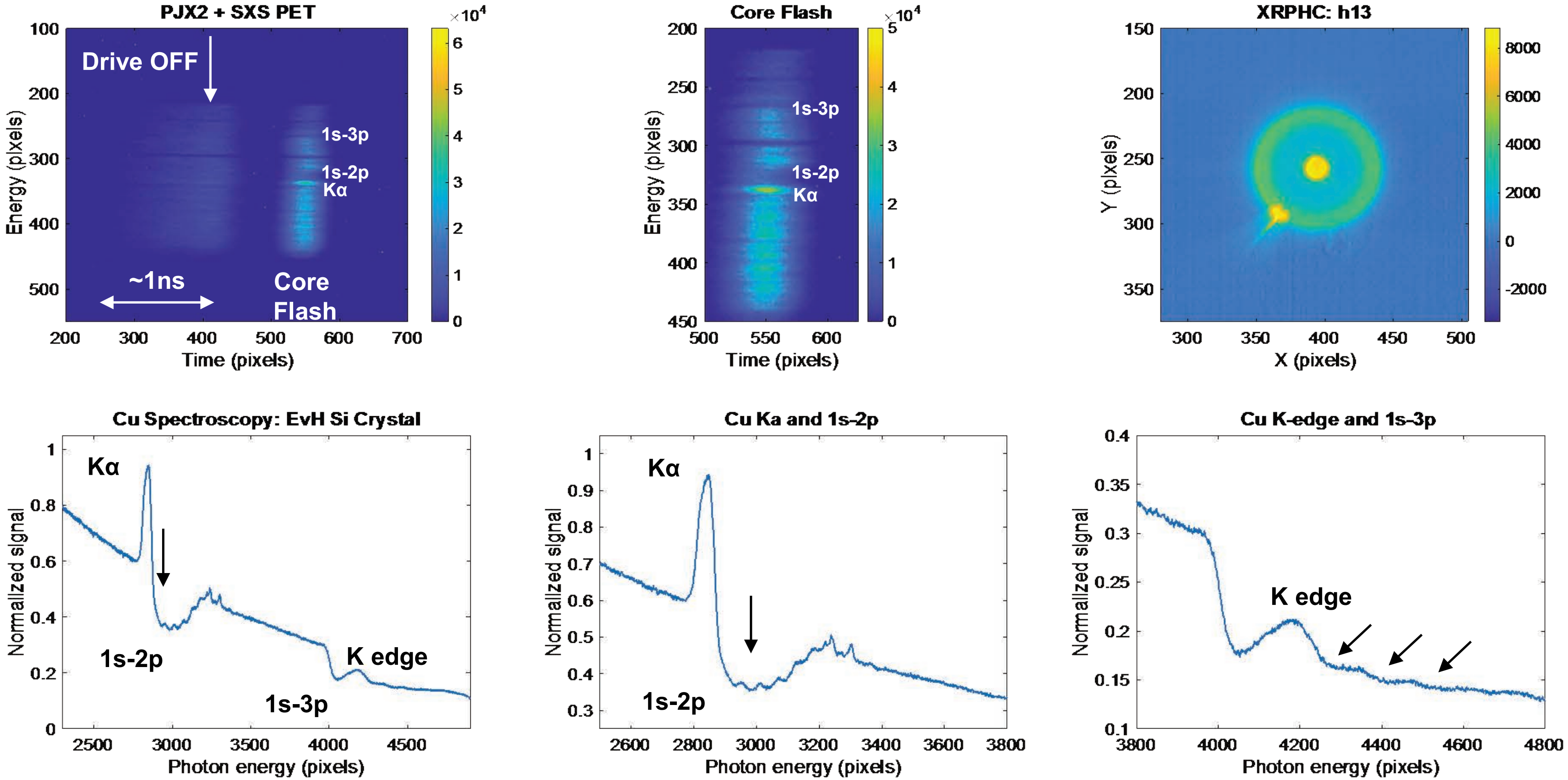
Thermal DFT calculations, benchmarked with precision experiments, may provide a unified picture to understand how HED matter behaves under extreme environments.

*S. X. Hu *et al.*, "Probing Extreme Atomic Physics at Petapascal Pressures," in preparation.
HED: high energy density

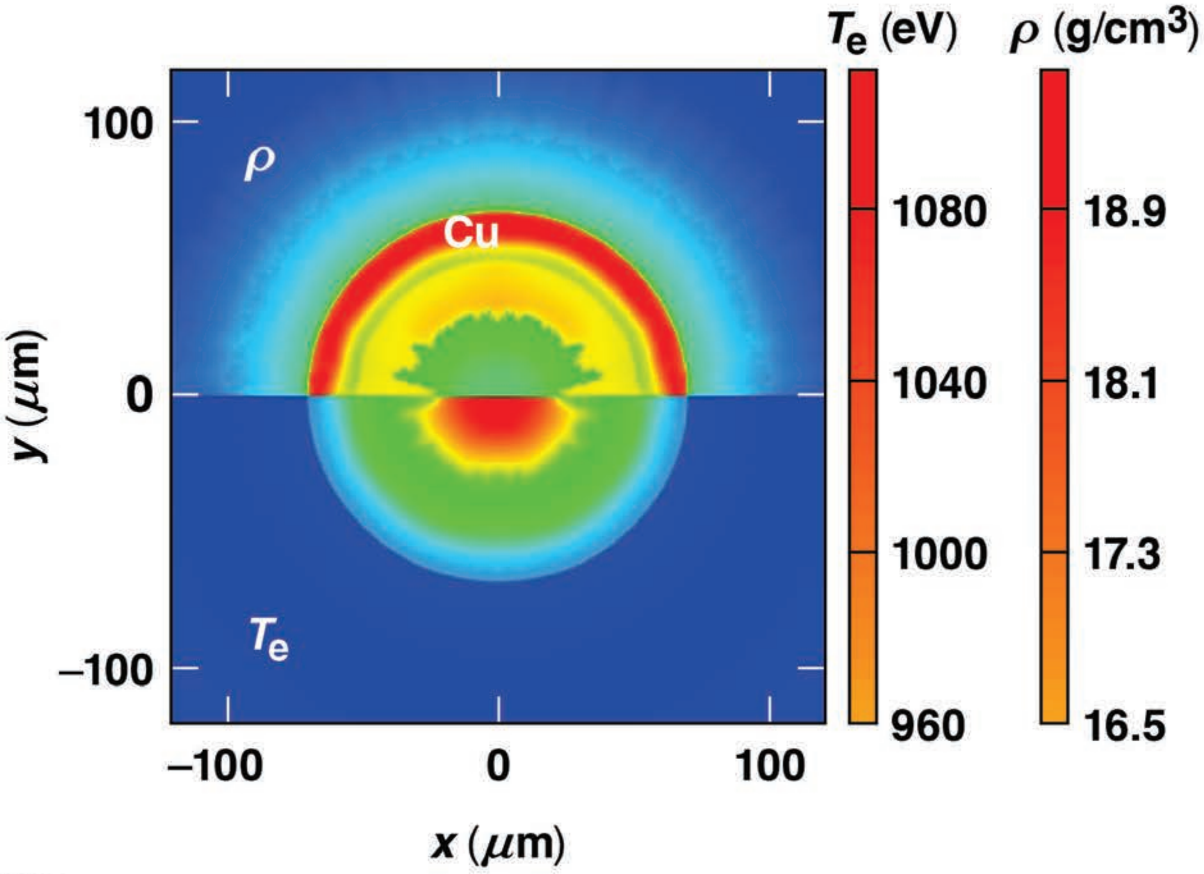
Thank You

Time-resolved spectroscopy for spherical implosions have successfully recorded the rich atomic physics at Gbar pressures

S97628: CH17um + CHCu(2at%)10um + <u>CH3um</u> + D2Ar(1at%) 20atm



DRACO simulations show that this implosion platform can provide the dynamic plasma conditions to study extreme atomic physics in an uncharted territory



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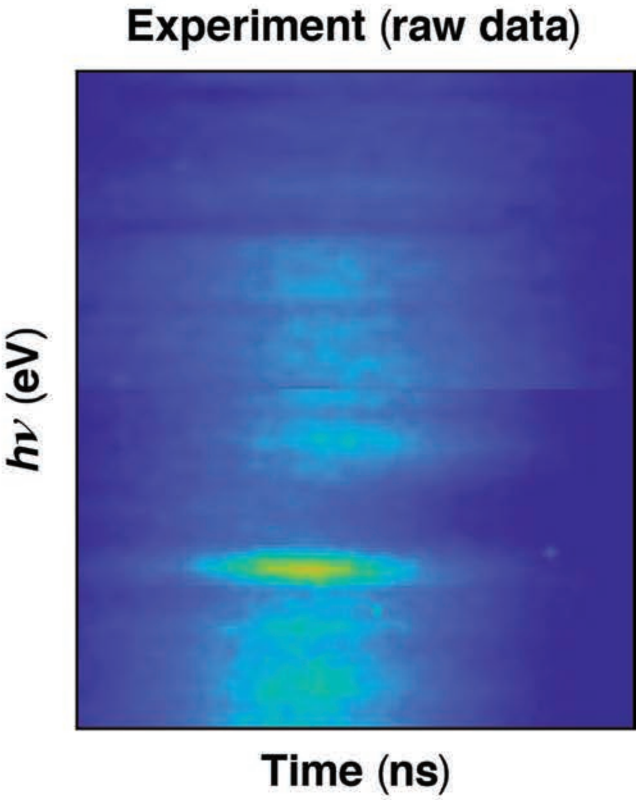

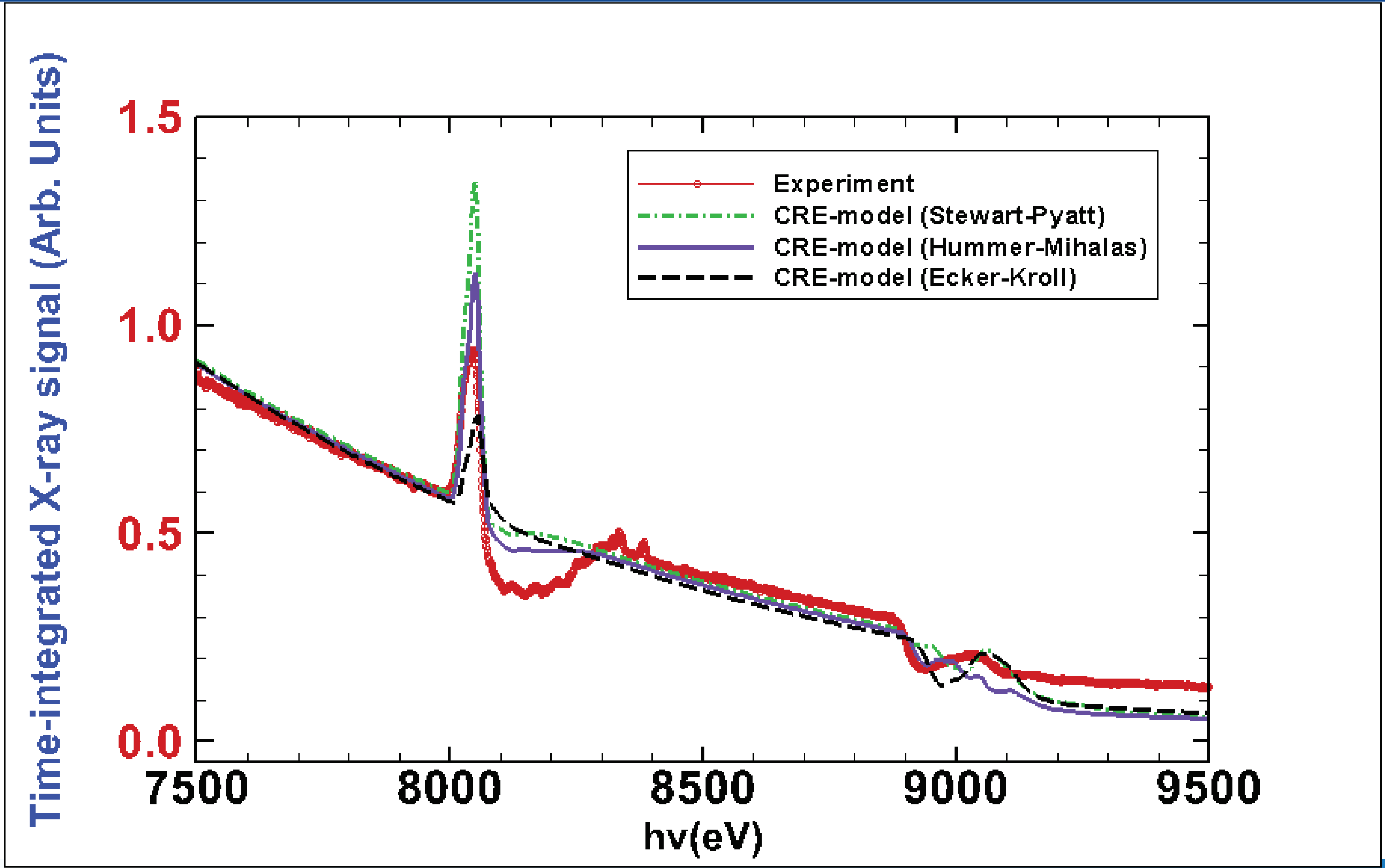

Time-integrated X-ray signal (Arb. Units)
1.5
1.0
0.5
0.0
7500
8000
8500
9000
9500
hv(eV)
Experiment
CRE-model (Stewart-Pyatt)
CRE-model (Hummer-Mihalas)
CRE-model (Ecker-Kroll)