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Temperature in Multielement Laboratory Photoionized Plasmas

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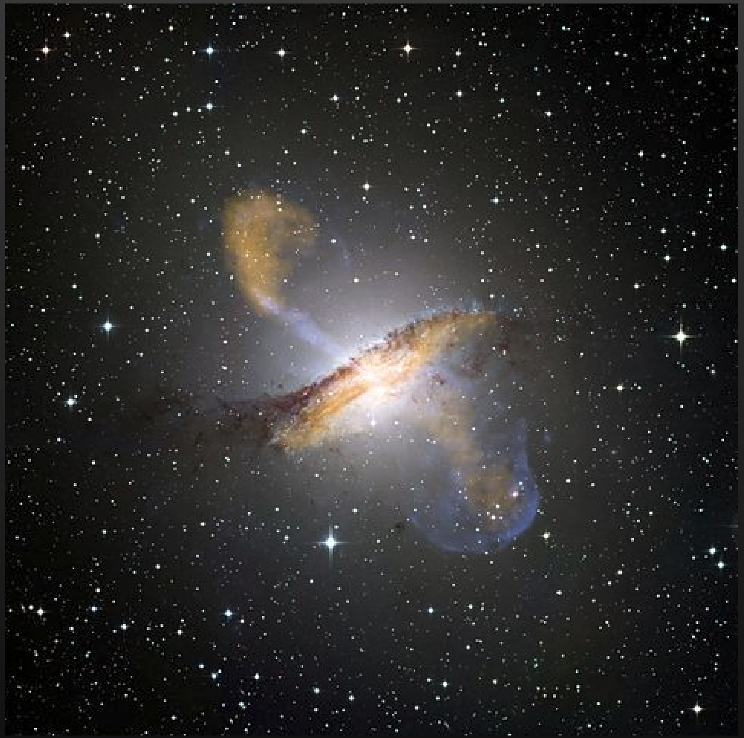
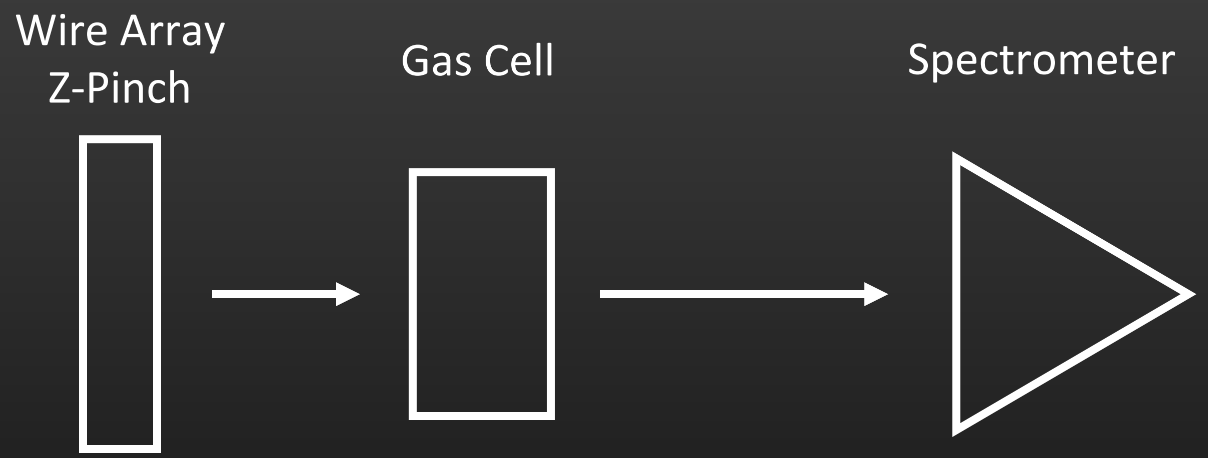
Laboratory photoionized plasmas can be used to improve astrophysics theory, modeling, and analysis

- Historically difficult regime to achieve in the lab
- Relevant to systems dominated by photoionization: black hole accretion disks, x-ray binaries, warm absorbers of active galactic nuclei, etc.
- Support analysis of spectra from x-ray telescopes (Chandra, XMM-Newton, etc.)
- Provide benchmark data for synthetic spectral models (CLOUDY, XSTAR, etc.)

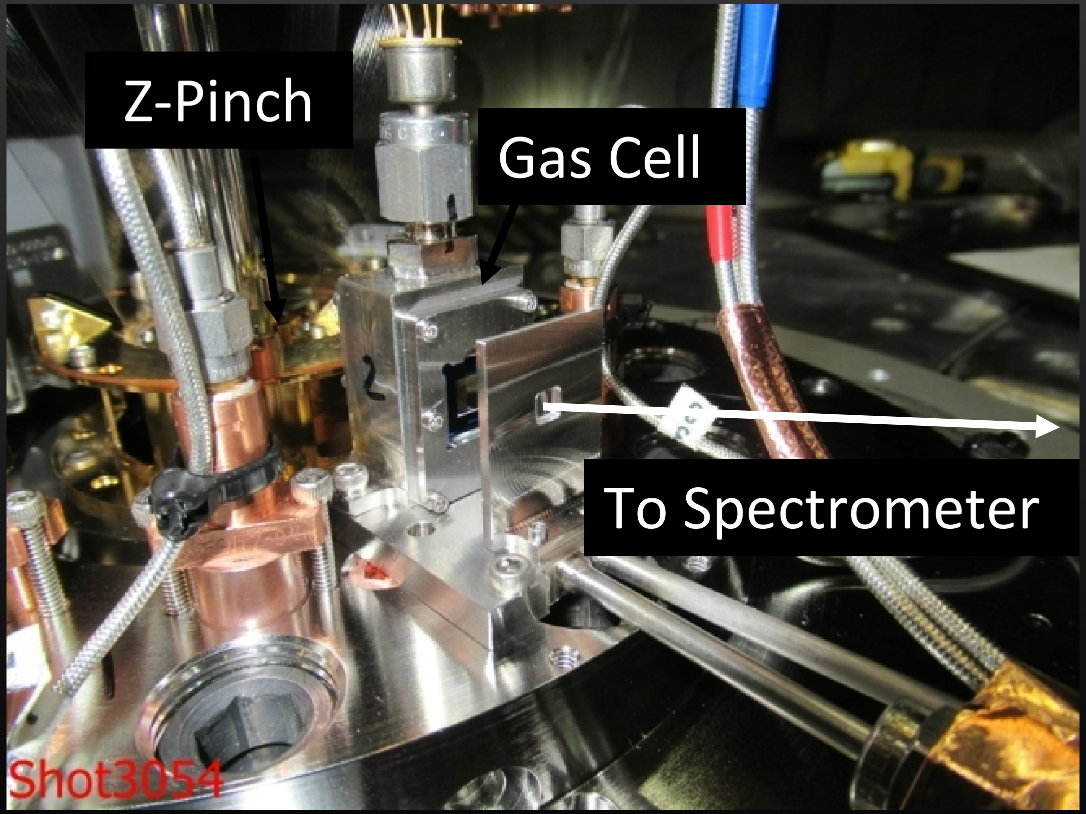


Composite of Centaurus A
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

A z-pinch x-ray source drives gas in a cell and backlights it for absorption spectroscopy

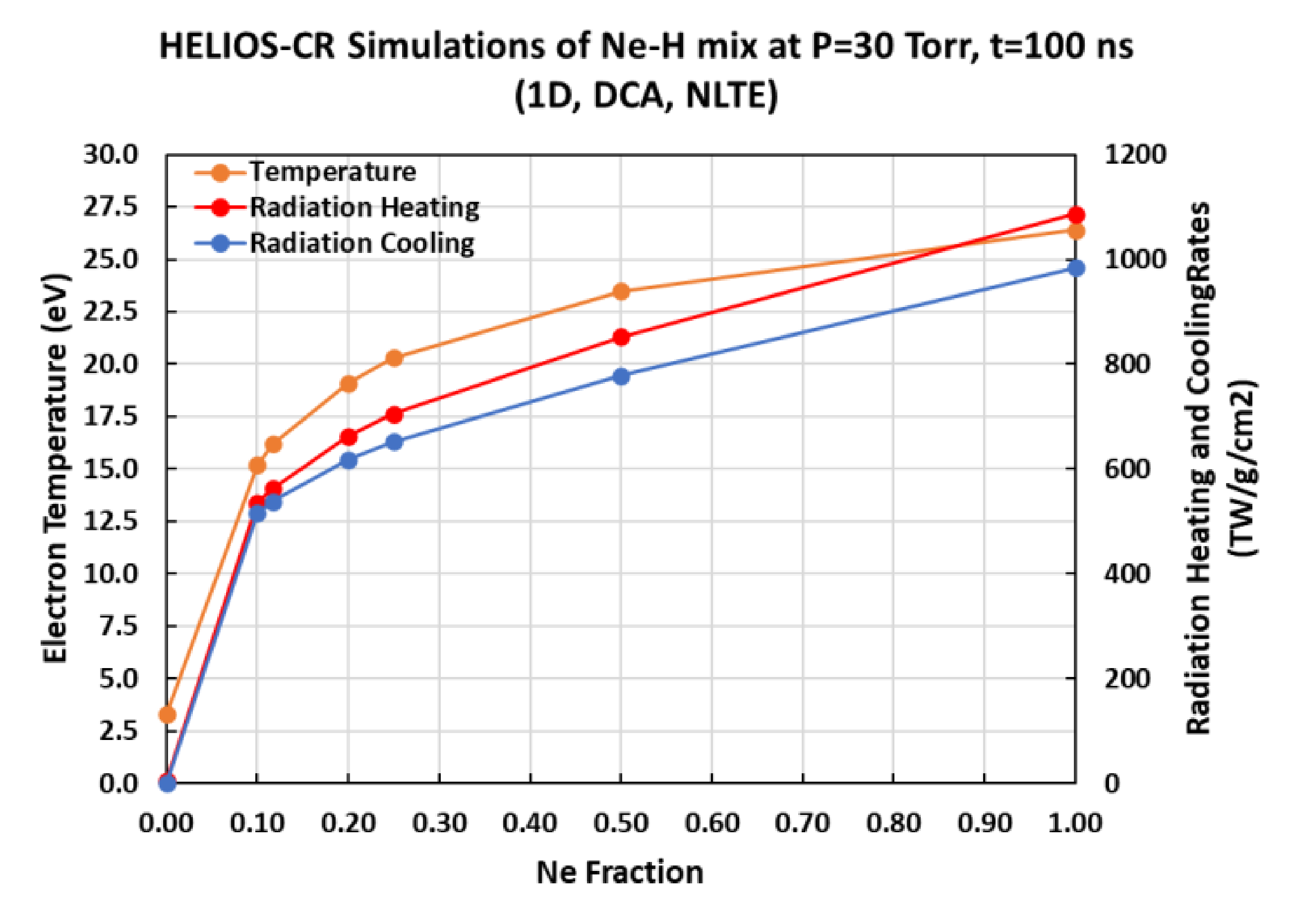


- Experiments conducted at Z Pulsed Power Facility at Sandia National Laboratories
- Z-pinch produces ~ 10^{12} W/cm^2 peak flux at cell
- Gas cell filled with Ne-H gas mixtures
- TREX spectrometer records Ne K-shell spectra

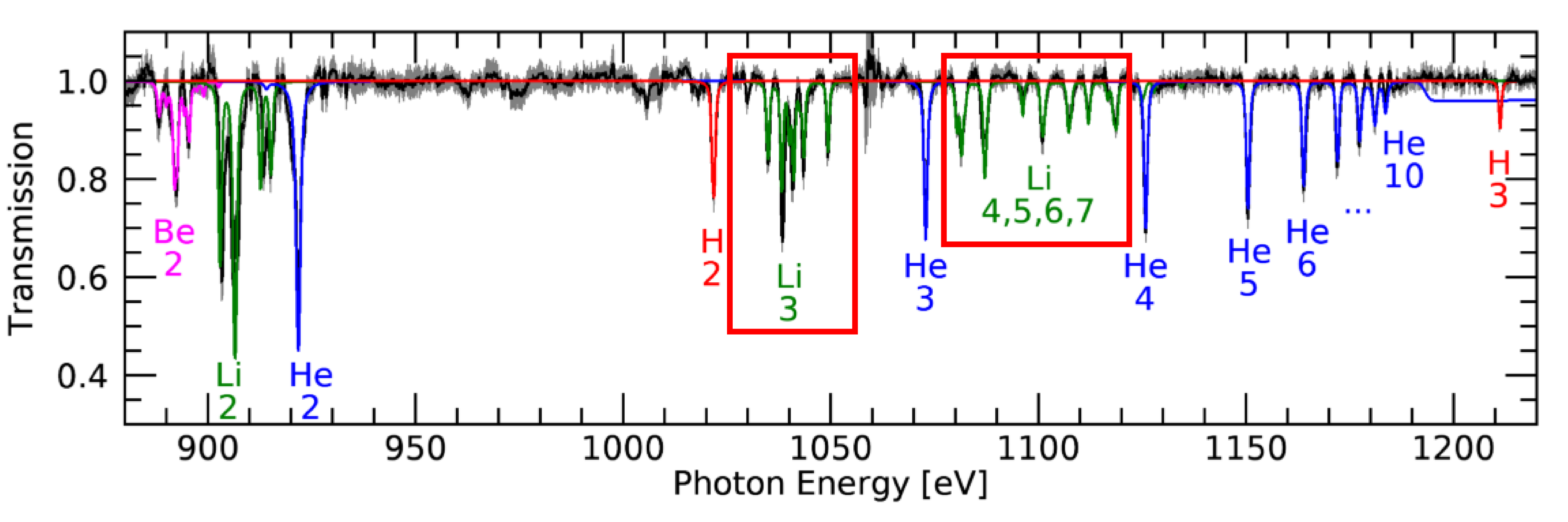


Multi-element laboratory plasmas are needed to better replicate astrophysical plasmas and study effects of trace elements

- Astrophysical plasma compositions are dominated by H and He
- Trace amounts of heavier elements play key roles in dynamics and observations of astrophysical plasmas
- Previous experiments only studied single-element (Ne) plasmas
- Simulations predict dramatic effects of Ne on net x-ray heating as reflected in the temperature of Ne-H mixed plasmas



Transmission spectra are analyzed using a synthetic spectra model fitting procedure



- Spectra are time-integrated
- Individual ion areal densities can be determined from the fitting procedure
- This analysis focused only on fitting Li-like Ne features
- Li-like Ne features come from either $1s^2 2s$ or $1s^2 2p$ initial configurations
- Temperature can be extracted from Li-like Ne features

Electron temperature is extracted from a Li-like Ne population ratio interpreted with a Boltzmann factor

Assumptions

- Population ratio equivalent to ion areal density ratio
- Population ratio < 3
- Relative populations dominated by electron collisions
- Population ratio remains close to the Boltzmann value
- $k_B T_e \sim \Delta E$
- Plasma electrons are in thermal equilibrium
- Overall CSD is NLTE

Li-like Ne configs: $1s^2 2s$, $1s^2 2p$

$$R = \frac{N_p}{N_s} = g e^{-\frac{\Delta E}{k_B T_e}}$$

$$k_B T_e = \frac{\Delta E}{\ln(g/R)}$$

$$\Delta E \approx 16.2\ eV, g = \frac{g_p}{g_s} = \frac{6}{2} = 3$$

$$\delta(T_e)/T_e = [(k_B T_e)/\Delta E]\,[\delta R/R]$$

R.C. Mancini *et al.*, *Phys Rev E*, vol. 101, no. 5, p. 051201 (R), 2020, doi: 10.1103/physreve.101.051201.

Initial temperature measurement results are promising but have some limitations

Shot #	Pressure (Torr)	Ne Fraction	Ne PP (Torr)	H PP (Torr)	Distance (cm)	$T_e\ (eV)$
Z2389	75	20.0%	15	60	4.3	24.7 ± 8.5
Z2410	93	9.7%	9	84	4.3	16.3 ± 3.2
Z2411	46.5	9.7%	4.5	42	4.3	16.6 ± 5.3
Z2412	46.5	9.7%	4.5	42	5.9	19.3 ± 8.5
Z2413	37.5	20.0%	7.5	30	5.9	16.4 ± 3.1

Limitations and Challenges

- Only one shot per set of variables
- Large measurement uncertainty
- Unknown time-integration effects
- Some shots (z2411 and z2412) have low signal to noise and poor distribution statistics

Initial comparison of equivalent Ne-H mix and pure Ne data show similar temperature despite additional H

Equivalent means same amount of Ne (atomic areal density) in each case
Position (x) relates to the strength of the x-ray flux

Ne-H Mix (single-shot averages)

$P\ (Torr)$	$X\ (cm)$	$n_e\ (cm^{-3})$	$T_e\ (eV)$
75 (20% Ne, 15)	4.3	7.85E+18	24.7 ± 8.5
37.5 (20% Ne, 7.5)	5.9	3.93E+18	16.4 ± 5.3

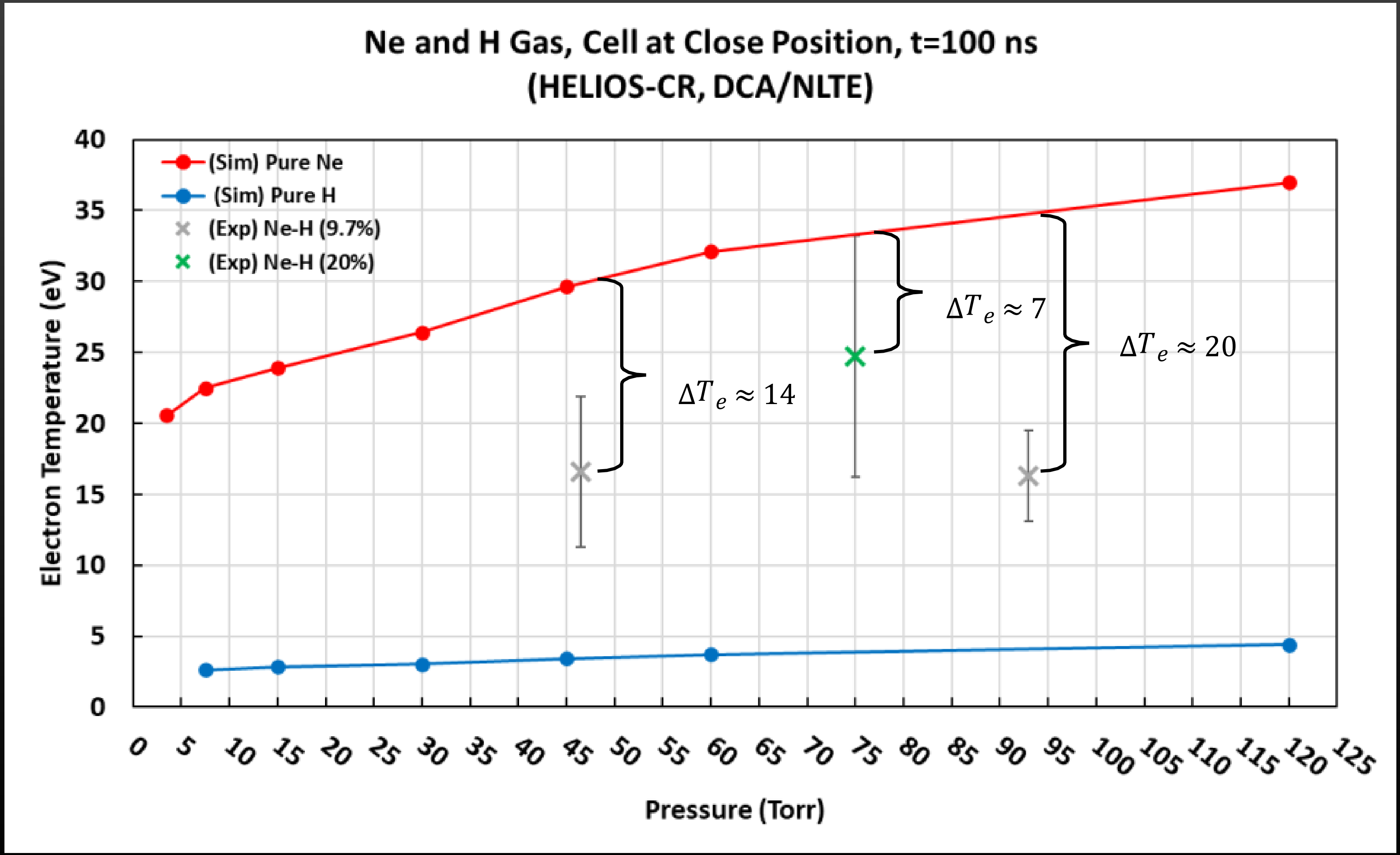
Pure Ne (multi-shot averages)*

$P\ (Torr)$	$X\ (cm)$	$n_e\ (cm^{-3})$	$T_e\ (eV)$
15	4.3	3.93E+18	$26.9^{+7.8}_{-8.0}$
7.5	5.9	1.96E+18	$17.7^{+3.1}_{-3.8}$

Comparison suggests additional electrons and ions from H do not significantly affect the temperature

*From D.C. Mayes, University of Nevada, Reno. ProQuest Dissertations Publishing, 2020. 28262596.

Simulations of pure Ne at same total pressure as Ne-H mix show significantly higher temperature



This is a work in progress report and there is still more to be done

- Further refinement of data processing and analysis
- More simulations (HELIOS, CLOUDY, etc.) to improve understanding of temperature behavior
- Conduct more Ne-H mix experiments to expand data set (March 2022)

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Thank You

Questions?

Data on Ne-H mixed plasmas was collected across multiple parameters

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Z2389	75	20.0%	15	60	4.3
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Z2411	46.5	9.7%	4.5	42	4.3
Z2412	46.5	9.7%	4.5	42	5.9
Z2413	37.5	20.0%	7.5	30	5.9

- 5 shots, 2 Ne fractions, 4 pressures, 2 positions
- All shots used Gen2 style cells with 5x5 mm Si_3N_4 windows

Calculations done *a priori* show mixed Ne-H plasmas have more electrons than pure Ne plasmas for the same amount of Ne

Pure Ne Total Densities

Pressure (Torr)	Atom Number Density (cm^{-3})	Electron Number Density (cm^{-3})*
4.5	1.47E+17	1.18E+18
7.5	2.45E+17	1.96E+18

Ne-H Mix Total Densities

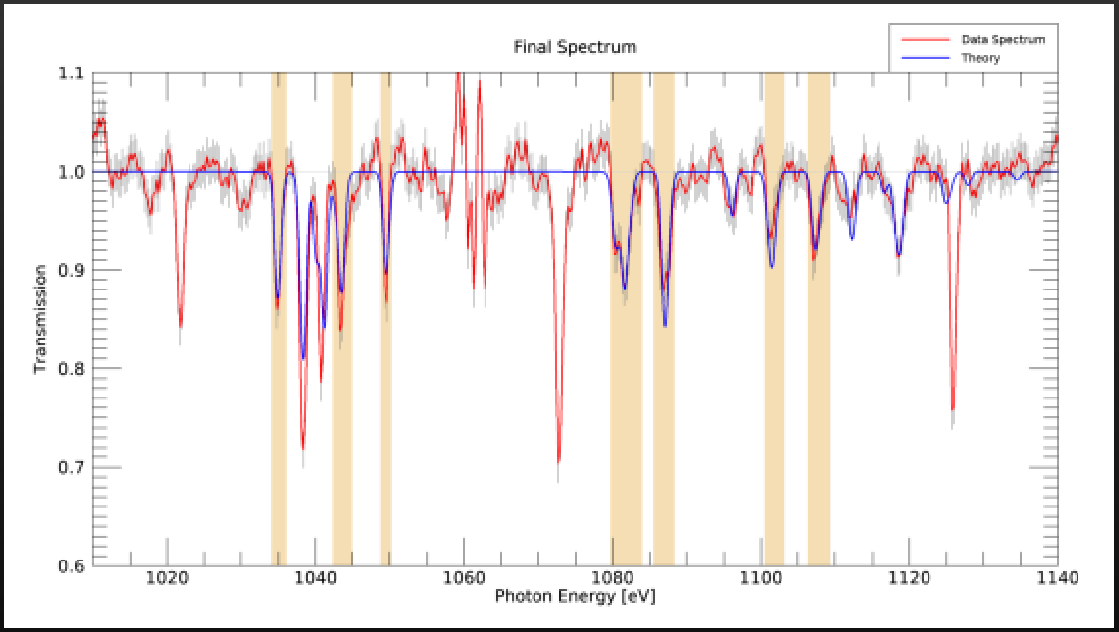
Pressure (Torr)	Atom Number Density (cm^{-3})	Electron Number Density (cm^{-3}) *
46.5 (9.7% Ne, 4.5)	2.90E+18	3.93E+18
37.5 (20% Ne, 7.5)	2.21E+18	3.93E+18

- Ne-H Mix @ 20% Ne has **x9 atom #** and **x2 electron #** vs equivalent Pure Ne
- Ne-H Mix @ 9.7% Ne has **x19.67 atom #** and **x3.33 electron #** vs equivalent Pure Ne

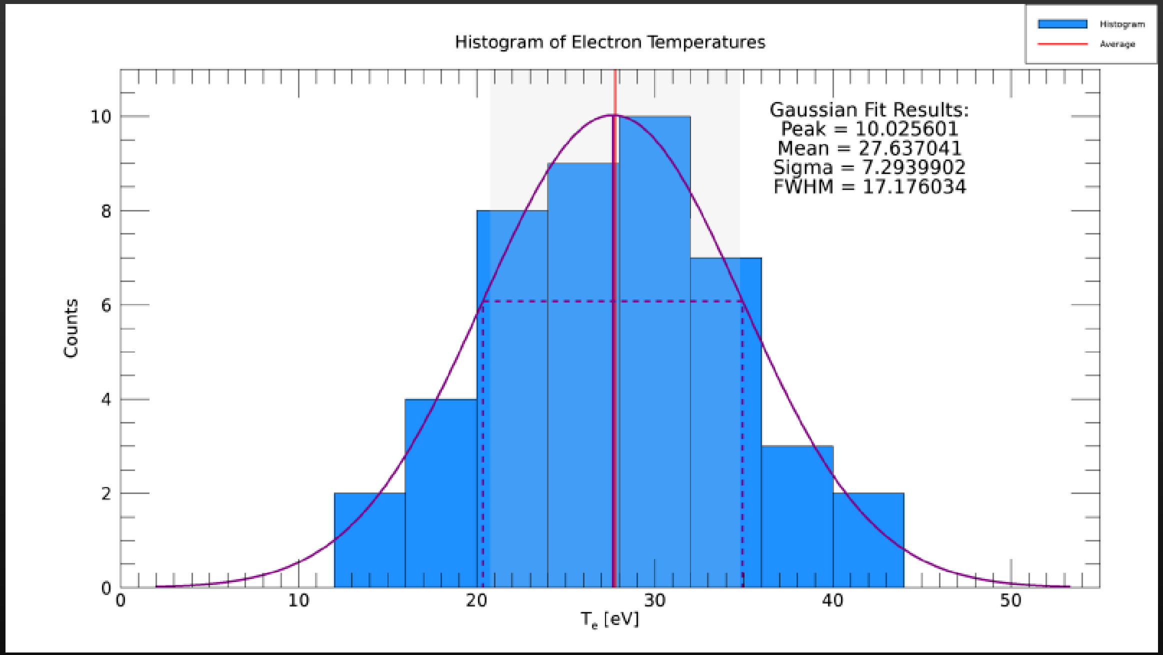
*Assuming $\bar{Z}_{Ne} = 8, \bar{Z}_H = 1$

Multiple combinations of Li-like Ne features are used to create a distribution of temperatures

Example: Data + Model Spectra & Line Combinations (z2389b)



Example: Histogram of Temperatures (z2389b)



- Combination of lines included in fit impact extracted temperature
- Some combinations are excluded due to high uncertainties in the measurement
- Final measurement of temperature taken as average of distribution