Stellar-Relevant Emission-Based Opacity Experiments at the Orion Laser Facility

HEDS Seminar Series

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on behalf of Orion team

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The Orion team is large, interdisciplinary, and international

- LLNL:
  - Greg Brown (PI, experiment lead)
  - Mark Foord (theory lead)
  - Madison E. Martin (design lead)
  - Ronnie Shepherd
  - Mike MacDonald
  - Klaus Widmann
  - Antonia Hubbard
  - Carlos Iglesias
  - Daniel Aberg
  - Michael Kruse
  - Duane Liedahl
  - Paul Grabowski
  - Rich London
  - Joe Nilsen
  - Mehul Patel
  - Dylan Cliche
  - Howard Scott
  - Bob Heeter
  - Heather Whitley
- AWE:
  - Dave Hoarty (PI)
  - J. Morton
  - S. Richardson
  - Colin Brown
  - B. Foote

Outline

- Motivation
- Experimental Platform
- Recent Fe Campaign
- Modeling Approaches
  - Radiation Hydrodynamics modeling
  - Atomic kinetics and radiation transfer calculations
- Ongoing & Future Work
- Summary

Opacity is an important physical property in the energy transport of HED systems and requires experimental validation of theory

- Radiation hydrodynamic design calculations rely on energy transport models that include material opacities as either theoretically based formulas or tables
- High energy density (HED) systems can include a large range of ionization stages which may require statistical methods
- Experimental validation of opacity theory is needed
- Disagreements between solar observations and models may be mitigated by increased opacity[1]
  - Bailey et al.[2]: measured iron opacity values 30-400% larger than predicted

n_e vs T in the Sun

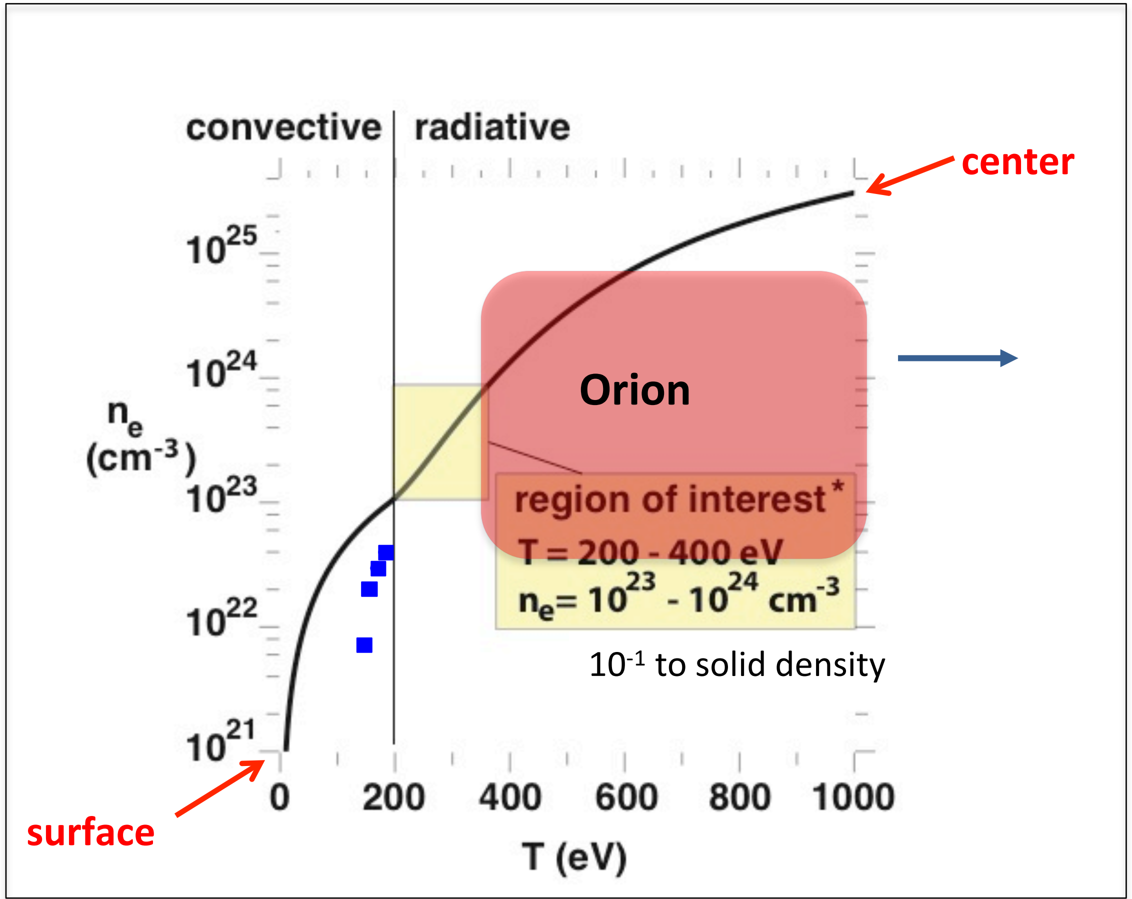


Figure adapted from London et al., APS, DPP, 2013.

[1] Bahcall et al. The Astro. J., 2005
[2] Bailey et al., Nature, 2015

Buried layer targets heated by short pulse lasers can be used to infer opacity

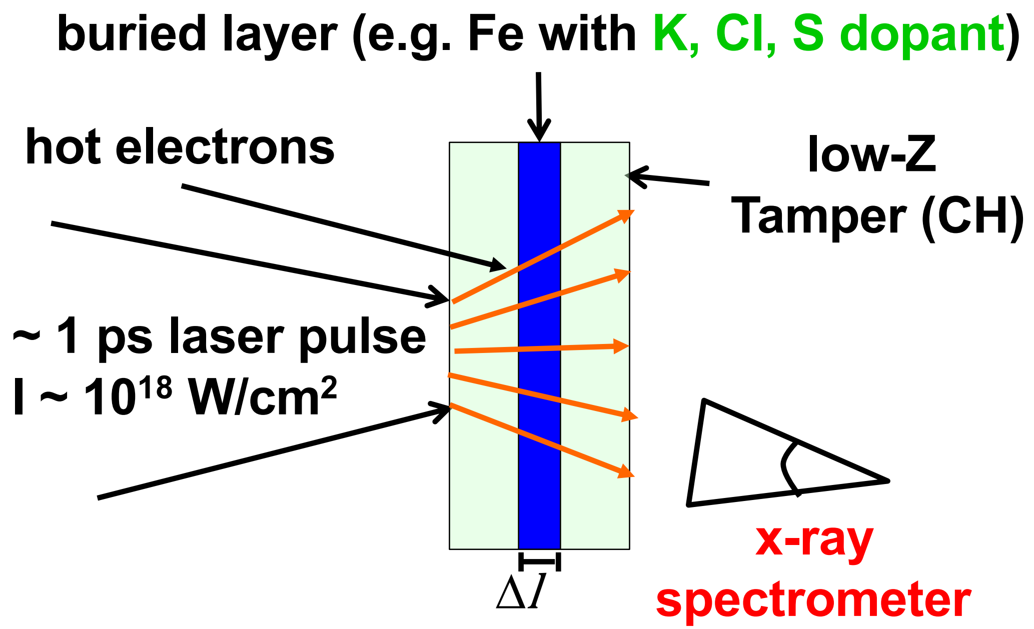


Figure adapted from R.A. London and J. I. Castor, HEDP, 2013
Related papers: Hoarty et. al, HEDP, 2007 & 2013 & 2017
Hoarty et al. are also working on an absorption-based platform

- Laser ➔hot electrons ➔heat target ➔x-ray emission
- High T at solid density
- Measure specific intensity (I_ν)
- Dopant (eg. Mg) used to infer T and ρ from emission
- Infer opacity (κ_ν):

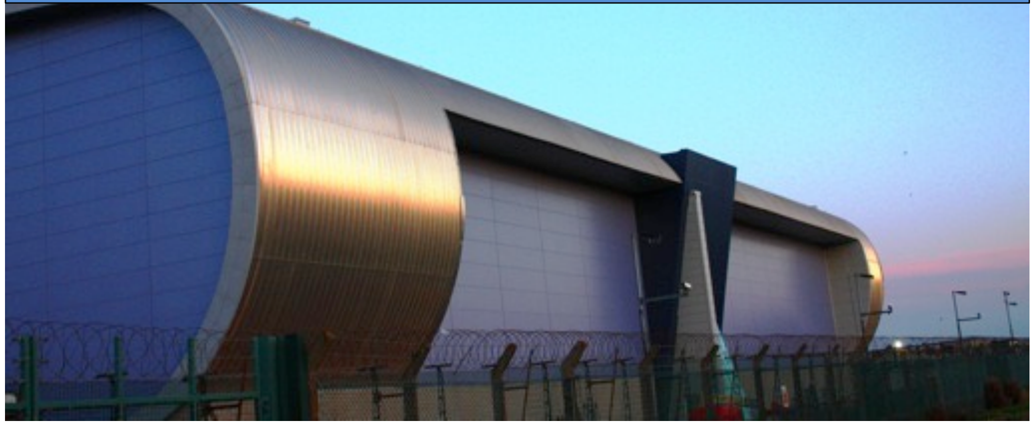
$$\kappa_\nu = \frac{-ln\left(1 - \frac{I_\nu}{B_\nu(T)}\right)}{\rho \Delta l}$$

- We are currently focused on directly comparing simulated emission spectra with measured emission spectra (I_ν)
  - explore sensitivities to modeling assumptions
  - understand plasma evolution

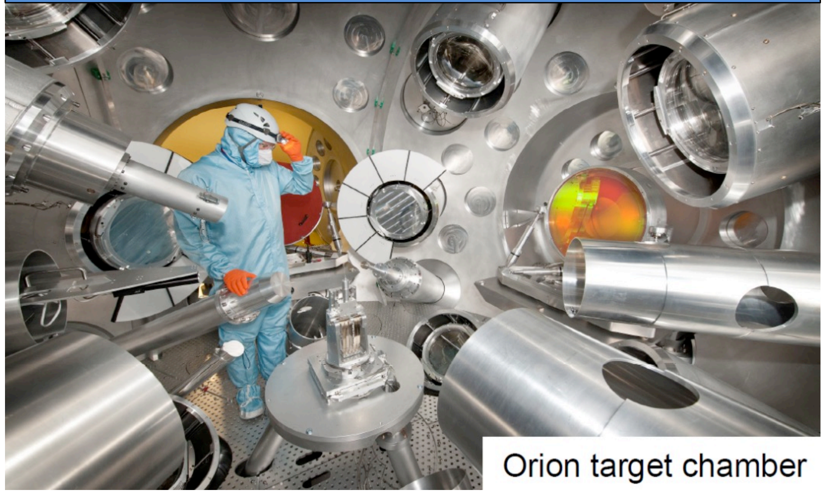
We use Orion Laser Facility at Atomic Weapon Establishment (UK) to access HED conditions

- Orion is a combined long and short pulse facility delivering:
  - 10 long-pulse beams (500J each, 0.1-10ns, 335nm)
  - 2 short-pulse beams (500J each, 500fs, 1054nm)

The Orion Laser Building



Target Chamber



Orion target chamber

- 1 short-pulse beam has been converted to green operation to increase pulse contrast (200J, 500fs, 527nm)
- 200 J is achieved using two independent doubling crystals

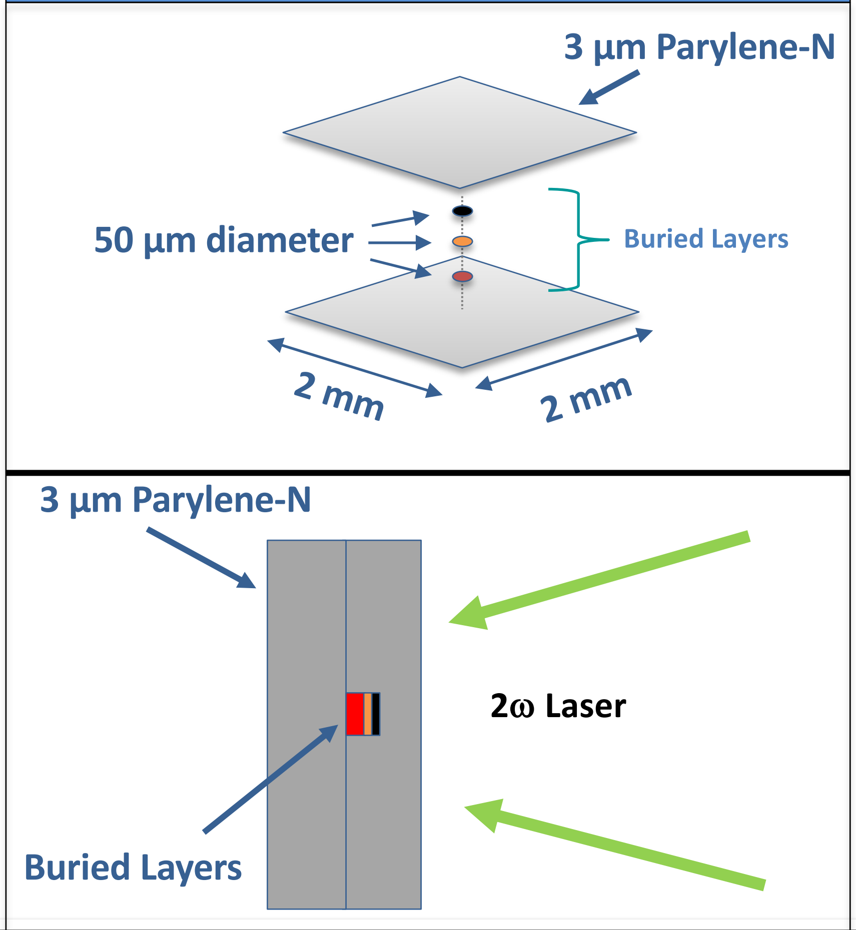
Orion provides access to a portion of phase space that is complementary to other facilities

We recently conducted an Fe Campaign with well characterized buried layer targets

- Characterized using:
  - PIXE (proton induced X-ray emission)
  - EDX (electron beam)
  - Profilometry

- Metrology results for FeS layer
  - layer thickness (174 ± 12) nm
  - composition: Fe 60.2 at%, S 39.8 at%
  - areal density:
    - Fe : 61 ± 4 μg cm^{-2}
    - S : 23 ± 2 μg cm^{-2}

Cartoon of target Assembly & Shot Orientation



Target Parameters	
Material	**Thickness (μm)**
Parylene-N	3
FeS	0.16
KCl	0.06
C	0.015
Parylene-N	3
Incident side of 2ω LASER	

Laser Parameters	
Parameter	**Value**
Δt	1 ps
energy	~ 165 J
Focus	100 μm
Irradiance	~ 2 $x10^{18}$ W/cm^2

We cover several bandwidths from several angles to ensure that the plasmas is well diagnosed

- For these shots, we fielded:
  - 2 time - resolved spectrometers:
    - Temperature inference
  - 4 time - integrated spectrometers:
    - Emission of interest (Fe L-shell)
    - Temperature & Density
  - 1 Pinhole Camera (GXD):
    - uniformity

Diagnostic Overview

Diagnostic	Crystal	Filters	Sees	View Angle	Front/Back
AXIS 608	RAP	8 μm Be	Fe L	25°	F
AXIS 609	CsAP	16 μm Be	S K	65°	B
OHREX-I	Quartz	51 μm Be	Fe K	19.3°	F
OHREX-I	KAP	51 μm Be	Fe L	19.3°	F
HBS	CsAP	8 μm Be	Fe L	70°	F
MK II	CsAP	16 μm Be	S, Cl Heα, Lyα, S β-lines	76°	F
Titan	PET	16 μm Be	S, Cl, K k-shell	76°	B
GXD	...	8 μm Be	Imaging	20°	B

Time-Resolved (shaded rows: AXIS 608, AXIS 609)

Measurements require lots of calibration, which is completed at both LLNL and AWE

- Crystals:
  - AWE: X-ray tube/Excaliber w/ double crystal spectrometers
  - LLNL: EBIT w/ quantum calorimeter (ECS)
- Filters:
  - LLNL: EBIT with ECS
  - AWE & LLNL: Profilometry
- Image Plate:
  - AWE: X-ray Tube/Excaliber sources

We use two main modeling approaches

HYDRA[1]:

- Parametric heating source
- Target and laser parameters
- Opacity model
- Radiation transport methods
- Electron conduction model

↓

- evolution of plasma conditions
- post-process for simulated emission

Cretin[2]:

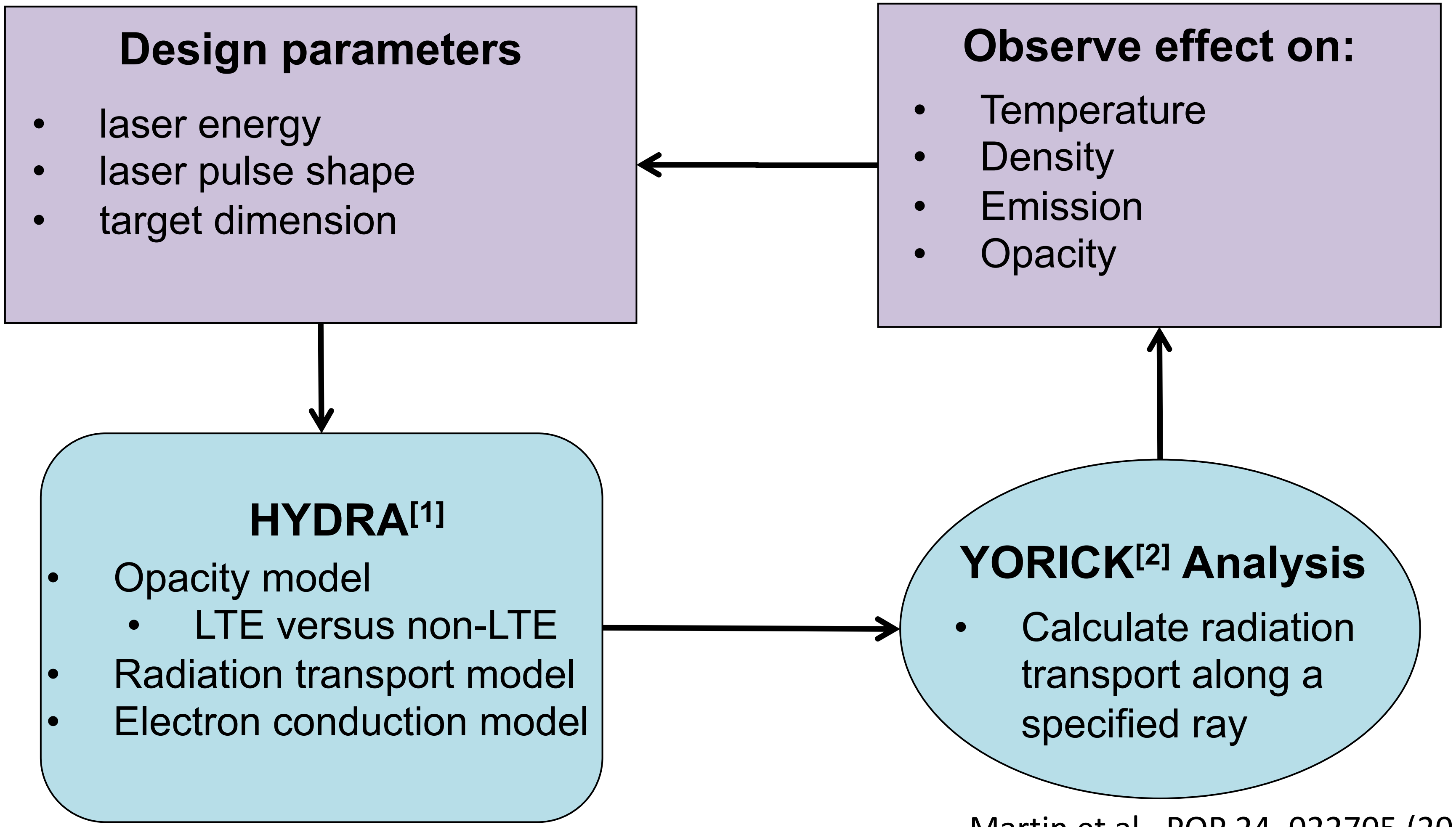
- Single pair of plasma conditions
- Time dependent atomic kinetics
- Optical depth effects
- Line shapes
- Radiation transfer effects

↓

- Simulated emission
- Ionization
- charge state distributions

[1] M. Marinak et al., POP, 1996, 1998, & 2001
[2] H. A. Scott, JQSRT 71, 689 (2001)

We use a 1D radiation-hydrodynamics modeling methodology to study sensitivities

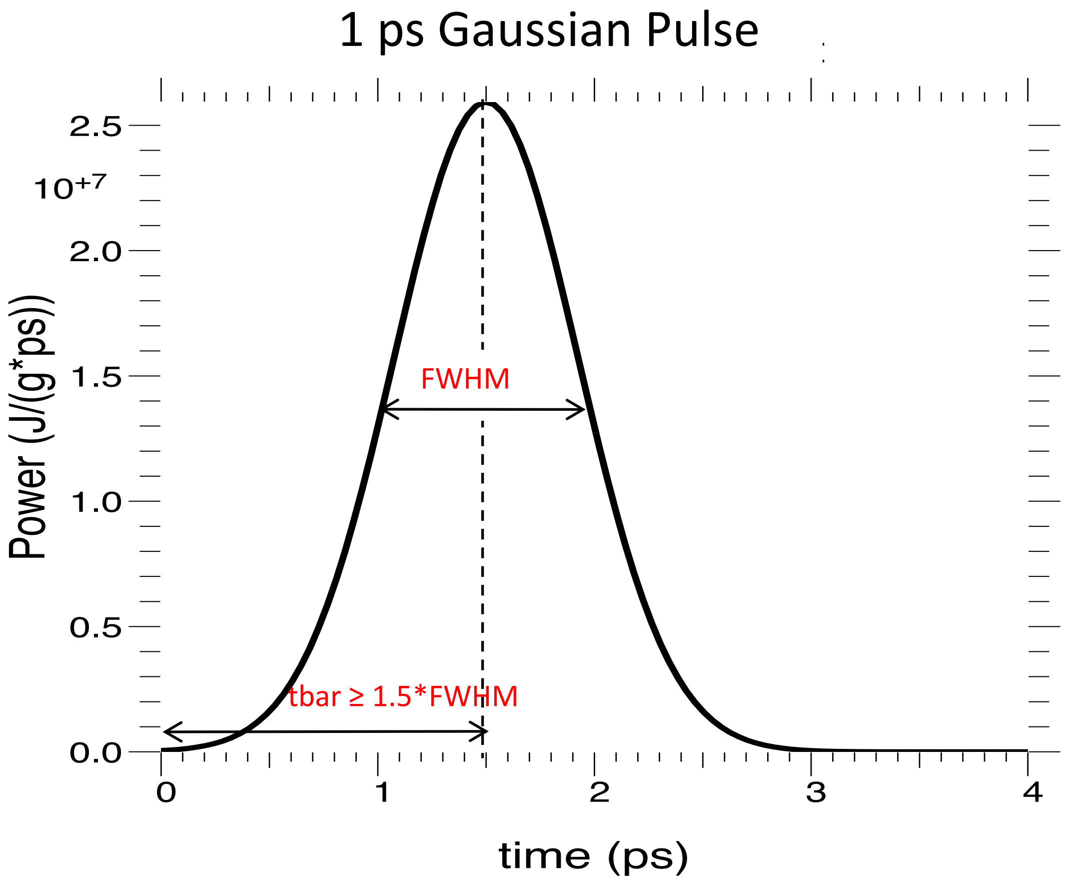


Martin et al., POP 24, 022705 (2017)
Martin et al., HEDP 26, 26-37 (2018)

[1] M. Marinak et al., POP, 1996, 1998, & 2001
[2] D. Munro, http://yorick.sourceforge.net/

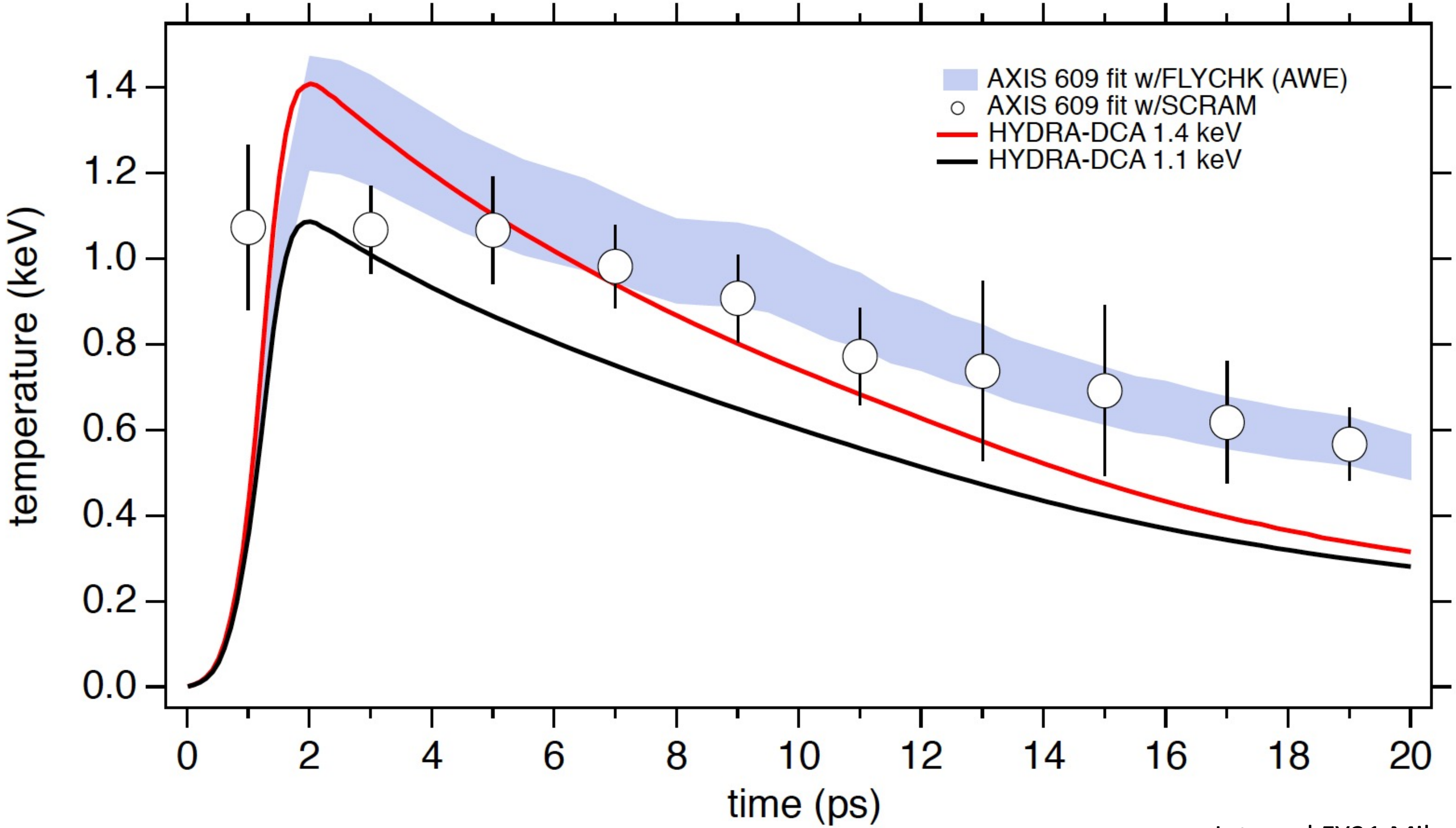
HYDRA was used to model buried layer targets

- Assume 1-Dimensional geometry
- Opacity is modeled using HYDRA DCA package
  - Relies on super-configuration-based atomic models
- Energy source
  - Do not model laser rays or hot electrons
  - Deposit internal energy (J/g) uniformly in target and proportional to laser pulse (conversion efficiency)



Martin et al., POP 24, 022705 (2017)

Parametric energy source is tuned to reach a similar peak electron temperature inferred for a specific experimental shot

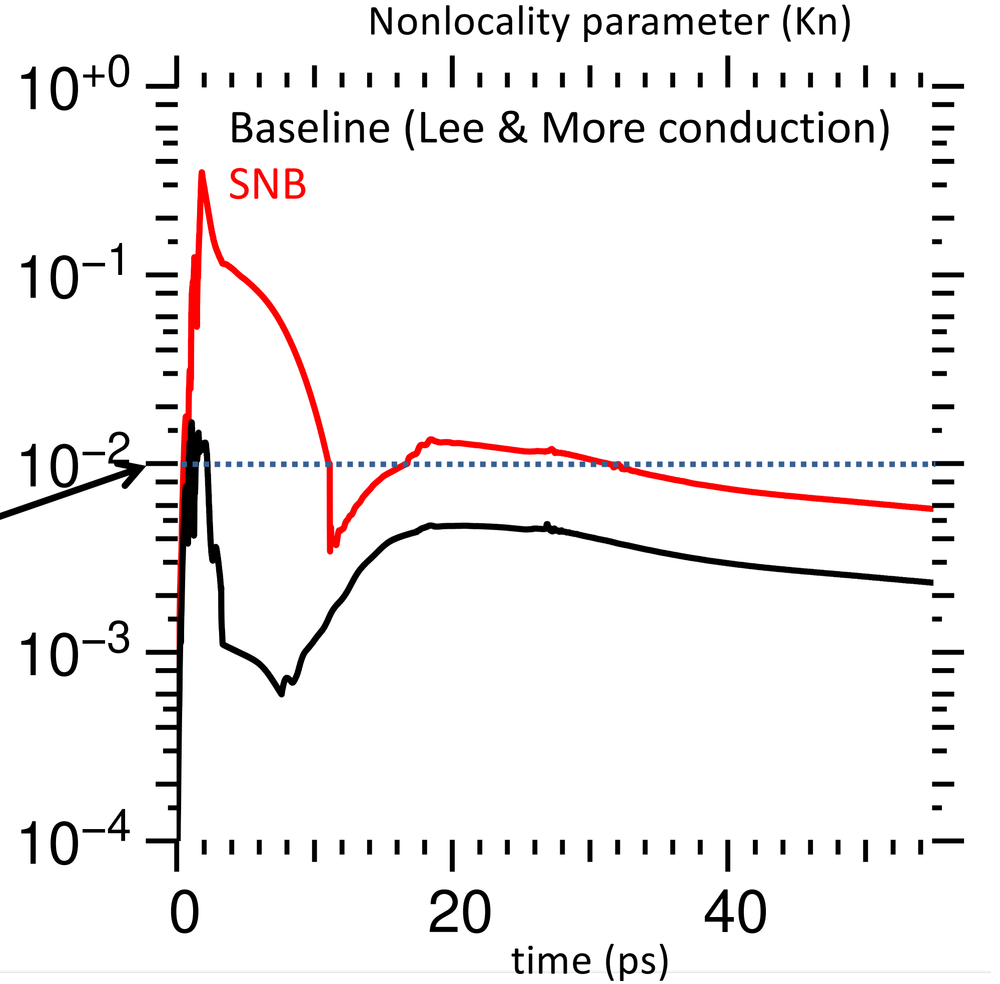


Internal FY21 Milestone Report: LLNL-TR-820896

Including nonlocal thermal transport effect may improve modeling

- Nonlocality parameter (Kn) is used to assess whether non-local transport is important
  - $Kn = \frac{\lambda_C}{L_T}$
  - $L_T = \frac{T}{|\nabla T|}$ (electron temperature gradient length scale)
  - λ_C (thermal collisional mean free path)

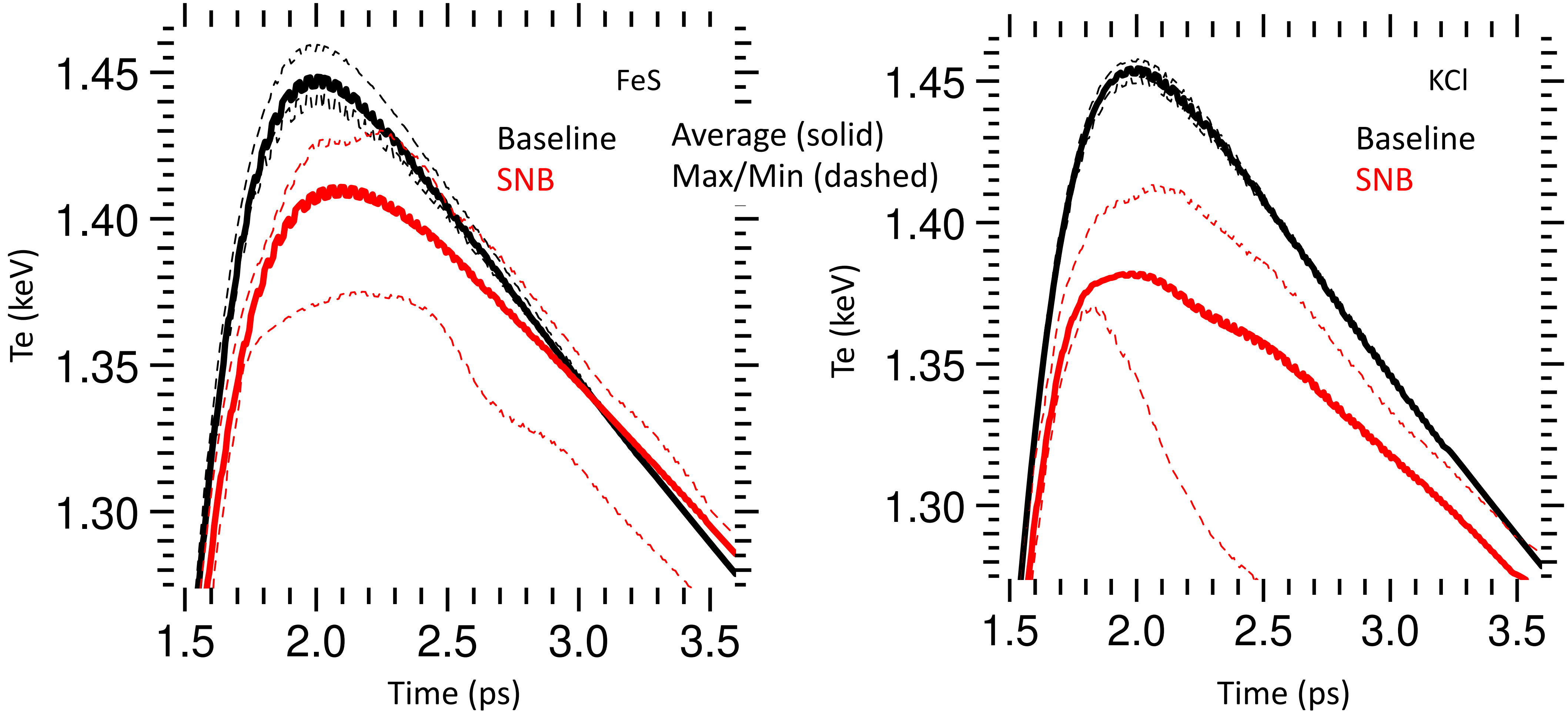
Threshold for potential importance



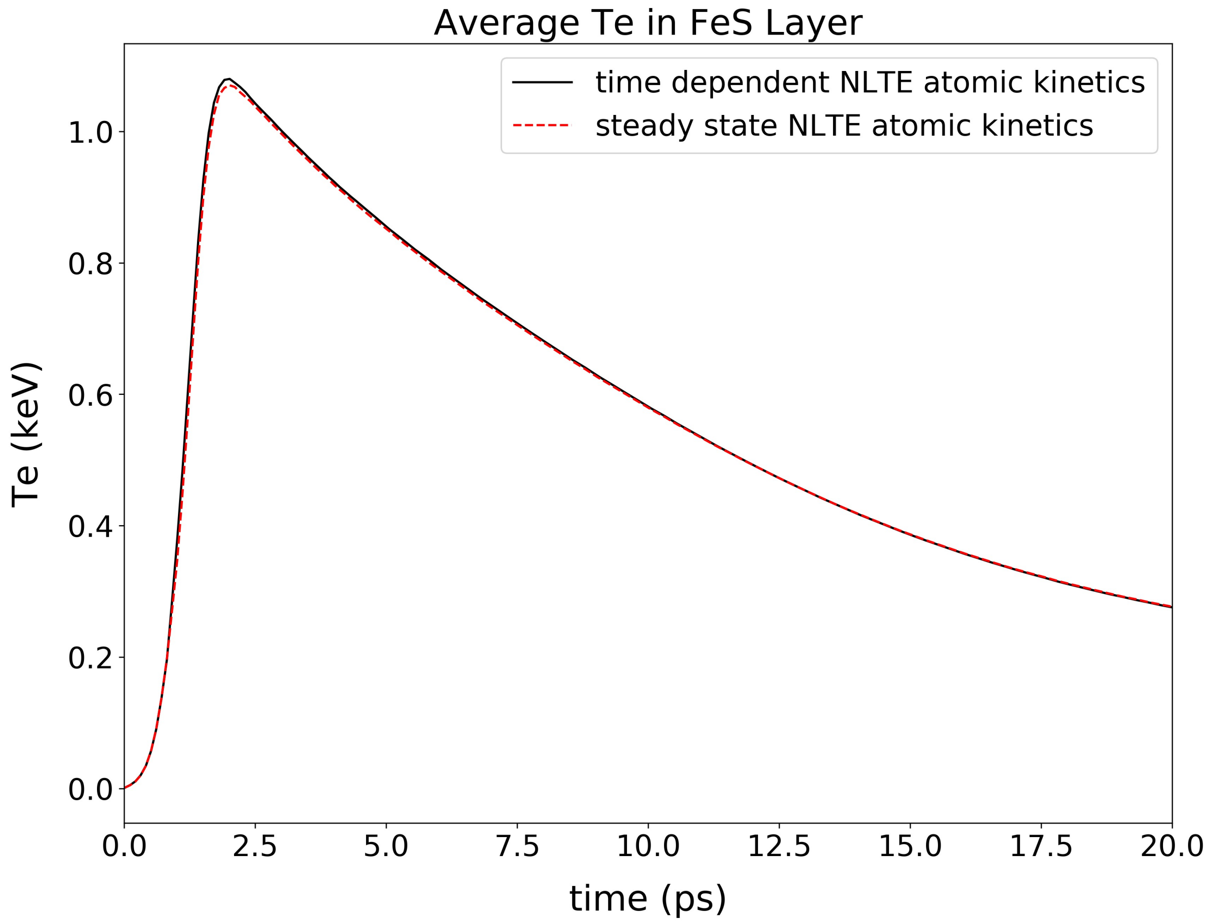
- HYDRA includes a nonlocal electron transport package to model electron thermal conduction for strongly driven plasmas
  - Extension of Schurtz, Nicolai, and Busquet (SNB) non-local thermal transport model[1]

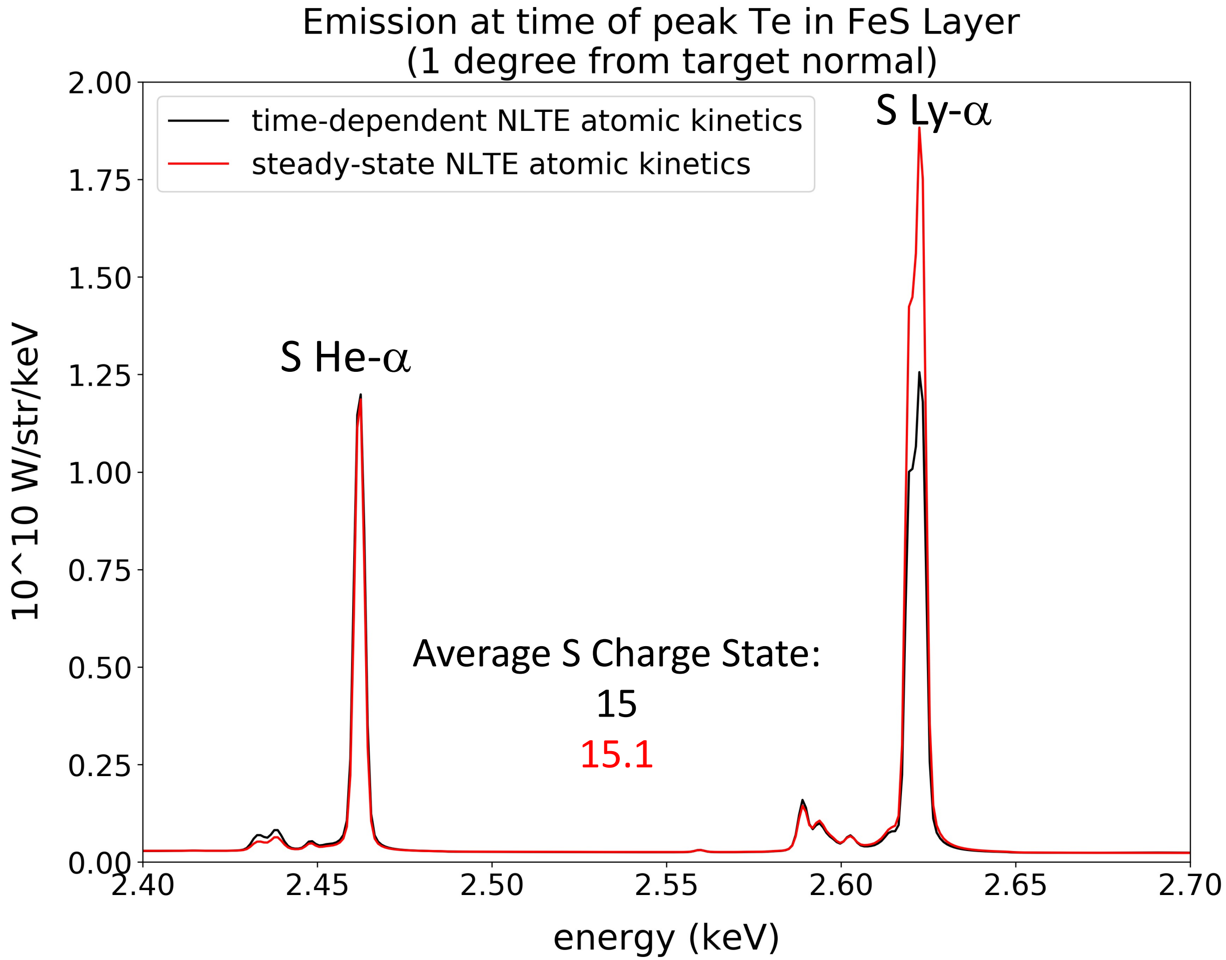
[1] Schurtz et al. POP 7, 4238 (2000)

Nonlocal transport predicts slightly lower peak temperature and a wider range of conditions over the layers



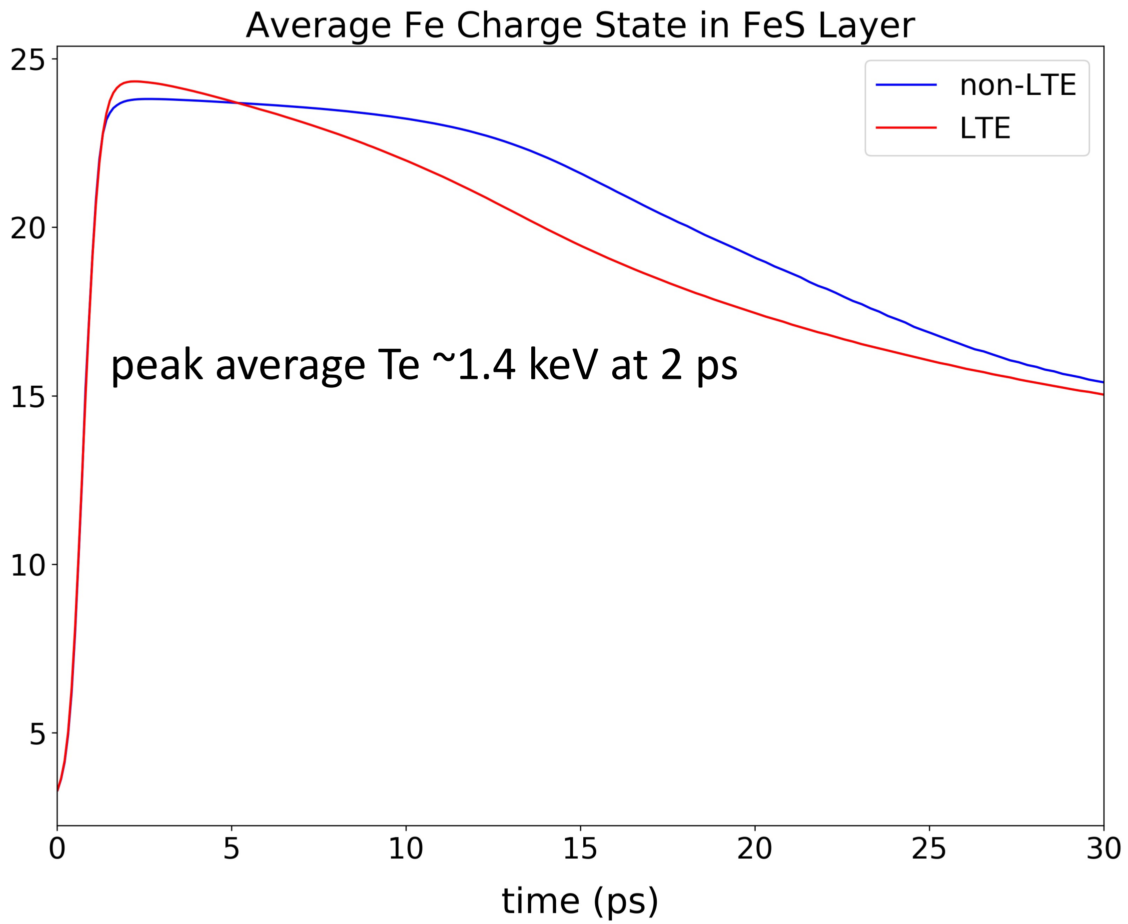
Ray tracing is used to study sensitivity of simulated emission for various assumptions

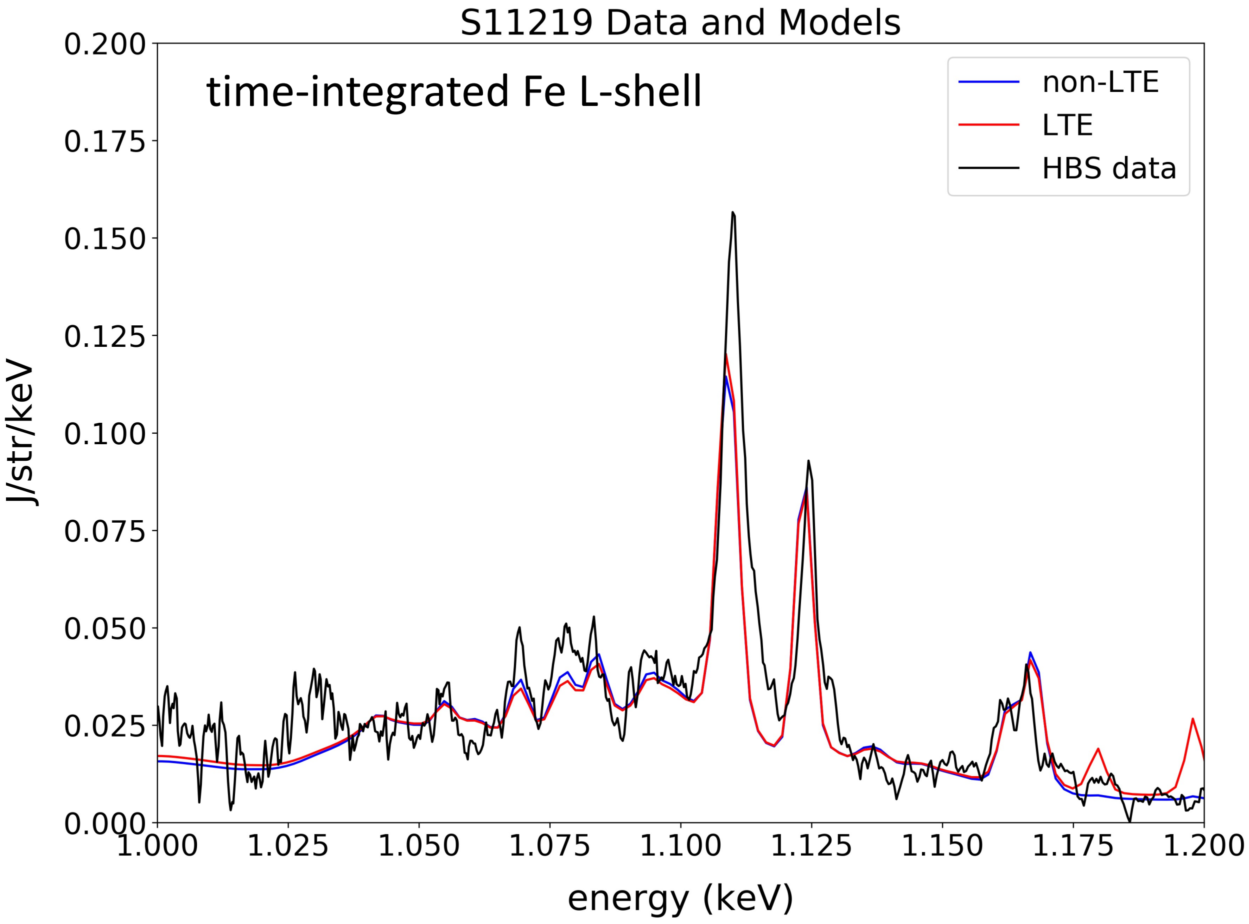




Assuming steady-state NLTE atomic kinetics has a small impact on average Te in FeS Layer but slightly increases S ionization

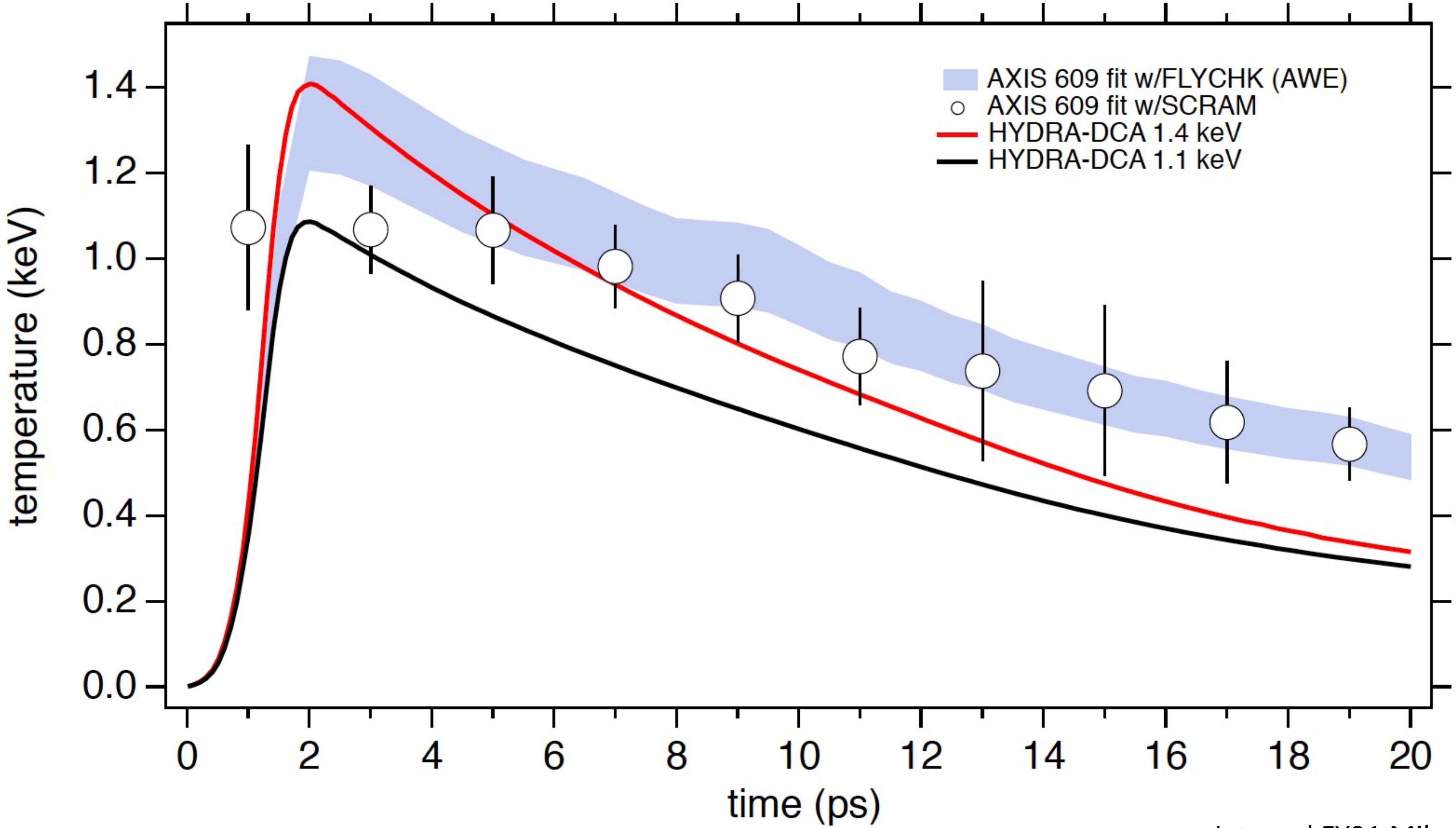
Ray tracing is used to compare multiple models to experimental data





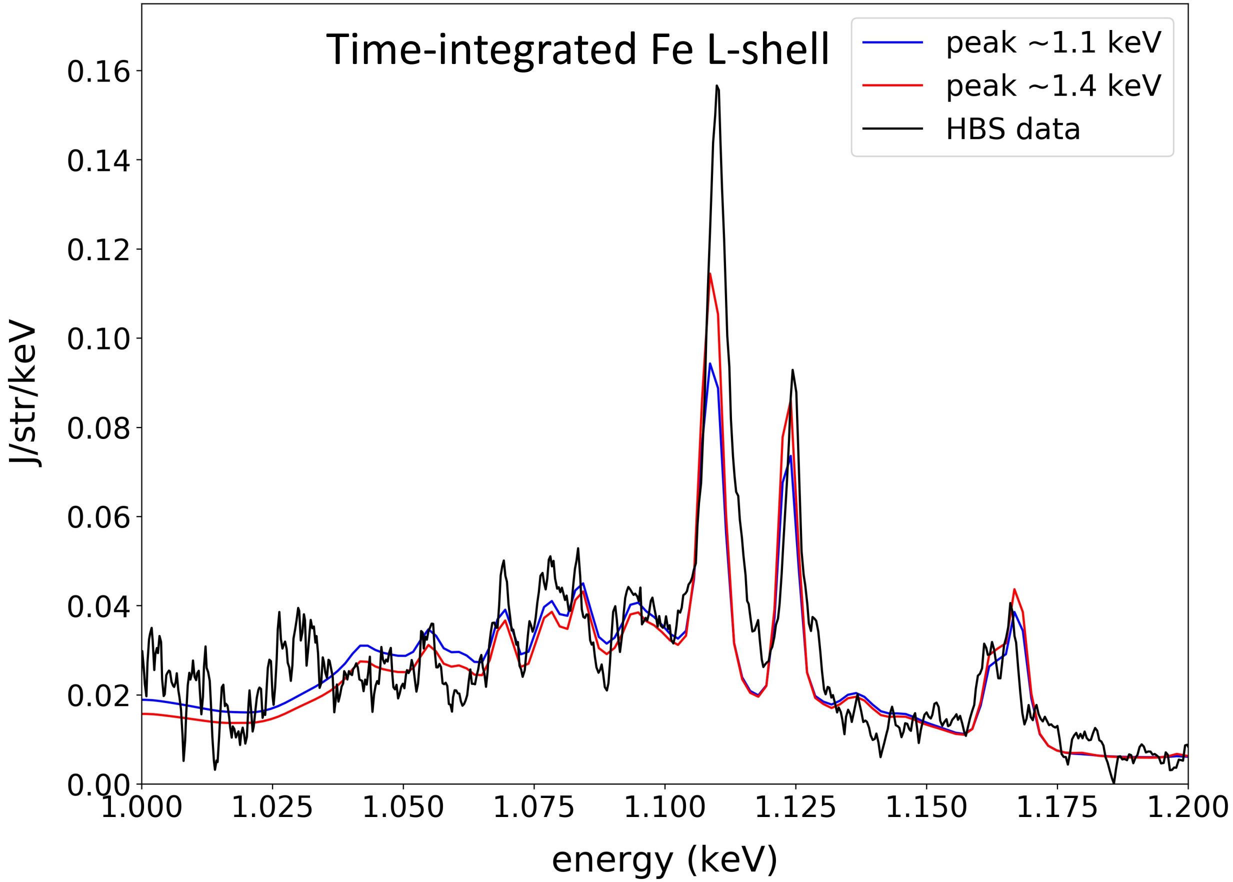
Both non-LTE and LTE models have reasonable agreement with the time-integrated Fe l-shell data

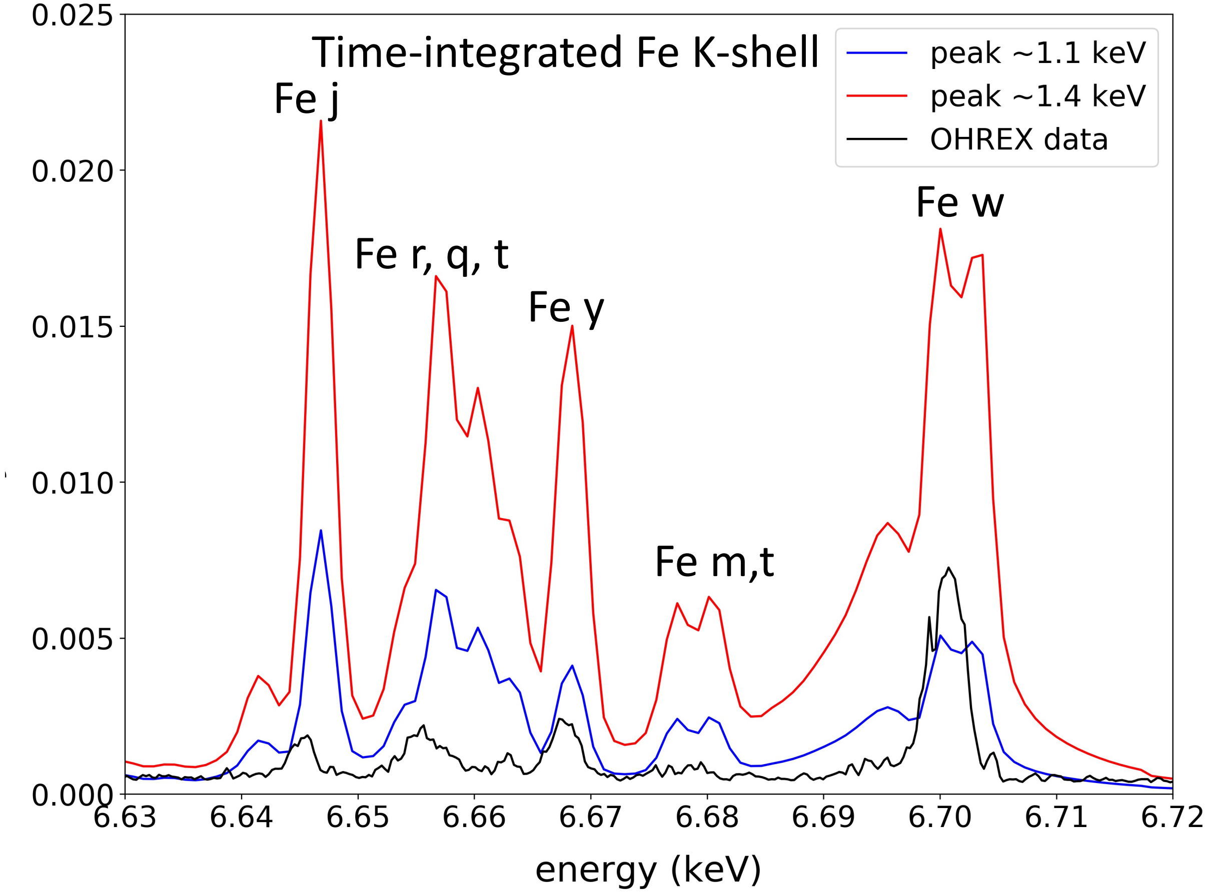
Parametric energy source is tuned to reach a similar peak electron temperature inferred for a specific experimental shot



Internal FY21 Milestone Report: LLNL-TR-820896

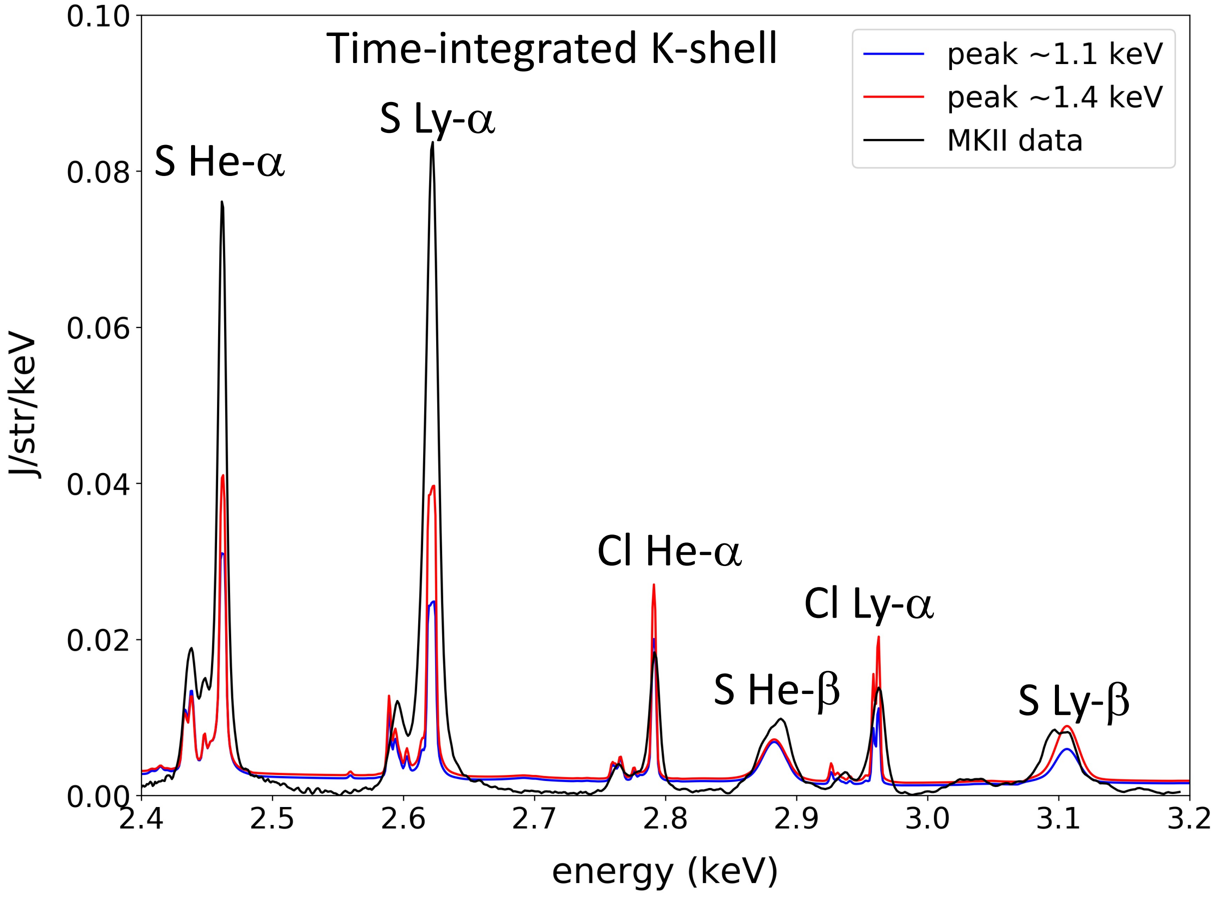
We have decent agreement with the Fe L-shell but have discrepancies with the K-shell spectra

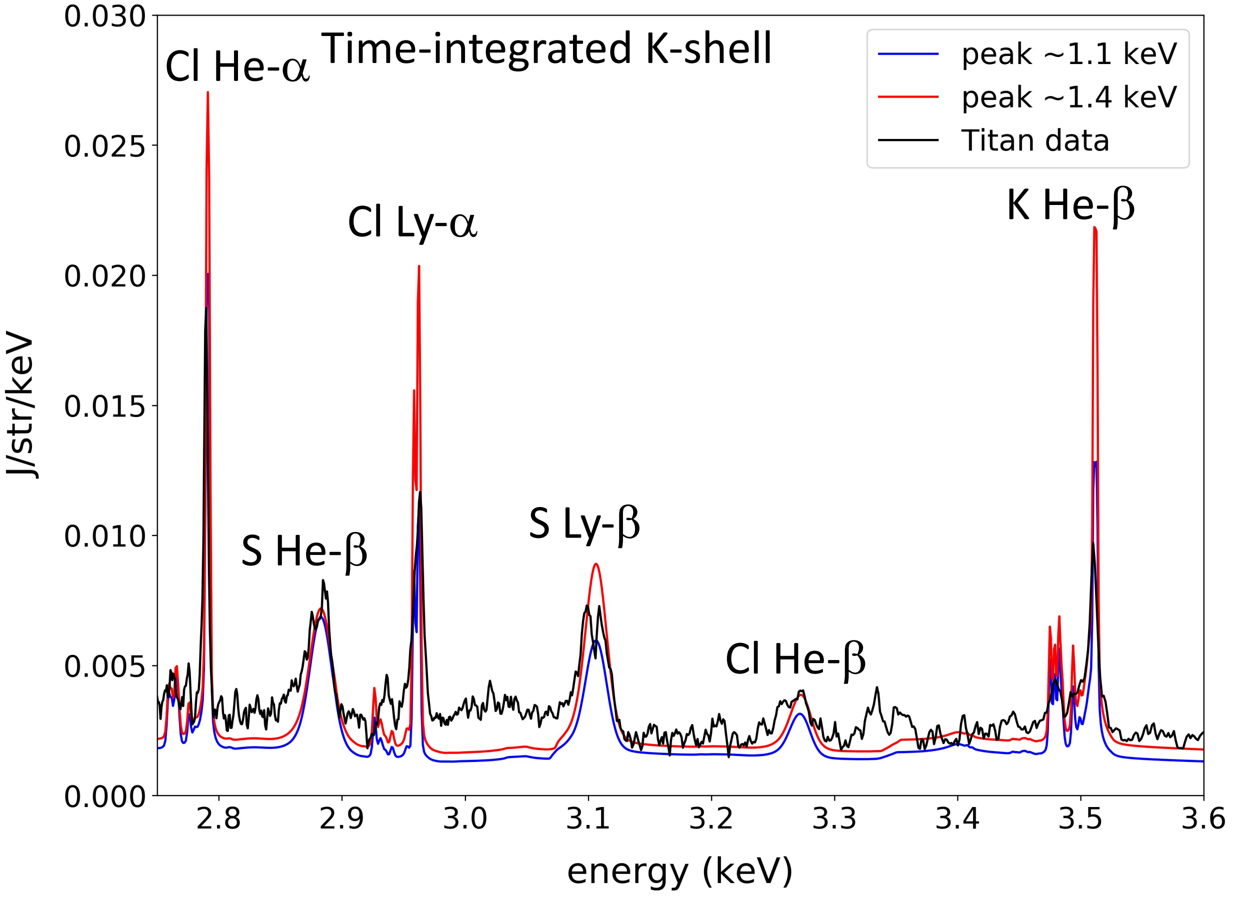




Both models have reasonable agreement with Fe l-shell but overpredict the Fe k-shell emission

We have decent agreement with the Fe L-shell but have discrepancies with the K-shell spectra





Both models underpredict S He-α and S Ly-α but the higher temperature model overpredicts Cl He-α, Cl Ly-α, and K He-β

We used 1D Cretin models to study sensitivities for comparison with data and other spectral codes including those used for temperature inference

Plasma Conditions
- For fixed density:
  - Te = 0.8-1.4 keV
- 1D slab of FeS (areal density conserved)
- Less expensive and not dependent on assumed heating in rad-hydro

Compare with Data and other Spectral Codes
- Measurement
- SCRAM (used for Te inference)
- ENRICO (non-LTE code)

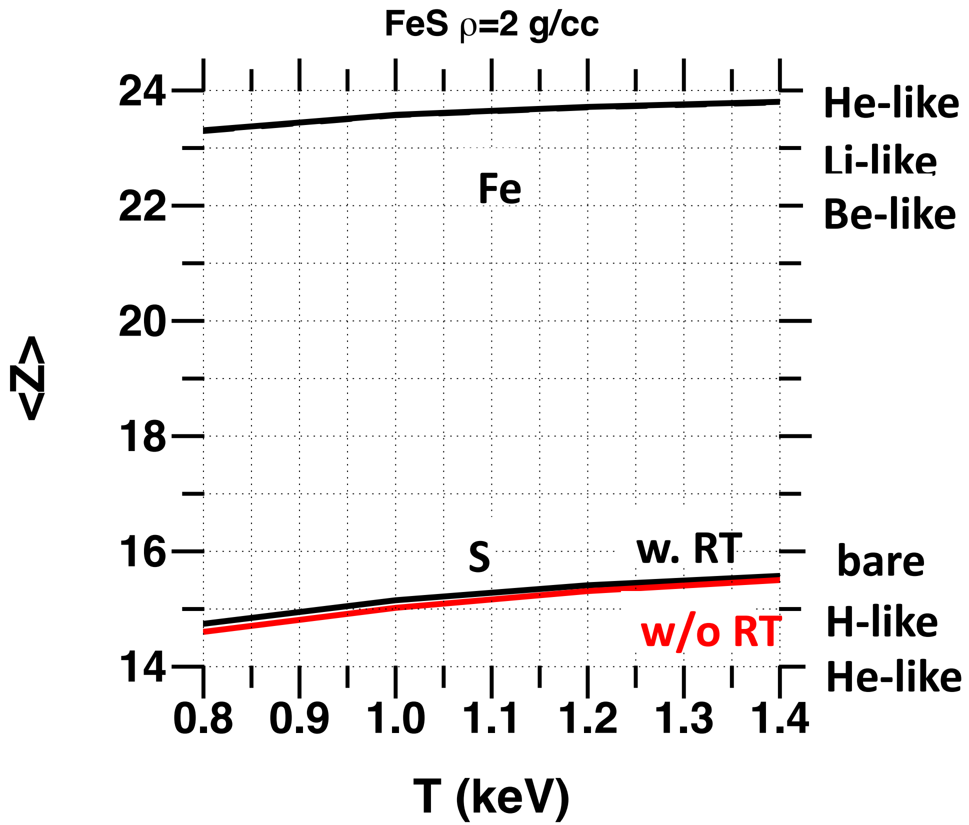
Cretin[1]
- No radiation transfer
- With radiation transfer
- Optical depth effects
- Ti effects

Output
- Ionization
- Charge state
- Emission

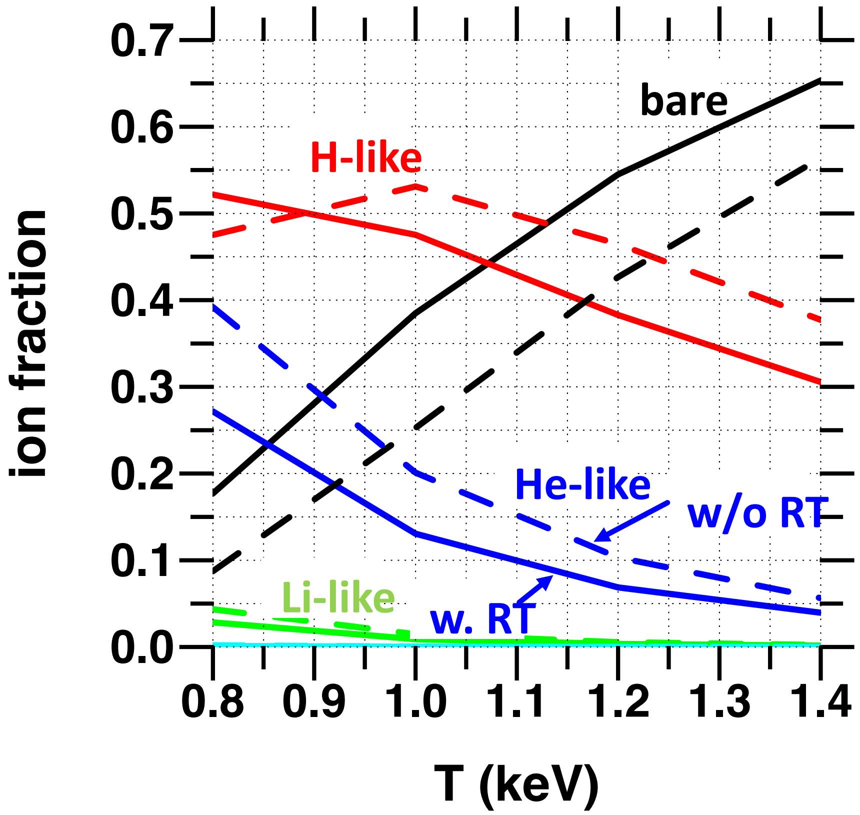
[1] H. A. Scott, JQSRT 71, 689 (2001)

Including radiation transfer has a small effect on average ionization but a larger effect on concentration of the main ionization stages of S

Average ionization vs Te



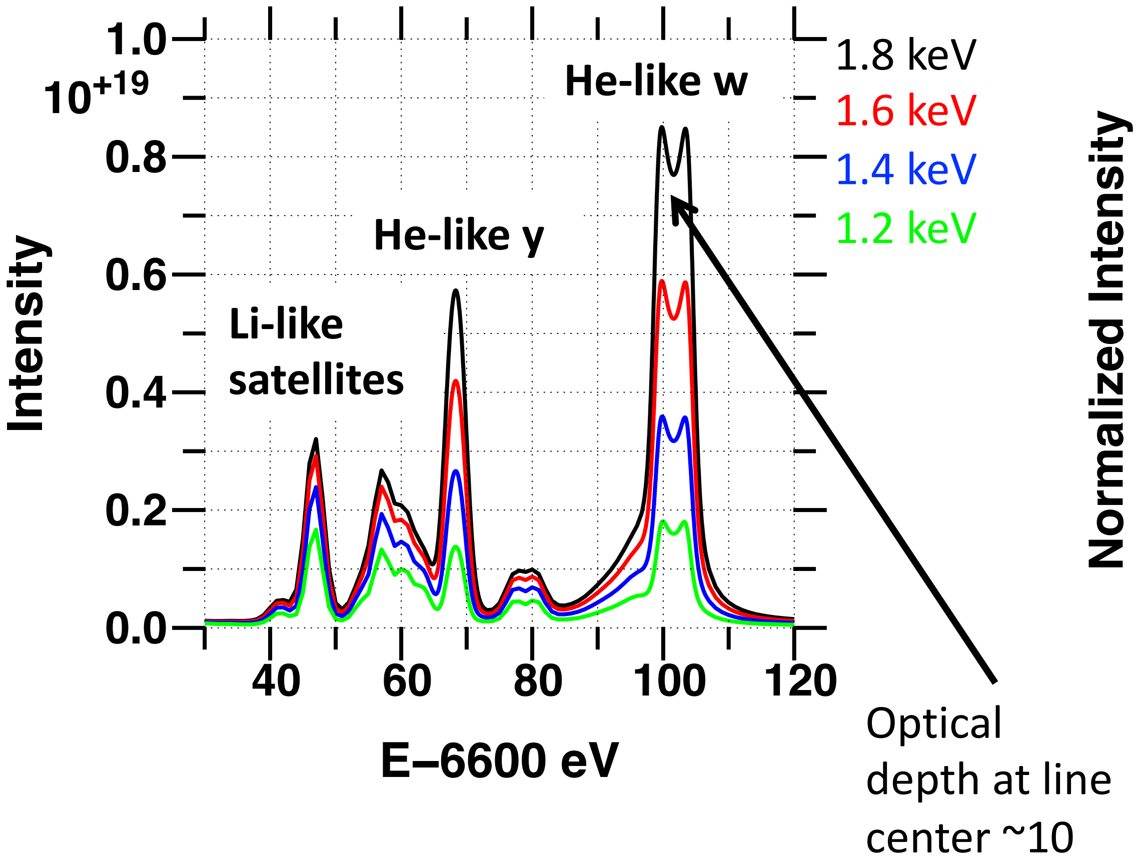
S ion fractions vs Te



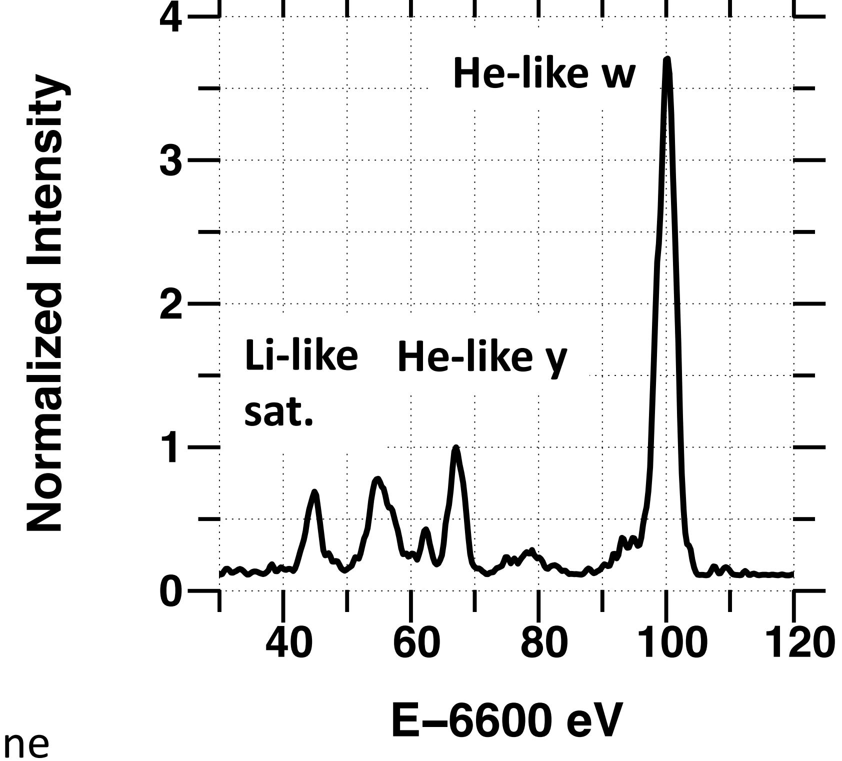
RT = radiation transfer

Simulated emission for OHREX line of sight demonstrates sensitivity of Fe K-shell emission to temperature

Fe He-alpha region for Te = 1.2 to 1.8 keV



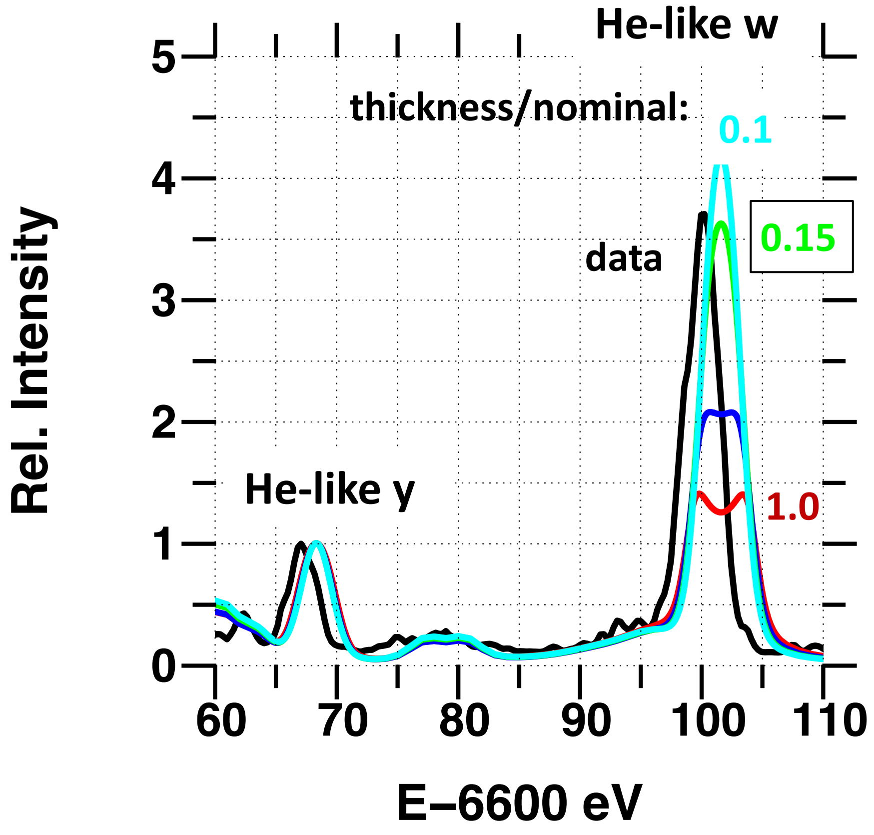
OHREX spectrum of Orion shot 11219 OHREX



R. London (2020)

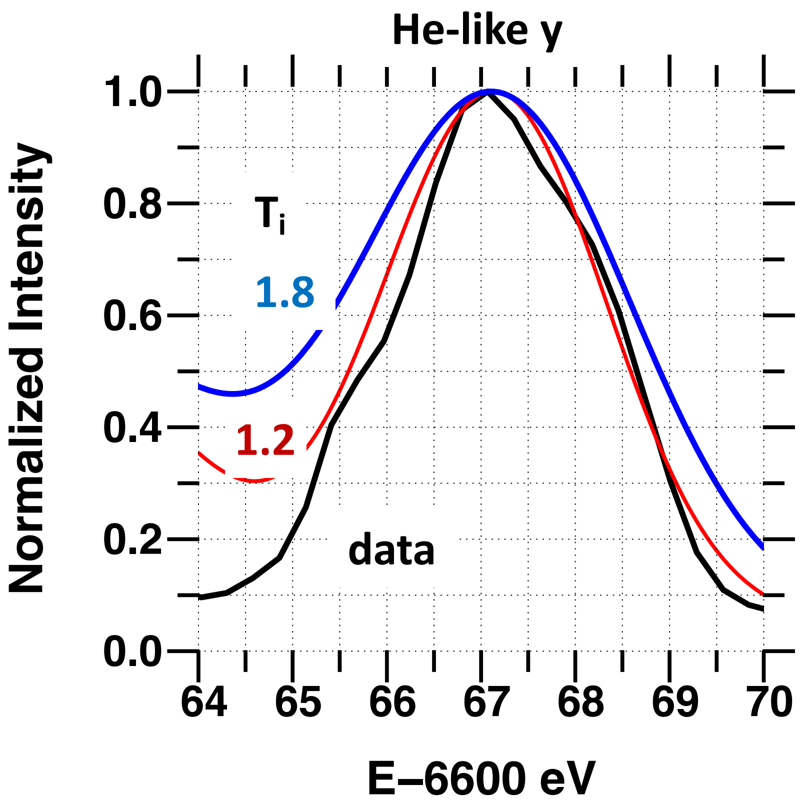
The He-like w line is better matched by a reduced areal density and He-like y line is better matched by a lower ion temperature

Effect of layer thickness on Fe He_α lines



Te = 1.8 keV

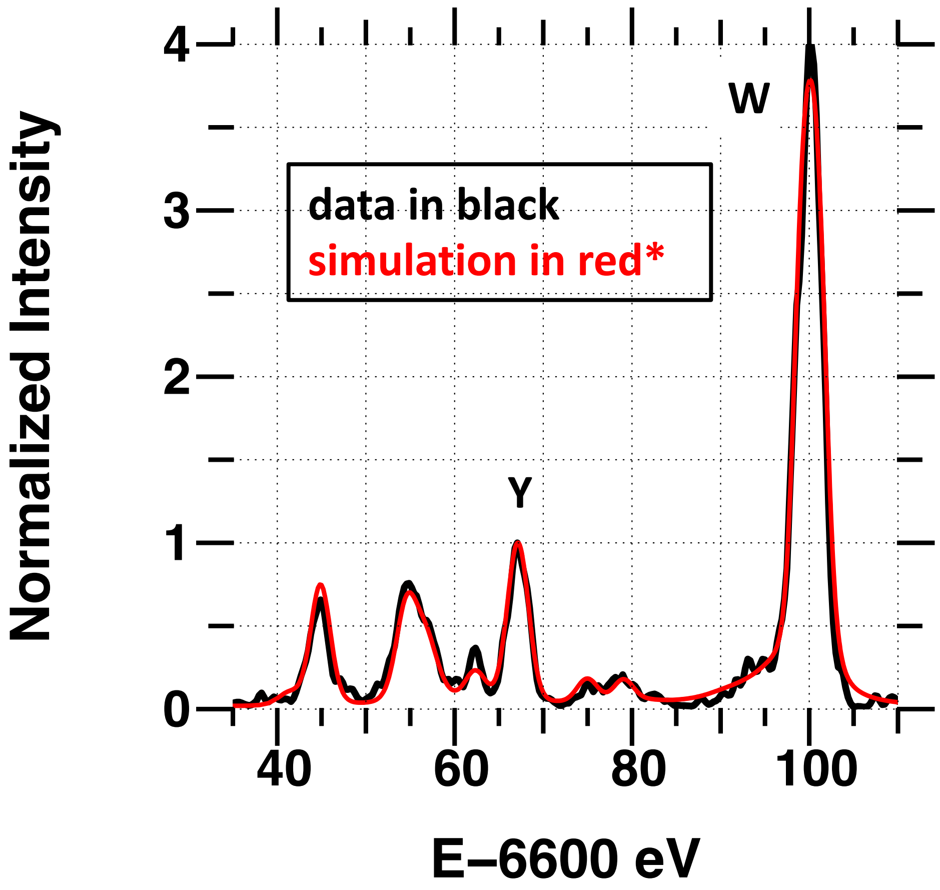
Effect of T_i on y line profile



Te = 1.8 keV; areal density 15 % of nominal

The best match to the OHREX data requires Te = 1.8 keV, Ti = 1.2 keV, and areal density that is 15 % of nominal

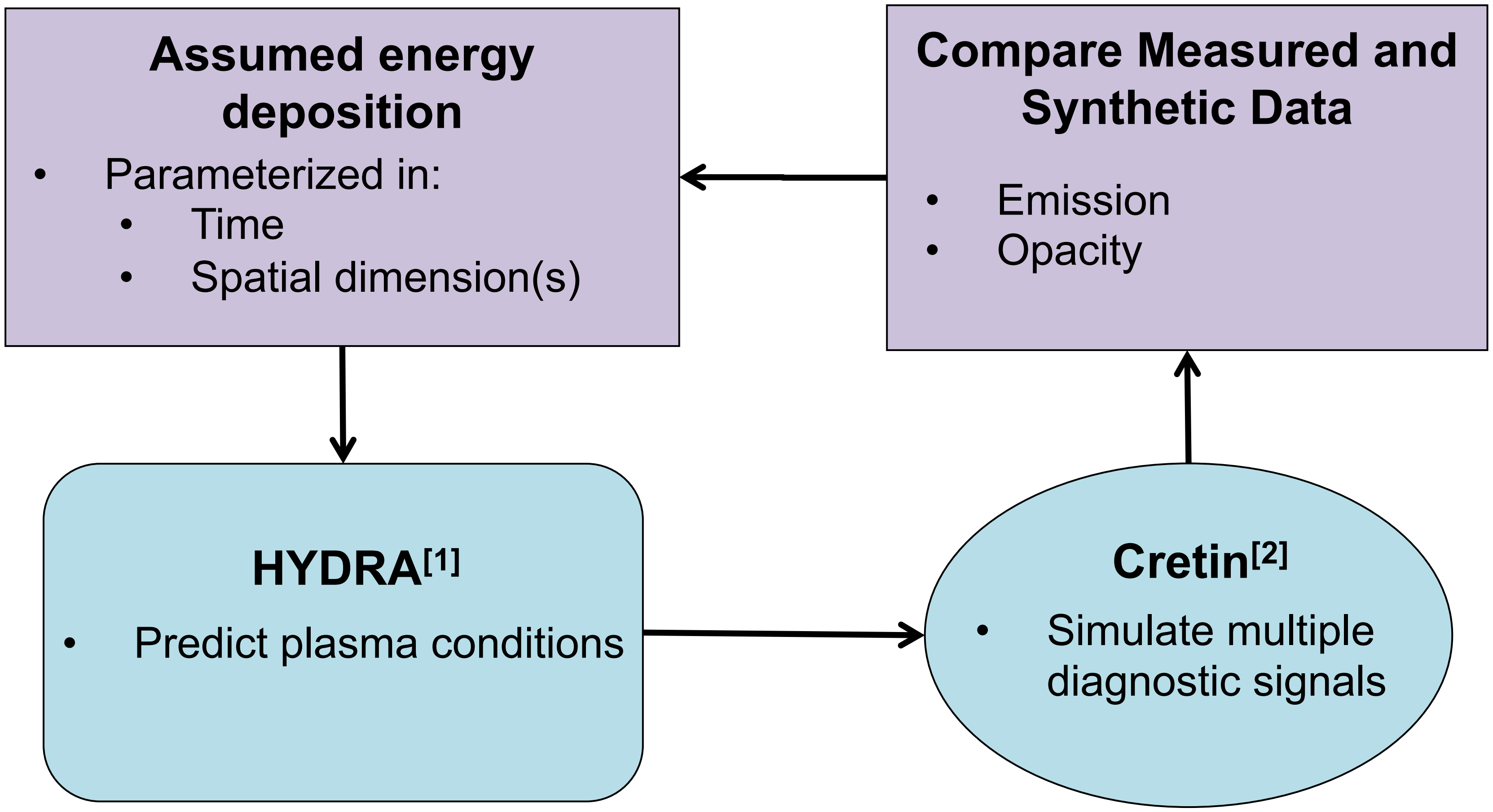
Best Cretin simulation and S11219 OHREX data



Parameters of Cretin fit
T_e = 1.8 keV
T_i = 1.2 keV
$\rho\Delta z$=15% of nominal

***simulated line positions have been shifted to match data**

Ultimate goal is to use a coupled methodology to characterize heating as informed by measurements



[1] M. Marinak et al., POP, 1996, 1998, & 2001
[2] H. A. Scott, JQSRT 71, 689 (2001)

Ongoing and future work is done in parallel and coordinated across Orion team

- Modeling and Design
  - Complete predictions and analysis of FY22 campaign using current HYDRA and Cretin models [Martin et al.]
  - Extend HYDRA models to include 2D effects [R. London, et al.]
  - Replace ray trace with post-processing using Cretin for simultaneously constraining plasma evolution and atomic kinetics by comparing simulated and measured spectra [D. Cliche, et al.]
  - Improve understanding of sensitivities of the Orion platform using our best available models [Martin, et al.]
- Experimental
  - Continue to improve calibration of spectrometers [Brown, MacDonald, Shepherd]
  - Complete software development to more efficiently reduce data and aid with preliminary analysis during future FY22 campaign [MacDonald]
  - Continue to develop multiple-temperature inference algorithm [MacDonald and Liedahl]
  - Complete installation and testing of STOHREX to provide time-resolved density diagnostics [Brown, et al.]
- Theory
  - Complete predictions and analysis of FY22 campaign using NLTE models (eg. SCRAM, ENRICO, Cretin) [Foord, et al.]
  - Improve accuracy, convergence, and speed of ENRICO [Foord, et al.]
  - Generate NLTE tables as part of Autonomous Multiscale SI [Gaffney et al.]

Summary

- Experimental validation of opacity theory is needed for HED conditions
- Short pulse lasers can be used to conduct opacity measurements
- We have conducted Fe emission experiments at AWE’s Orion Laser Facility
- A previously developed 1D HYDRA methodology was used to study sensitivities to radiation transport, non-local electron transport, and assumed atomic model
- Cretin was used to investigate radiation transfer and plasma conditions on ionization and emission
- We have only discussed a small fraction of the ongoing work associated with this campaign and milestone