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Sandia National Laboratories

Re-analysis of plasma temperature and density for stellar iron opacity experiments

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U.S. DEPARTMENT OF ENERGY NNSA

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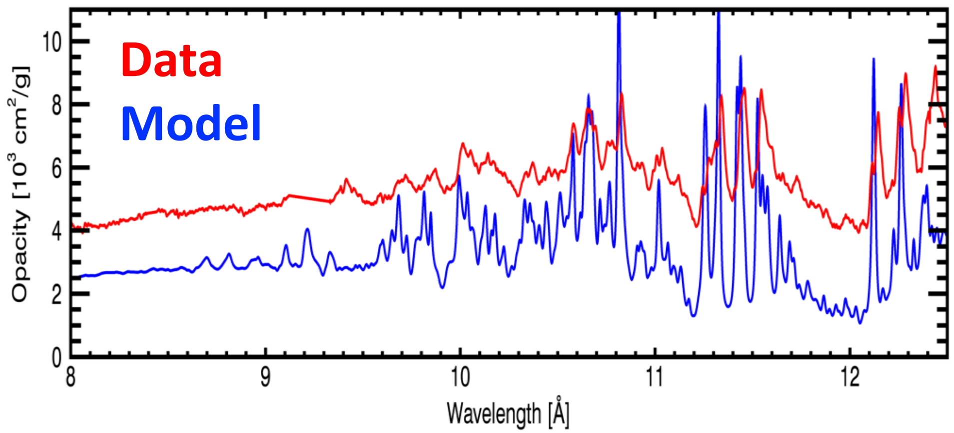
Summary: Plasma temperature and density analysis are refined for Sandia iron opacity experiments



Motivation: Fe opacity measured at solar interior temperature disagree with calculated opacity
→ Are temperature (T_e) and density (n_e) accurate?

What we did: Refined temperature and density analysis

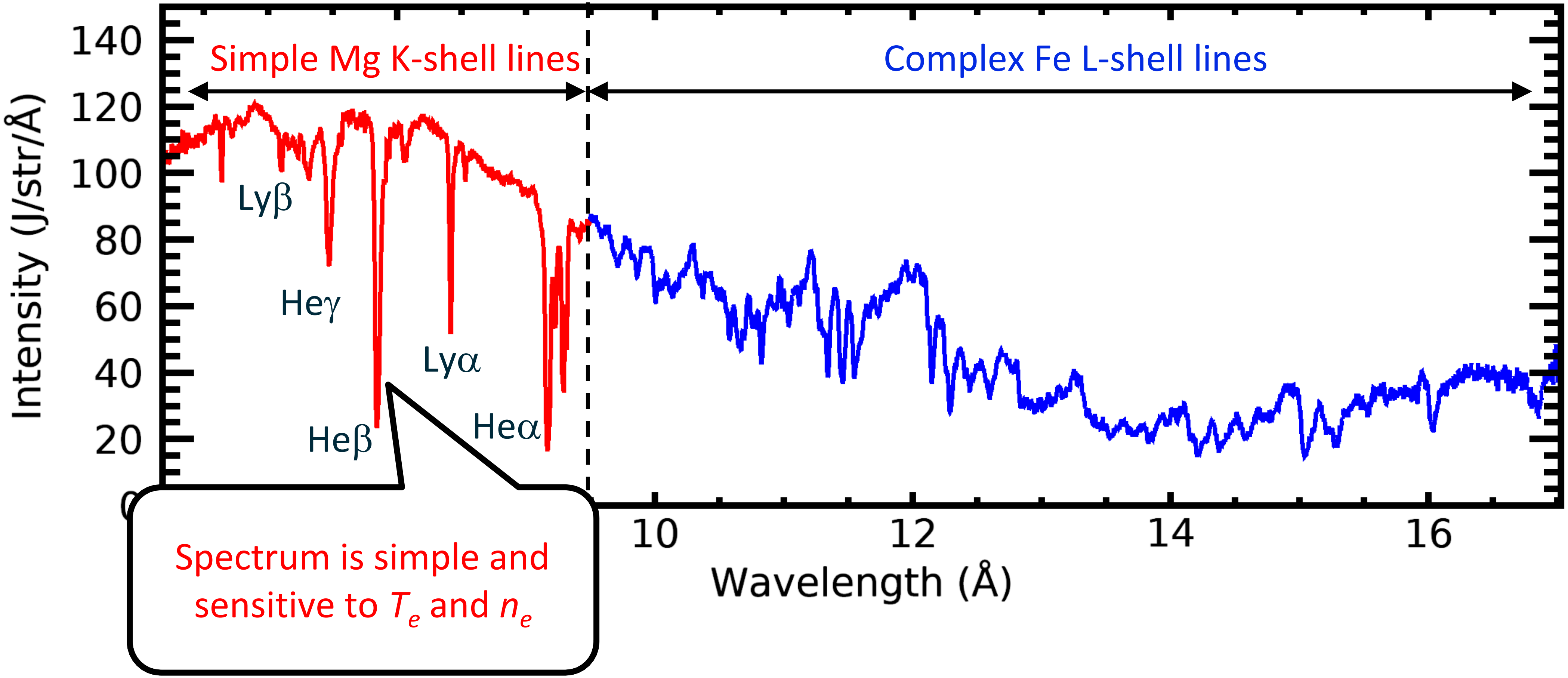
1. Line-shape calculations
2. Background determination
3. T_e, n_e analysis method

Result:

- **New line shape increases Te and ne by 2% and 20%**
- **New analysis incorporates inconsistencies into uncertainties**

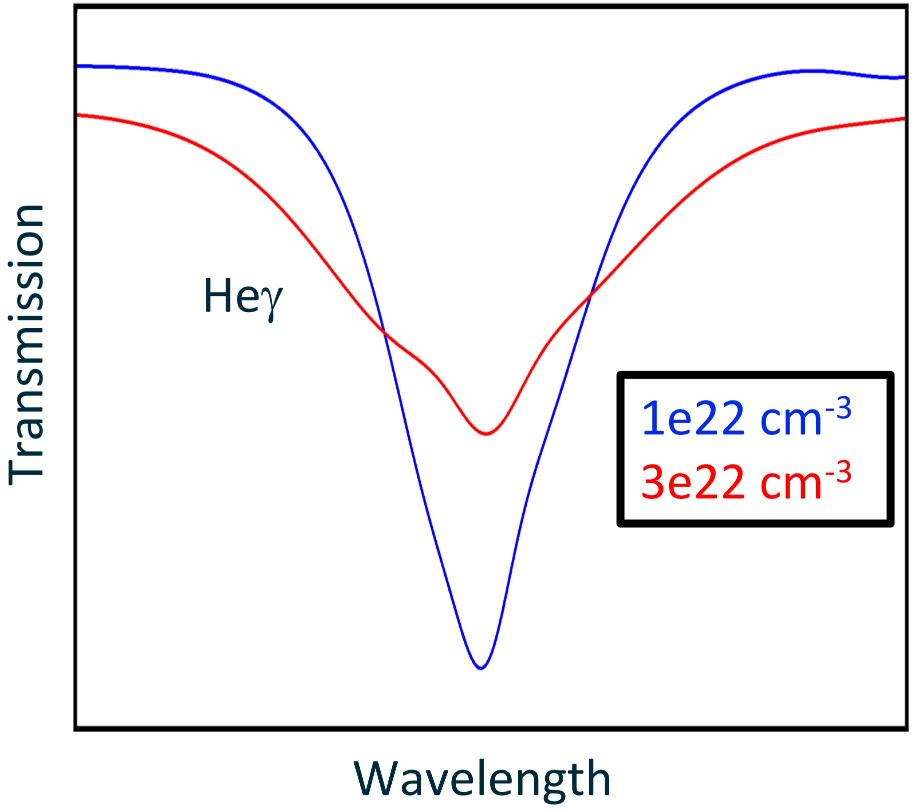
Change in temperature and density is +1% and +26%, respectively, which are small to explain the previously reported Fe model-data discrepancy

Temperature and density is analyzed by mixing Mg into the Fe opacity sample and analyzing its simple spectra

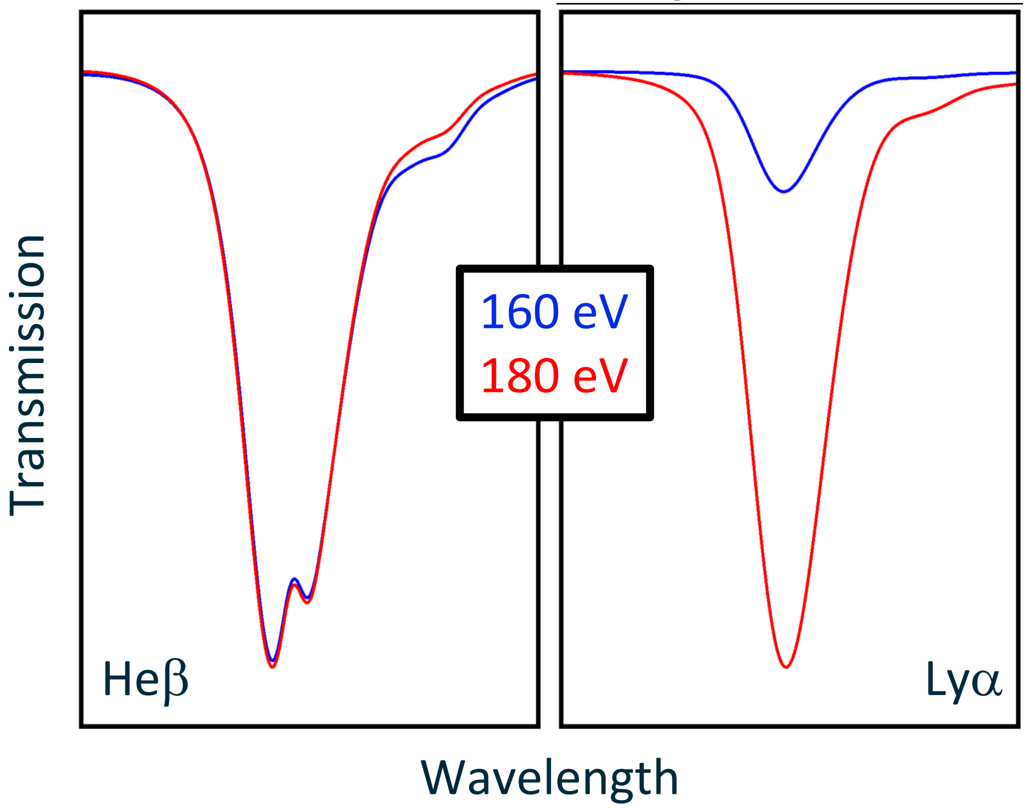


Electron density (n_e) and temperature (T_e) are inferred from Mg line broadenings and line ratios

Electron density (n_e) by line widths

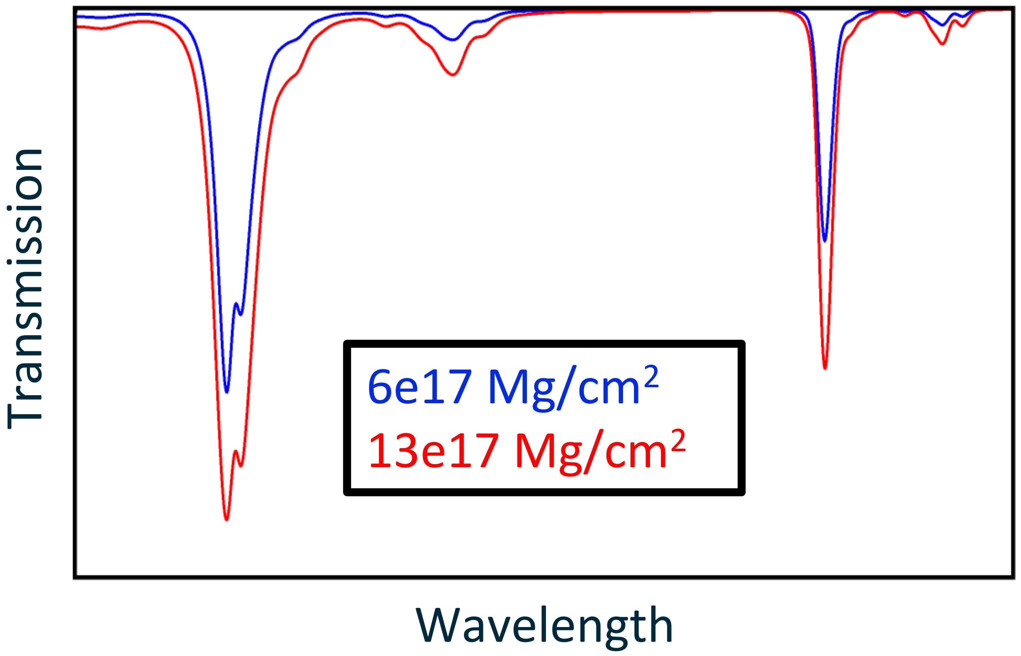


Electron temperature (T_e) by line ratios

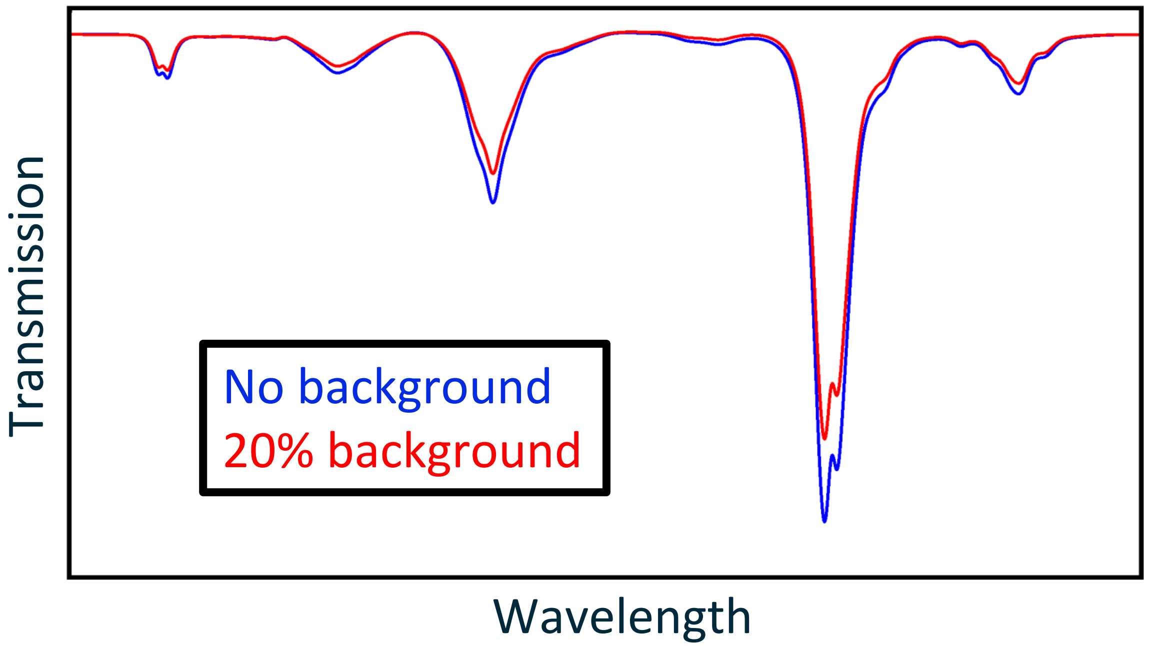


Mg areal density and residual background can be inferred from line depths and saturation on the strong lines

Mg areal density (ρL) by line depths



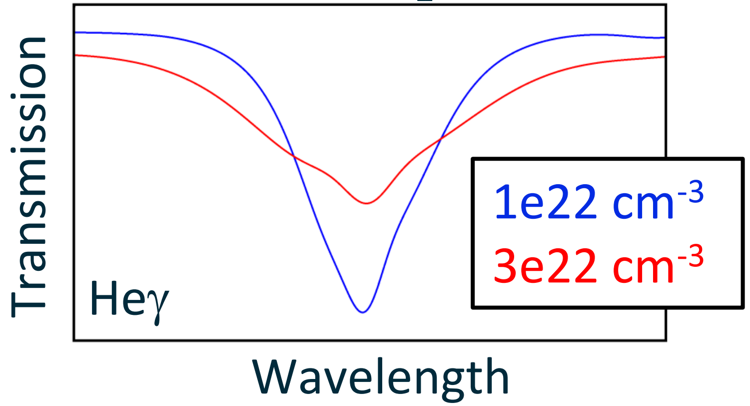
Background (*b*) by line saturation



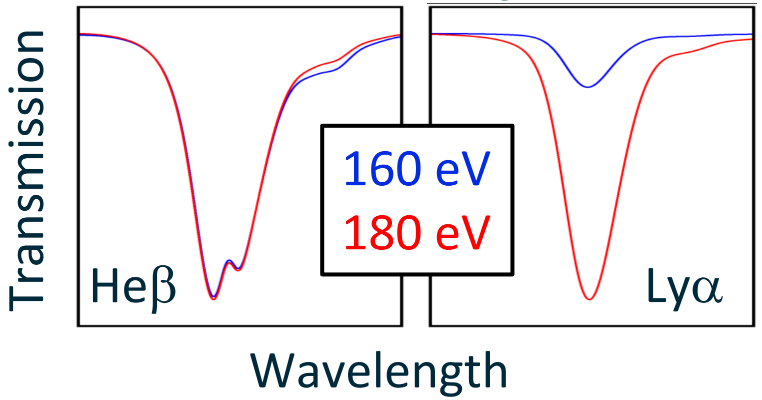
Tracer Mg spectroscopy can constrain n_e, T_e, ρL, and *background* simultaneously

Mg is mixed into Fe opacity sample for plasma-diagnostic purposes

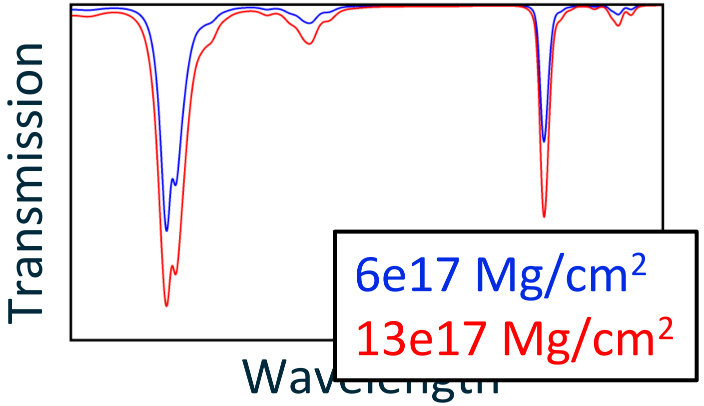
Electron density (n_e) by line widths



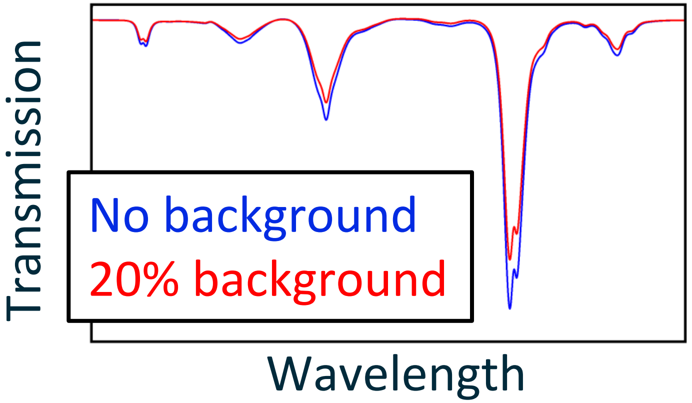
Electron temperature (T_e) by line ratios



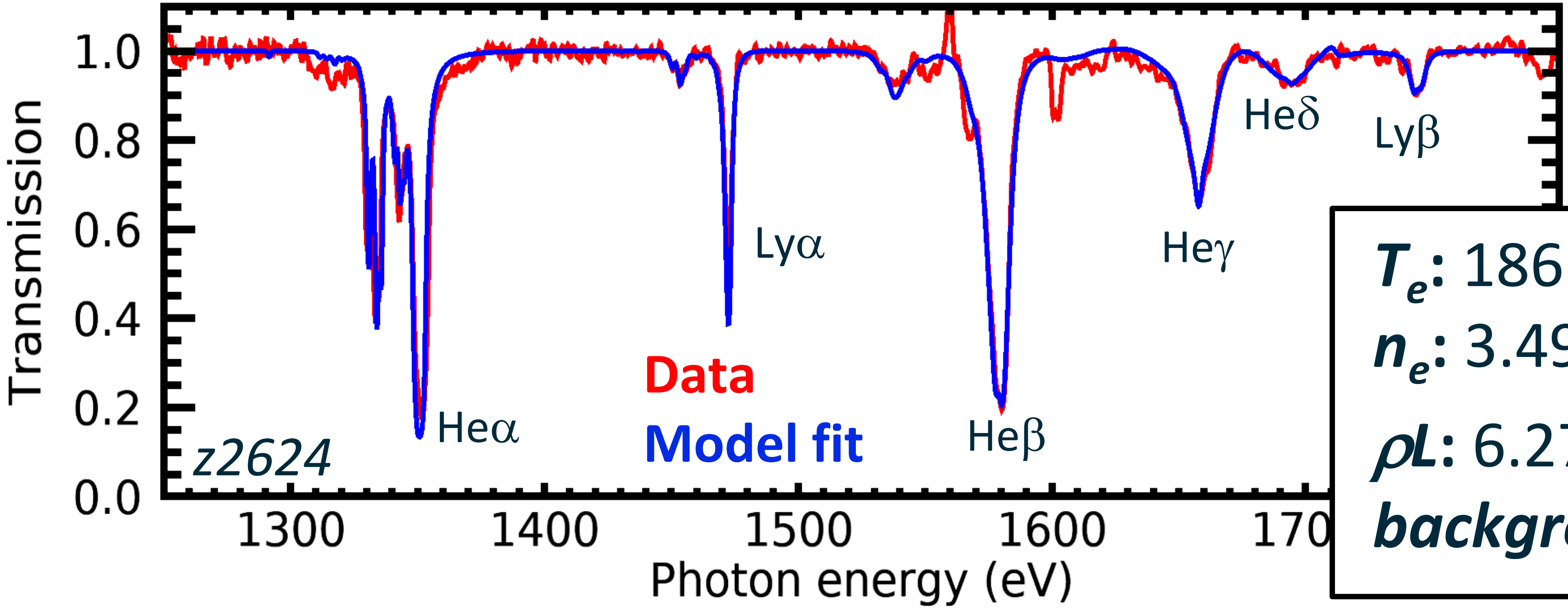
Mg areal density (ρL) by line depths



Background (b) by line saturation



n_e, T_e, ρL, and *background* are precisely determined by simultaneous fit to all the Mg lines



T_e: 186.07 eV (±0.4%)
n_e: 3.49x10^{22} cm^{-3} (±1.7%)
ρL: 6.27x10^{-5} g/cm^2 (±2%)
background: 7.4 J/sr/Å (±12%)

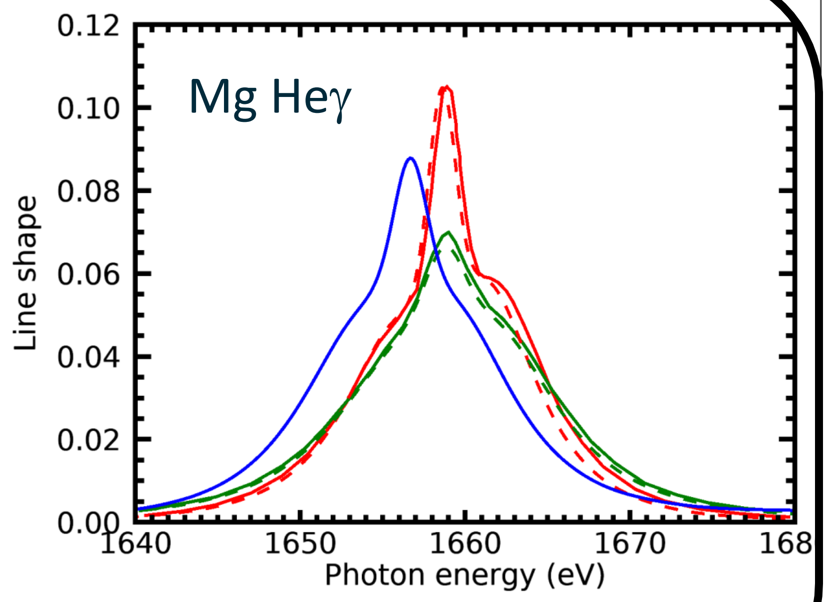
3 concerns:

1. **Is line-shape calculation accurate? [1, 2]**
2. **Is background determination accurate?**
3. **Does the analysis capture realistic uncertainties?**

[1] Nagayama *et al* HEDP (2016) [2] Iglesias *et al* HEDP (2016)

T_e and n_e diagnostics are improved by refining (i) line-shape theory, (ii) background determination, and (iii) analysis method

Line-shape theory:
- Add missing physics called electron capture [1]
- Remove 3 common approximations [2]

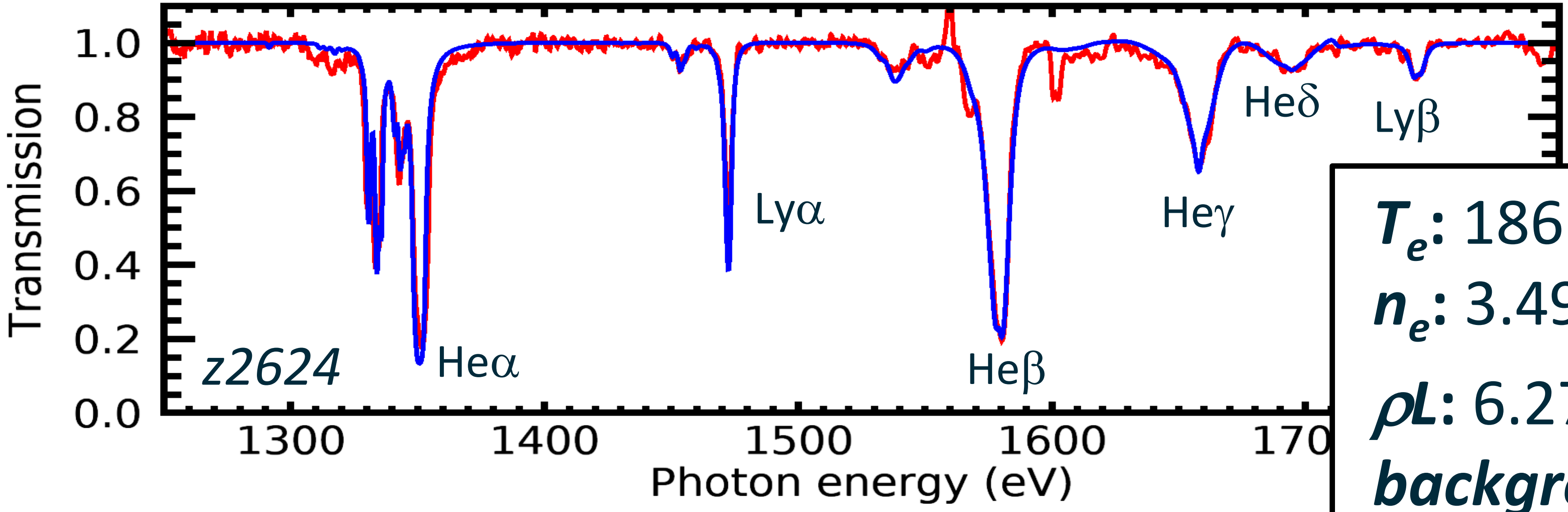


Background determination [3]:
- Model-data-comparison method
- Dual-backlight-intensity method

T_e and n_e analysis method:
- Breakdown analysis

[1] T. Gomez et al PRL (2020) [2] T. Gomez et al submitted to PRL (2021) [3] G. Dunham et al RSI (2021)

Simultaneous fits to all Mg lines produces too small uncertainties in T_e and n_e due to unrealistic assumptions



***T_e*: 186.07 eV (±0.4%)**
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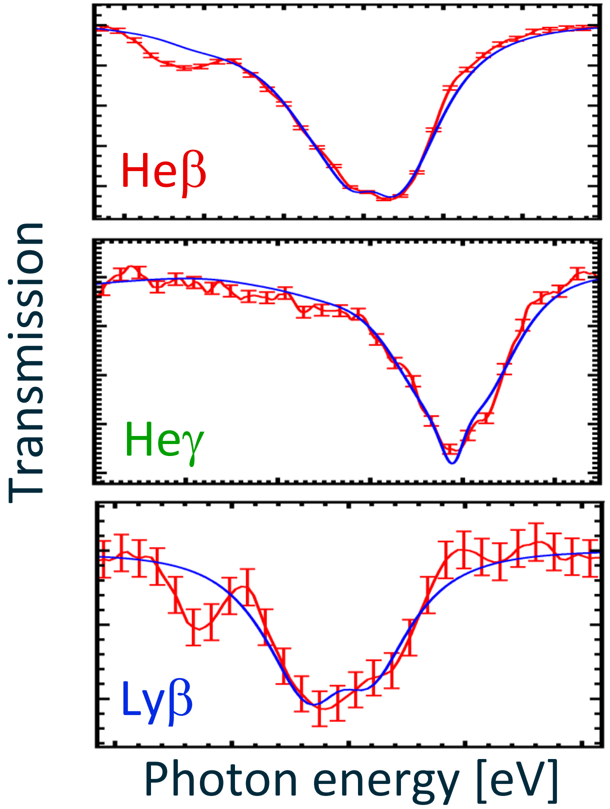
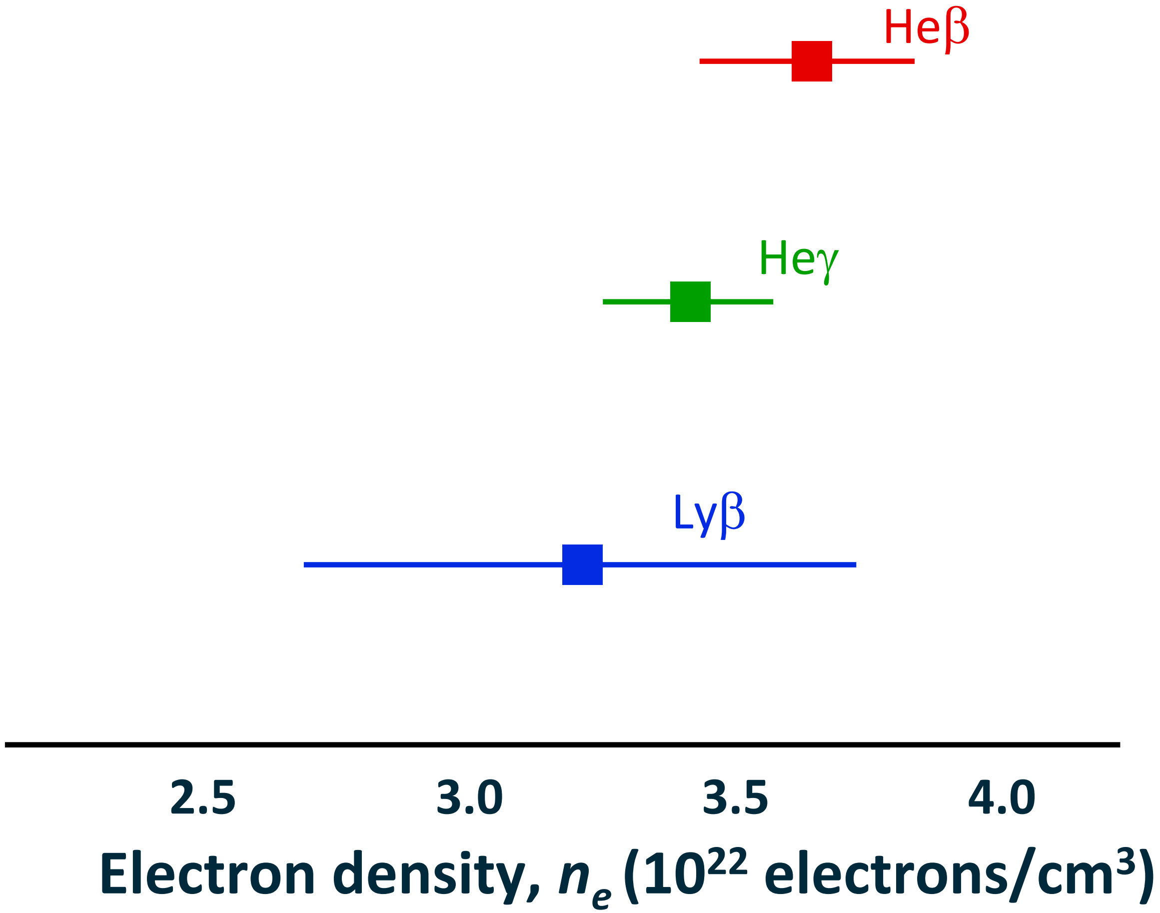
Analysis assumptions:

- **Spectral model** is perfect (atomic data, density effects, line shapes, etc)
- **Experimental** plasma is spatially/temporally uniform and LTE
- **Data processing is perfect**, and uncertainty on the data is independent and random

The analysis returns unrealistically small T_e and n_e uncertainties even if these assumptions fail and different lines suggest inconsistent values

When we have multiple constraints on n_e, we can precisely determine n_e





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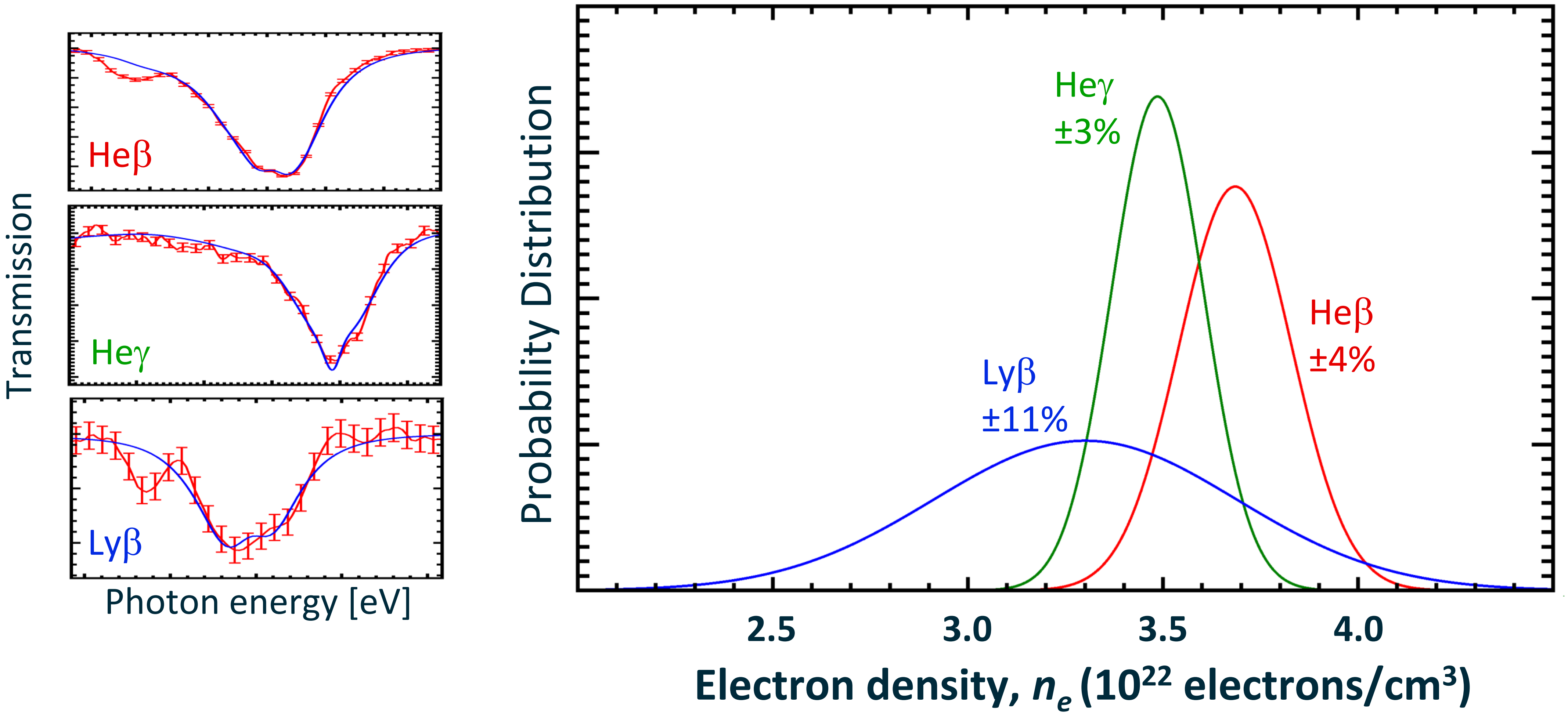

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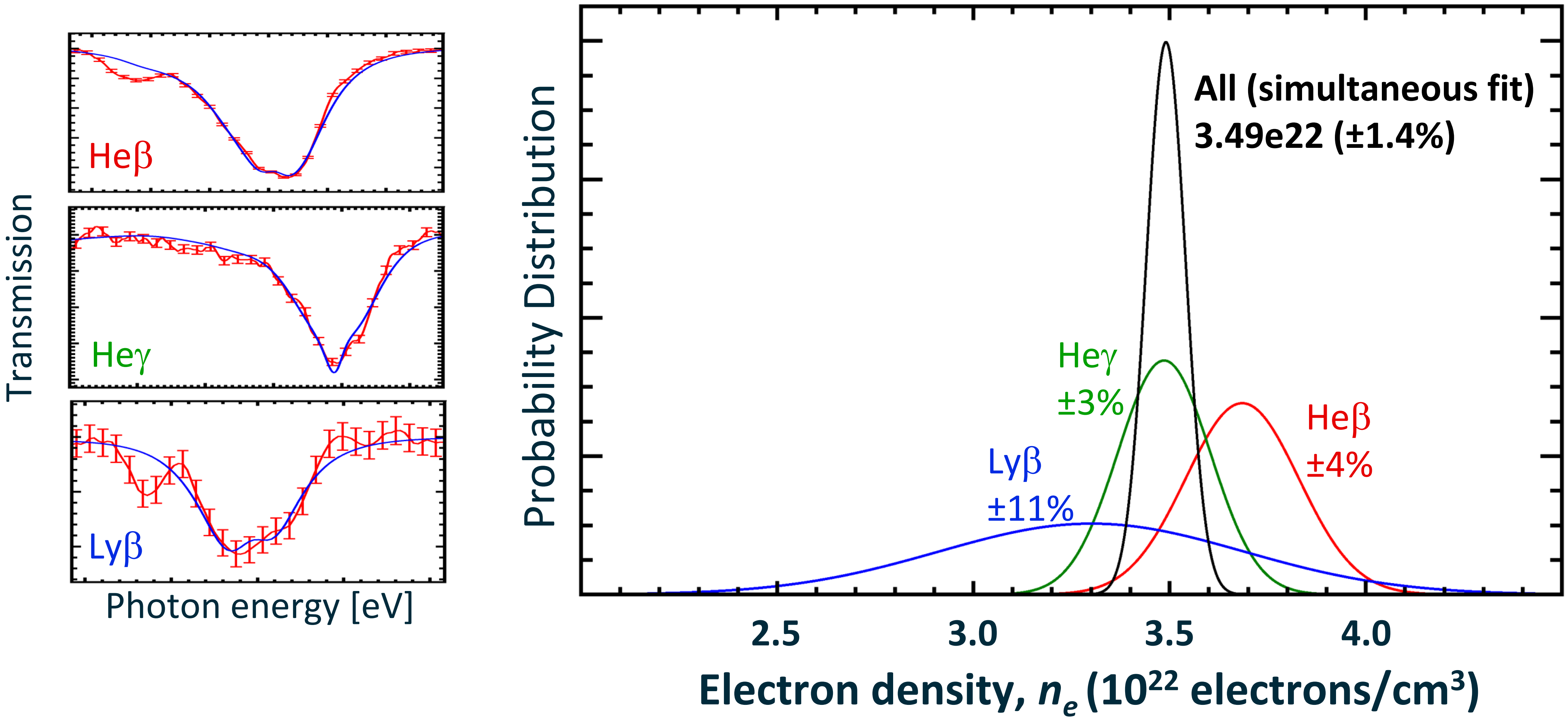
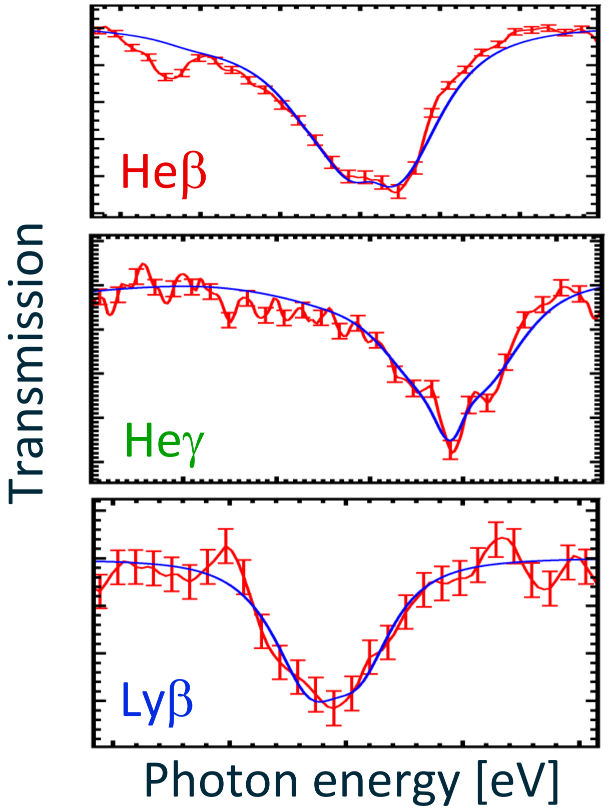
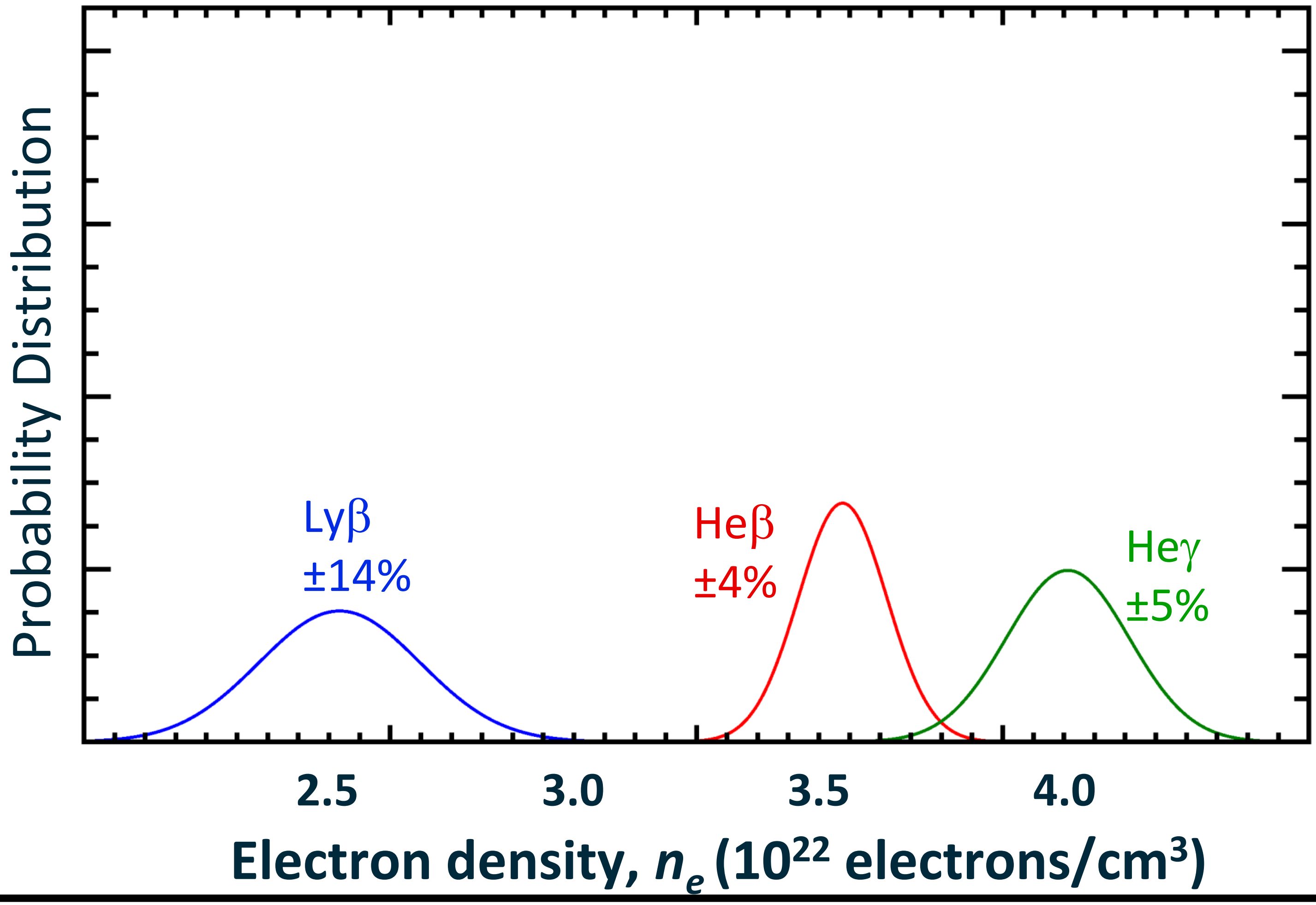


We can determine n_e very precisely by analyzing all ne sensitive lines simultaneously

Fits to the whole spectrum give equally precise results even when different lines disagree with each other





- **Inconsistencies are most likely caused by failure of the analysis assumptions**
- **We want to incorporate the inconsistencies into uncertainty instead of giving precise**

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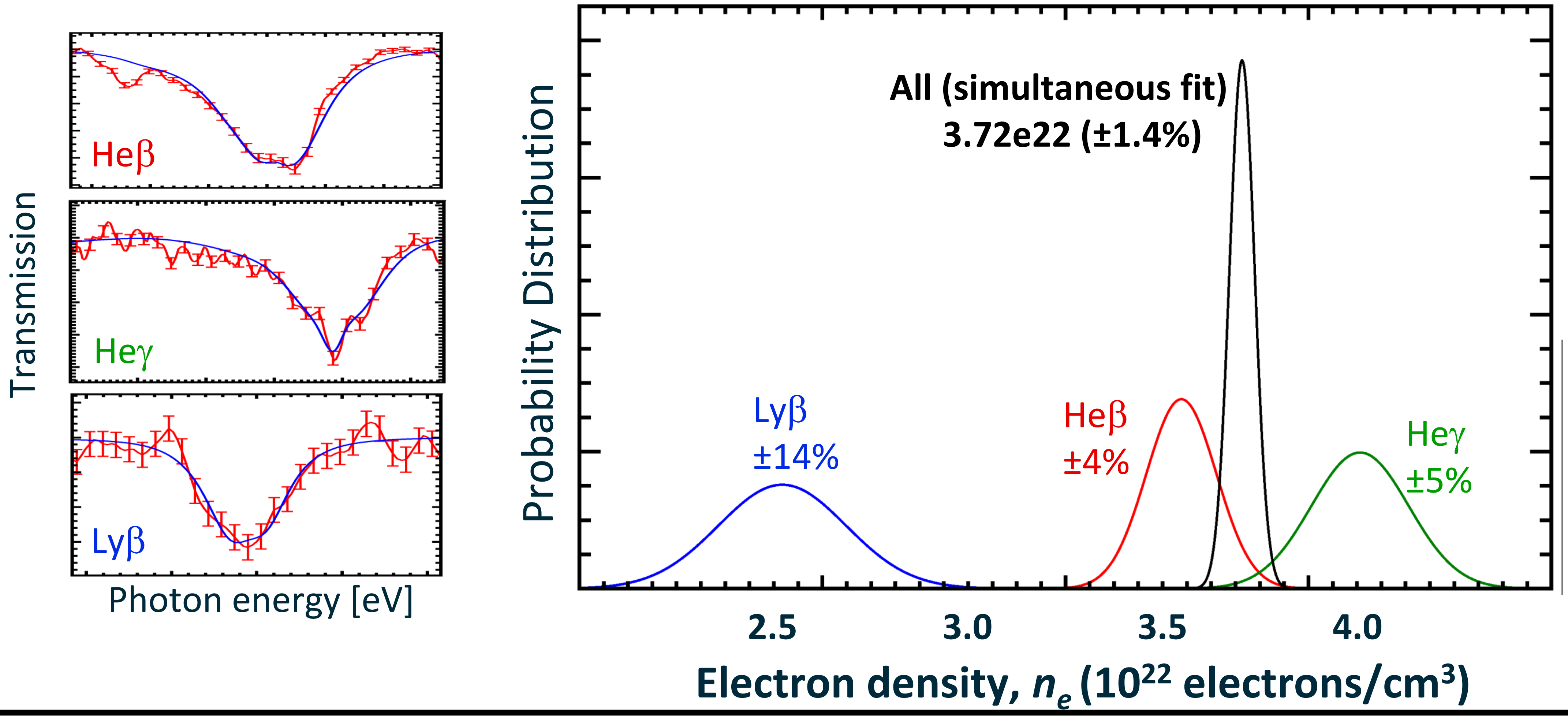

- **Inconsistencies are most likely caused by failure of the analysis assumptions**
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New

Focus on one parameter at a time and take the average and standard deviation from all line-ratios, -broadening, and depths analyses

Step1: Preliminary: Simultaneous fit to all lines

Step2: Background: Determine and subtract background from the data [1]

Step3: $\boldsymbol{n_e}$**:** Analyze Mg Heβ, Heγ, Lyβ line shapes [2,3]

Step4: ρL: Analyze Mg Heβ and Heγ line depths

Step5: $\boldsymbol{T_e}$**:** Analyze 11 temperature sensitive line ratios

Less Correlation More

*** Errors due to preceding steps are propagated to the first order**

[1] G. Dunham HEDP (2021) [2] T. Gomez PRL (2020) [3] T. Gomez submitted to PRL (2021)

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Step1: Preliminary: Simultaneous fit to all lines

Step2: Bac ... ata [1]

Step3: n_e: ...

Step4: ρL: ...

Step5: T_e: ...

Pros:

- **More realistic uncertainties**
- **Be aware of inconsistencies**
  → Clues for problems
- **Clear on what physics we rely on for each parameter**

Cons:

- **Tedious**
- **Parameter correlation is approximated to the 1st order**

Less Correlation More ↓

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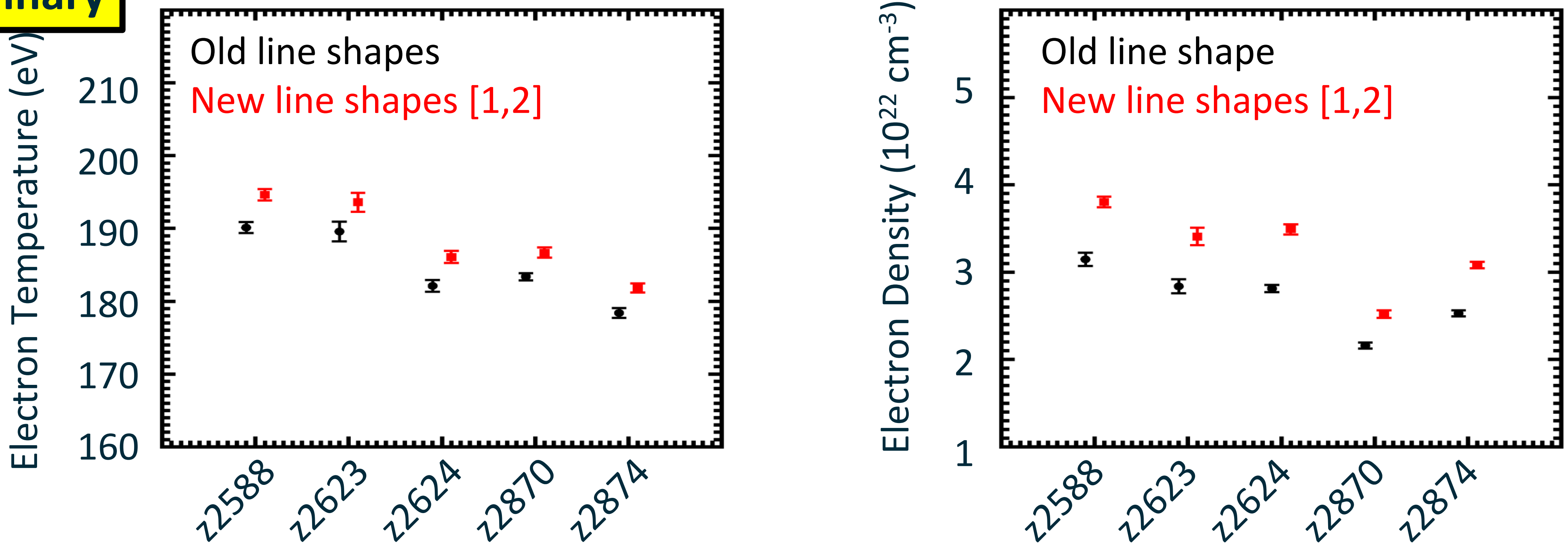
New line-shapes increased inferred T_e and n_e by 2% and 20%, respectively

Preliminary



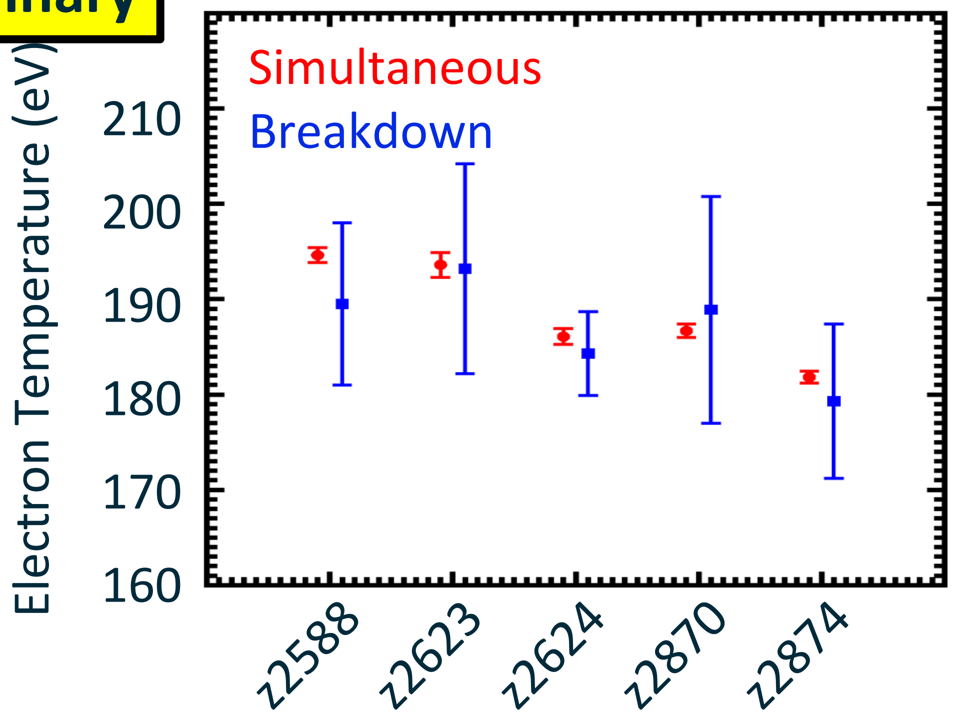
185±5 eV (±3%) → 189±5 eV (±3%)

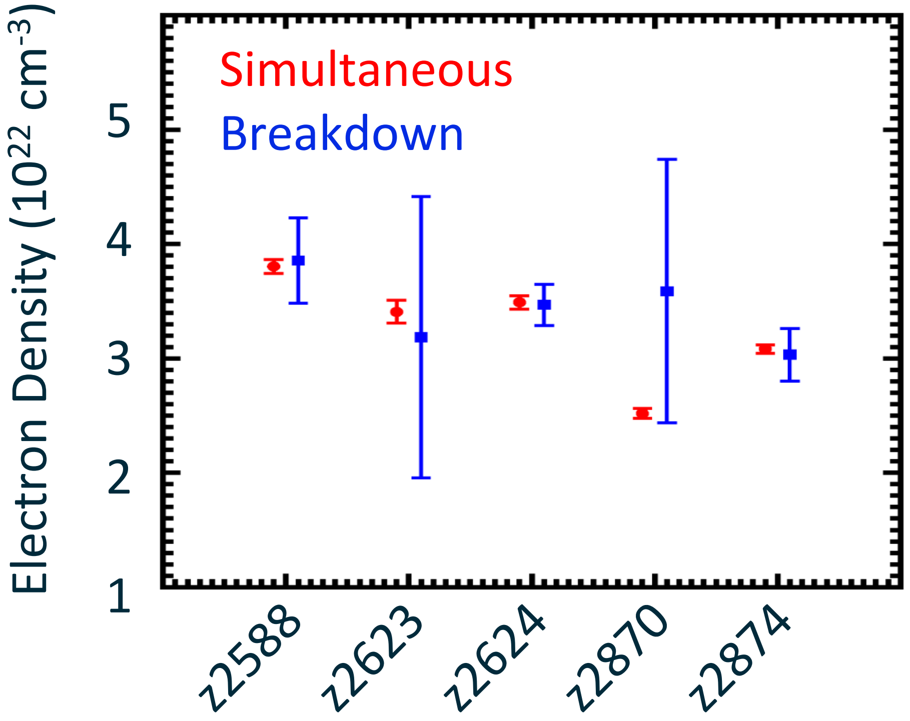
$(2.7\pm0.4)\times10^{22}$ cm^{-3} (±14%) → $(3.3\pm0.5)\times10^{22}$ cm^{-3} (±15%)

[1] T. Gomez et al PRL (2020) [2] T. Gomez et al, submitted to PRL (2021)

Breakdown analysis produced more realistic individual uncertainties with little impact on the average values

Preliminary





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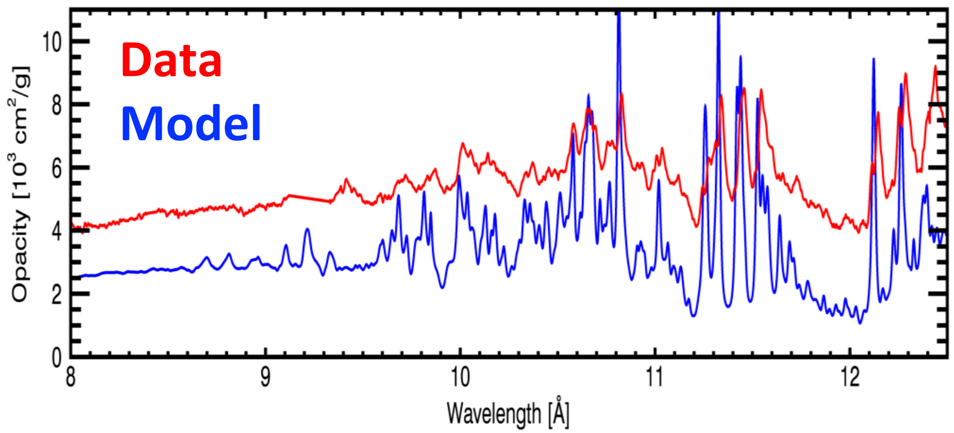
$(3.3\pm0.5)\times10^{22}$ cm^{-3} (±15%)

$(3.4\pm0.3)\times10^{22}$ cm^{-3} (±10%)

Summary: Plasma temperature and density analysis are refined for Sandia iron opacity experiments



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Change in temperature and density is +1% and +26%, respectively, which are small to explain the previously reported Fe model-data discrepancy

- Clarify the final number is standard deviation
- Make the summary shorter
- Show the latest comparison
- Raise WD as another application