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Spectroscopic study of Al wire array stagnation on Z

B. Jones[1], Y Maron[2], C. A. Jennings[1], J. E. Bailey[1], G. A. Rochau[1], C. A. Coverdale[1], S. B. Hansen[1], E. P. Yu[1], D. J. Ampleford[1], P. W. Lake[1], G. Dunham[1], M. E. Cuneo[1], V. I. Fisher[2], V. Bernshtam[2], A. Starobinets[2], L. Weingarten[2], S. Pinhas[2]

[1]Sandia National Laboratories

[2]Weizmann Institute of Science

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Outline

- **Spectroscopic analysis of K-shell radiators is employed to study z-pinch stagnation, coupling various interesting physics**
  - **Non-LTE plasma atomic physics**
  - **Opacity in radiation transport calculations**
  - **Doppler effects on line shapes**
  - **Gradients and 3D instability structure**
- **Here, we study an Al wire array implosion using a multi-shell, collisional-radiative analysis treatment to infer plasma properties**
  - **Electron temperature and ion density**
  - **Radial implosion velocity and isotropized velocity**
  - **Gradients and opacity**
- **The analysis characterizes the stagnating plasma and provides data for comparison with 3D MHD numerical modeling**
  - **> 50 cm/μs radial velocity from Doppler splitting**
  - **~1 % of initial mass at T_e > 1 keV in the core at start of stagnation**

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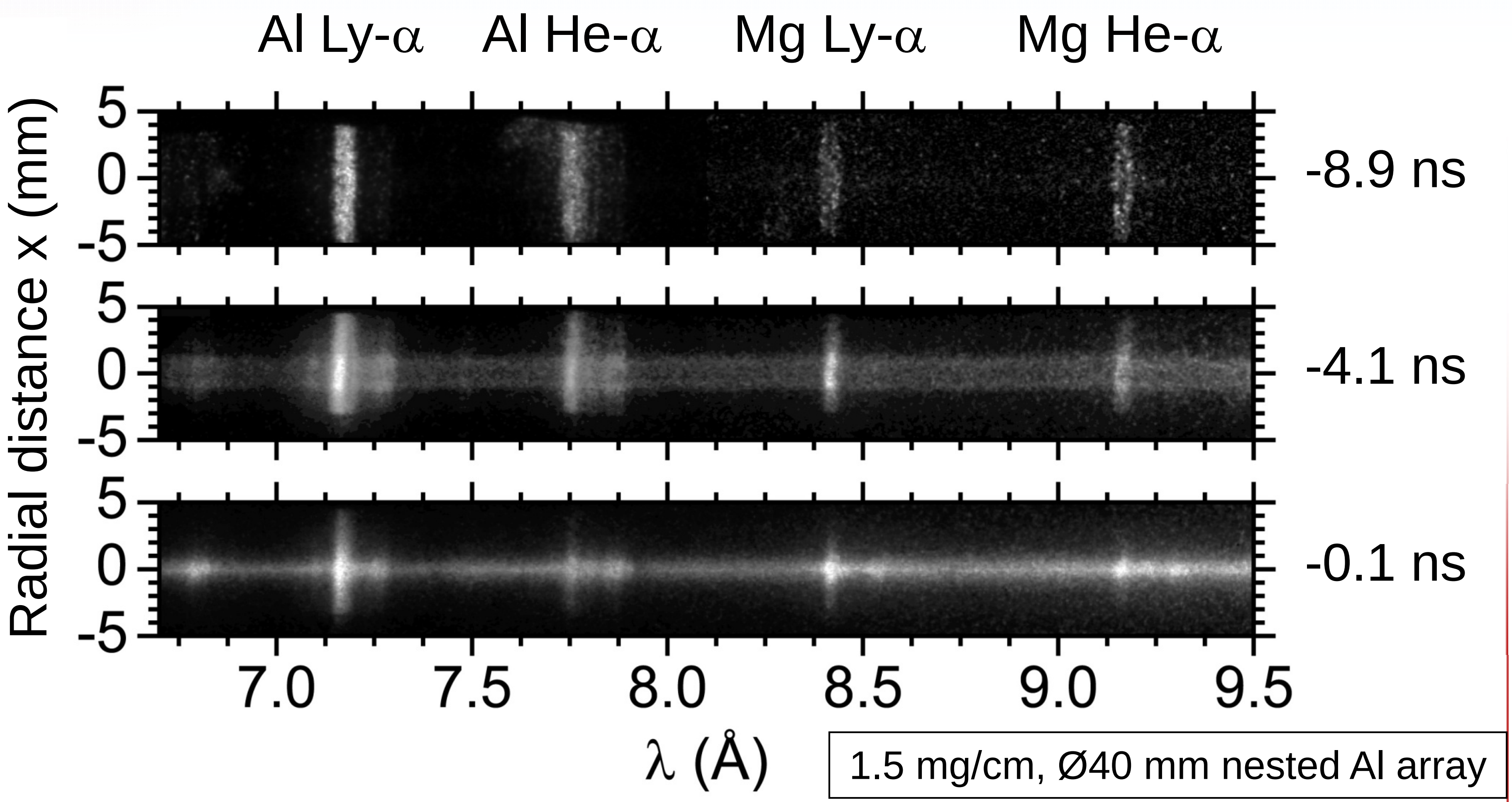
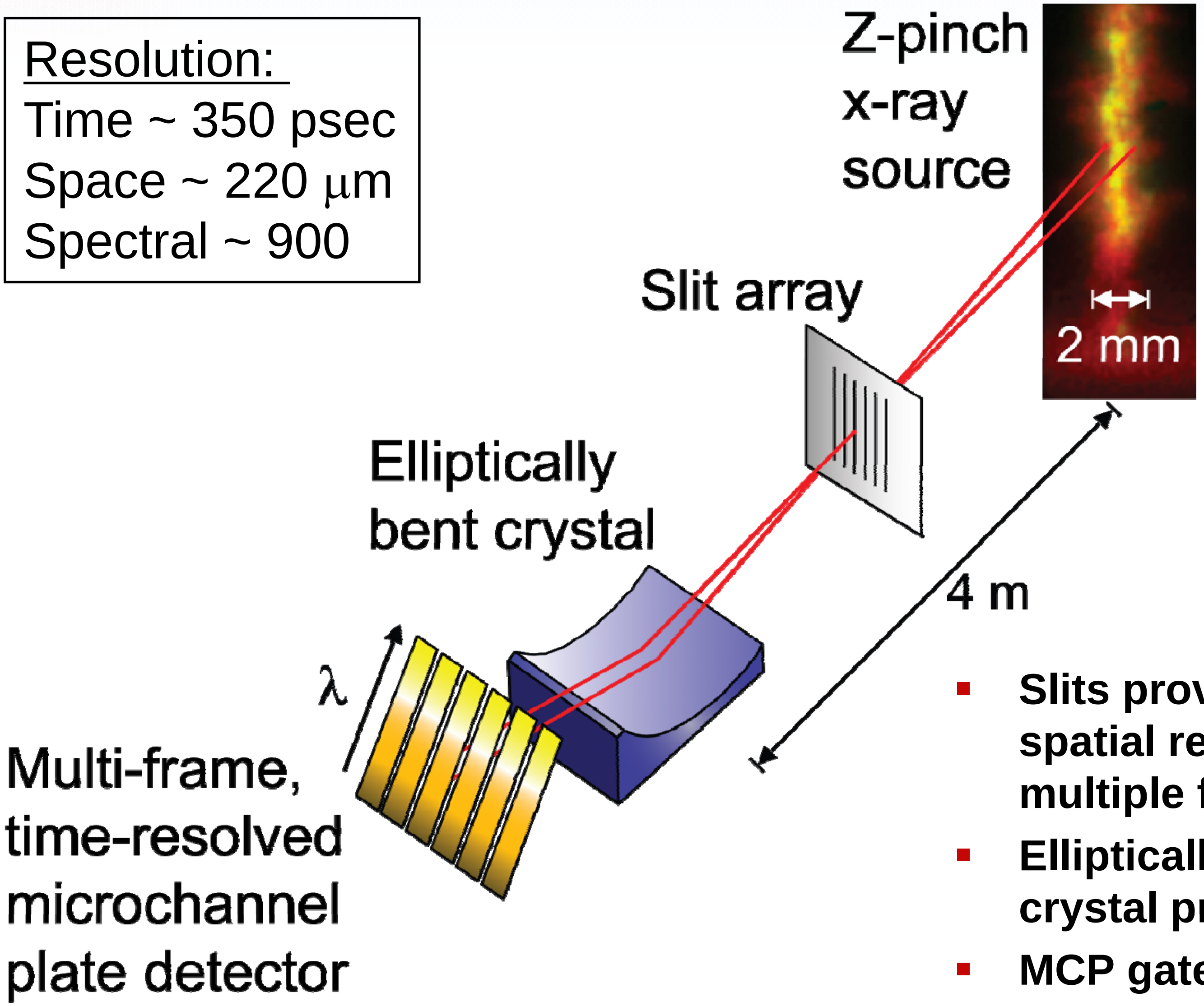
Information about plasma conditions and structure are encoded in the time-gated, radially-resolved spectra



- **Continuum and satellite emission on axis near time of peak x-ray power**
- **Line emission from large radius at all times**
- **Doppler effects, e.g. splitting in Mg He-α at early times**

Time-resolved elliptical crystal (TREX) spectrometers measure gated radially-resolved K-shell spectra on Z

Resolution:
Time ~ 350 psec
Space ~ 220 μm
Spectral ~ 900



- Slits provide 1D (radial) spatial resolution for multiple frames
- Elliptically bent mica crystal provides dispersion
- MCP gated detector

J.E. Bailey *et al*., PRL **92**, 085002 (2004).

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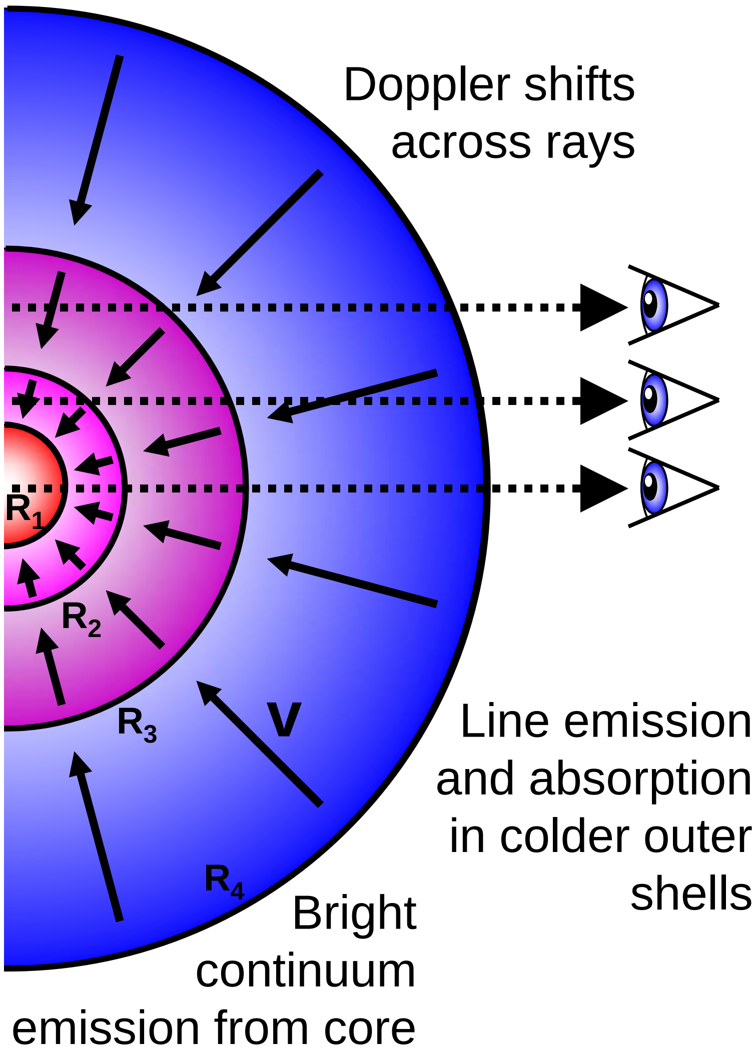
Analysis strategy: Match spectra and power using collisional-radiative model over several plasma zones



- **Number of concentric shells chosen to match spectral features in experiment**
  - **Shell radii motivated by experimental data, e.g. radius of line or continuum emission**
- **Collisional-radiative model applied to each shell to constrain plasma conditions by matching data**
  - **Line ratios along specified line of sight (T_e)**
  - **Total K-shell power emitted from plasma, continuum emission (n_i)**
  - **Doppler effect where available (v)**
  - **Isotropized velocity (u_{3D}) also included in calculated line widths**
- **Radiation transport carried out along representative rays accounts for opacity**
  - **Abel inversion was avoided due to concerns with strong line opacity**
  - **Doppler shifts/broadening accounted for in transport modeling**

V. I. Fisher *et al*., High Energy Dens. Phys. **3**, 283 (2007).

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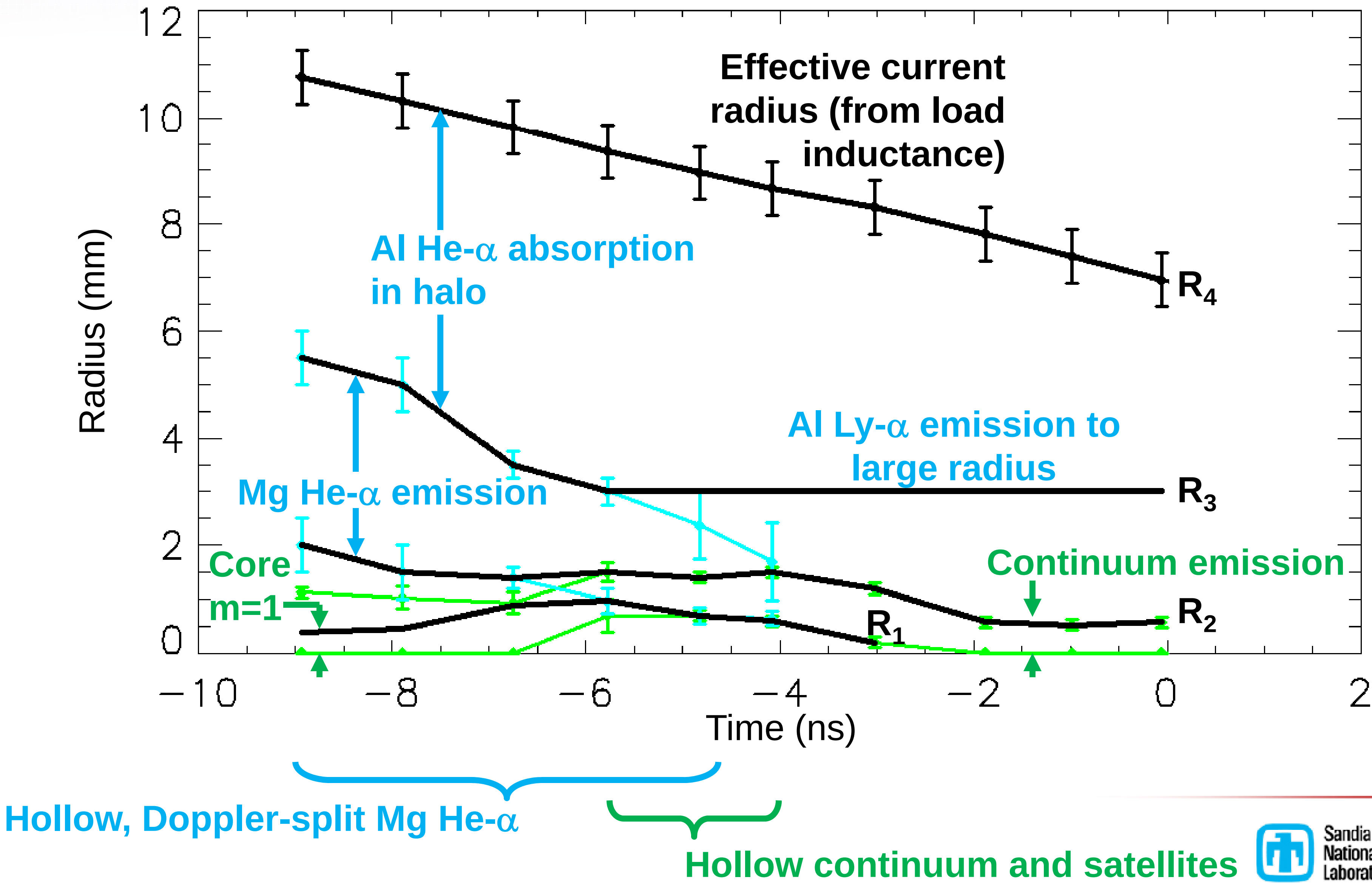
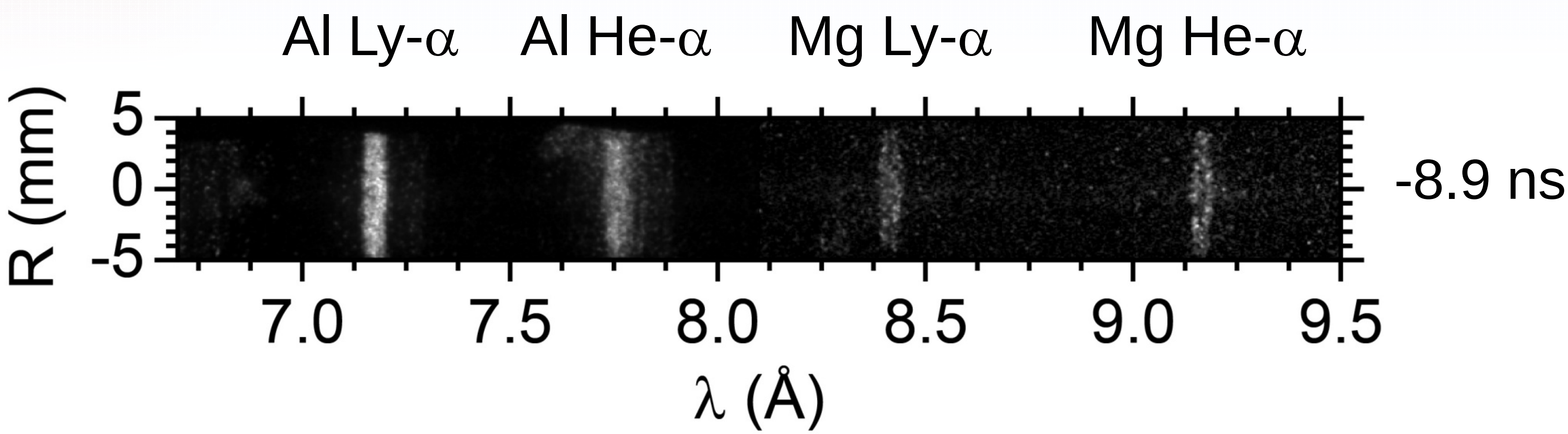
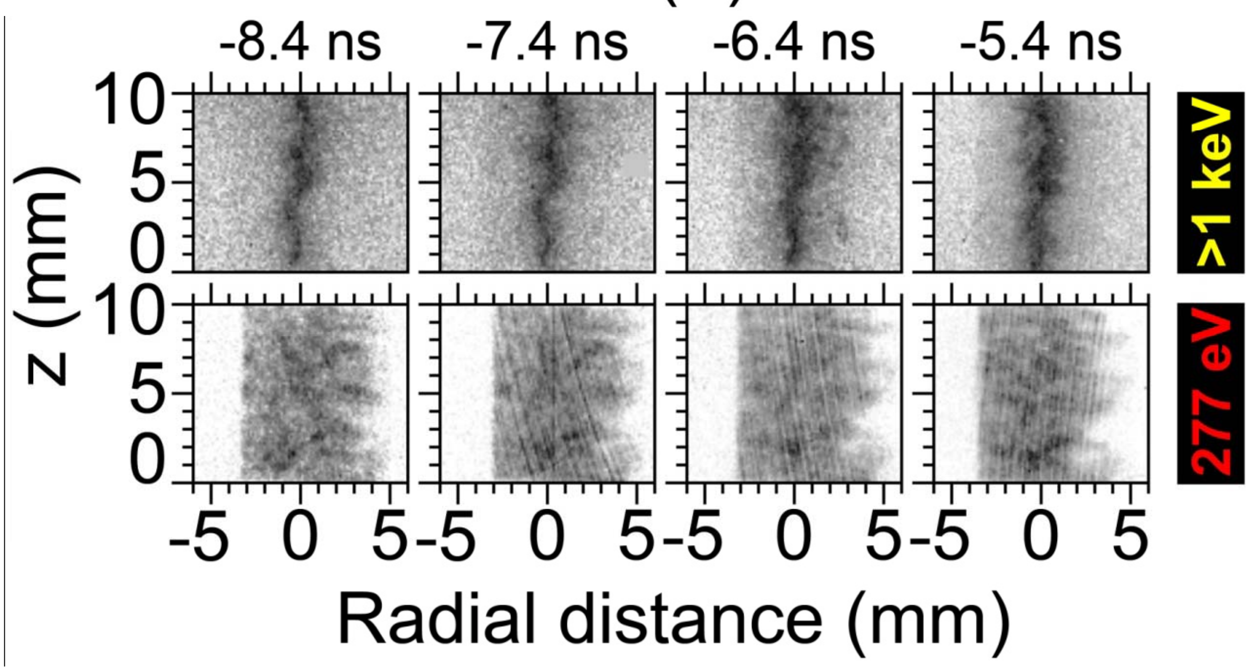
Radius in each zone is chosen based on observed spectral features and motivated by data



From early times, there is a core region on axis producing >1 keV (continuum) emission

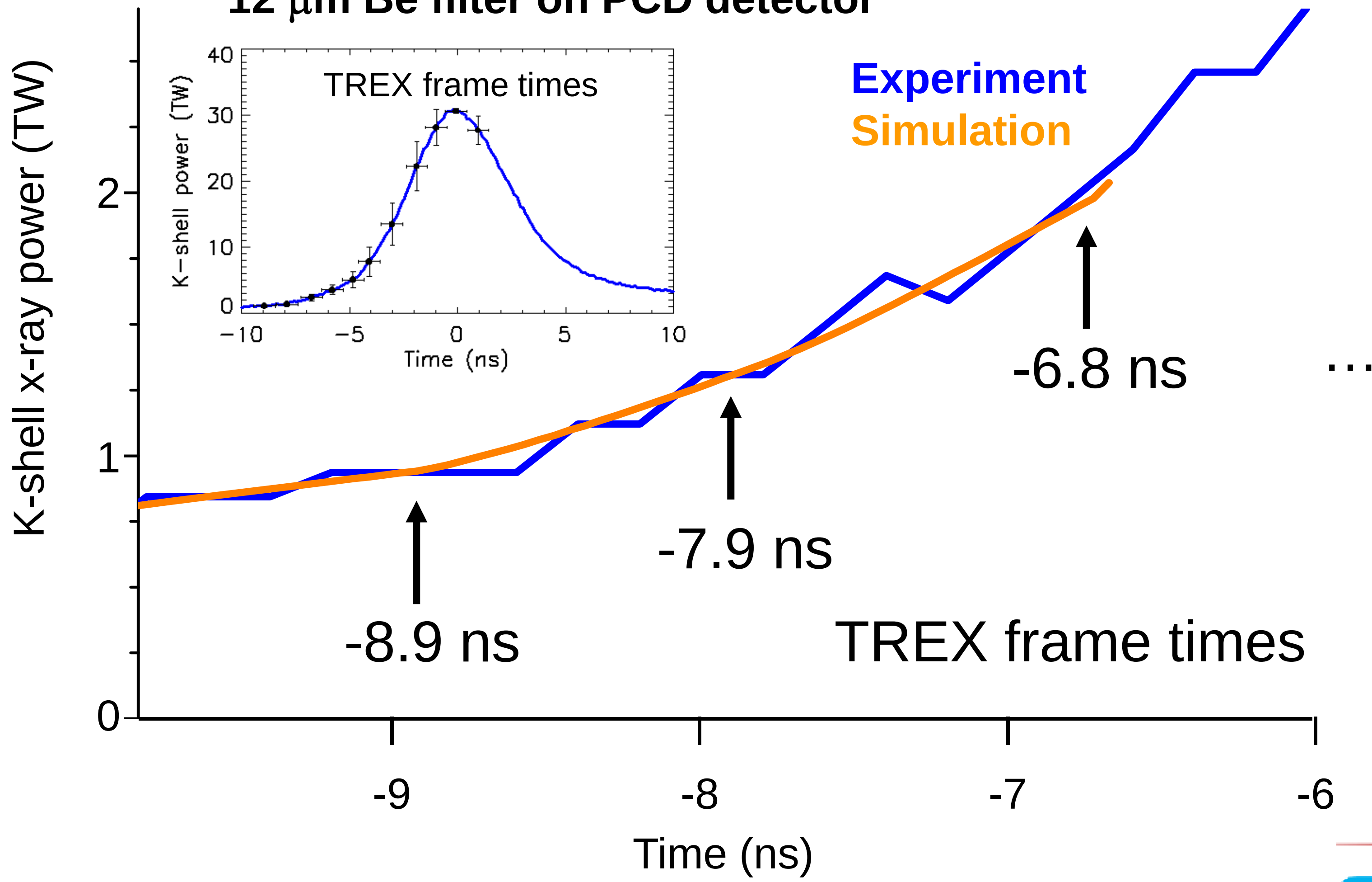




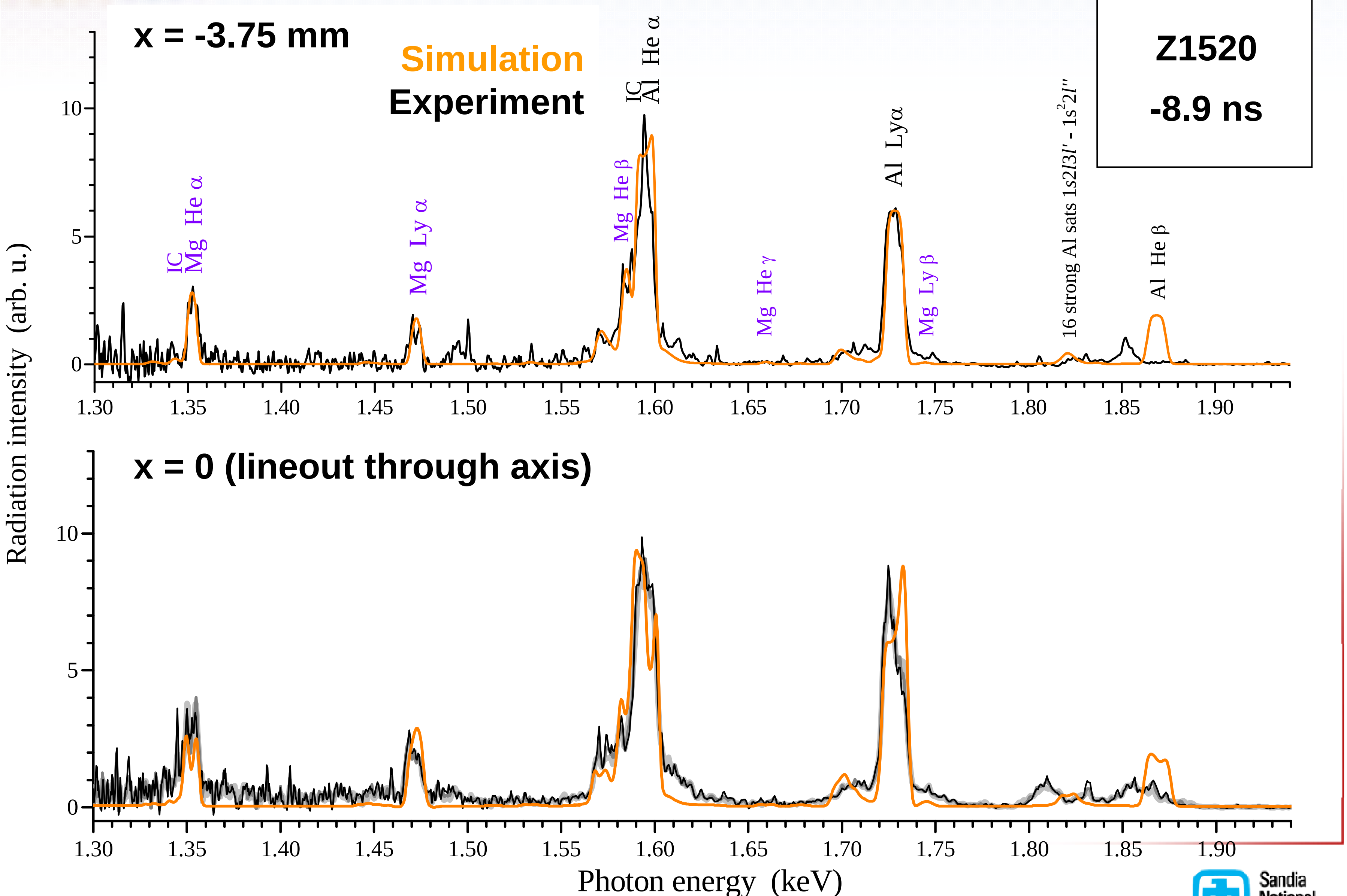
- **Core size defined based on radius of core with m=1 structure**

Time-dependent collisional-radiative kinetic modeling matches K-shell power and spectral features over a sequence of frames

- **Here we focus on spectrometer frames early in the x-ray pulse**
- **K-shell x-ray power is measured (±30%) and modeled through 12 μm Be filter on PCD detector**



Conditions in each shell adjusted to match spectral lineouts at various distances from the axis



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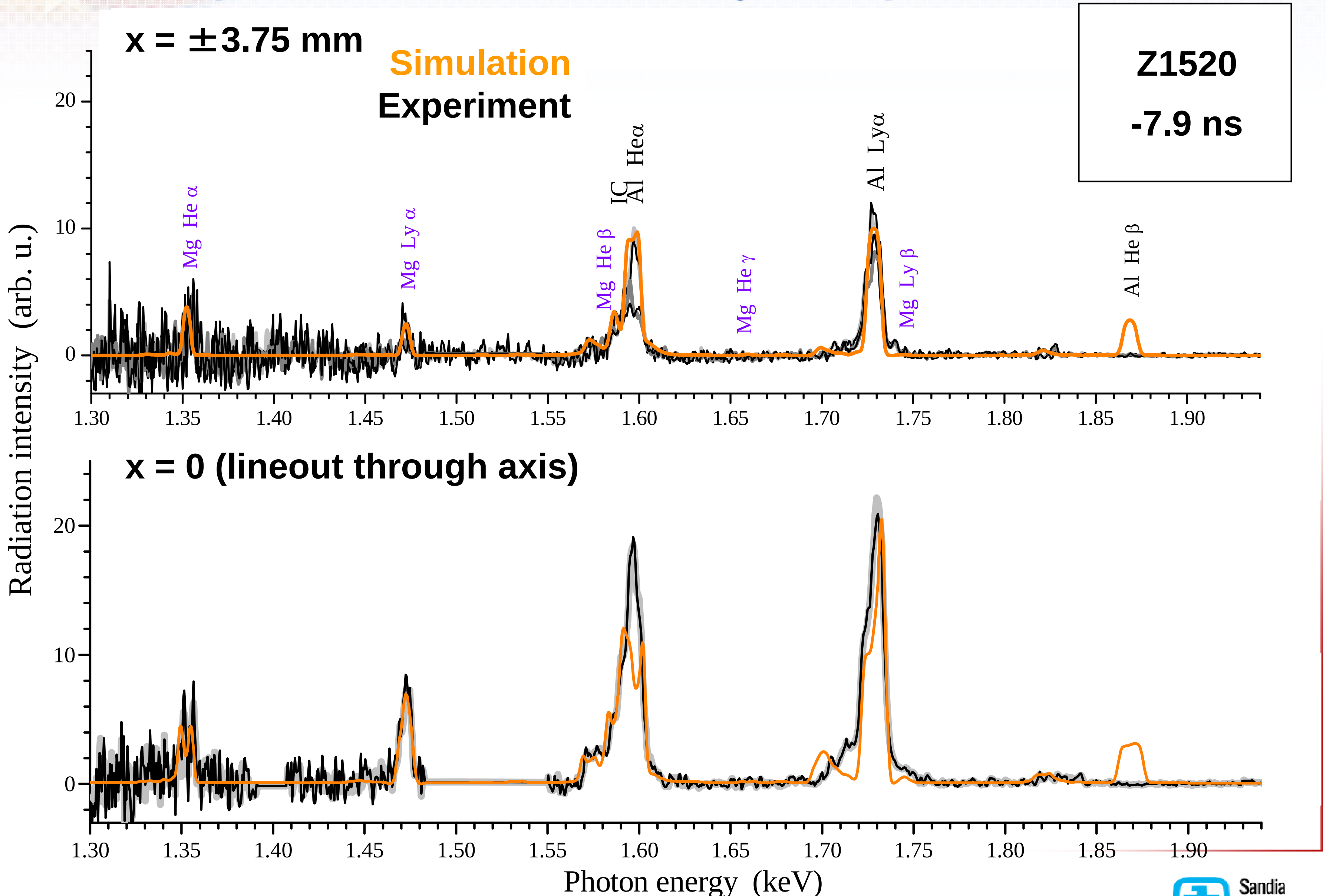
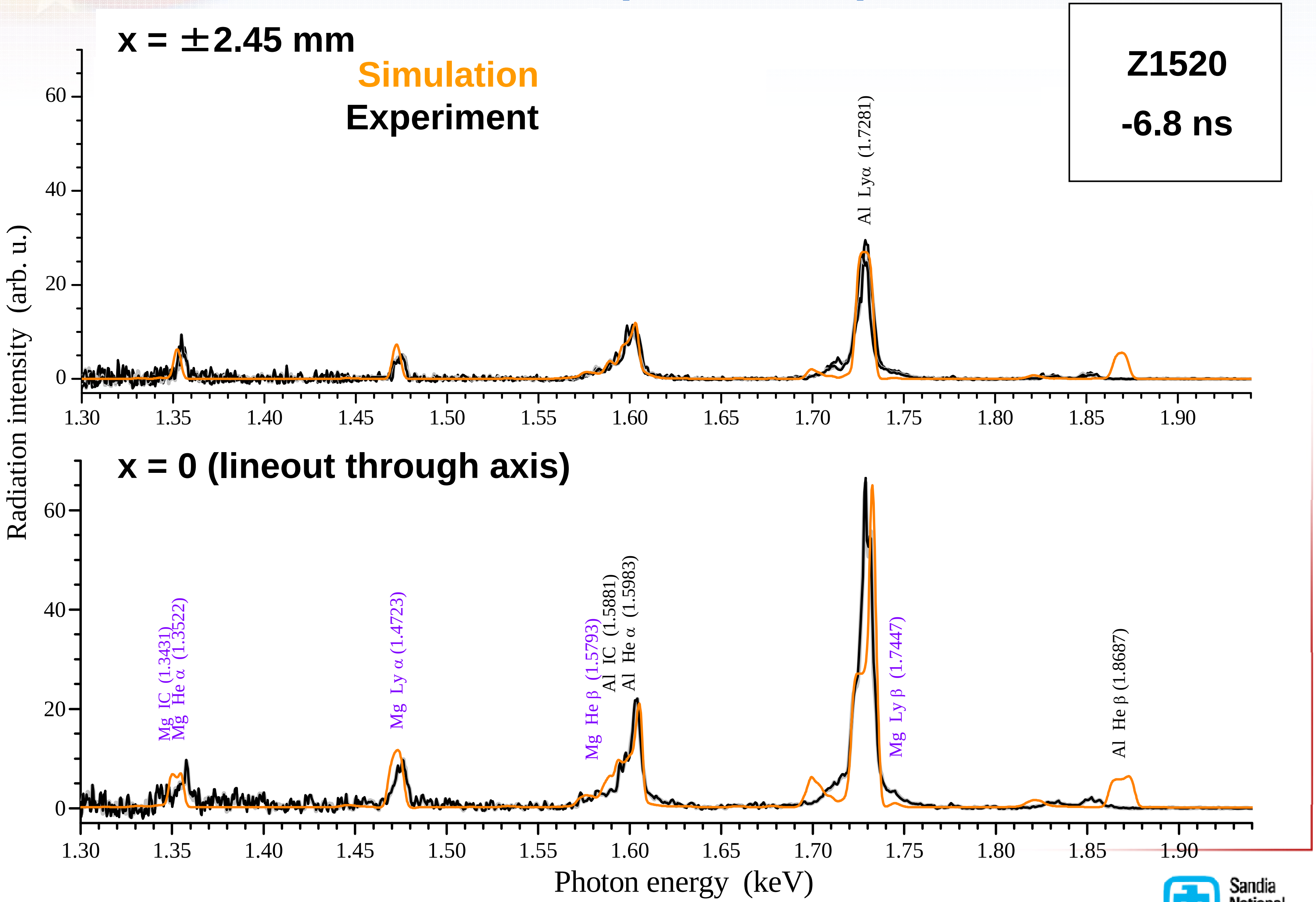
1520 A2A4 4 shells K13 / 132

On- and off-axis spectra generated by radiation transport calculations through the plasma zones



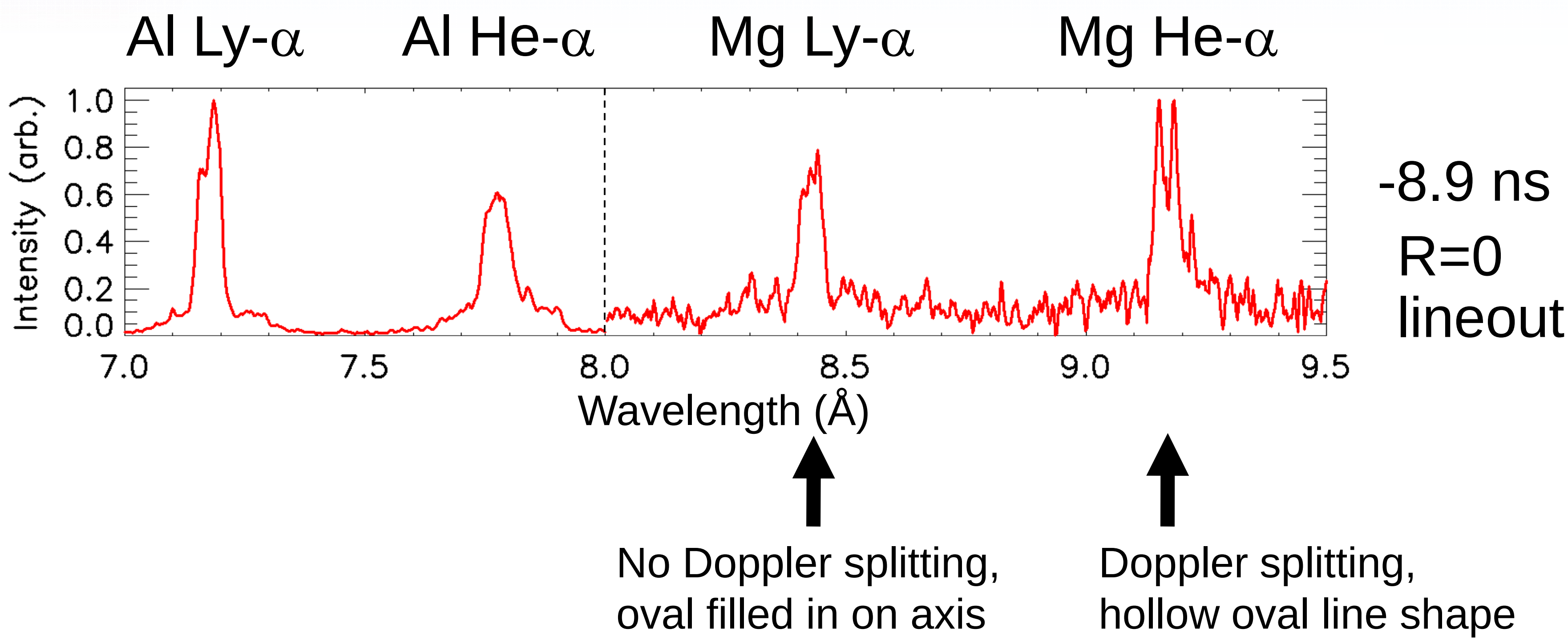
1520 A2A4 4 shells K13 / 132

Opacity in the halo is important in determining Al He-α line shape and amplitude



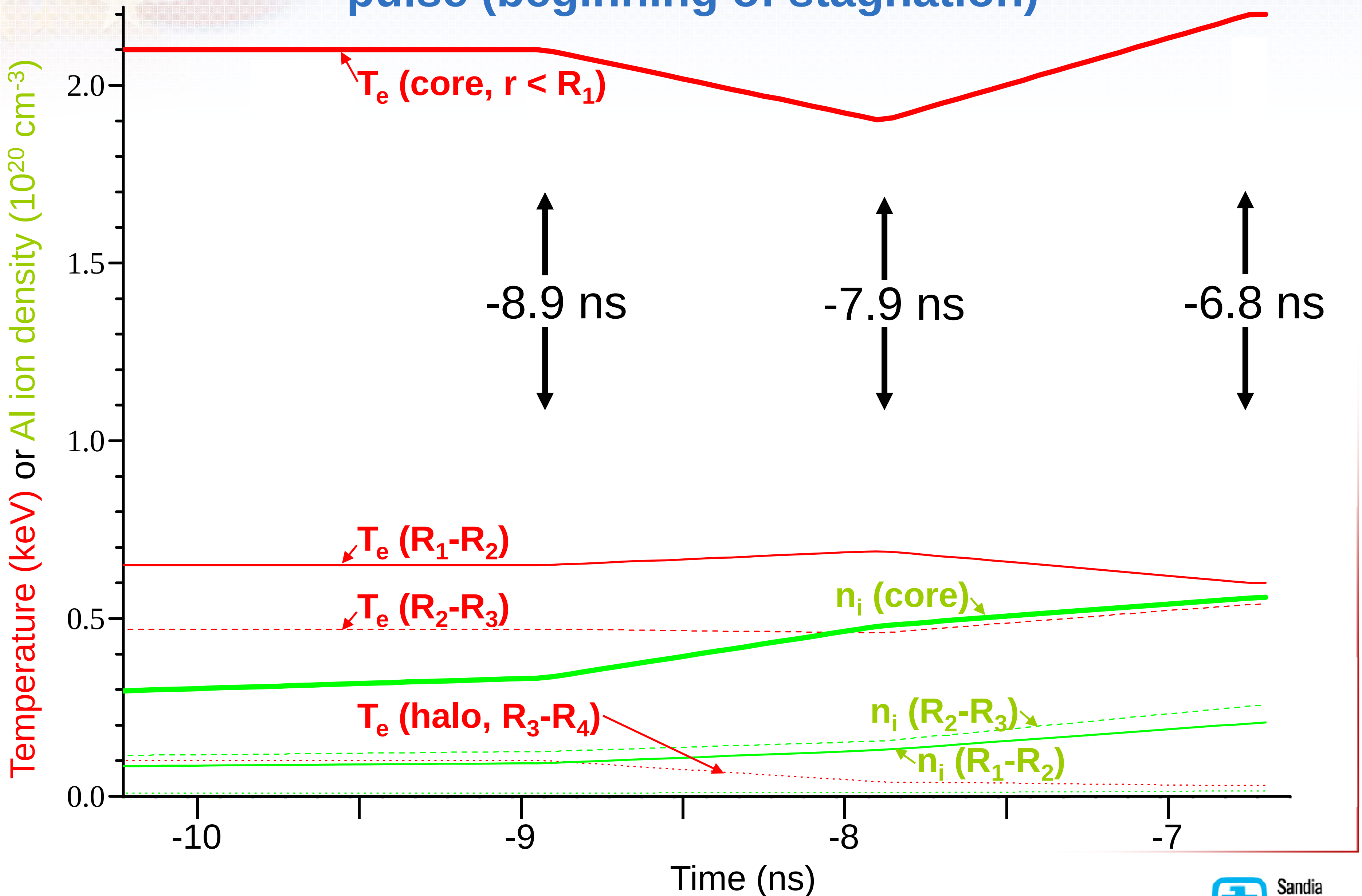
1520 A2A4 4 shells K13 / 132

The plasma core on axis must be hot to explain line profiles given Doppler effects



- **Clear Doppler-split oval in Mg He-α suggests there is no Mg He-α emission from on axis**
- **Mg Ly-α emission is seen on axis (along with Al Ly-α and Al He-α)**
- **Therefore, there is plasma on axis and it is hot enough to have burned through He-like Mg**

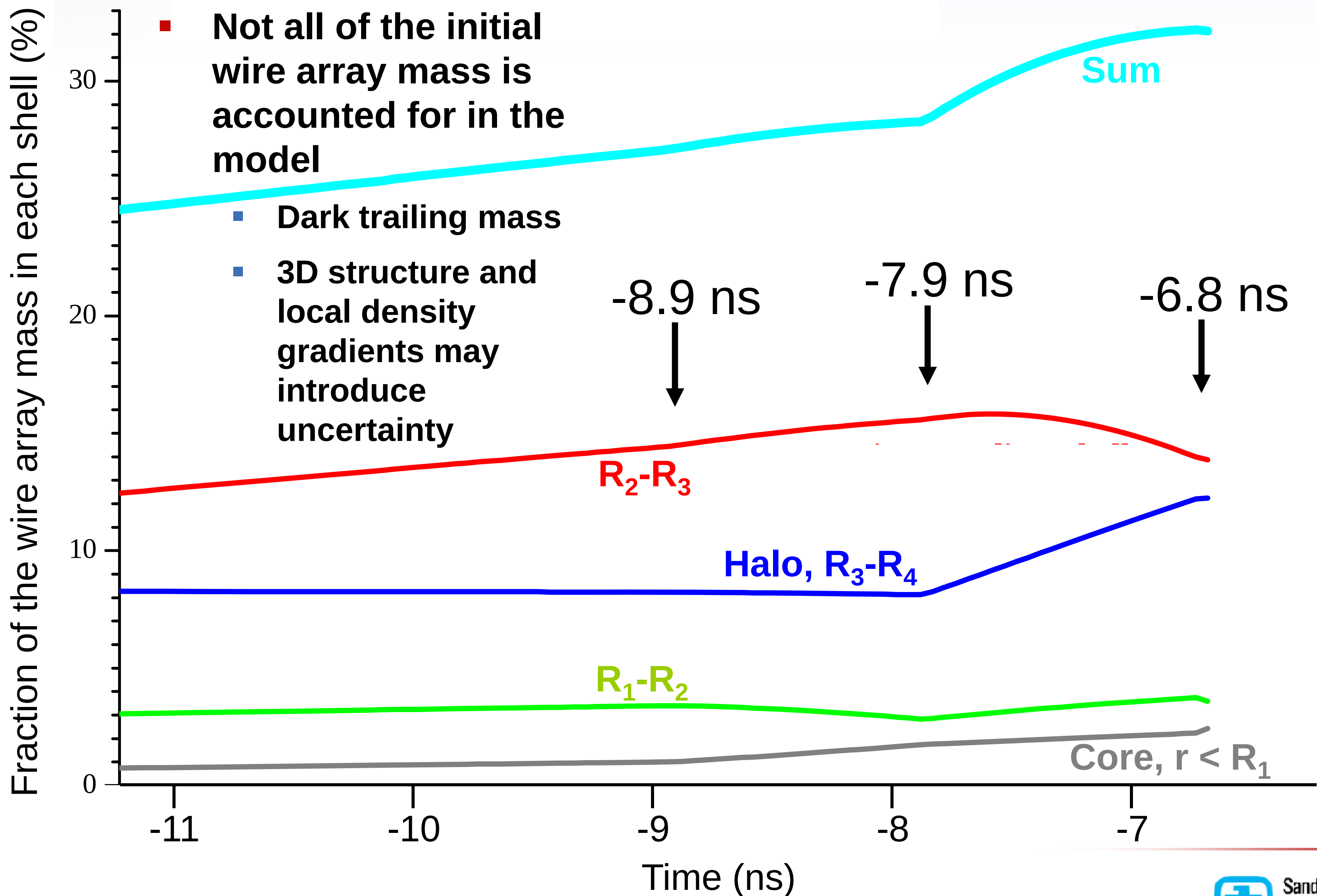
A hot, dense core is inferred at the foot of the x-ray pulse (beginning of stagnation)



1520 A2A4 4 shells K13 / 132

Only a small fraction of the mass is in the core at the start of stagnation (~1%)

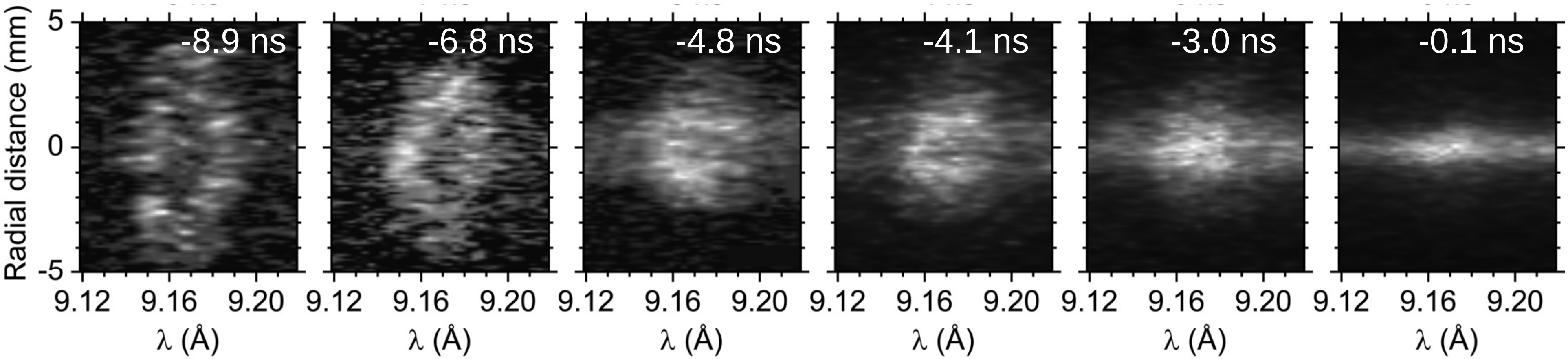
- **Not all of the initial wire array mass is accounted for in the model**
  - **Dark trailing mass**
  - **3D structure and local density gradients may introduce uncertainty**



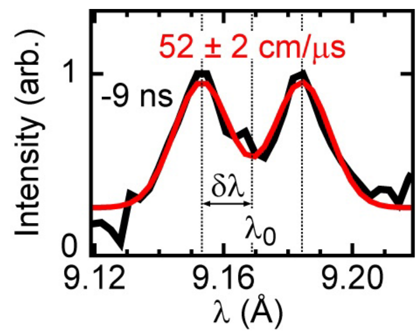
1520 A2A4 4 shells K13 / 132

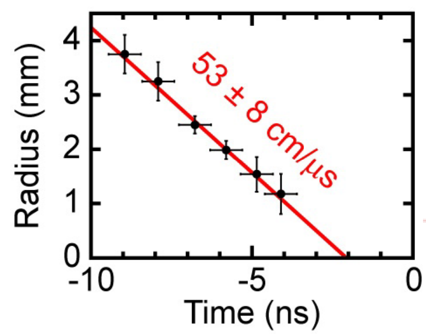
Doppler splitting in Mg He-a dopant line provides a measure of emissivity-weighted velocity

Z1520, Ø40 on 20 mm nested Al 5056 wire array, 1.5 mg/cm, Mg He-α



- **Doppler splitting is seen at early times, providing experimental measure of velocity in region of the plasma emitting this line**
- **Smaller velocity error bars from single-frame, instantaneous Doppler measurement than from fitting trajectory for multiple frames**
- **Splitting disappears before peak x-ray power, perhaps as kinetic energy is thermalized**
- **Line is broad at the time of peak x-ray power**





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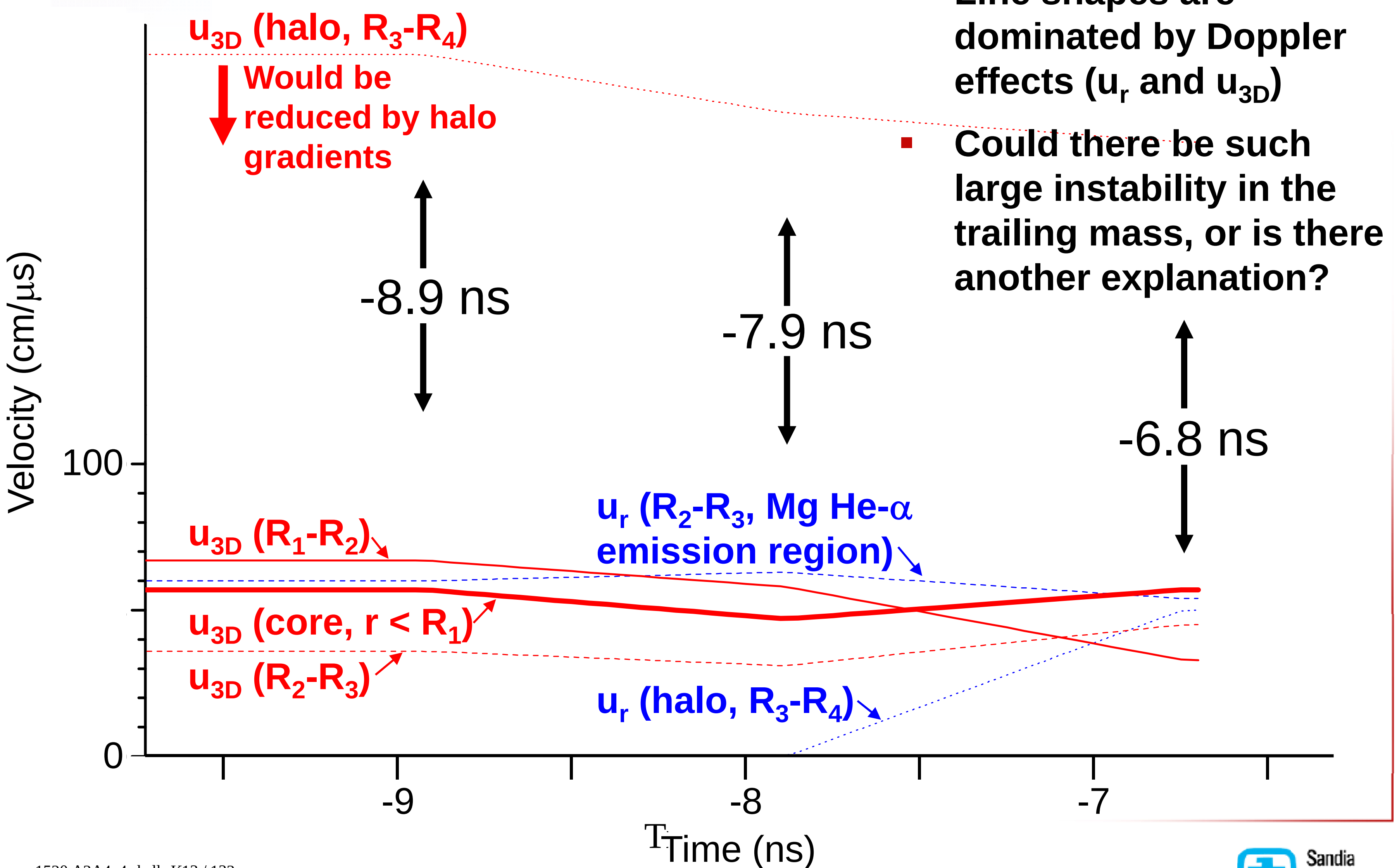
Large isotropized velocity is required in halo model in order to attenuate Al He-a to the level seen in experiment

- **Line shapes are dominated by Doppler effects (u_r and u_{3D})**
- **Could there be such large instability in the trailing mass, or is there another explanation?**



1520 A2A4 4 shells K13 / 132

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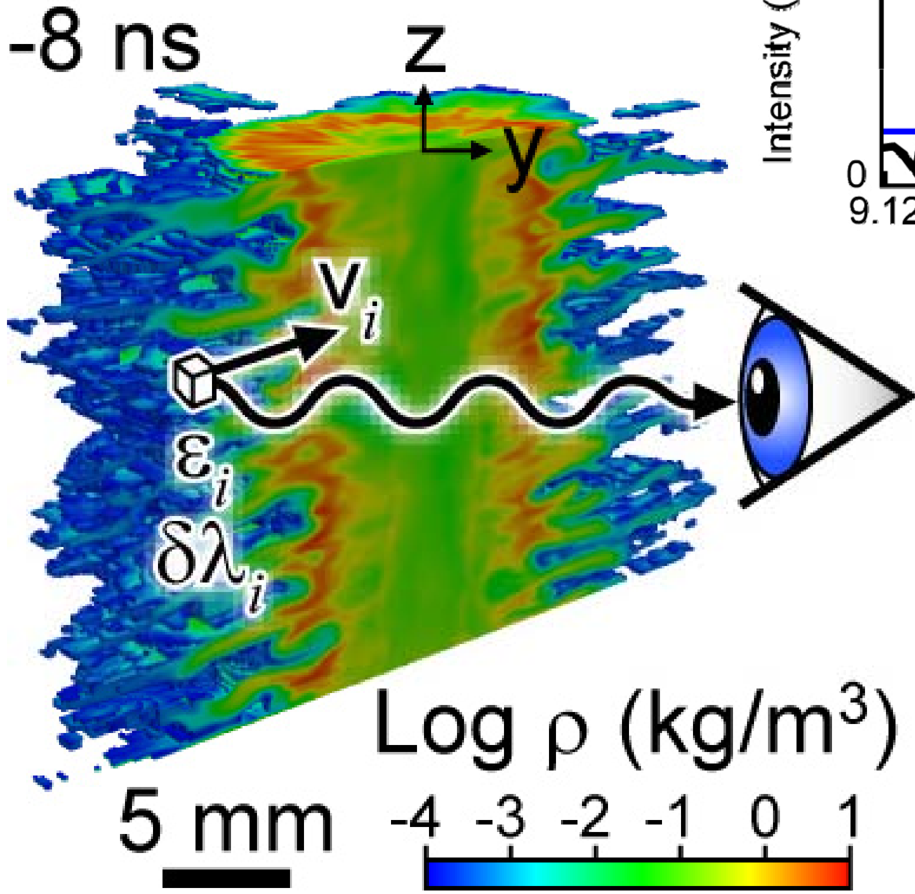
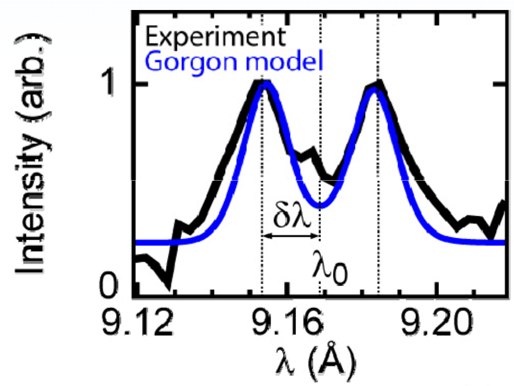
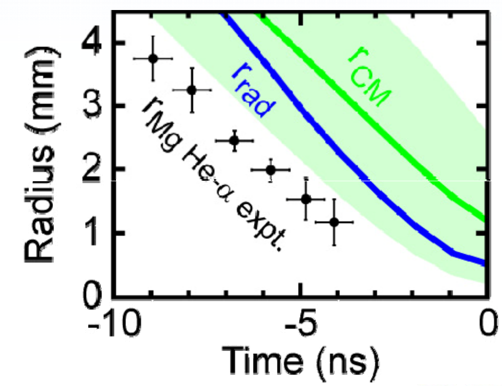
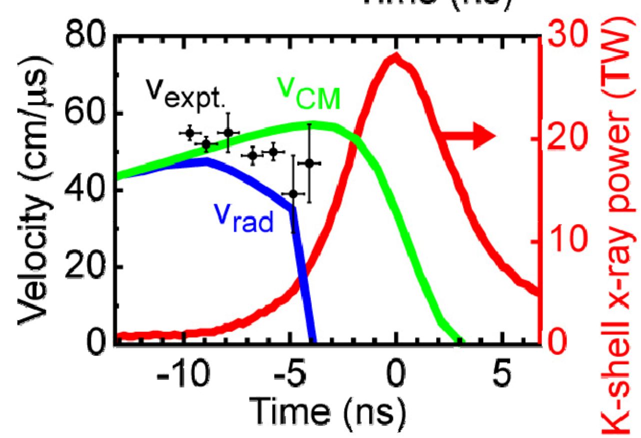
Doppler velocity inferred from Gorgon 3D MHD simulations agrees reasonably with experiment



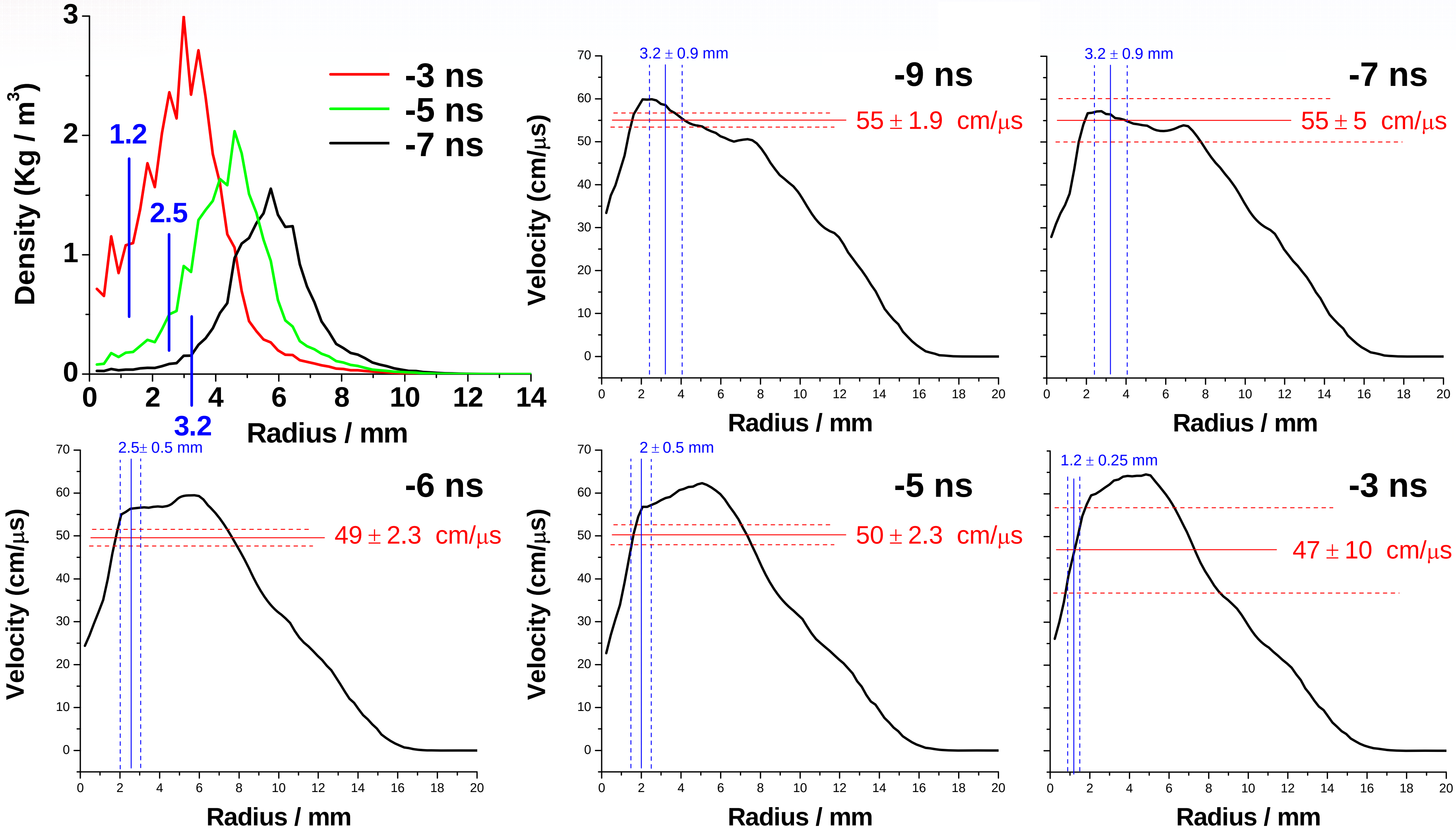






- **Emissivity from each cell contributes at wavelength** $\frac{\delta\lambda}{\lambda_0} = \frac{\vec{v}_i \cdot \hat{y}}{c}$
- **Line shape smoothed for instrumental resolution λ/Δλ=900**
- **Emission region leads center of mass, and slows down on axis first. Future work: model Mg He-α instead of total emissivity**

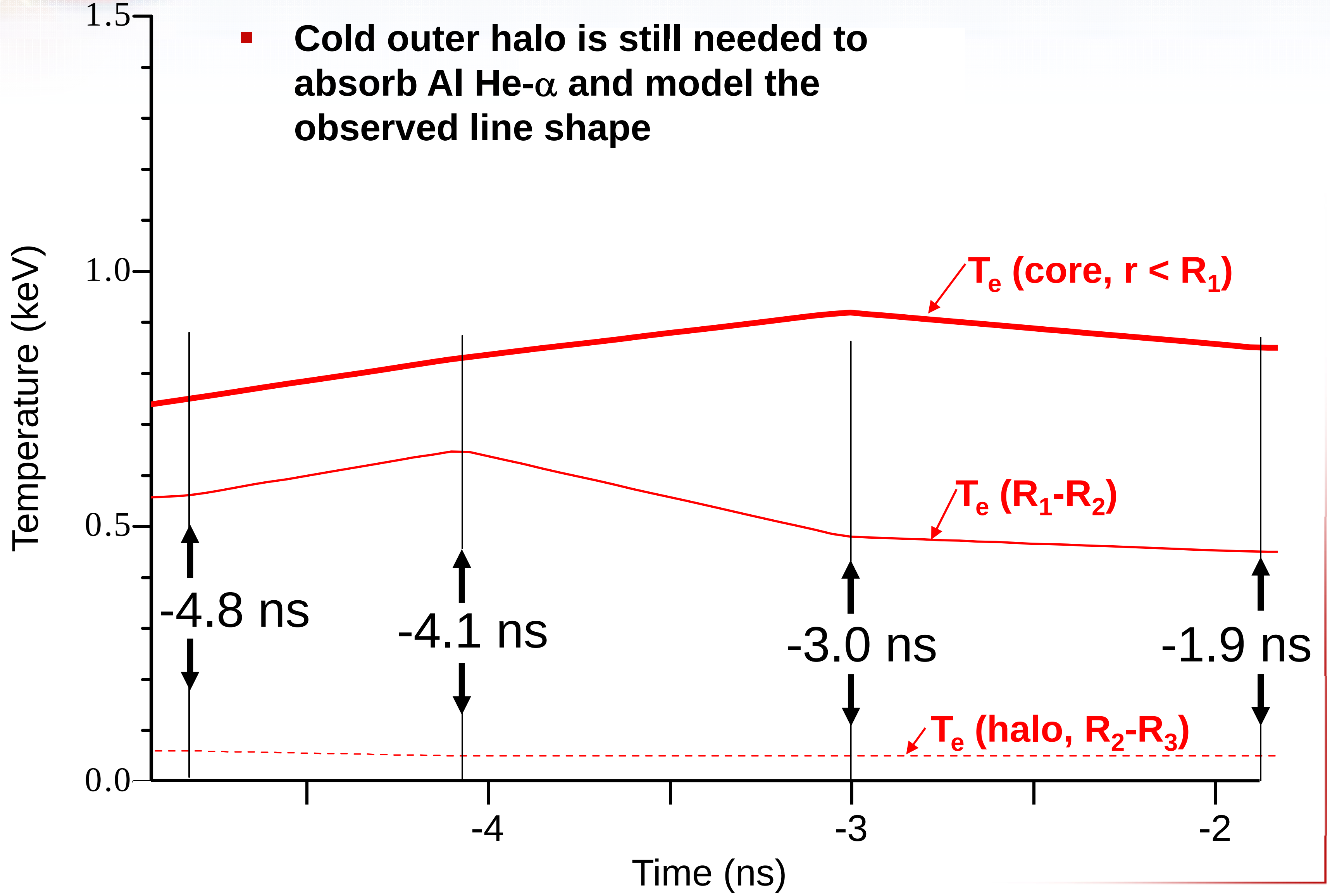
Emission is from the leading edge of the dense imploding shell in Gorgon 3D MHD model



- **Reasonable agreement with measured Doppler velocities (red) at positions of Mg He-α emission (blue)**

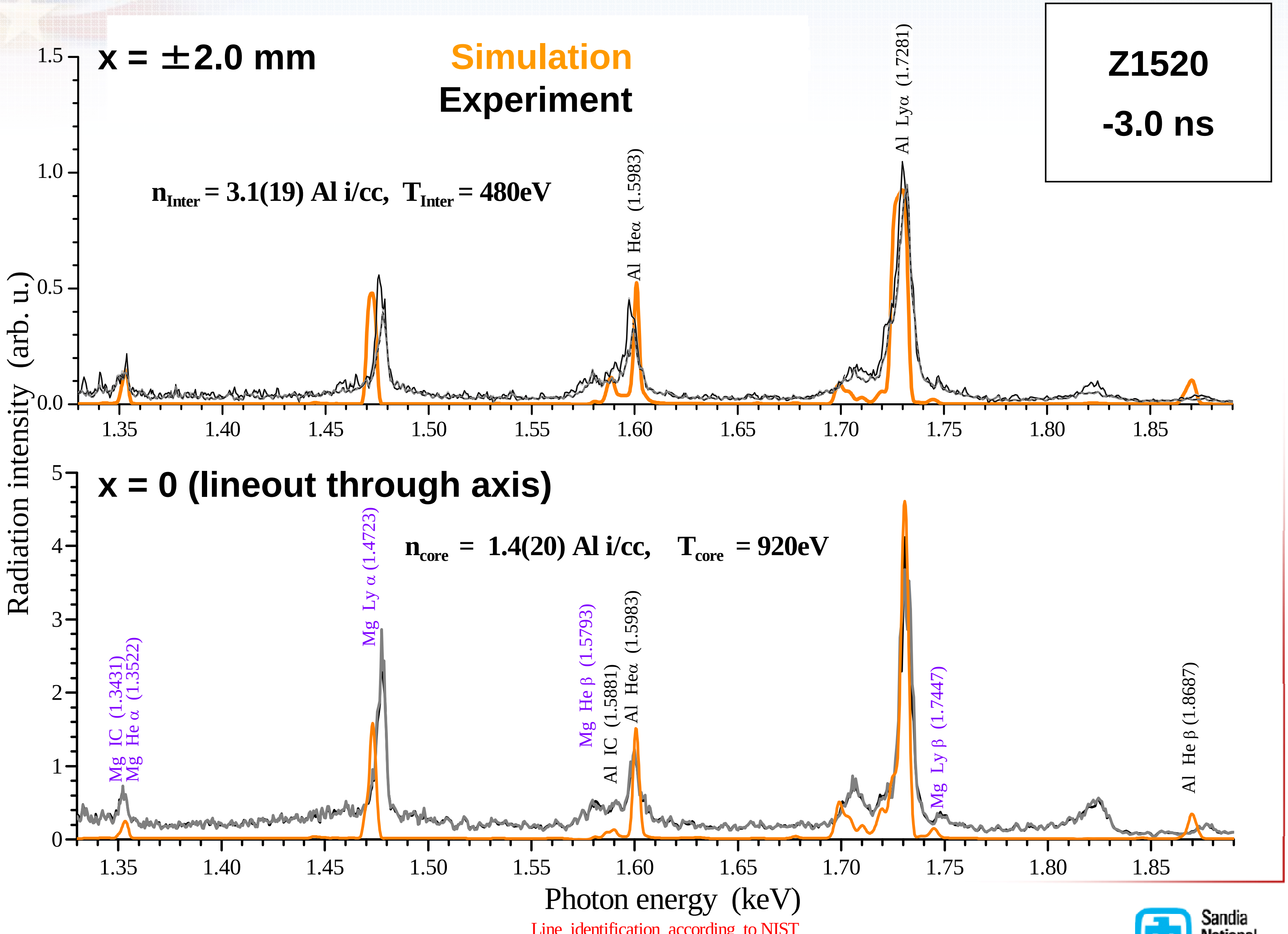
High temperature in core is needed to explain the observed K-shell line emission near peak power

- **Cold outer halo is still needed to absorb Al He-α and model the observed line shape**



YN\1520peri2mm, NewDB & scans in Phys Un\7

Al and Mg resonance lines are reasonably explained



YN\1520peri2mm, NewDB & scans in Phys Un\7YM

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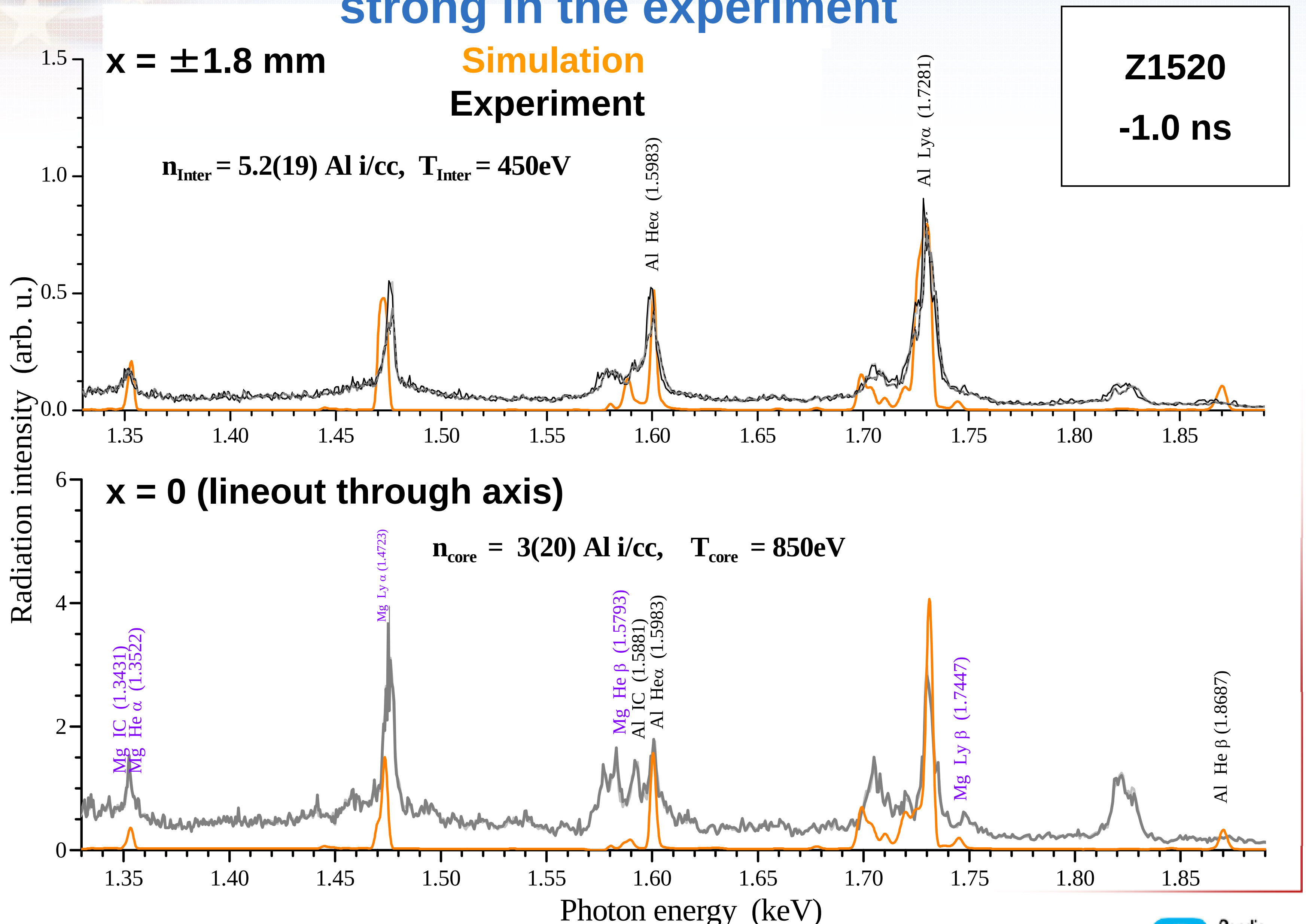
Continuum emission and satellites become quite strong in the experiment



Line identification according to NIST

YN\1520peri2mm, NewDB & scans in Phys Un\7YM

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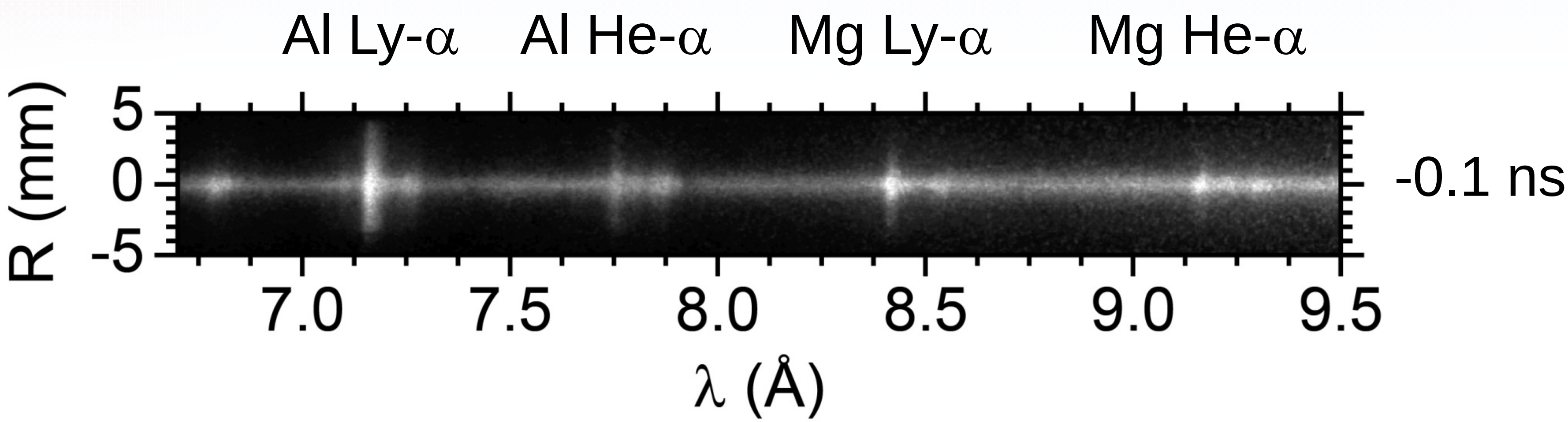
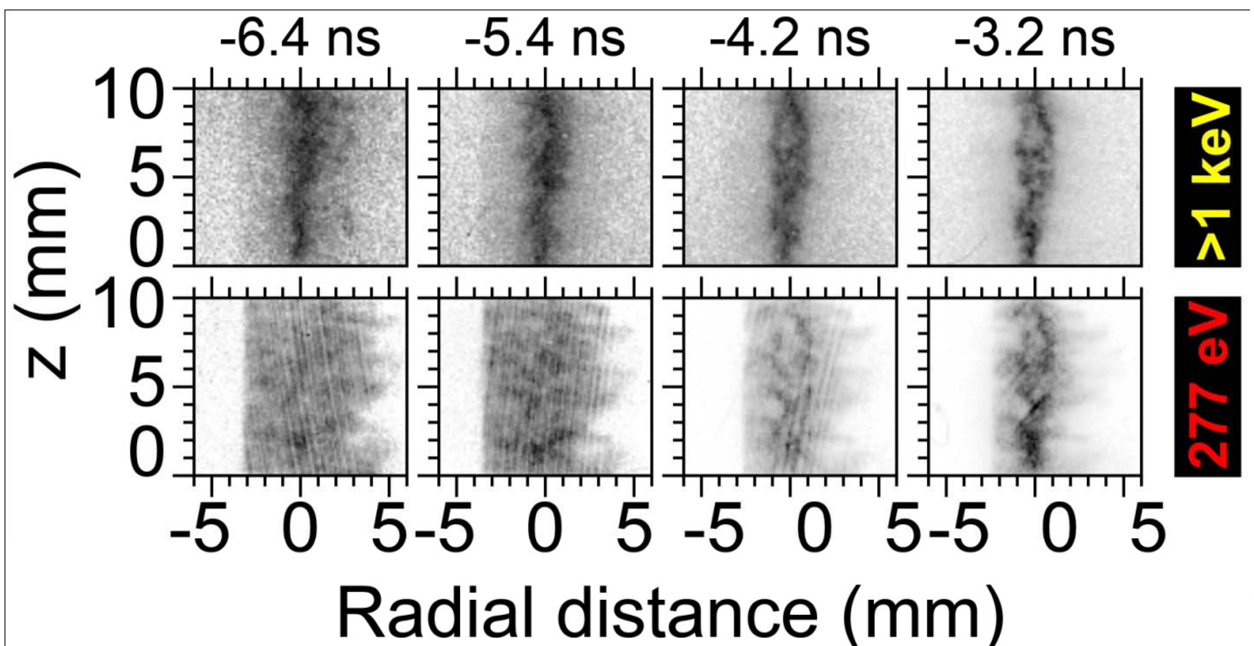
Strong continuum emission between K lines likely due to evolving structure in the core





- **Corresponding bright regions in core at 277 eV and >1 keV**

Summary

- **Intense K-shell x-ray source studies on Z provide an opportunity for spectroscopic study of z-pinch plasma stagnation**
- **Line ratios, shapes, and K-shell power together constrain the inferred plasma conditions in a multi-shell model**
- **Doppler splitting of K-shell emission lines, or Doppler shifted absorption, provide a method to measure implosion velocity**
  - **Reasonable agreement seen with velocities predicted through 3D MHD Gorgon numerical modeling**
  - **Doppler effects, opacity, and plasma gradients determine line shapes**
- **A hot, dense core forms on axis early in the x-ray pulse, containing initially only ~1% of the total array mass but emitting brightly**
- **A cold, outer halo is required to attenuate Al He-α line emission,**
  - **Puzzle: Large inferred isotropized velocity in this trailing material**
- **Structure in the core may explain both line and continuum emission seen in the experiment (future work)**

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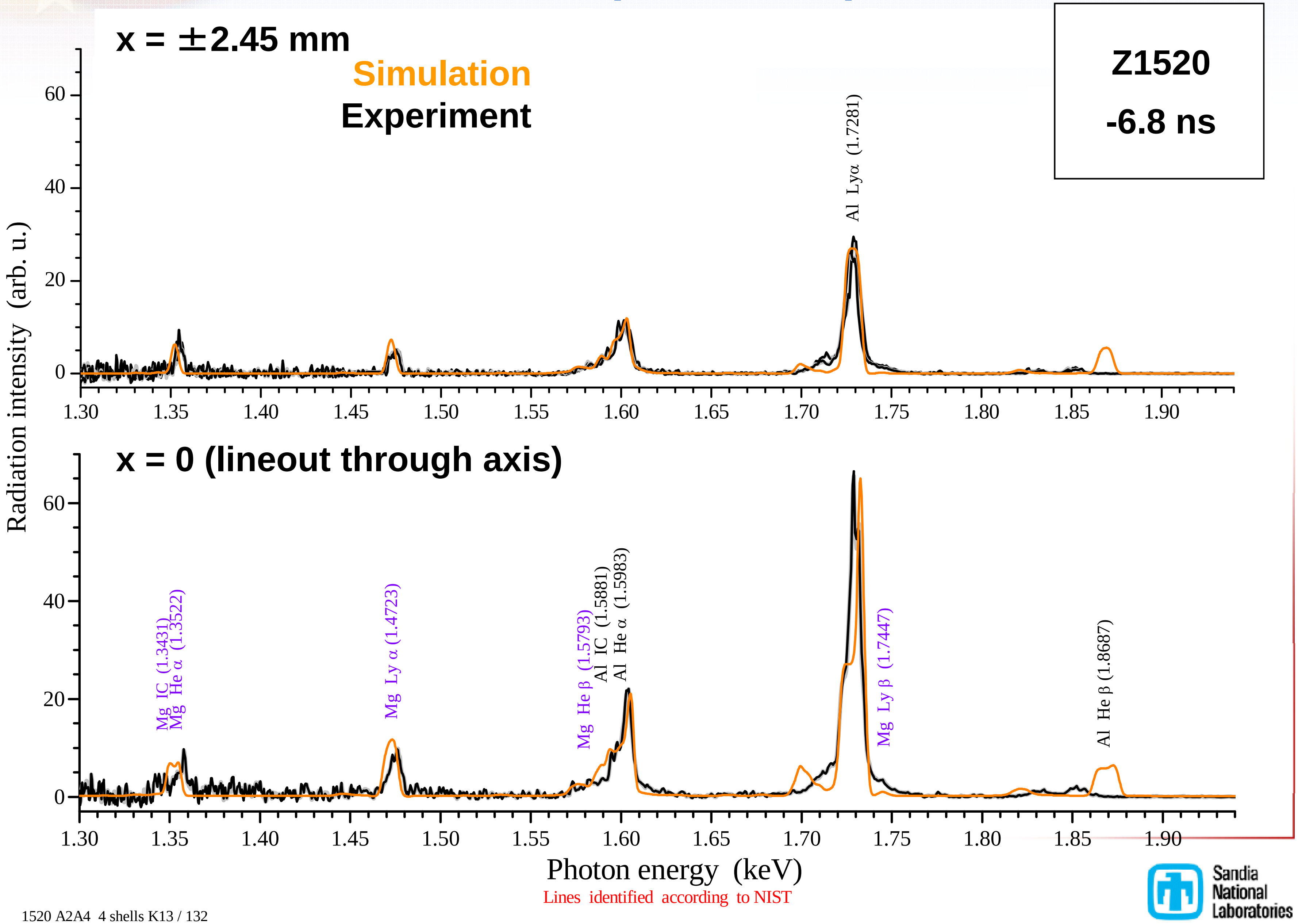
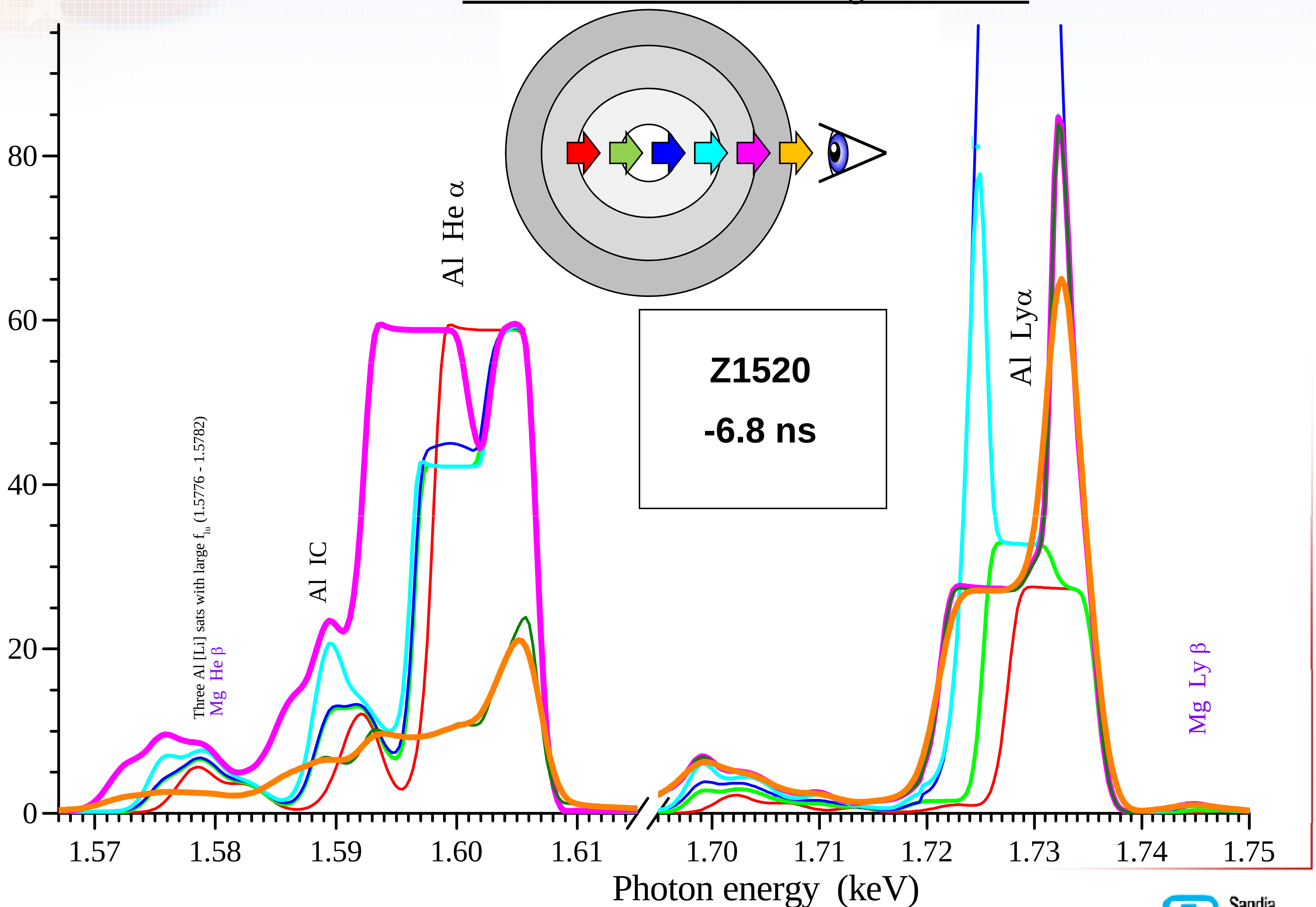
Backup

Opacity in the halo is important in determining Al He-α line shape and amplitude



Radiation on 6 interfaces along central LOS



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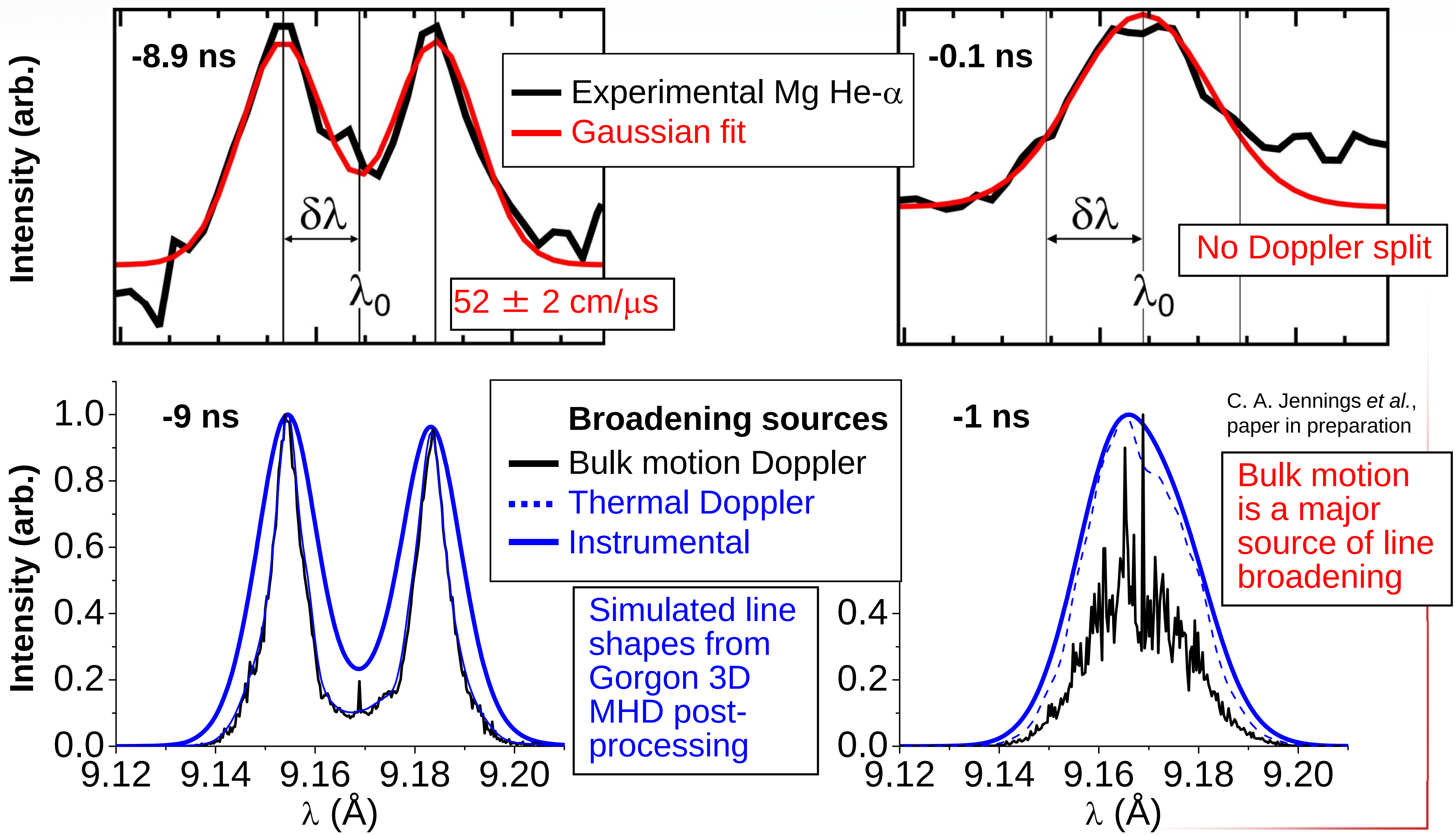
Doppler broadening due to residual bulk motion as well as ion temperature contributes to line widths



- **Tabulated SCRAM/SC total emissivities** S.B. Hansen *et al.*, HEDP **3**, 109 (2007). H.A. Scott and S.B. Hansen, HEDP **6**, 29 (2010).
- **Simulated line shapes do not include opacity, satellites**

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