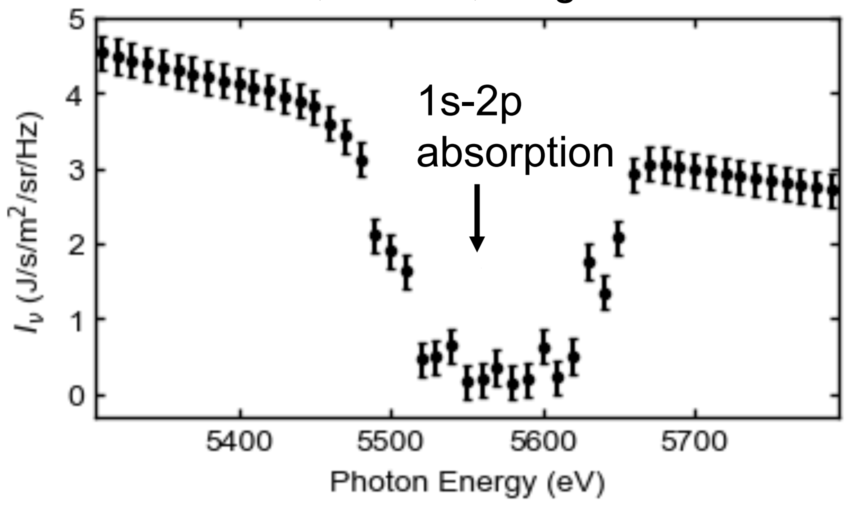
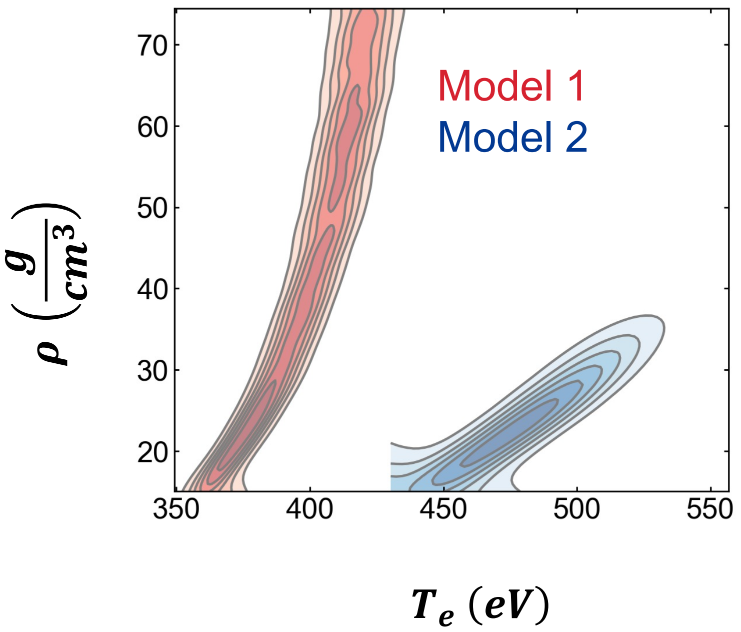
Constraining continuum lowering models at high energy densities

Synthetic spectrum
Cr, 400 eV, 40 g/cm^3



Inferred parameter distributions



David Bishel
University of Rochester
Laboratory for Laser Energetics

64th Annual Meeting, Division of Plasma Physics
Spokane, WA
October 17 – 21, 2022

Collaborators

P. M. Nilson, D. A. Chin, S. X. Hu, E. Smith, R. Epstein,
J. R. Rygg, G. W. Collins
University of Rochester, Laboratory for Laser Energetics

J. J. Ruby, E. V. Marley
Lawrence Livermore National Laboratory

I. E. Golovkin
Prism Computational Sciences

Summary

A synthetic study of continuum lowering models is guiding experiments to inform modern descriptions of continuum lowering.

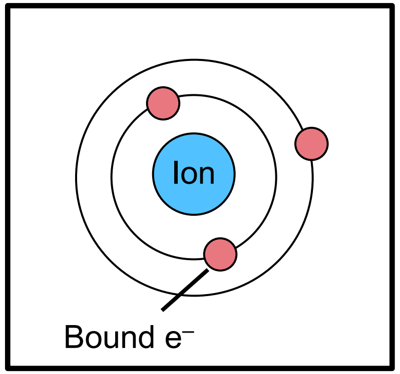
- **The intricate relationship between observed spectra and the underlying atomic physics requires careful consideration of where in phase space experiments should probe.**

- **K-shell absorption lines are demonstrated to be a sensitive measure of charge state for $T > 100\ \mathrm{eV}$ and $\rho > 10\ \mathrm{g/cm^3}$ in Cr.**

- **Combined with a temperature measurement, K-shell absorption discriminates between Ecker-Kroll and Stewart-Pyatt continuum lowering models**

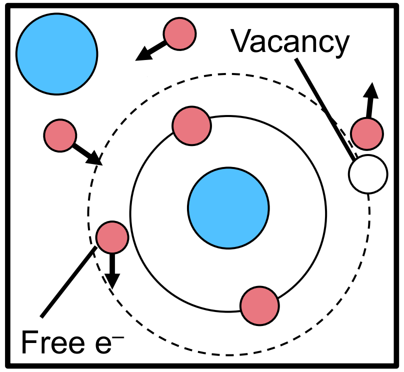
Traditional continuum lowering models approximate the electrostatic interaction between an ion and the circumfluent plasma.

Isolated atom

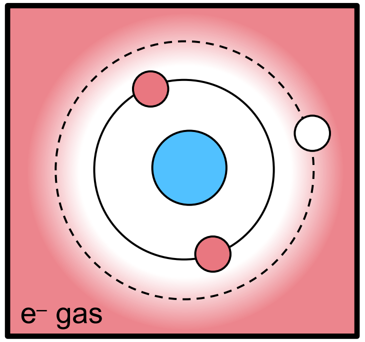


"Isolated atom" model breaks down at high densities.

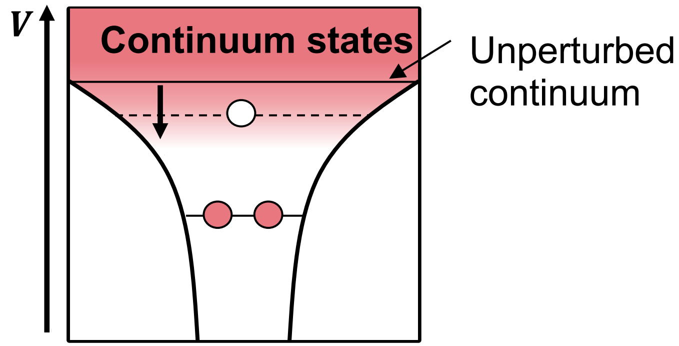
Dense plasma



Plasma approximated as an electron gas.



Plasma potential expressed analytically, allowing solution of ionic system



Ionization rate balance

Ion, electron densities

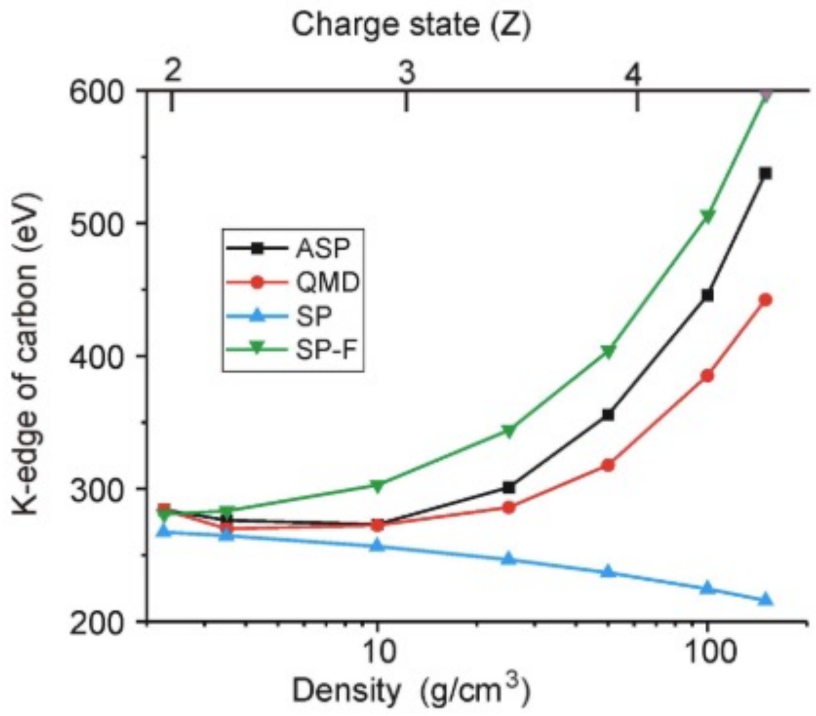
Ionization potential

Continuum lowering

$$\frac{N_{i+1}N_e}{N_i} \propto (kT)^{3/2}\exp\left(-\frac{\chi_i - \Delta E_c}{kT}\right)$$

Other formalisms exist beyond continuum lowering, each with different predicted EOS, material, and radiative properties of dense plasmas.

- **"Traditional" continuum lowering models (Ecker-Kroll, Stewart-Pyatt*)**
- **"Modern" thermodynamic models****
- **Density-functional-theory–based average ion models †**
- **…**



Rosmej 2018‡

ASP = atomic-solid-plasma
QMD = quantum molecular dynamic
SP = Stewart-Pyatt
SP-F = Stewart-Pyatt w/ Fermi Blocking

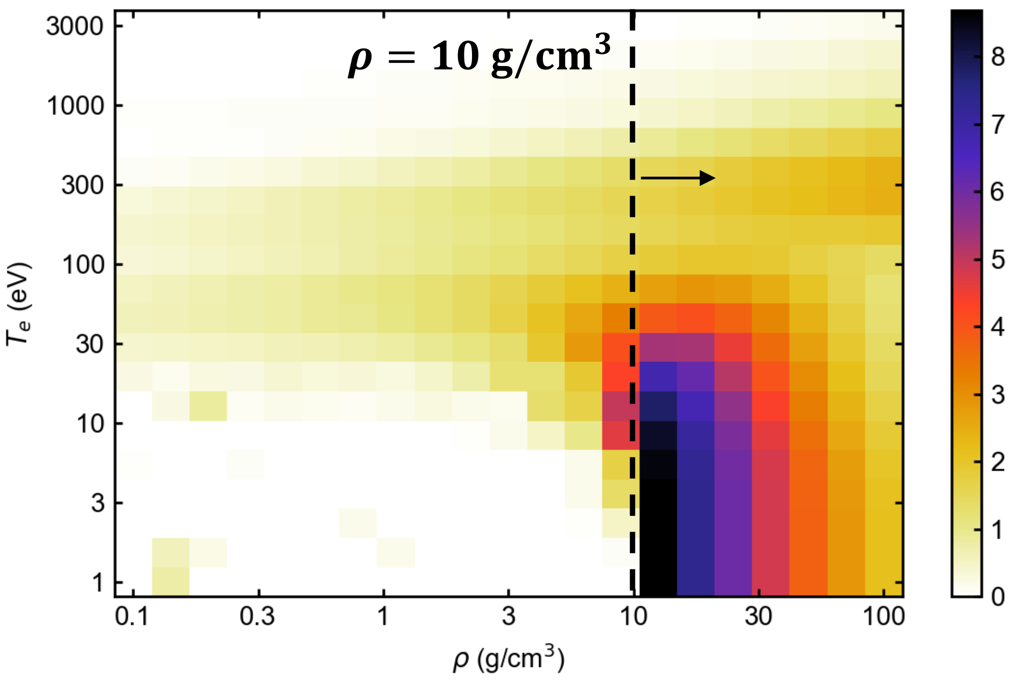
A framework is needed for designing experiments which discriminate between (or even discard) proposed models.

* Stewart & Pyatt, *Astrophys. J.* 144, 1203 (1966).
Ecker & Kröll, *Phys. Fluids* 6, 62–69 (1963).
** Crowley, *High Energy Density Phys.* 13, 84–102 (2014).
† Murillo *Phys. Rev. E* . 87, 1–19 (2013).
‡ Rosmej, F. B. *J. Phys. B At. Mol. Opt. Phys.* 51, (2018).

To demonstrate this framework, we consider Ecker-Kroll and Stewart-Pyatt.

Difference in predicted charge state for Cr

$$\bar{Z}_{EK} - \bar{Z}_{SP}$$

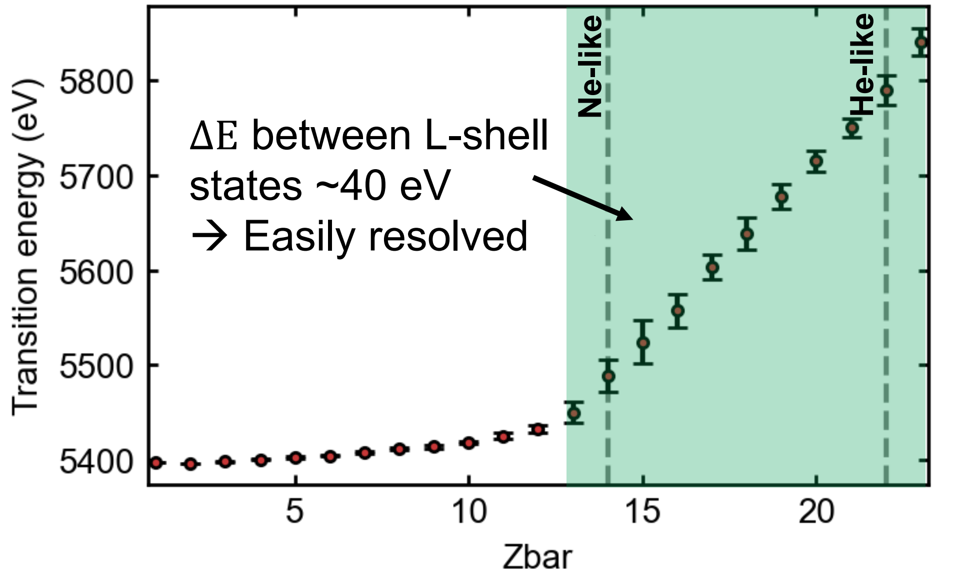


Densities $\rho > 10\ \mathrm{g/cm^3}$ discriminate between models.

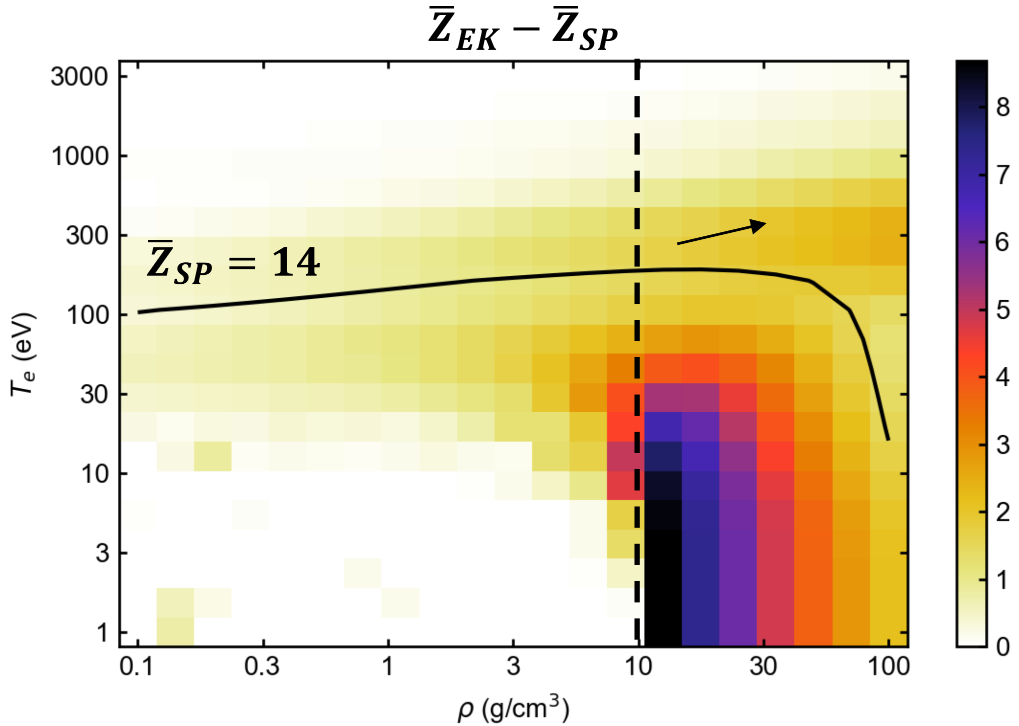
Stewart, J. C. & Pyatt, K. D. *Astrophys. J.* 144, 1203 (1966).
Ecker, G. & Kröll, W. *Phys. Fluids* 6, 62–69 (1963).

X-ray absorption spectroscopy of inner-shell transitions is amenable to probing high-density plasmas.

Cr $\overline{h\nu}_{1-2}(Z)$ from average ion calculation*



L-shell charge state requires $T_e > 100$ eV

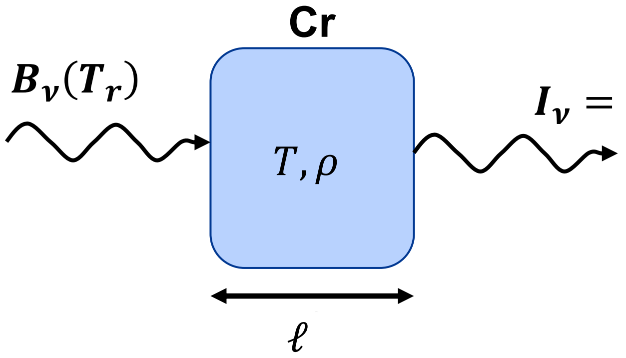


Candidate experiment: 1s-2p absorption of L-shell ions at 10s of $\mathrm{g/cm^3}$, 100s of eV

* H. Mayer, *Los Alamos Tech. Rep.* 5–9 (1947).
S. Atzeni and J. Meyer-ter Vehn, *The Physics of Inertial Fusion* (2004).

An idealized case tests the ability for the proposed experiment to discriminate models.

Backlit uniform slab model

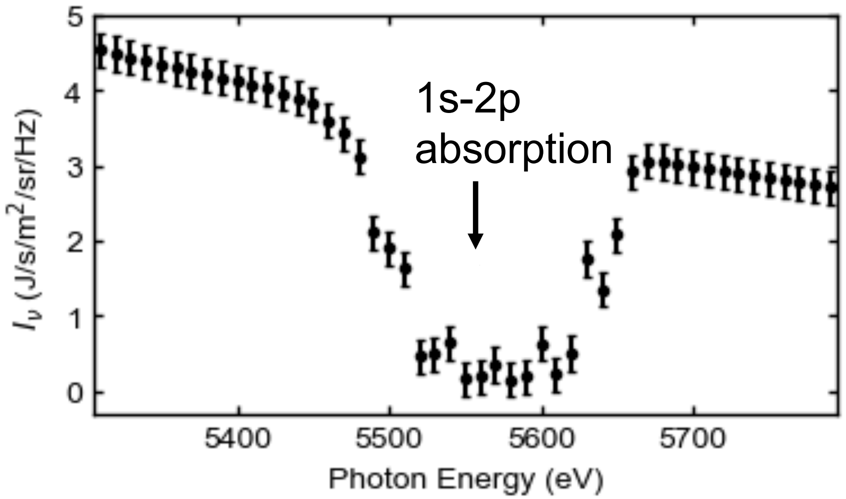


$$I_\nu = B_\nu(T_r)e^{-\alpha_\nu \ell} + \frac{j_\nu}{\alpha_\nu}\left(1 - e^{-\alpha_\nu \ell}\right)$$

+ noise
+ constant background

Synthetic spectrum (EK)

$T = 400 \text{ eV}, \rho = 40 \text{ g/cm}^3$

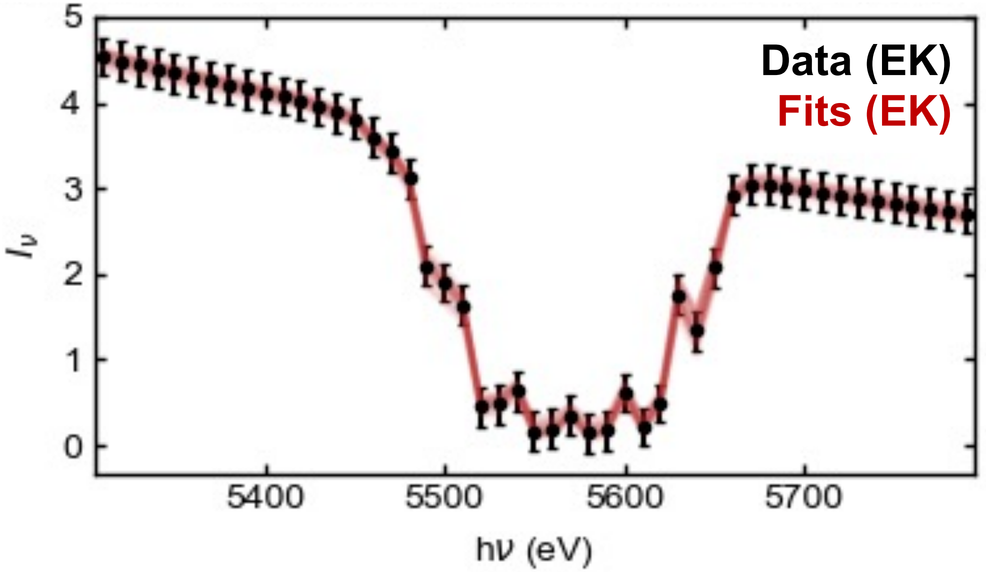


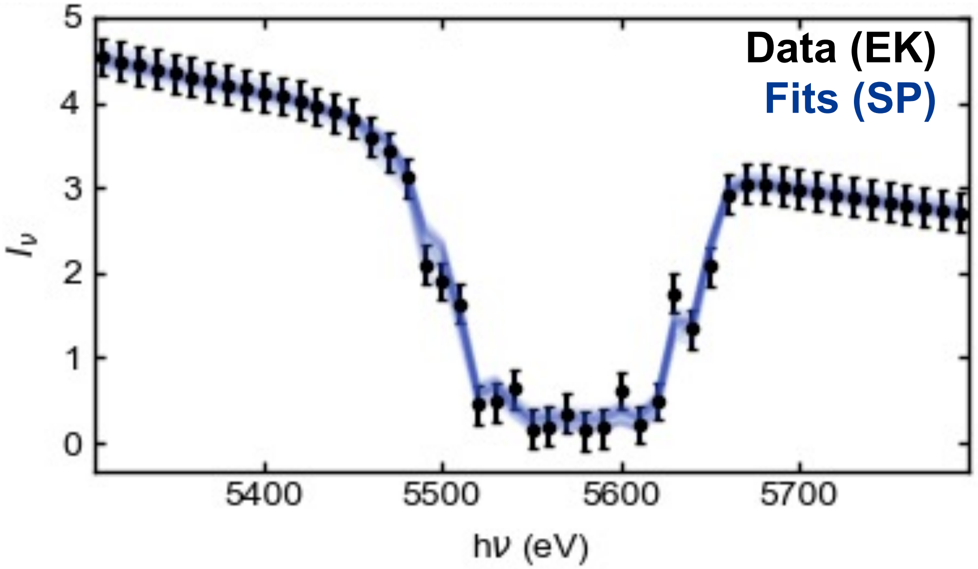
Bayesian inference is used to infer plasma conditions given different continuum lowering models.

* j_ν, α_ν from PrismSPECT atomic structure and kinetics code
J.J. MacFarlane et al, Inert. Fusion Sci. Appl. 2003 457 (2004).

Both models produce reasonable fits to the synthetic data.

Plausible fits from Bayesian inference*,†

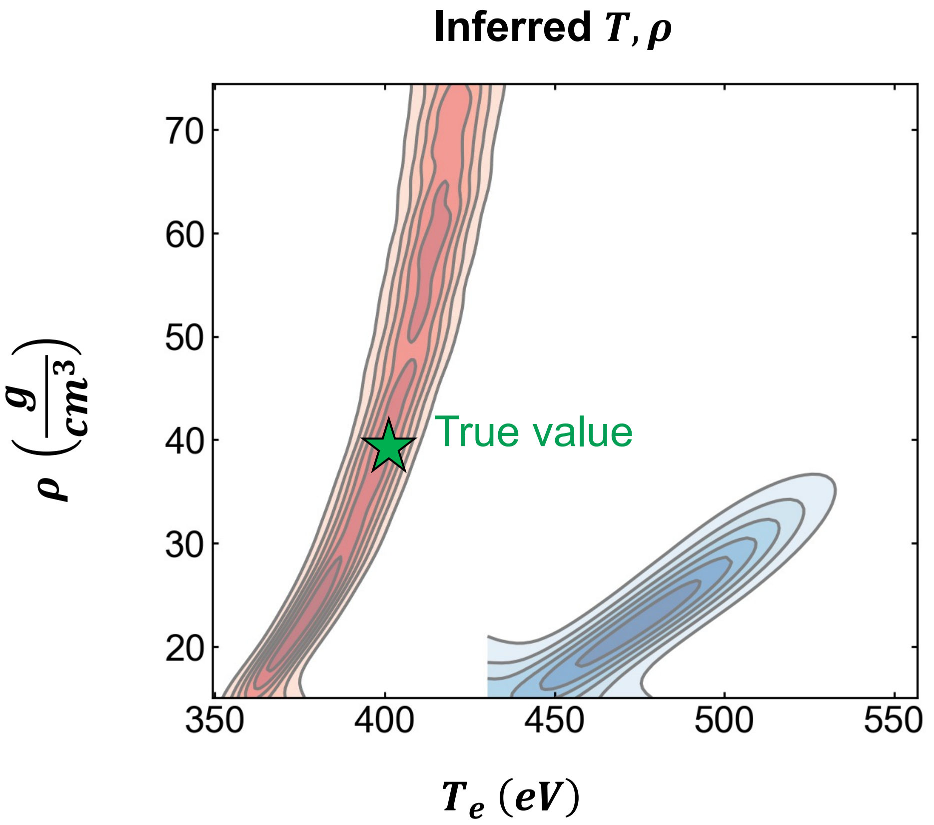




Spectrum *alone* does not constrain continuum lowering model.

* D. Sivia and J. Skilling, *Data Analysis: A Bayesian Tutorial,* 2012.
† Numerical sampling implemented in numpyro:
E. Bingham *et al., J. Mach. Learn. Res.* 20, 1–6 (2019).
D. Phan *et al., arXiv* (2019).

The inferred plasma conditions can discriminate between models.

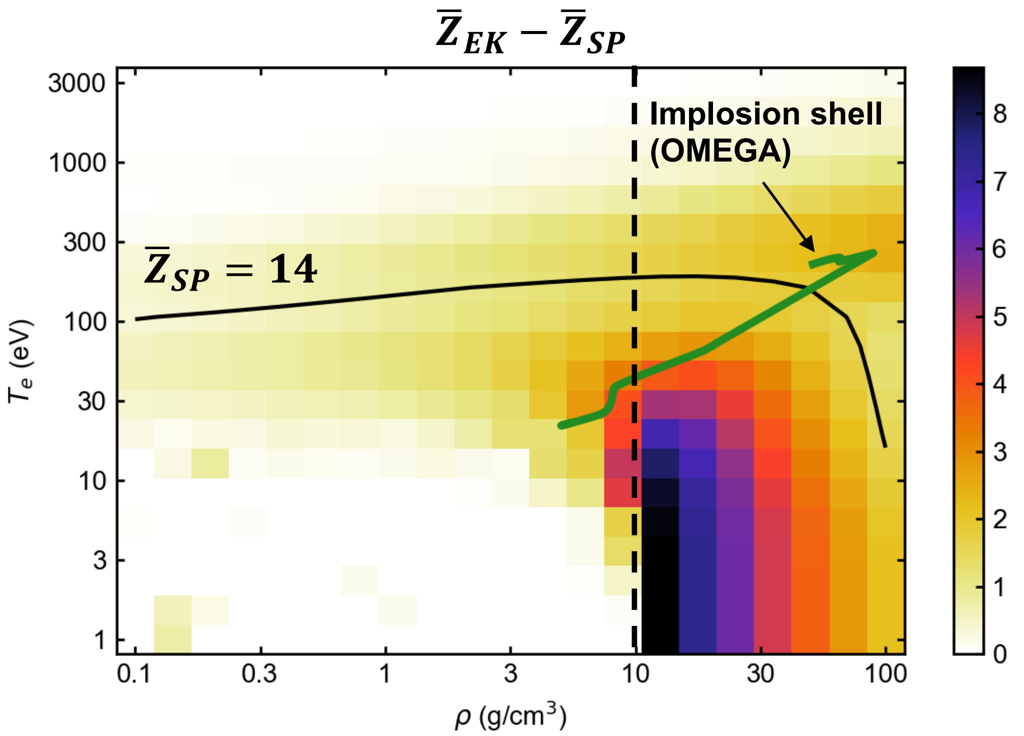


1. **Ecker-Kroll captures the true (T, ρ)**
2. **Ecker-Kroll and Stewart-Pyatt require mutually exclusive (T, ρ) to reproduce synthetic spectra**

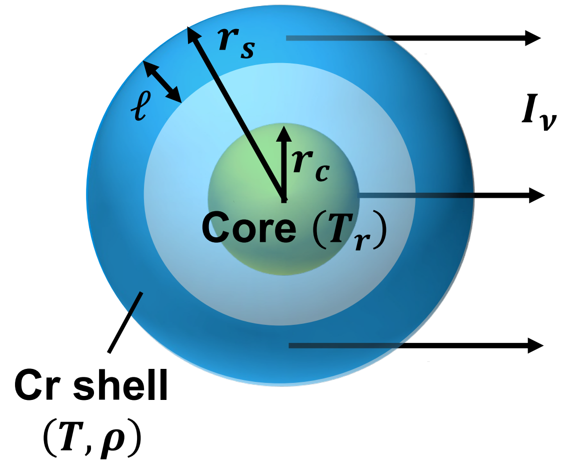
Measurement of temperature and 1s-2p absorption discriminates between EK and SP.

This model is being extended to geometries which can create 100-eV, 10-g/cm^3 plasmas.

Implosions access requisite conditions



Spherical geometries require additional parameters, enable new avenues for constraint



See E. Smith, TO05.00010, Thursday morning for constraint of thermodynamic states in implosions

Summary

A synthetic study of continuum lowering models is guiding experiments to inform modern descriptions of continuum lowering.

- **The intricate relationship between observed spectra and the underlying atomic physics requires careful consideration of where in phase space experiments should probe.**

- **K-shell absorption lines are demonstrated to be a sensitive measure of charge state for $T > 100\ \mathrm{eV}$ and $\rho > 10\ \mathrm{g/cm^3}$ in Cr.**

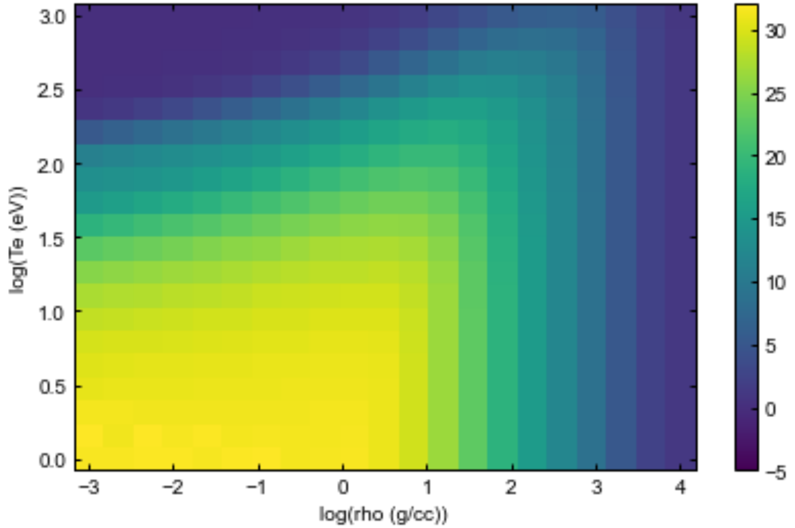
- **Combined with a temperature measurement, K-shell absorption discriminates between Ecker-Kroll and Stewart-Pyatt continuum lowering models**

Backup Slides

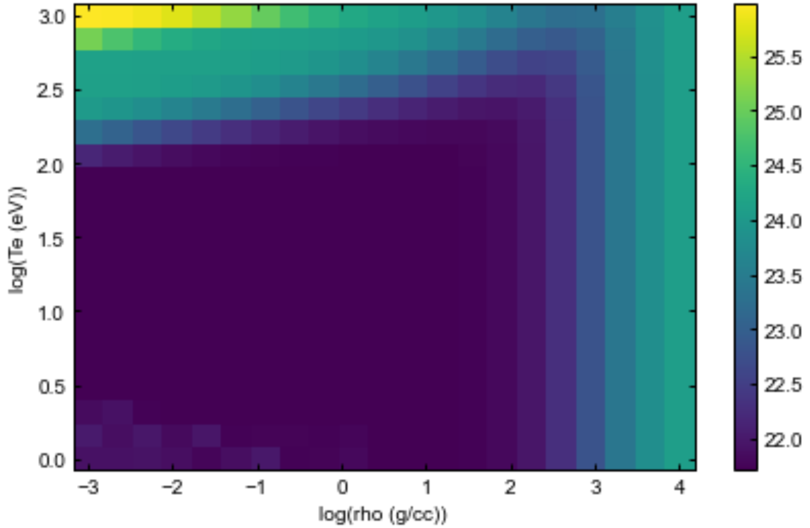
The screened hydrogenic model* is a computationally inexpensive atomic model for estimating material and radiative properties.

- Considers a fictitious average ion, having fractional charge and electron populations
  - One-electron atomic structure, modified by screening of a given shell by all other electrons
  - Can be implemented with varying degrees of detail (quantum numbers)
- Quick enough to generate ionization state, radiative properties for a radiation hydrodynamic code

Screening of $n = 2$ shell by all outer shells



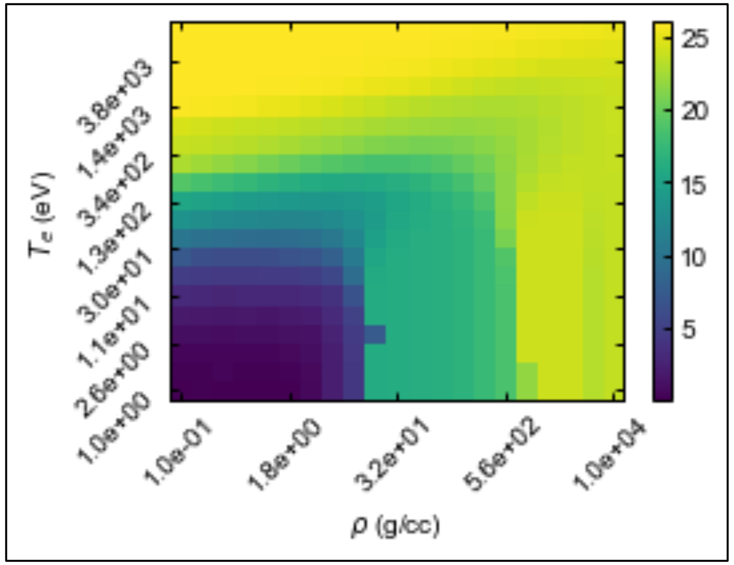
Effective nuclear charge experienced by $n = 2$ shell



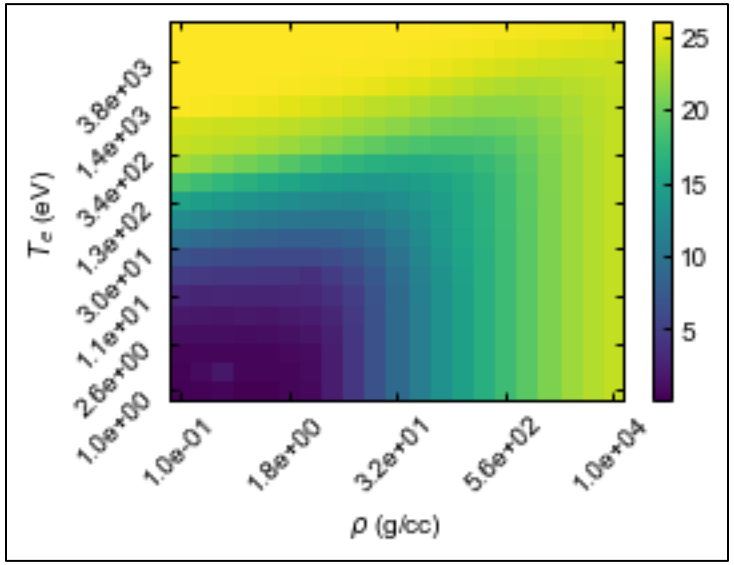
* H. Mayer, *Los Alamos Tech. Rep.* 5–9 (1947).
S. Atzeni and J. Meyer-ter Vehn, *The Physics of Inertial Fusion* (2004).

Ecker-Kroll exhibits ”threshold-like” ionization events, whereas that in Stewart-Pyatt is more continuous.

Ecker-Kroll



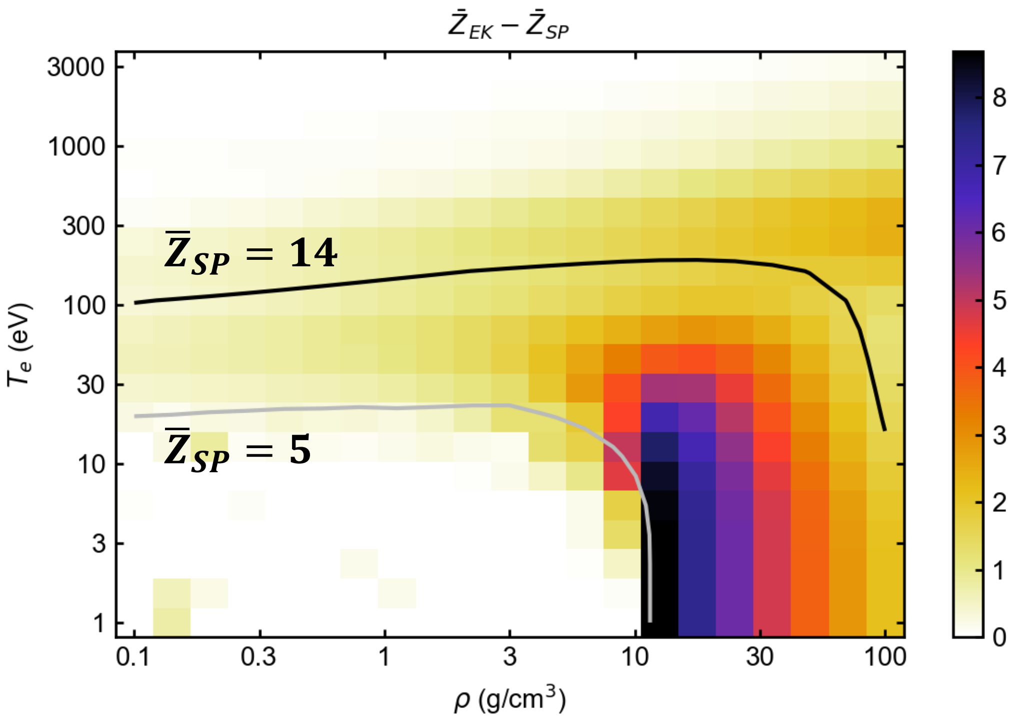
Stewart-Pyatt



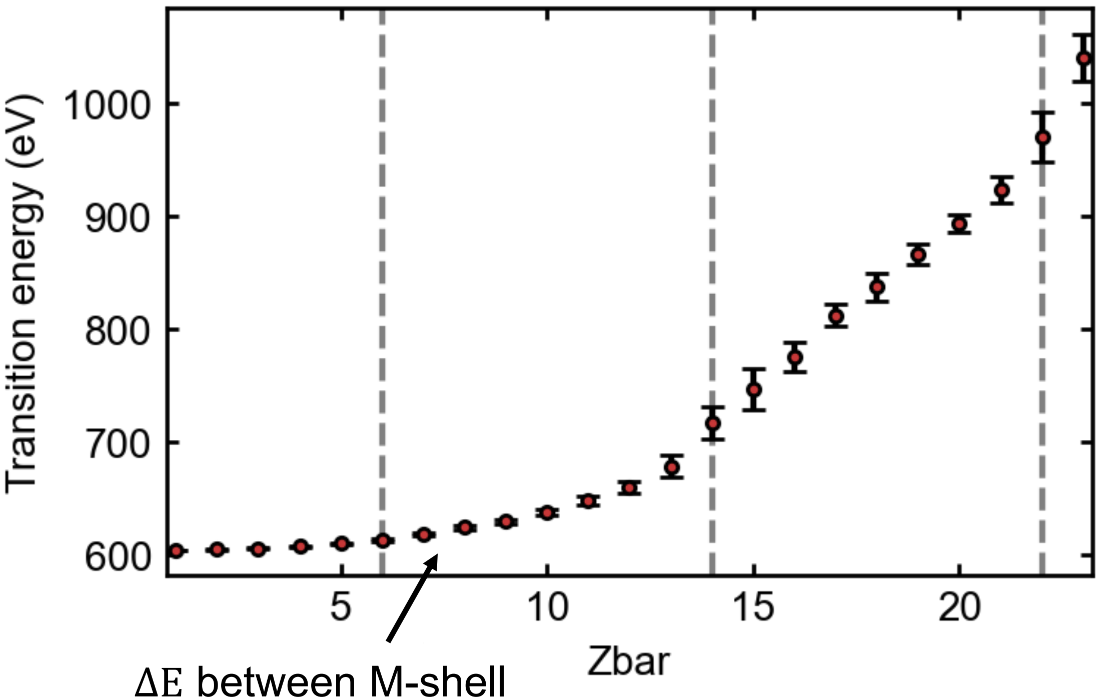
- Threshold-like L-shell pressure ionization at ~ 10 g/cc
- Minor ionization up to 500 g/cc
- Threshold-like K-shell pressure ionization at ~ 500 g/cc.

- Continuous ionization across full span of ρ

Pursuing $\Delta\bar{Z}$ "bump" may be difficult in dense systems



Cr $\overline{h\nu}_{2-3}(Z)$ from average ion calculation*



ΔE between M-shell states ~10 – 20 eV
→ $\frac{E}{\Delta E} \approx 60$

Lower transition energies
→ Less penetrating