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Temperature and density measurements from stellar interior oxygen opacity experiments using K-shell spectroscopy

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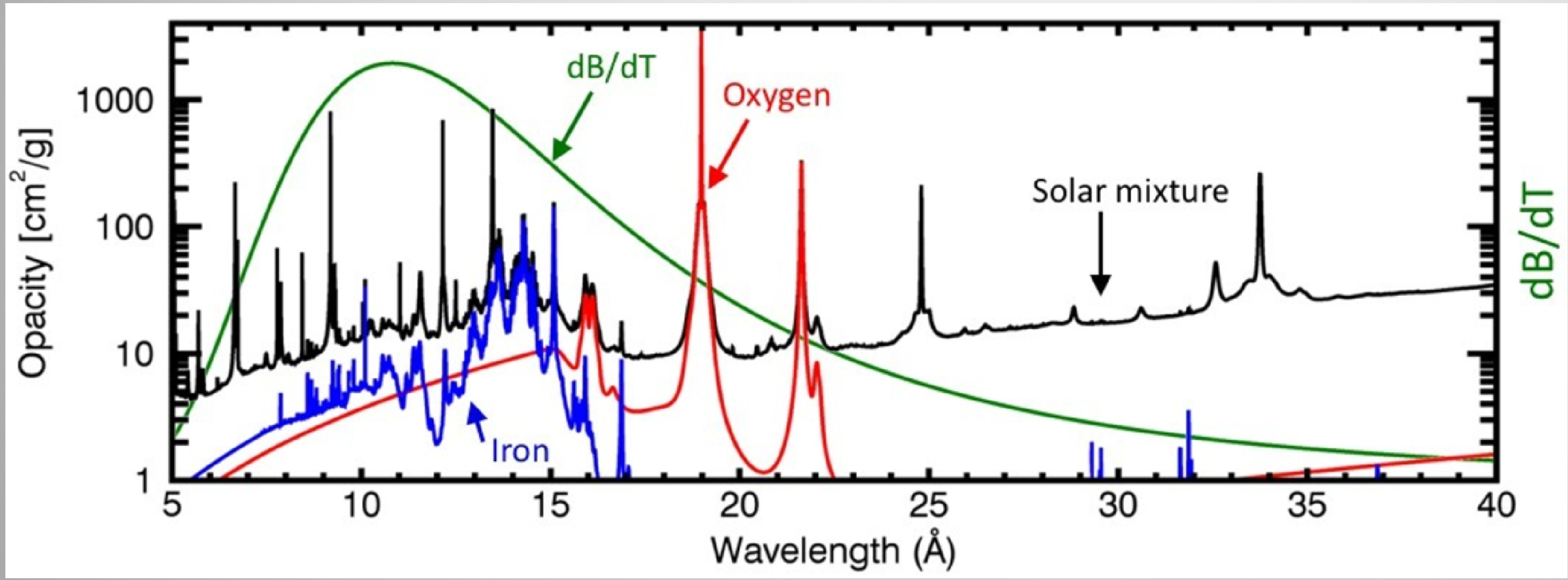
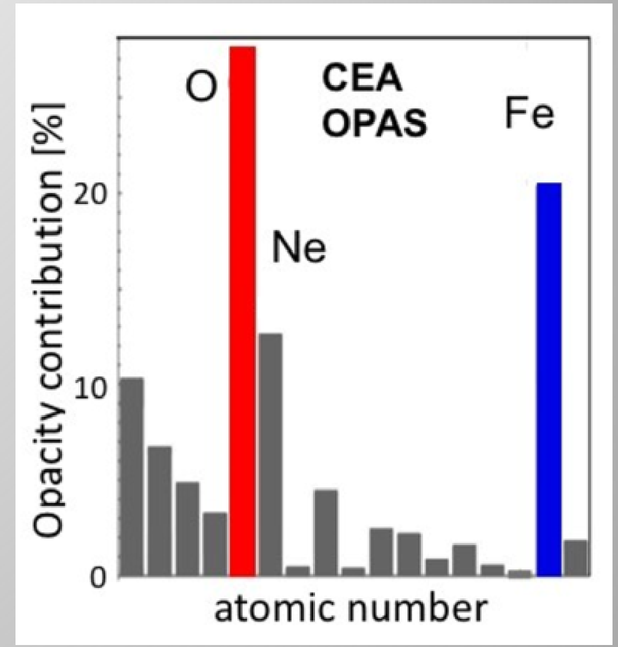
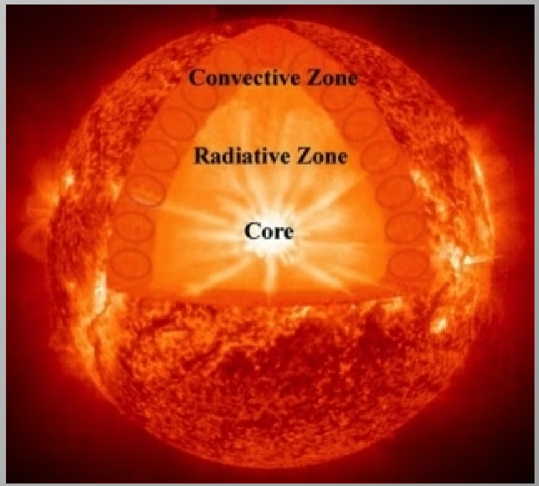
Oxygen opacity measurements are essential to resolve the solar problem





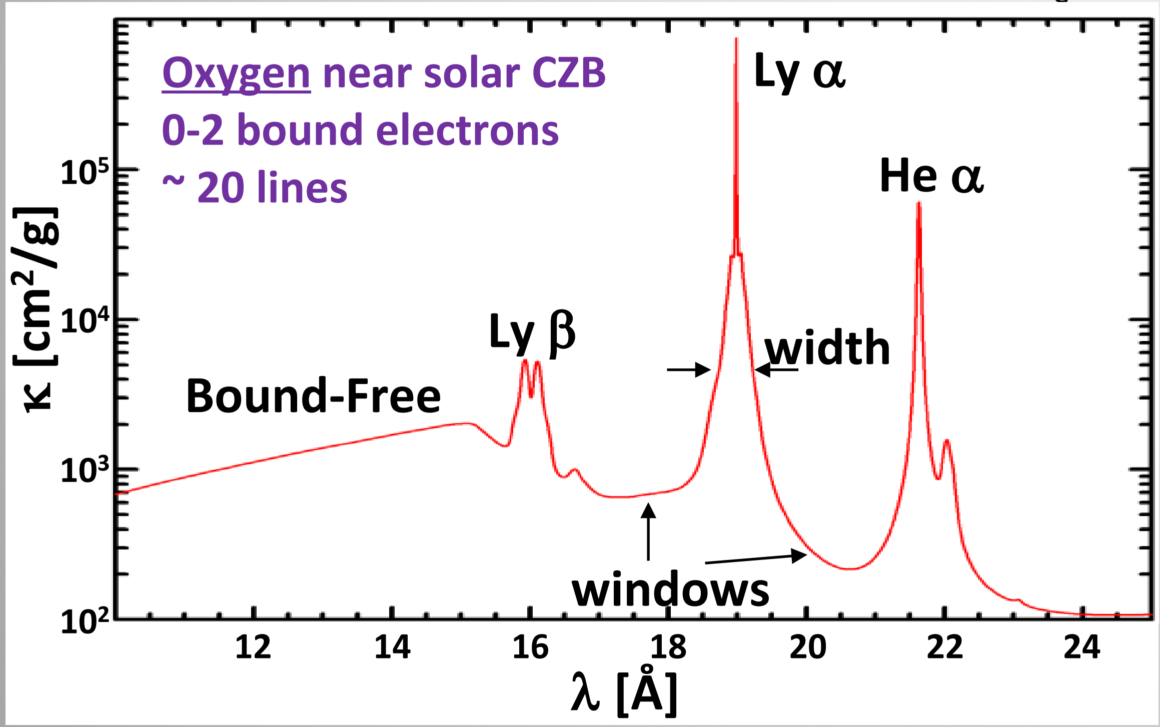
- Oxygen is a dominant source of opacity near the convection zone base (CZB).
- If oxygen measurements are:
  - lower than models predict, it could partially cancel the improved agreement between solar models and helioseismology resulting from past Z iron opacity experiments [Bailey et al., Nature 2015].
  - higher than predicted, it will further help to resolve the solar problem.

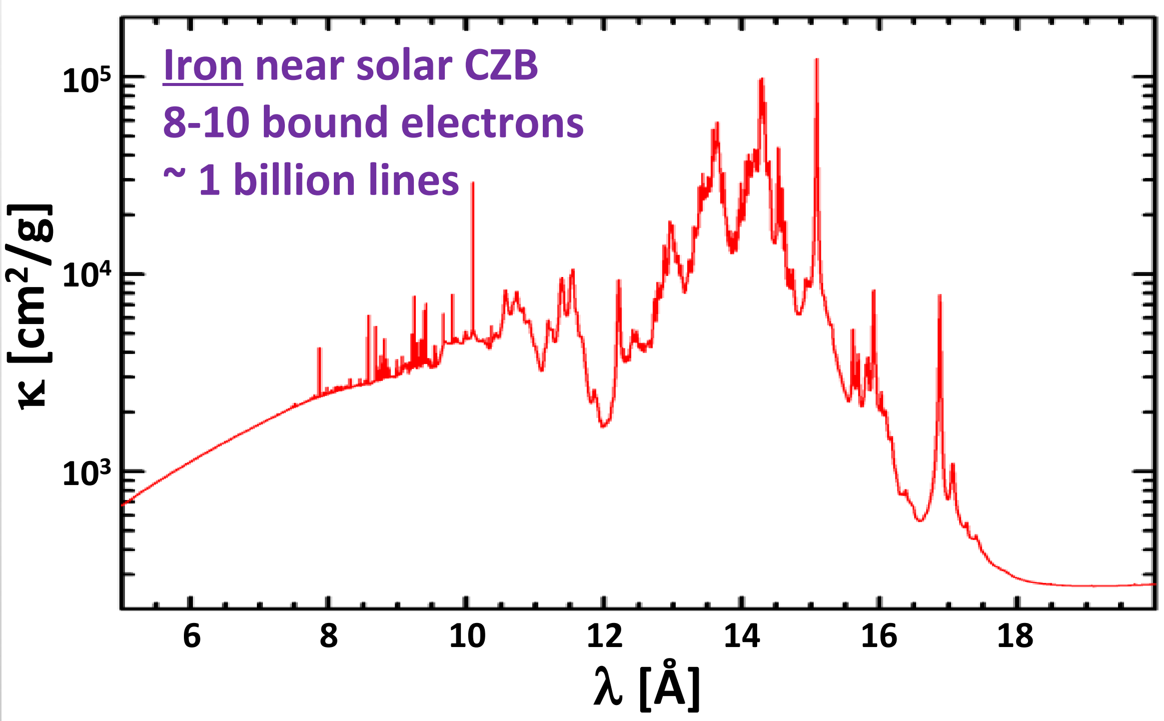


Basu and Antia, *Phys Reports* (2008); Serenelli, *ApJ* (2009); Blancard, *ApJ* (2012); Seaton, *MNRAS* (1994)

Oxygen opacity spectra are challenging because they are strongly affected by approximations for plasma density effects

OP model; T_e = 192 eV; n_e = 1e23 e/cc



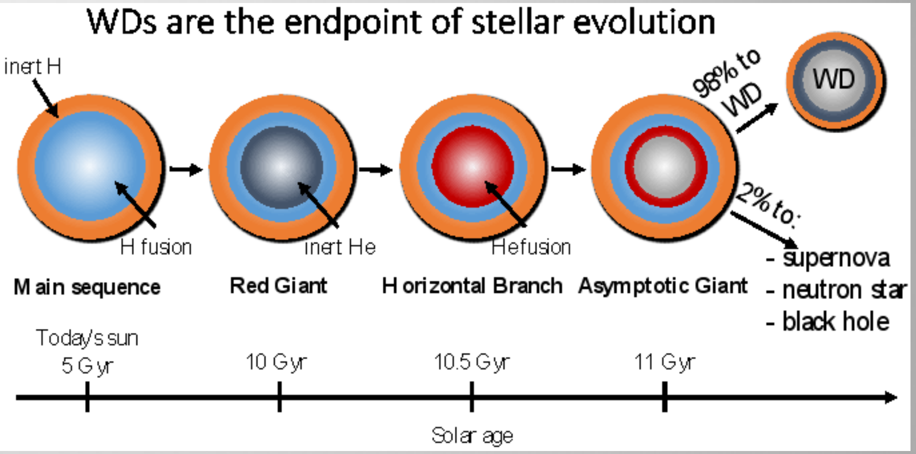


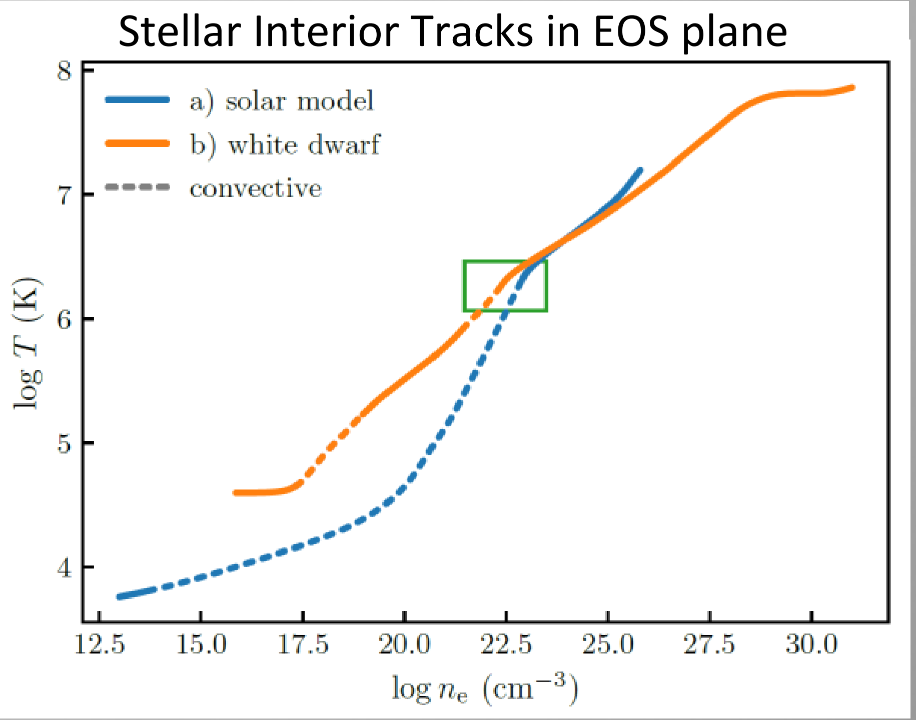
- Bare atoms have bound-bound or bound-free absorption.
  - ***Oxygen opacity is highly dependent on level of ionization.*** Iron is less affected by small ionization changes.
- Density effects:
  - Line broadening
  - Ionization potential depression
  - Occupation probability

Affected features:
- Opacity windows
- Bound-free absorption
- Ionization balance

Stellar evolution and the age of the universe can be constrained using WD stars; Accurate oxygen opacity is important for WD cooling models

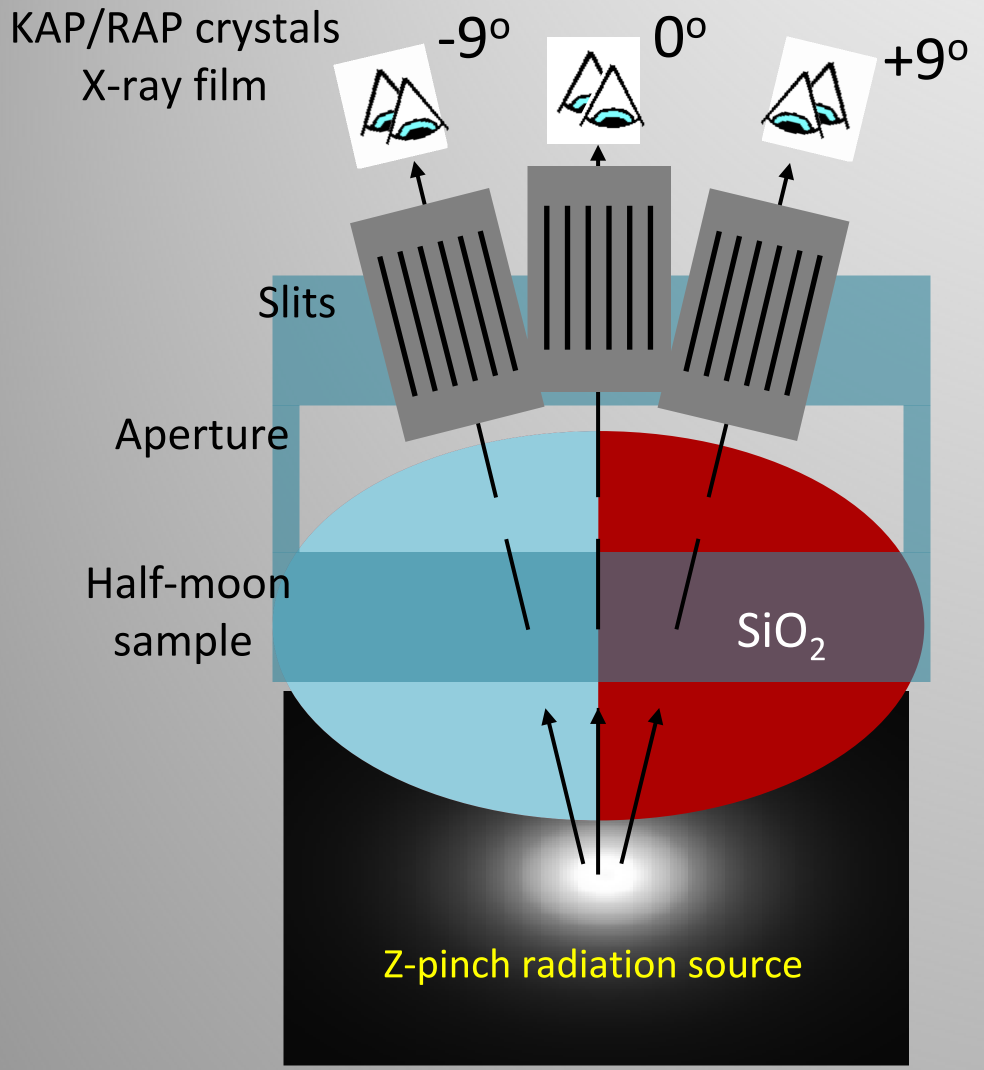
- White dwarfs (WDs) are "burned out" remnants of stars.
  - 98% of all stars will become WDs, including the Sun.
  - Cores are ~ 50:50 mixture of Carbon and Oxygen.
- WDs only cool with time, so surface temperature reveals their age.
  - WD cooling models constrain the age of our galaxy. [Winget et al. (1987)]
  - **Accurate opacities are required for WD cooling models.**
- "DQ" class WDs have Carbon and often Oxygen in their atmospheres.
  - These may be "failed Type Ia supernovae".
  - Studying them may help us understand how Type Ia supernovae are produced.
  - **DQ WD convection zone base (CZB) conditions have similar temperature and density as the solar CZB.**



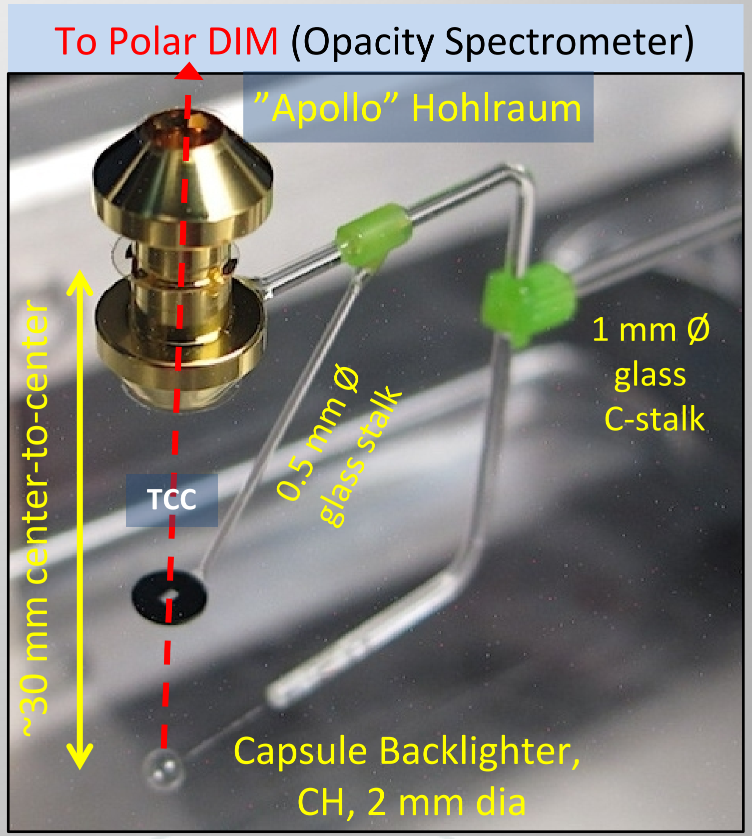


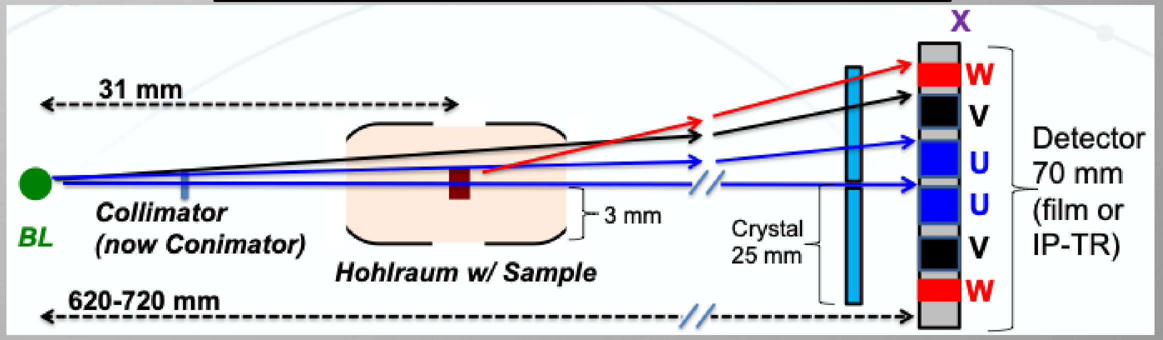
Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform



NIF Opacity Platform





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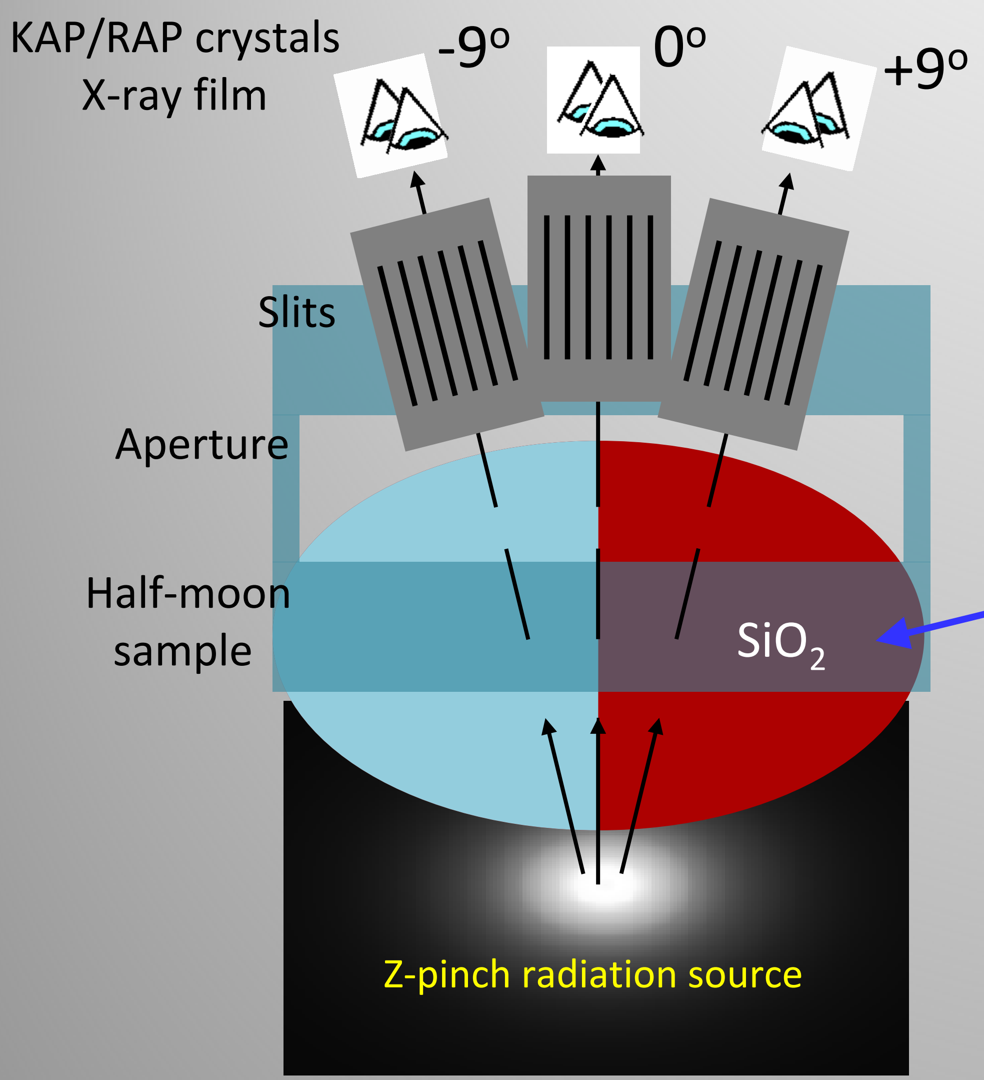

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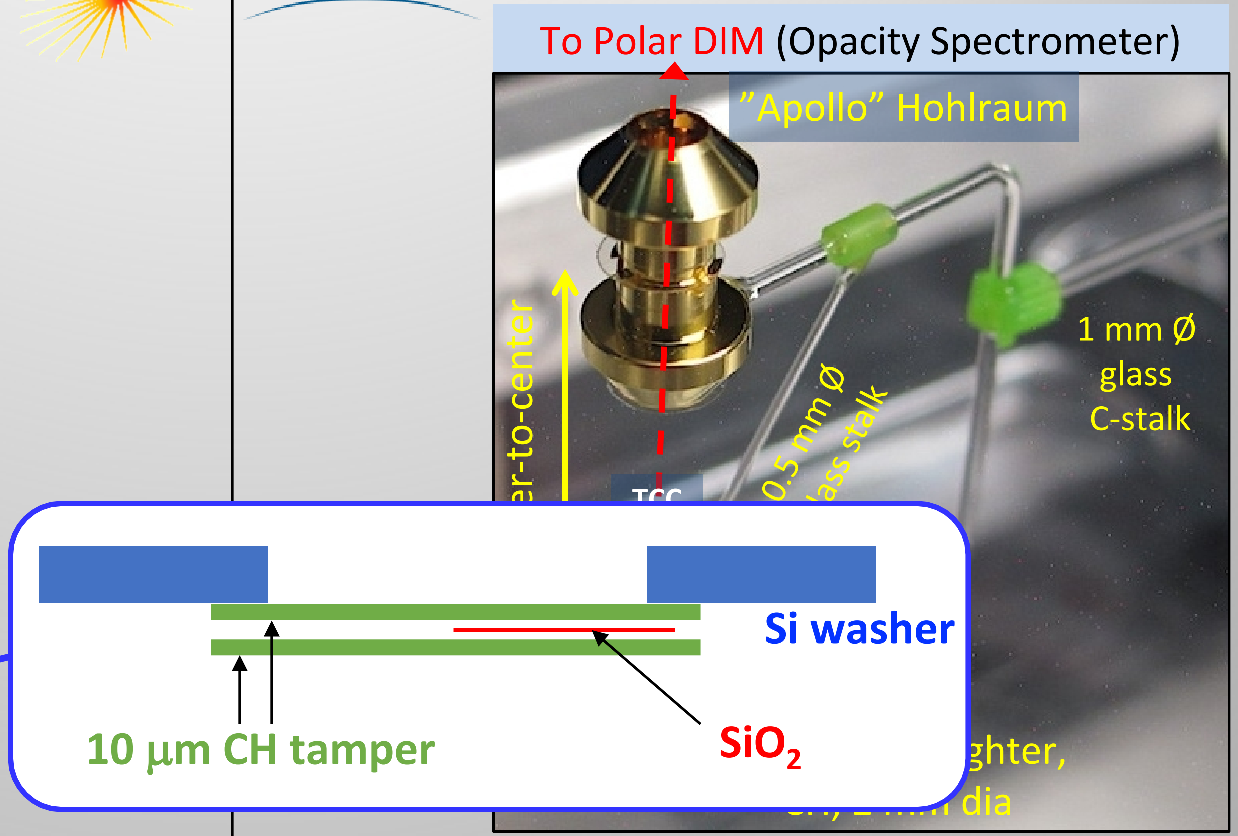

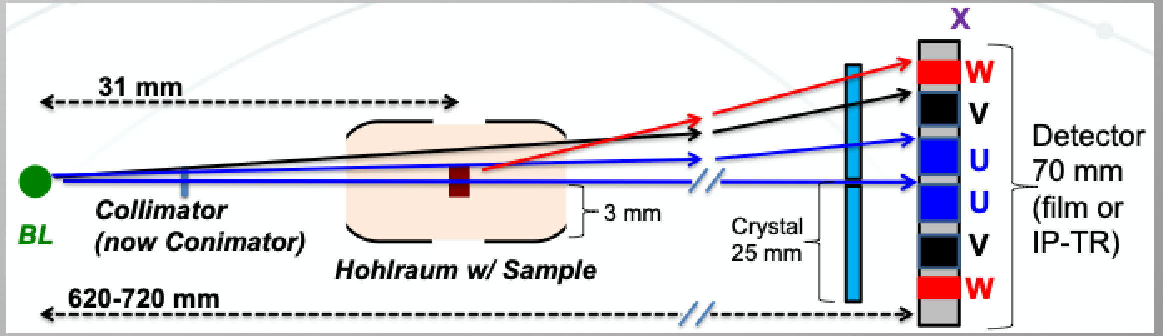

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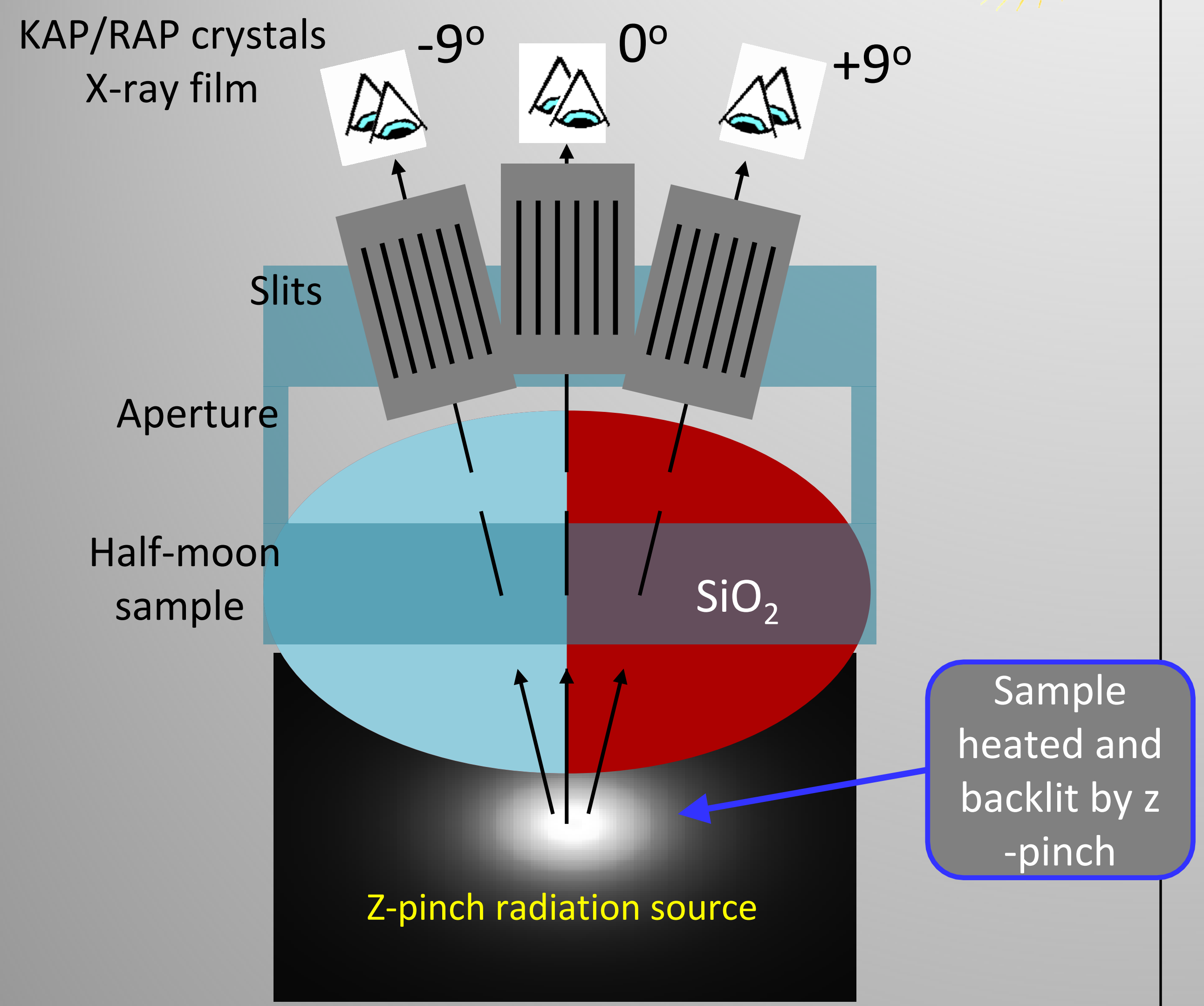

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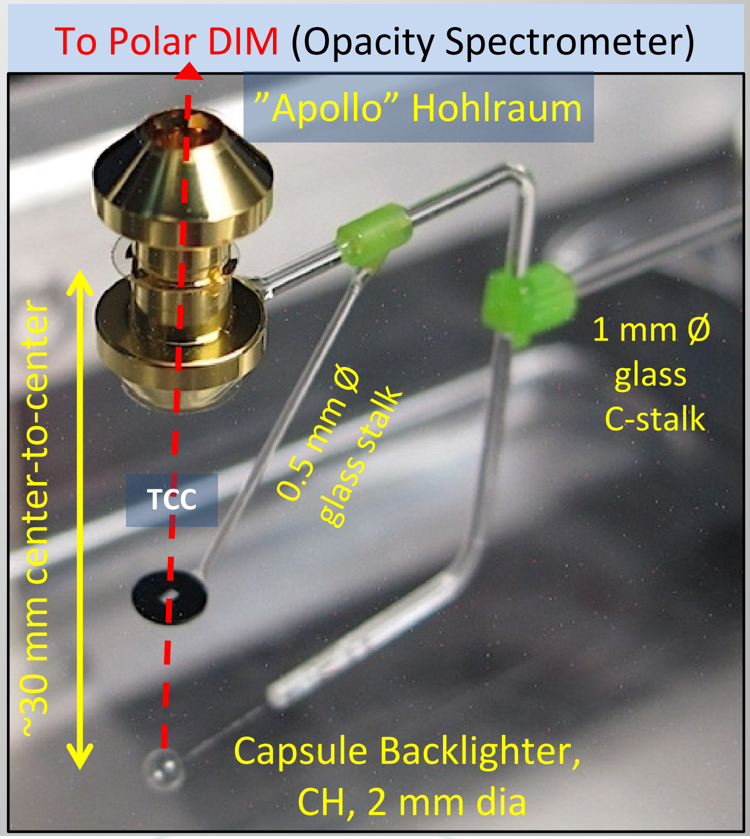

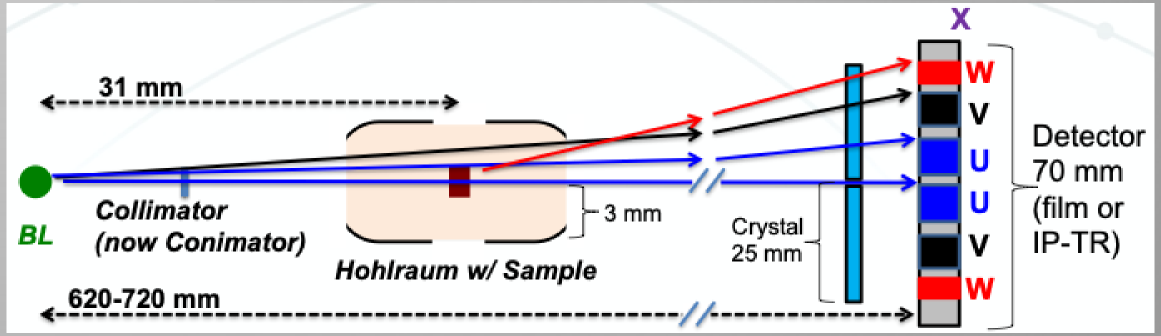

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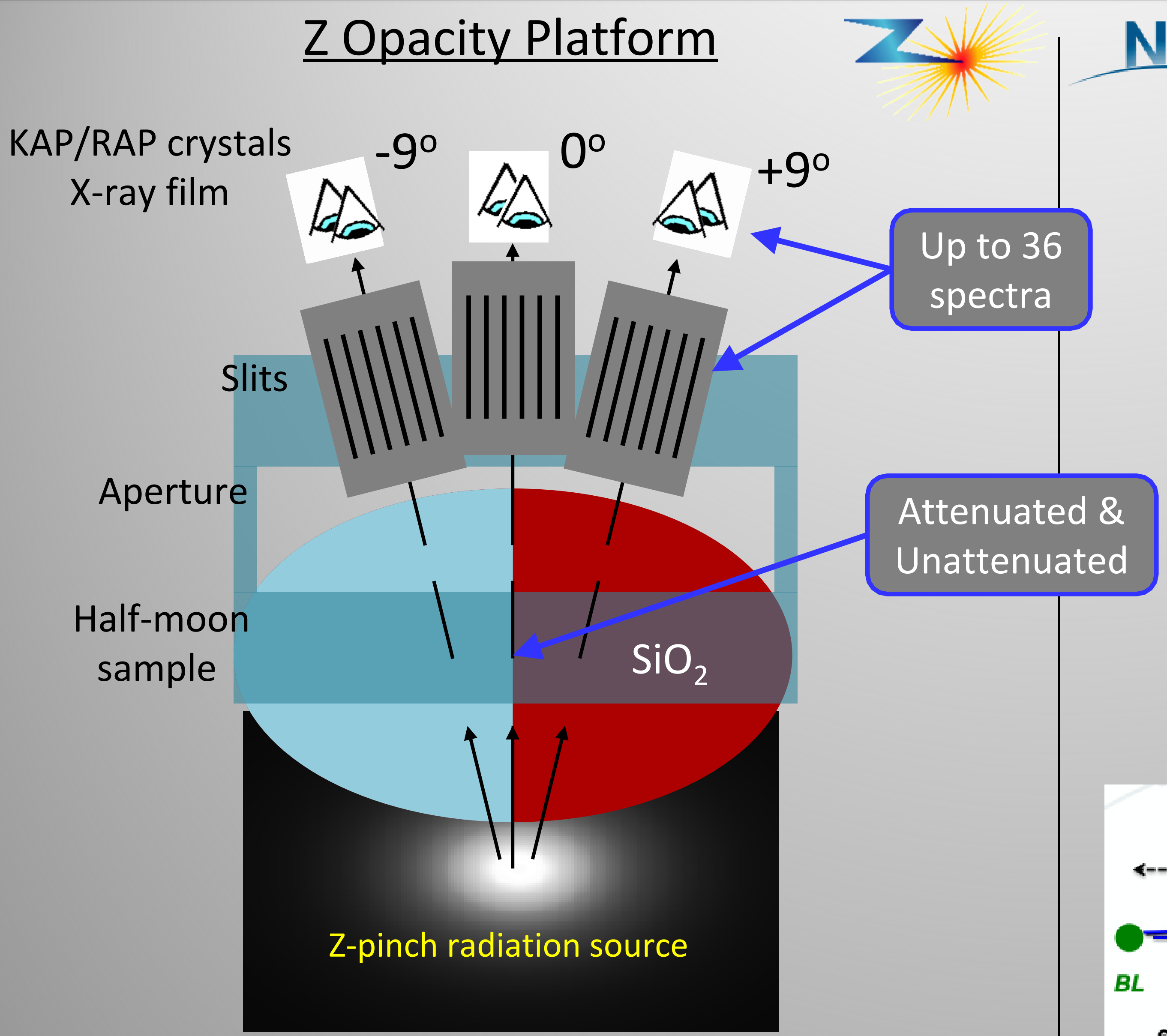

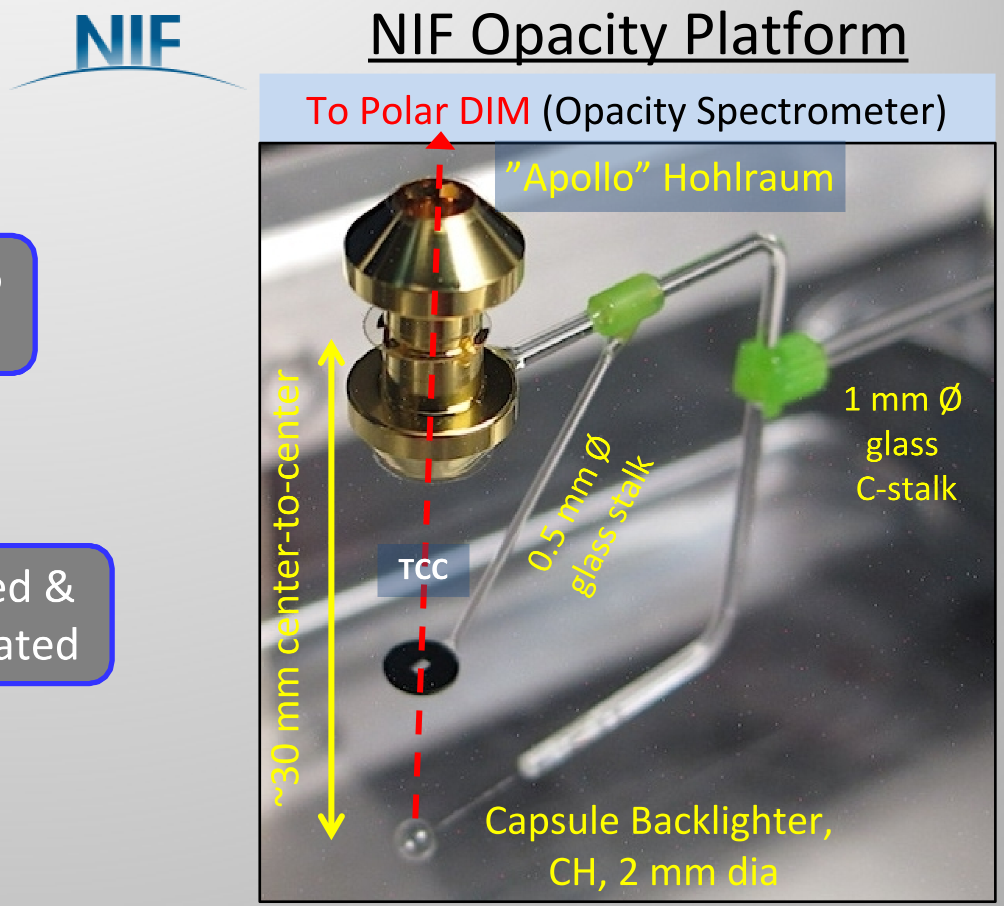

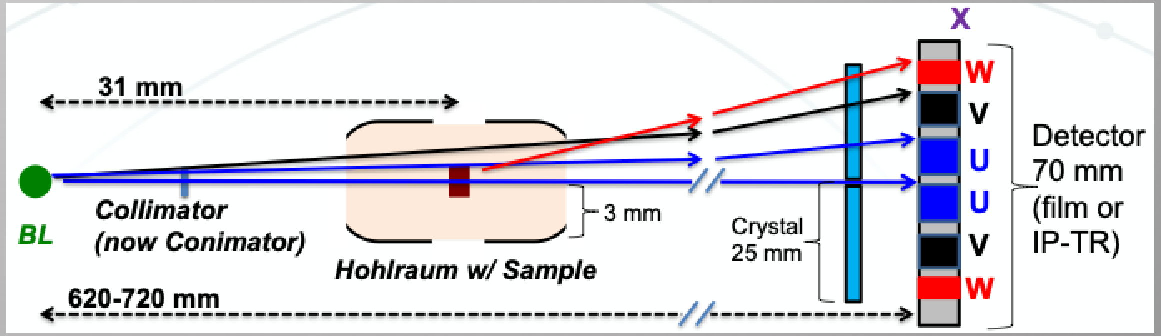

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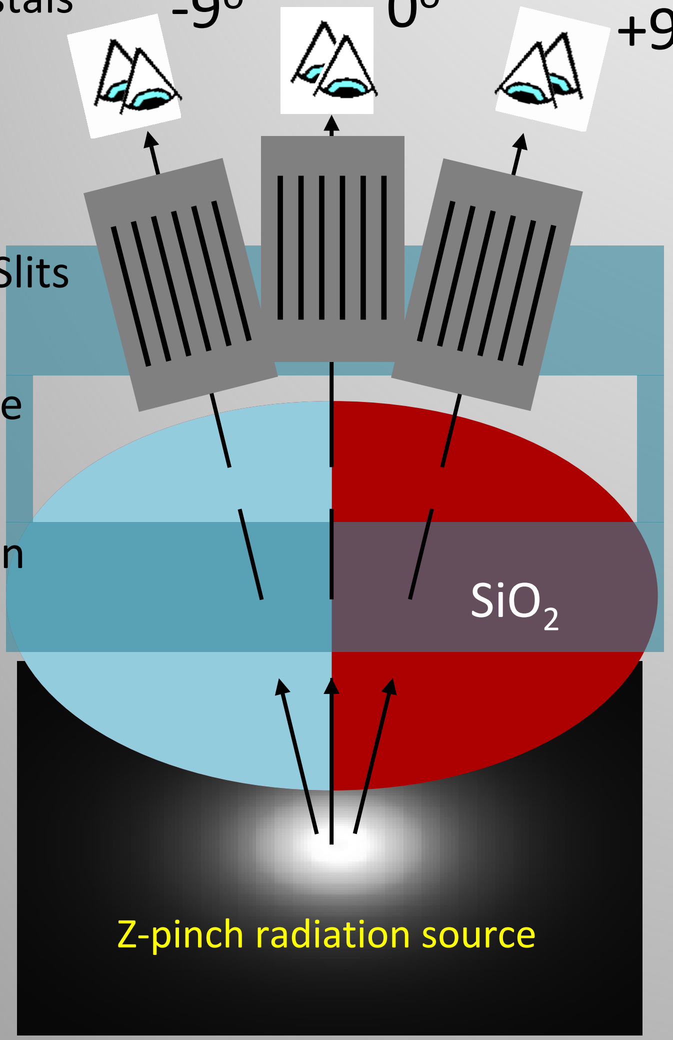

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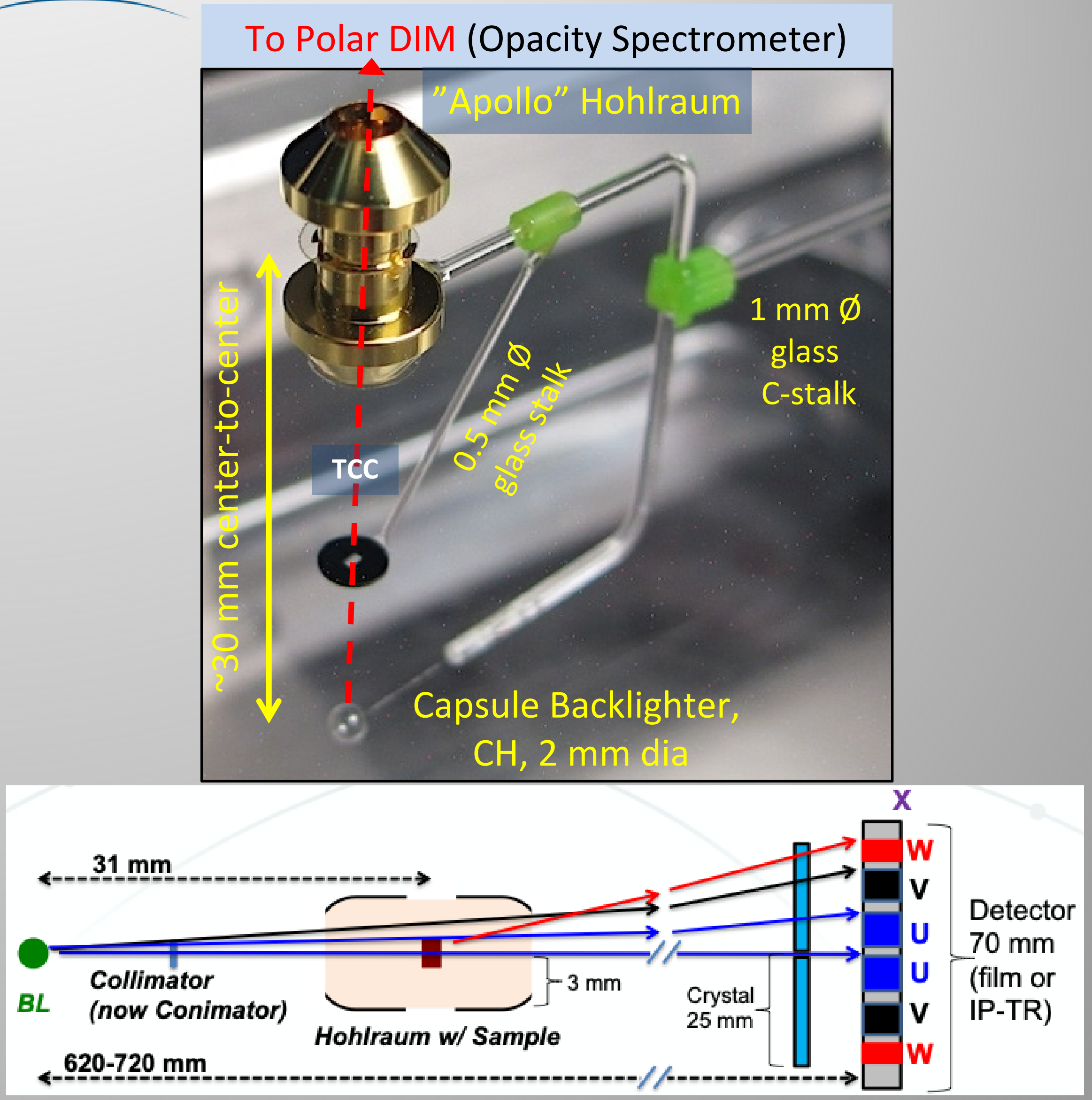

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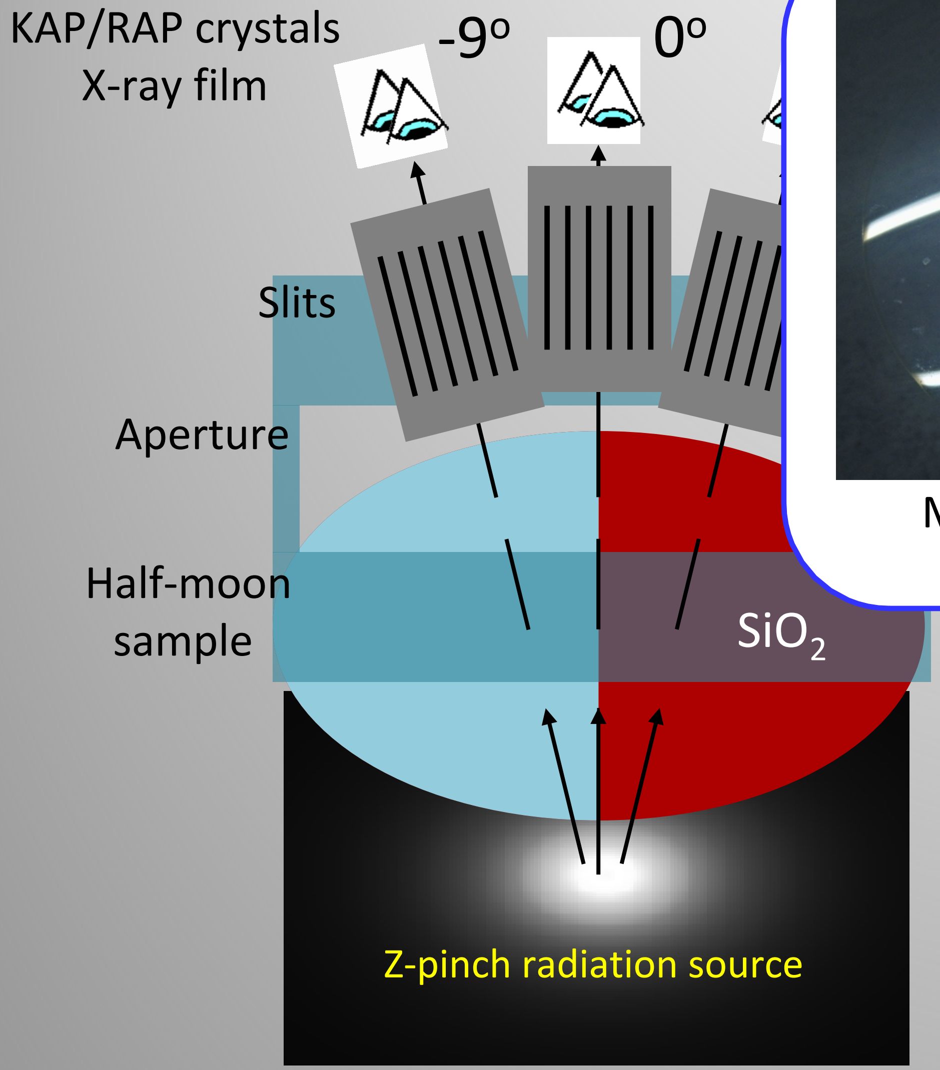
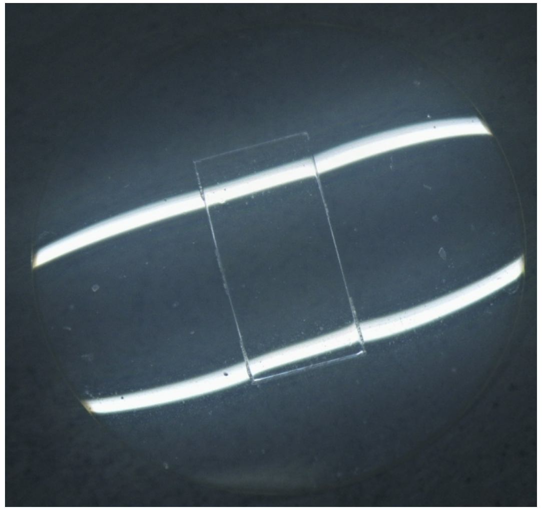
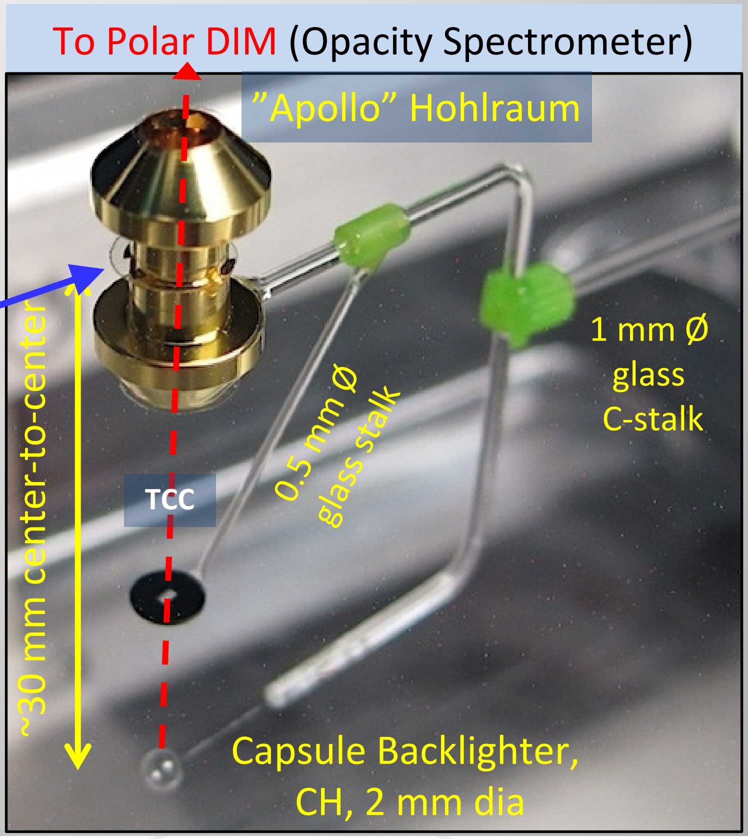
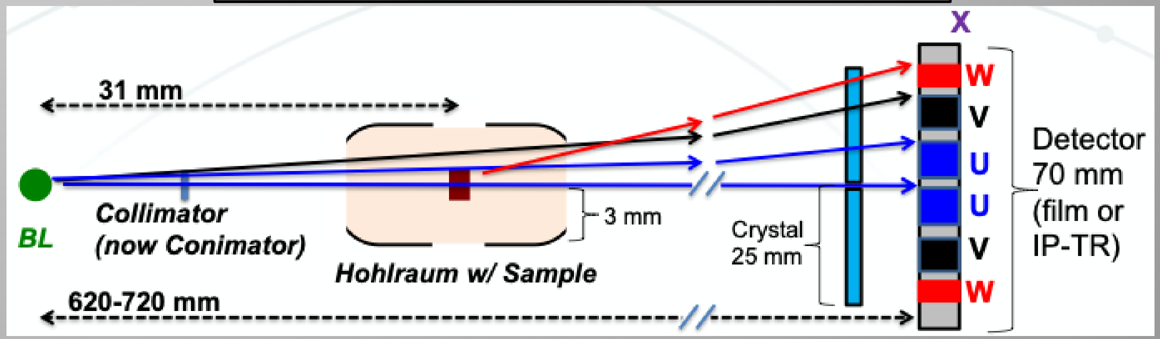




MgO or MgO+SiO_2 with CH tamper

NIF Opacity Platform





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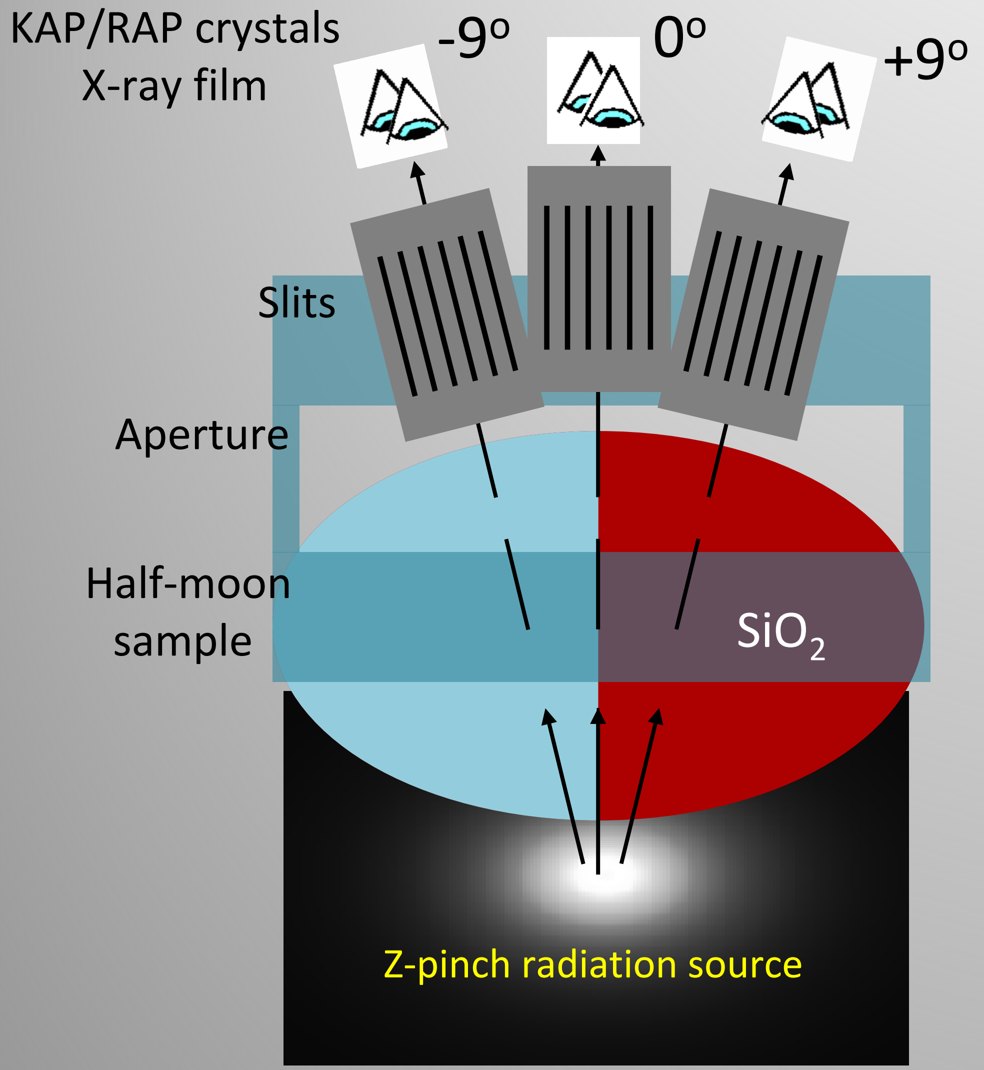

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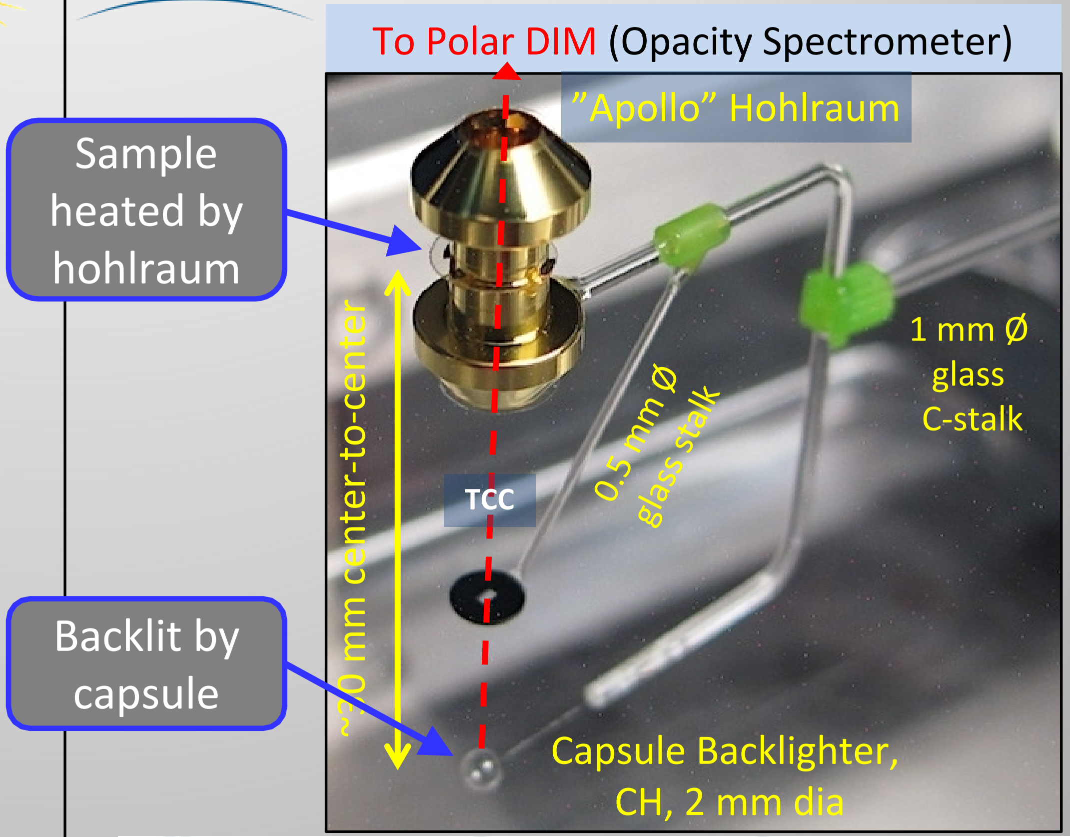

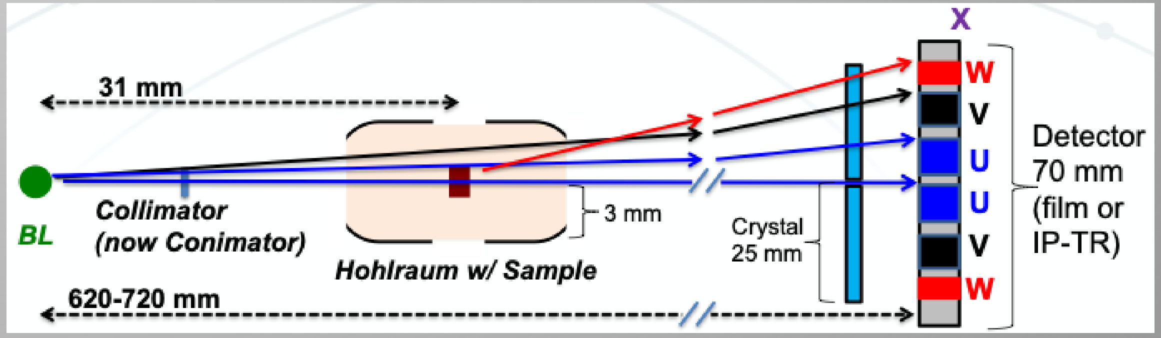

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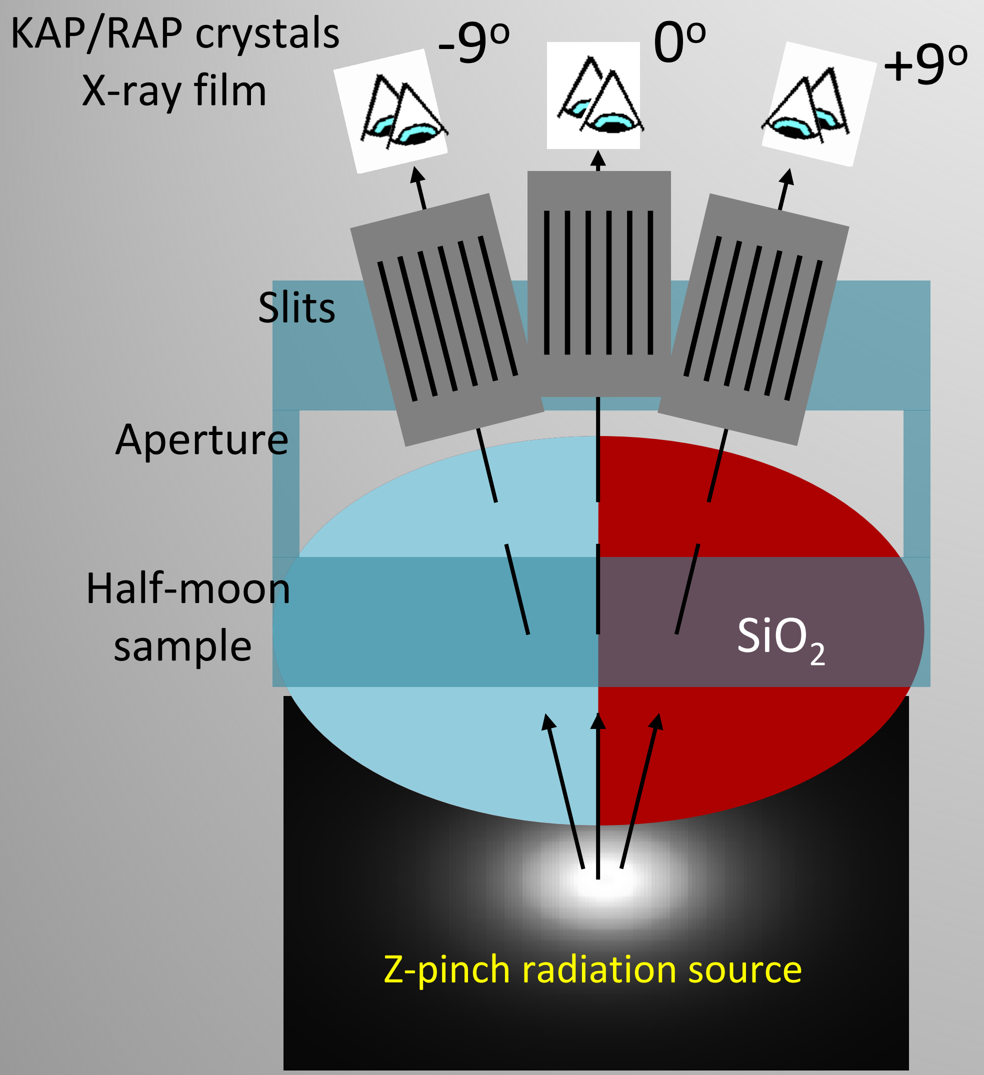

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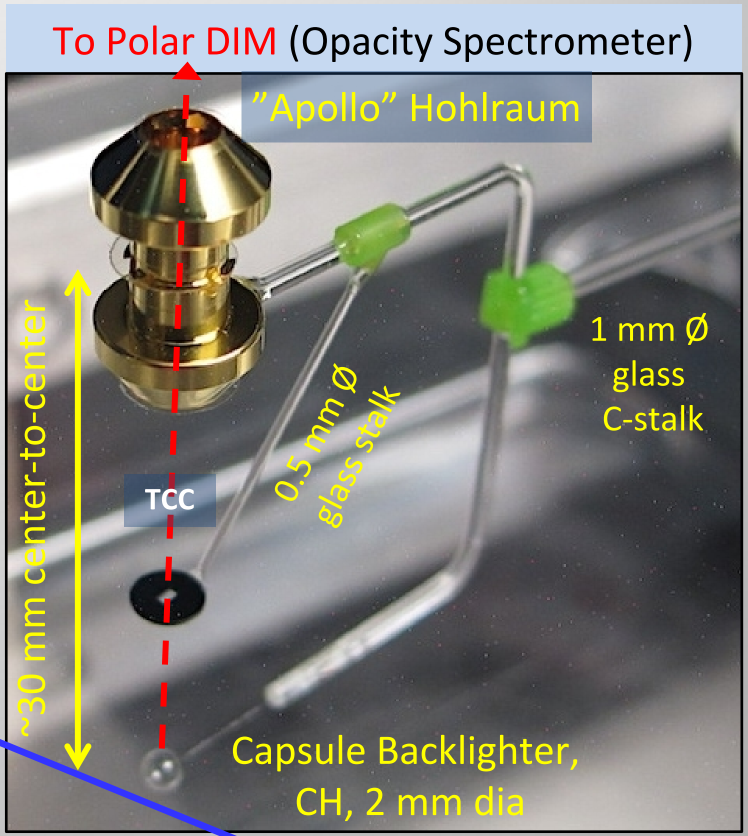
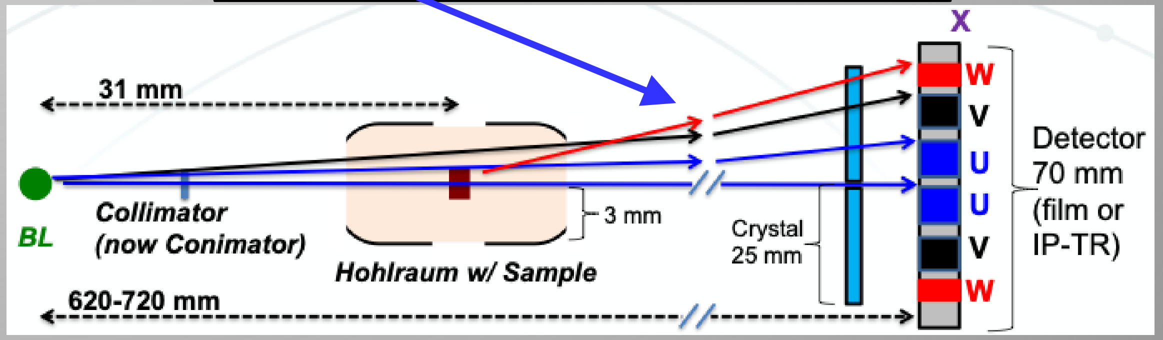


Absorption, backlighter, & emission



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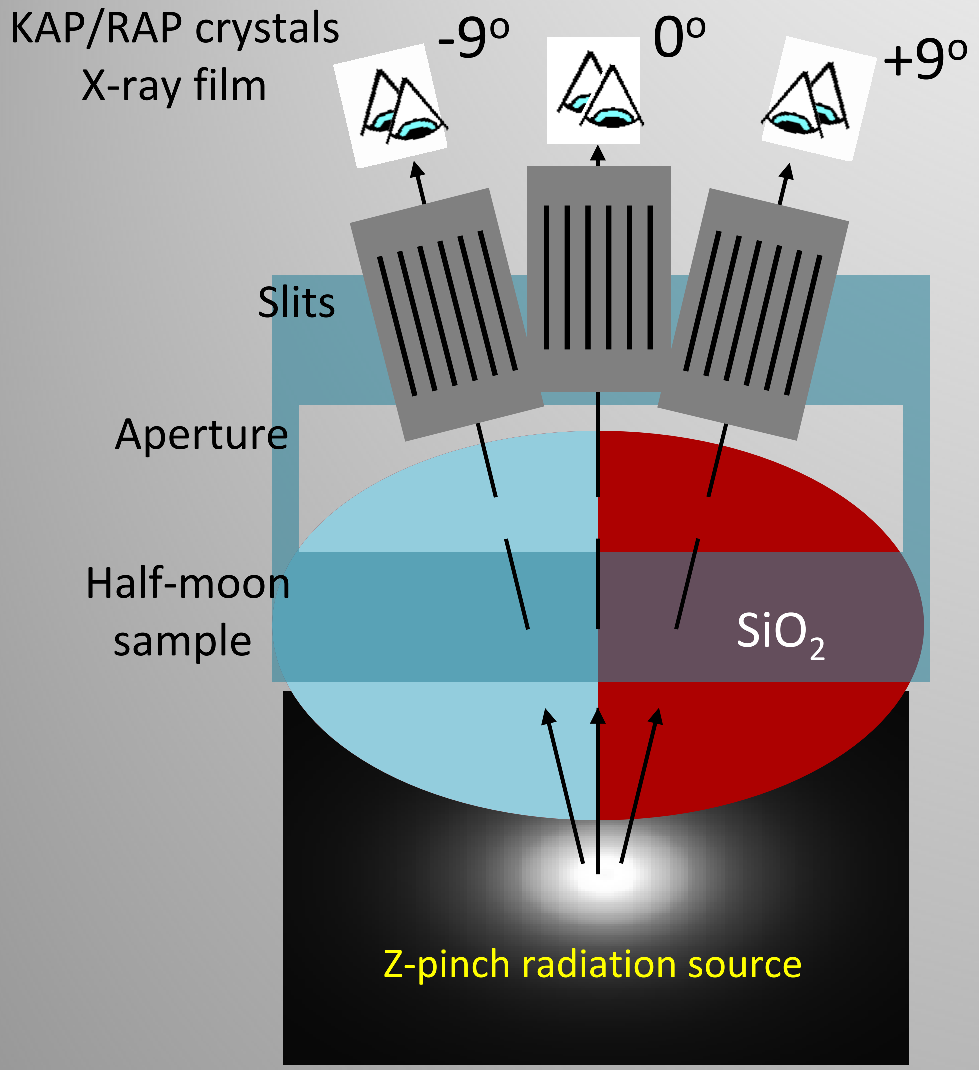

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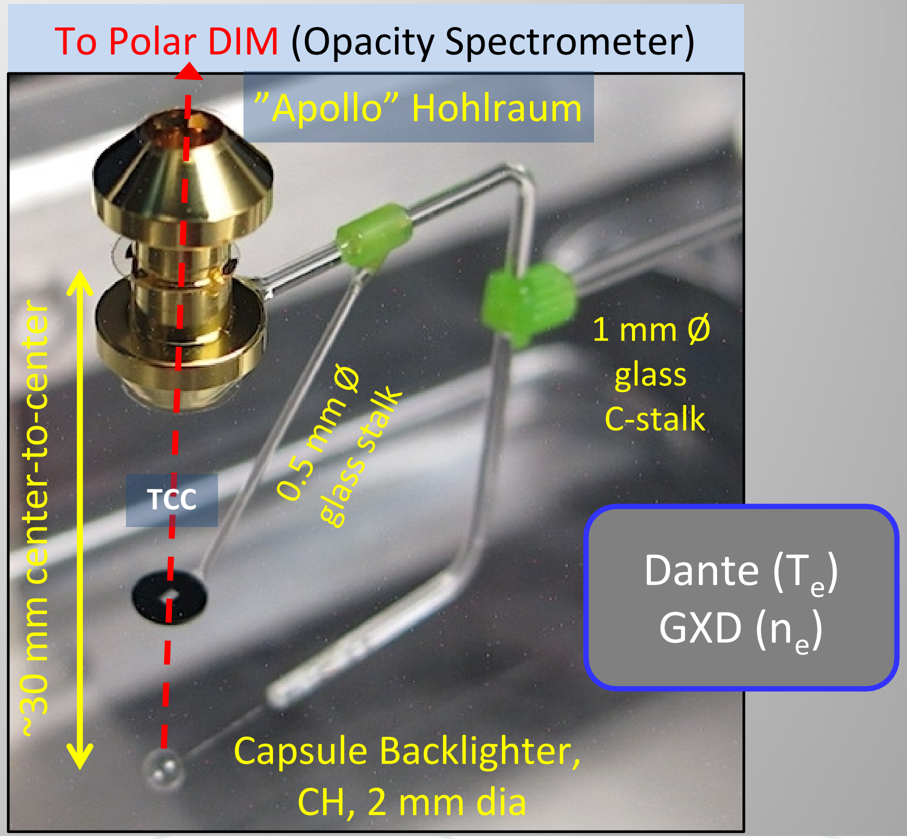
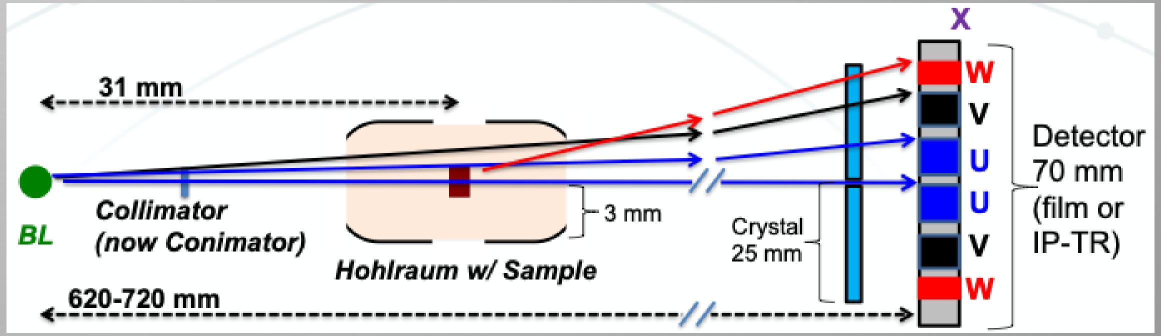
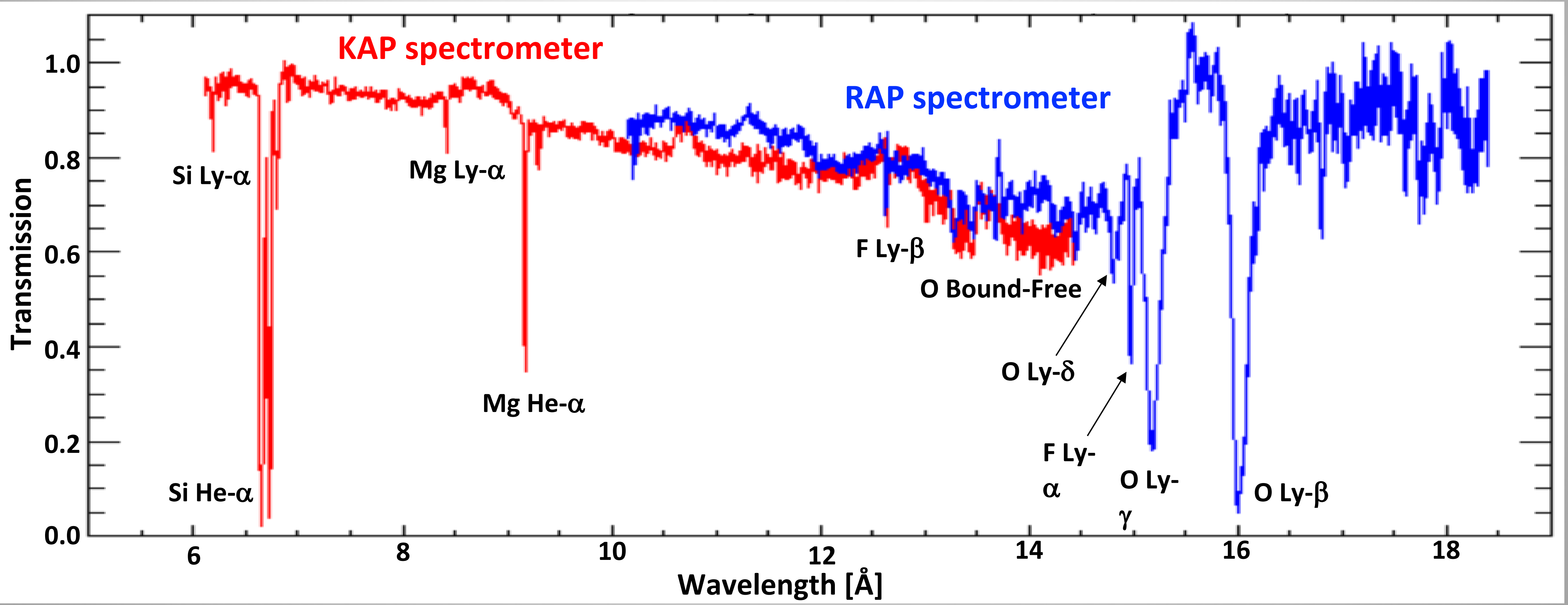


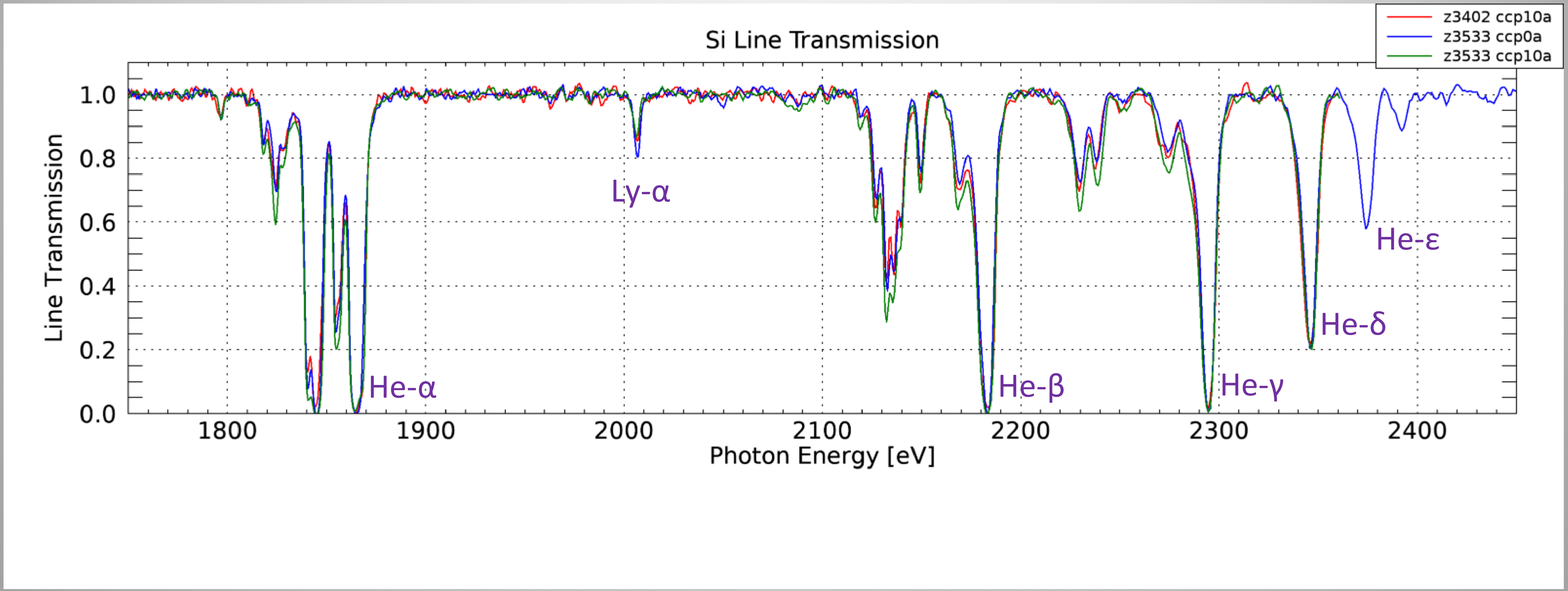


Oxygen and Silicon transmission have been successfully measured



- Accurate opacity is only obtained for T ~ 0.15-0.85.
- We have had 3 shots so far with SiO_2 samples.
- Spectrometer ranges have been extended to shorter λ (~ 5.0 Å) for Si and to longer λ (~ 19.5 Å) for O.

Silicon line transmission shows good reproducibility between the first two shots



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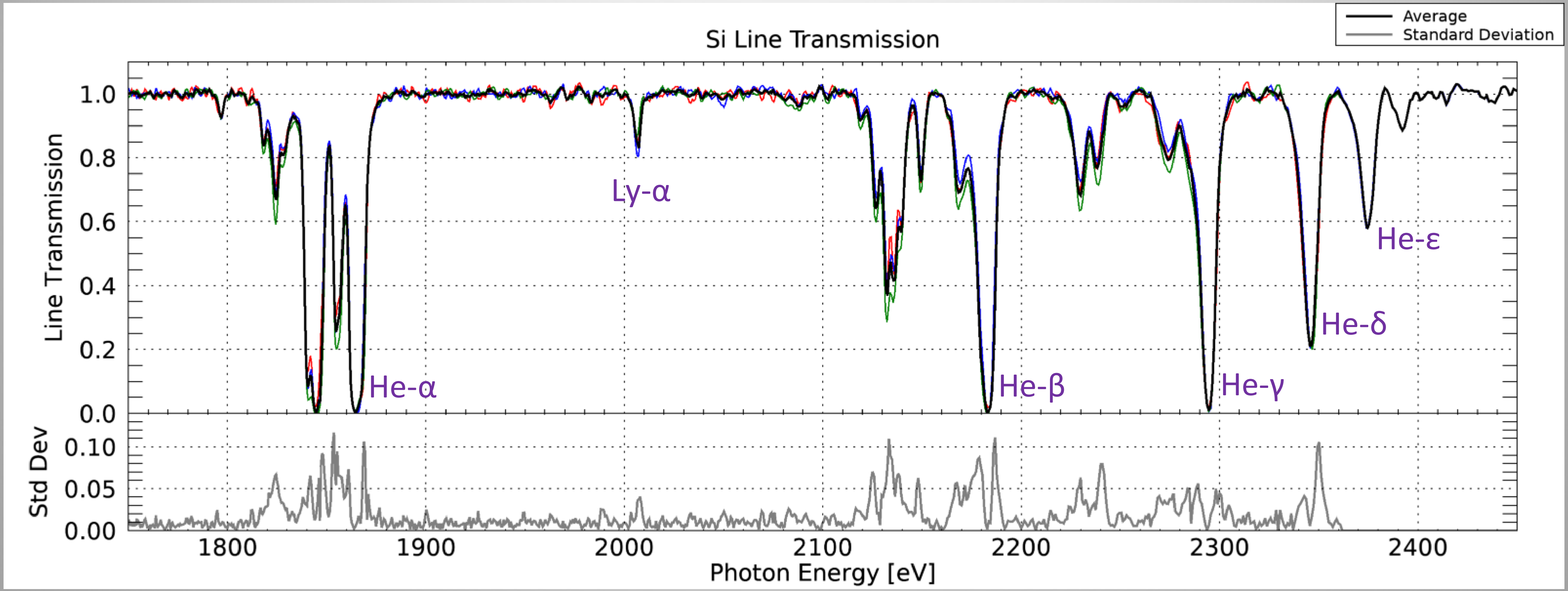

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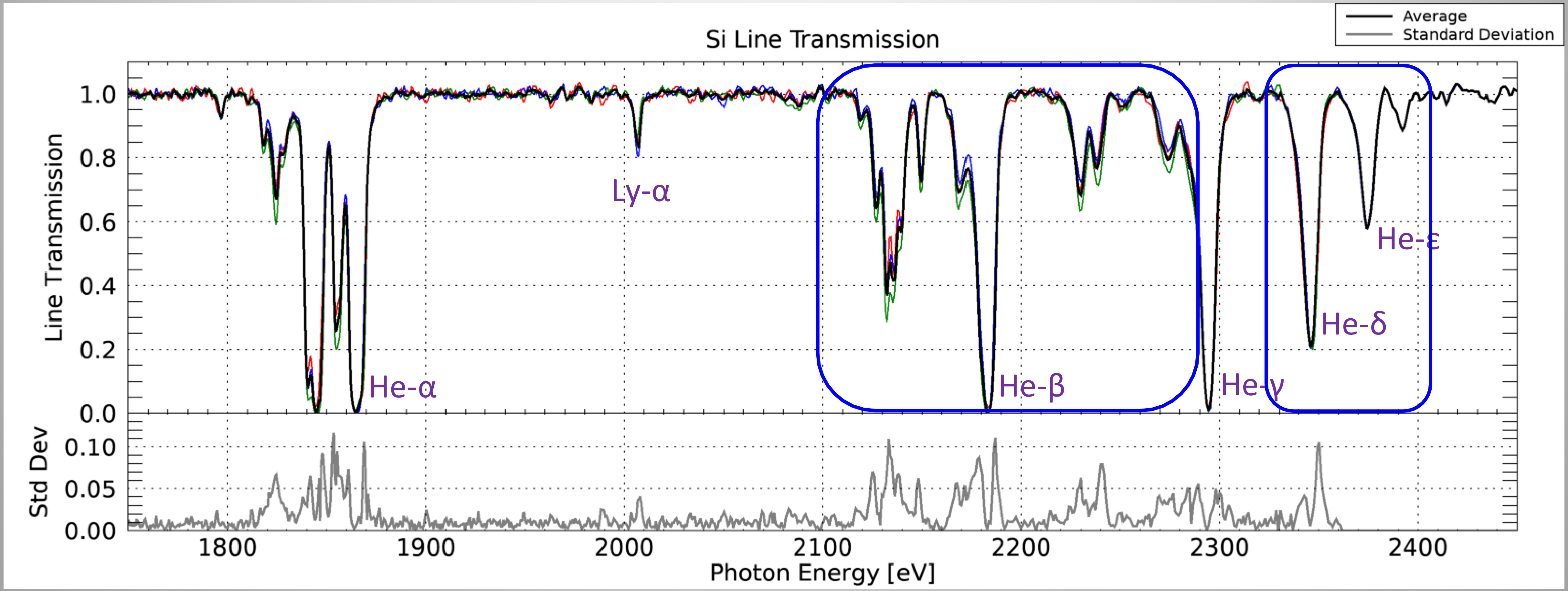
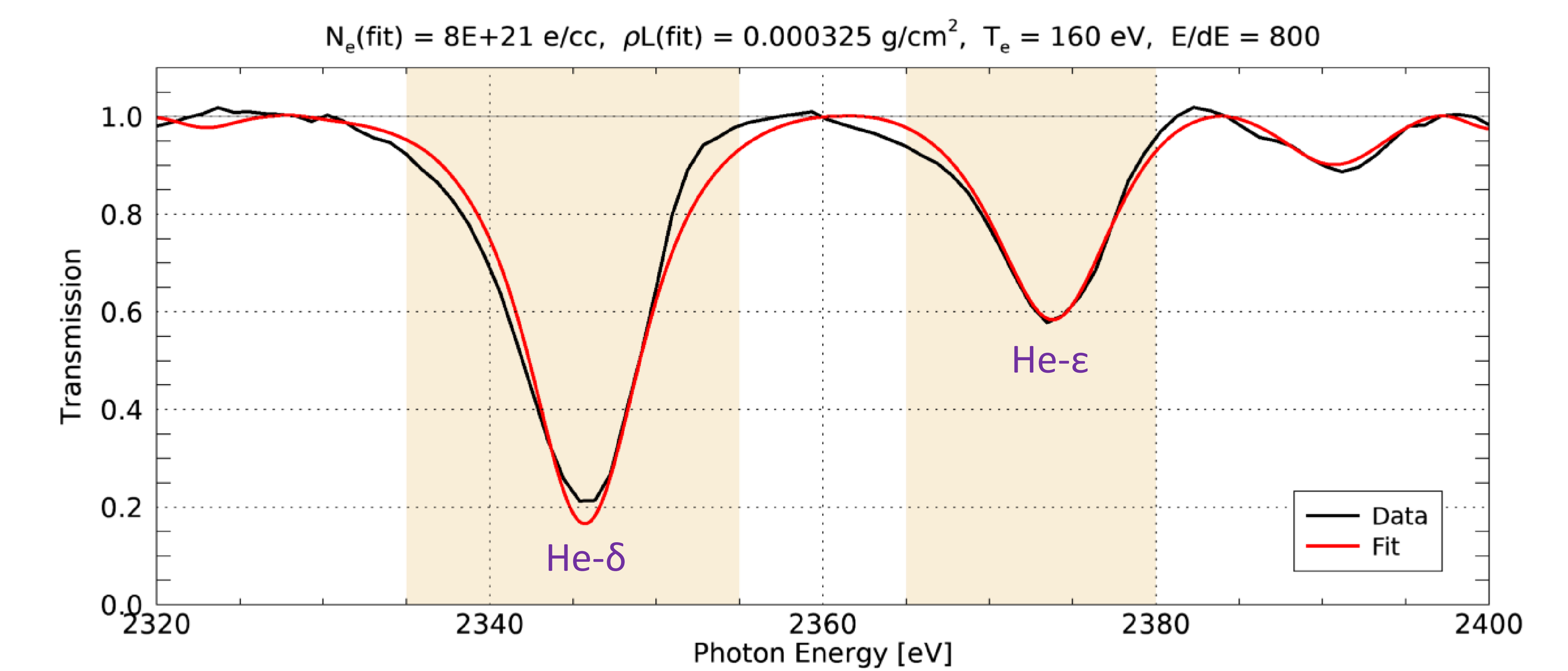
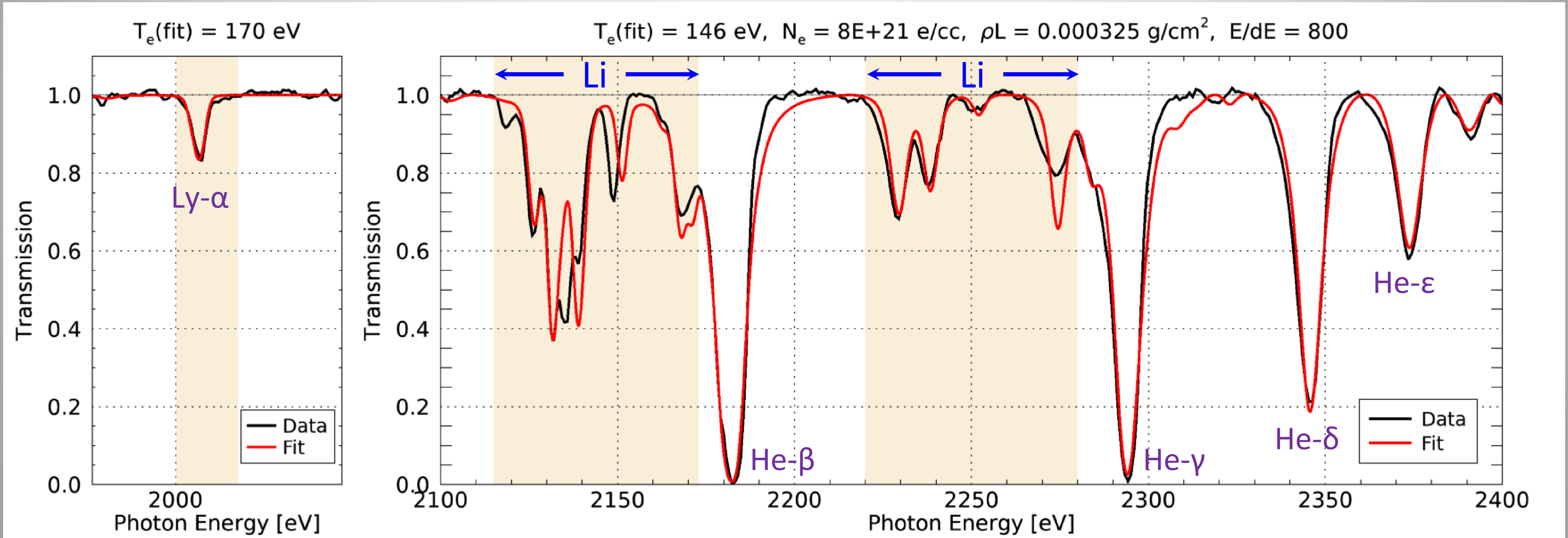


- Electron density is inferred from Si He-δ and He-ε line broadening.
- Electron temperature inferred from He-like/Li-like and H-like/He-like Si line ratios and ratios of rarely-observed Li-like satellites.

Electron density is inferred from Si He-δ and He-ε line broadening, N_e ~ 8e21 e/cc

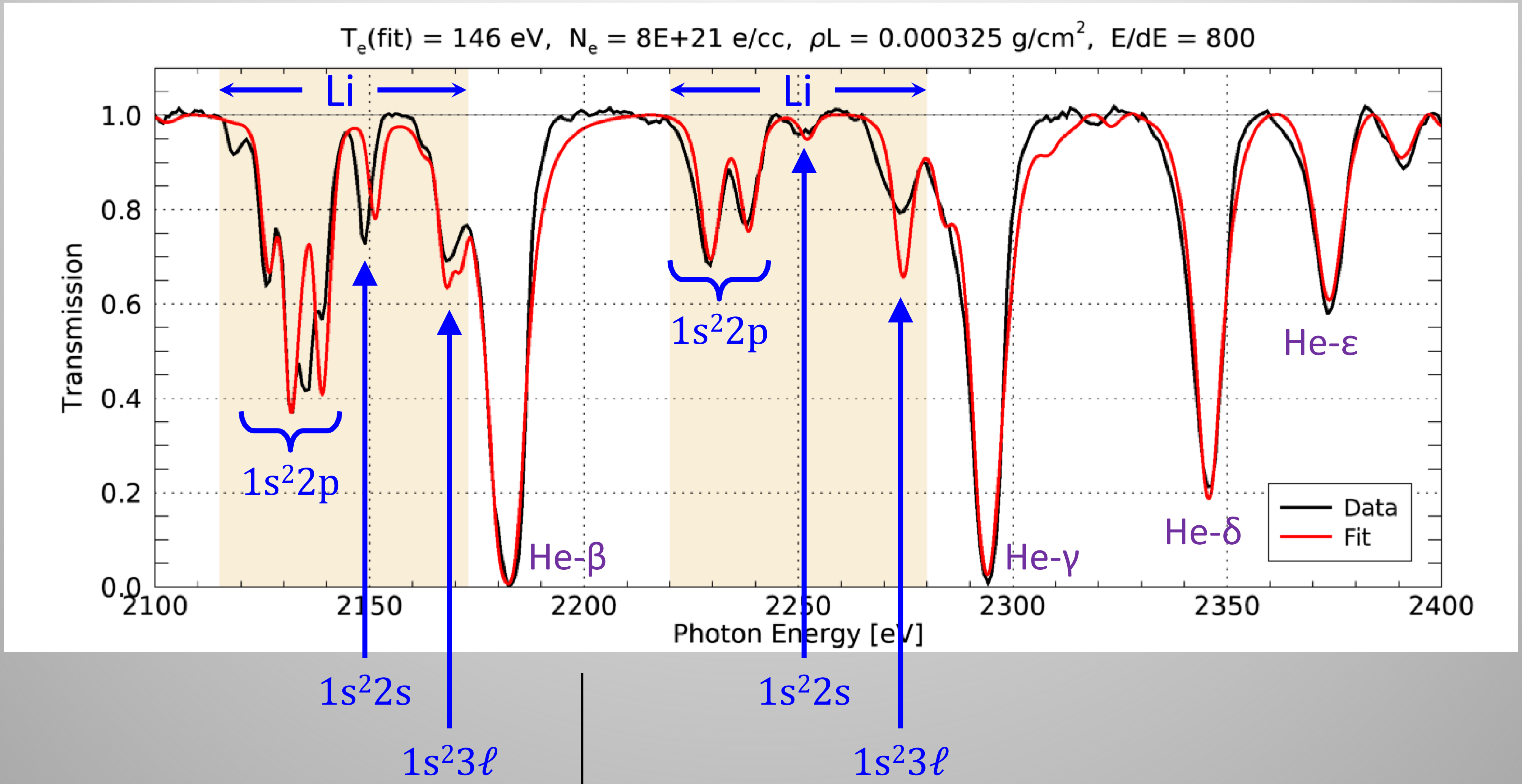


Electron temperature inferred from He-like/Li-like and H-like/He-like Si line ratios



- Li-like features indicate lower T_e, ~150 eV.
- Ly-α indicates higher T_e, ~170 eV

Temperature can also be inferred from population ratios from the Li-like satellites.



Transitions from n=1 to n=3

Transitions from n=1 to n=4

Temperature can also be inferred from population ratios from the Li-like satellites.

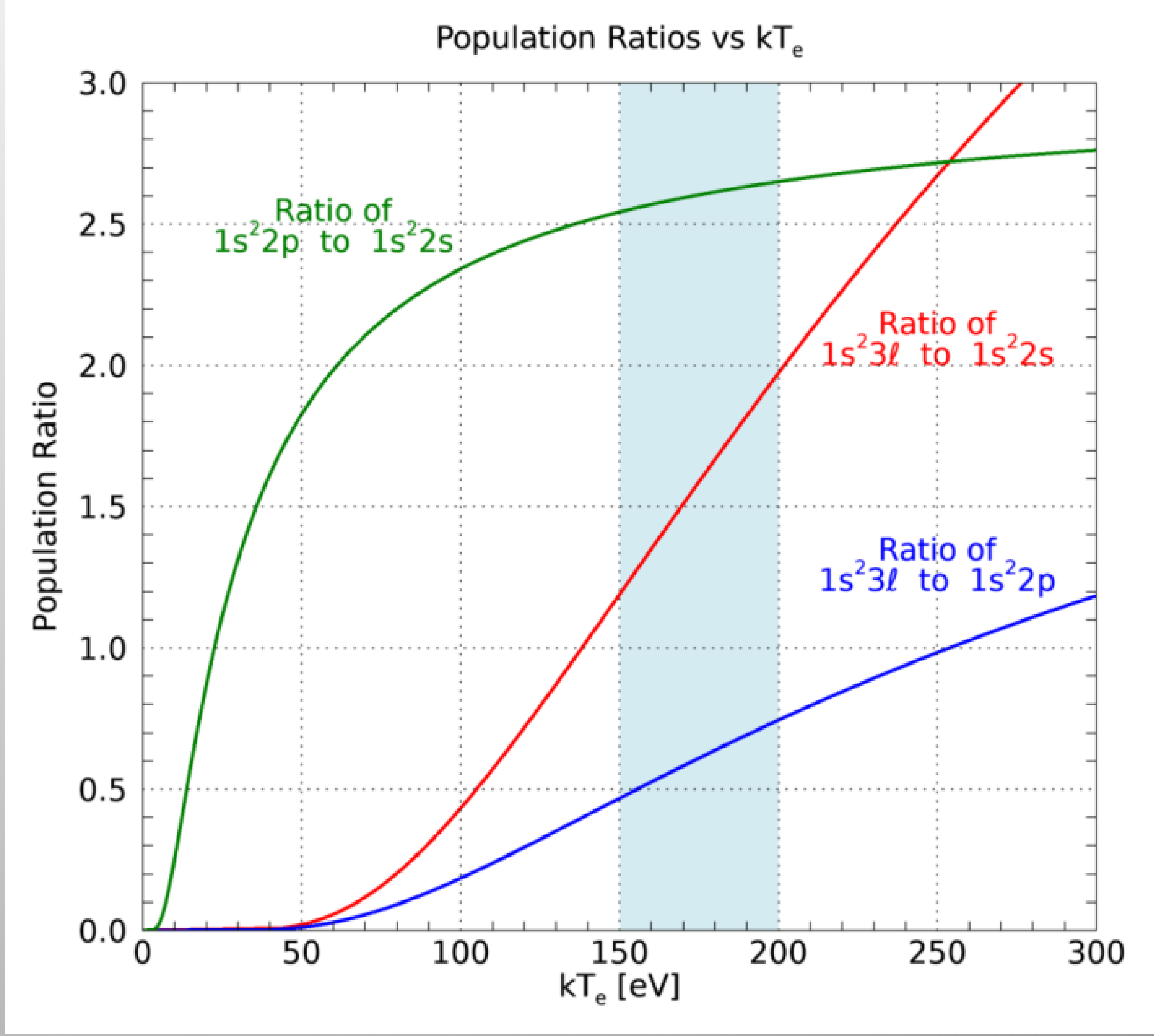
$$\frac{N_3}{N_2} = \frac{g_3 \exp\left(\frac{-E_3}{kT}\right)}{g_2 \exp\left(\frac{-E_2}{kT}\right)} \quad \rightarrow \quad kT_e = \frac{\Delta E}{\ln\left(\frac{g_3}{g_2} \cdot \frac{N_2}{N_3}\right)}$$

$$\frac{\delta T}{T} = \left(\frac{kT}{\Delta E}\right)\frac{\delta R}{R}$$

ΔE = 24.8 eV

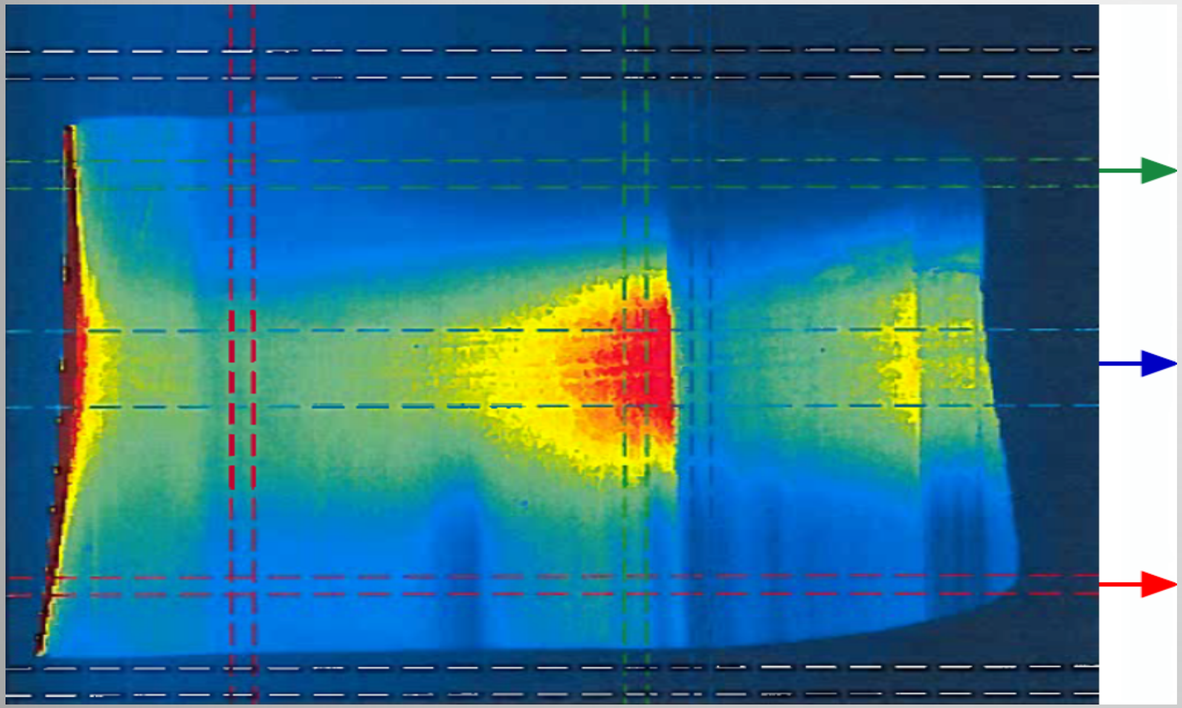
ΔE = 304 eV

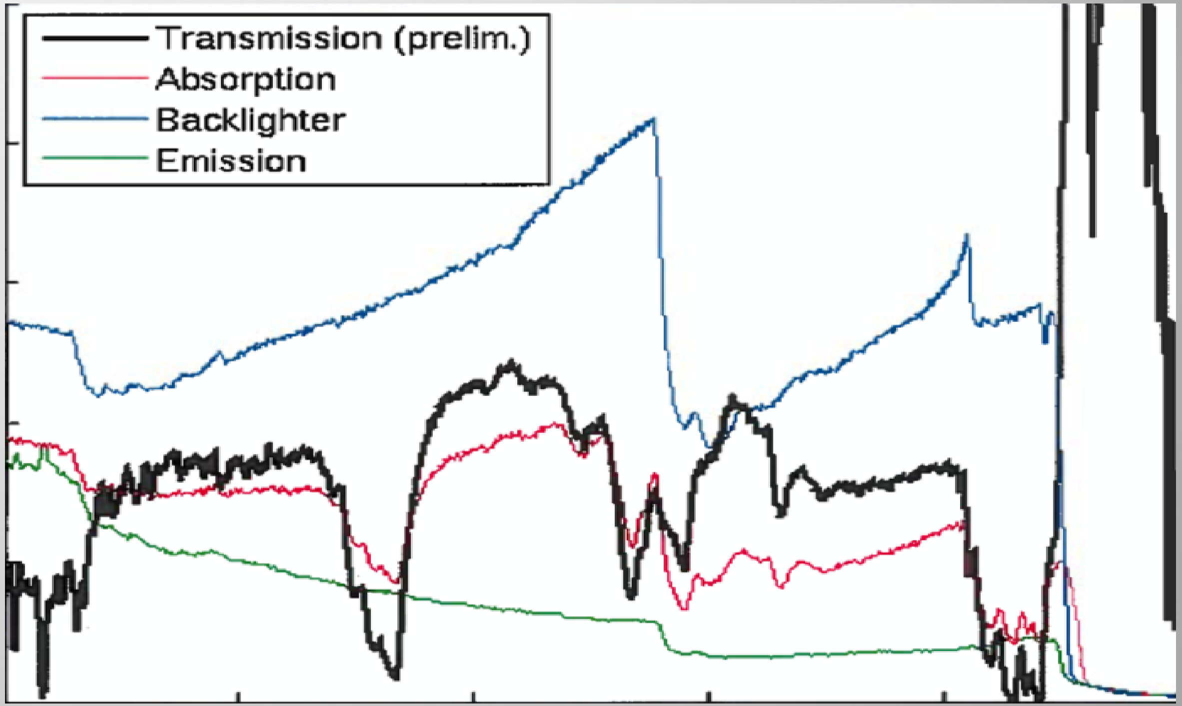
ΔE = 279 eV

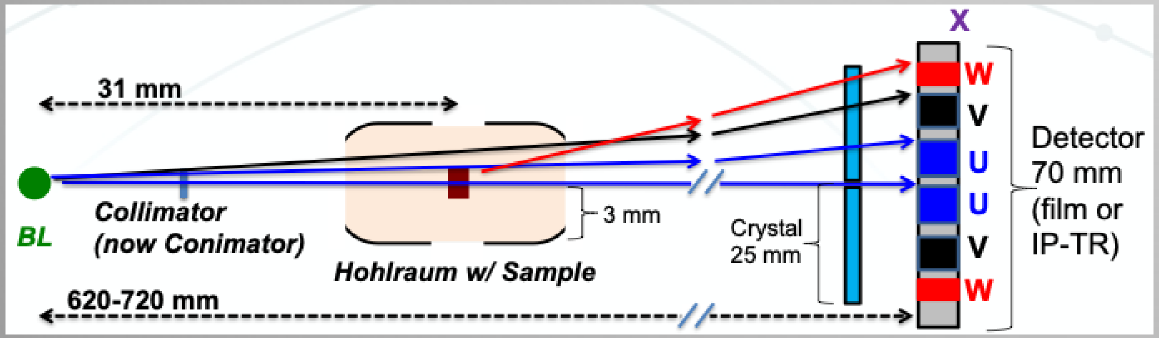


- The $1s^2 2p$ to $1s^2 2s$ ratio has been useful in diagnosing photoionized plasmas.
- Using the $1s^2 3\ell$ to $1s^2 2\ell$ ratios may provide another method to infer T_e.

We had our first shot day in June and successfully recorded transmission data

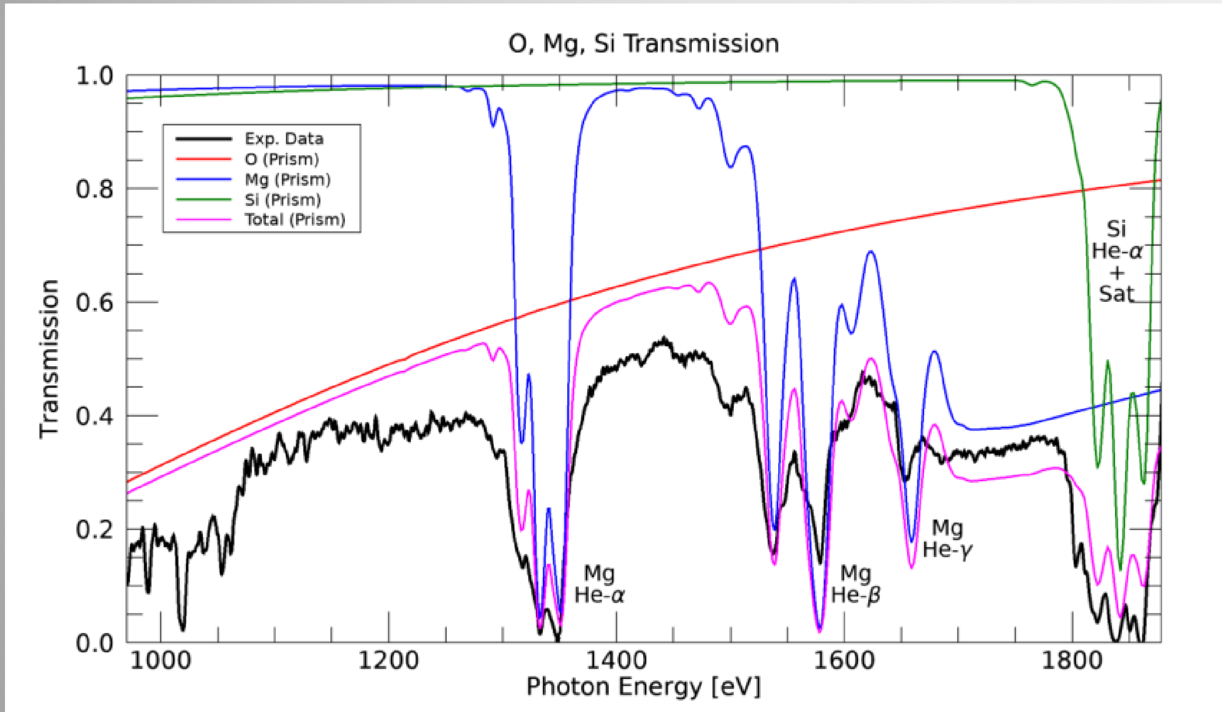


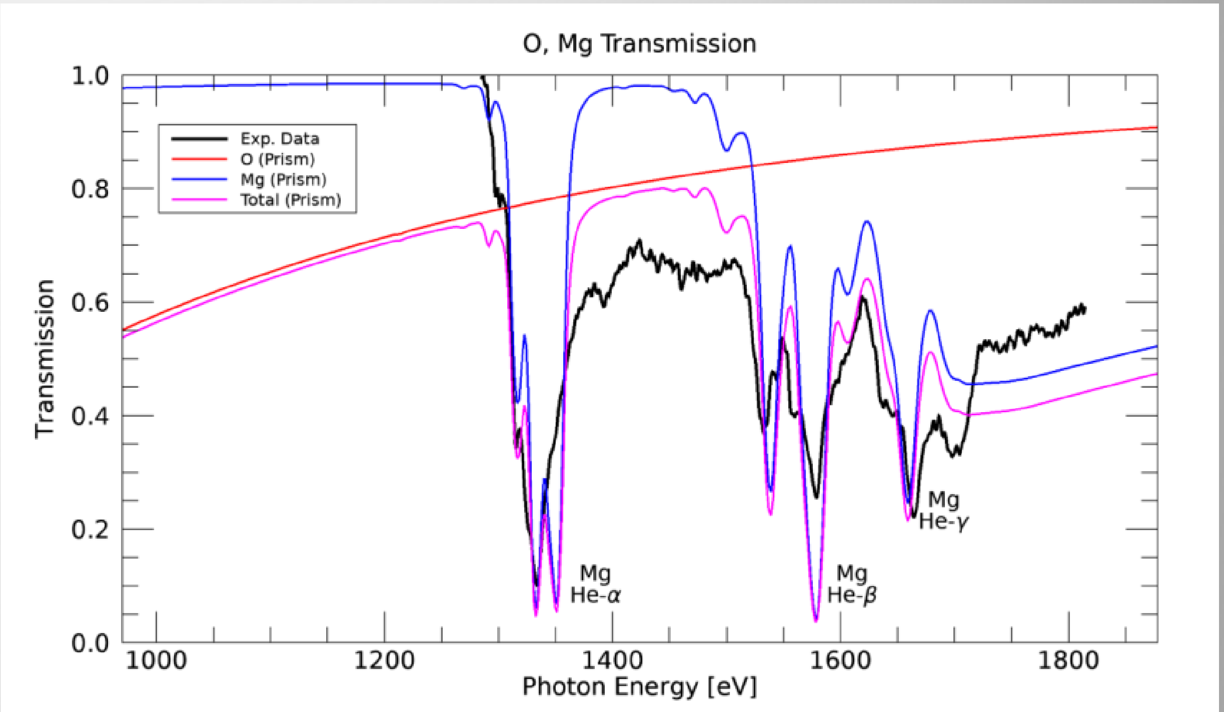




- All spectral elements required to extract transmission are recorded in a single shot.
  - Backlighter continuum, target absorption, and self-emission.

We successfully recorded transmission data from MgO+SiO_2 and MgO samples



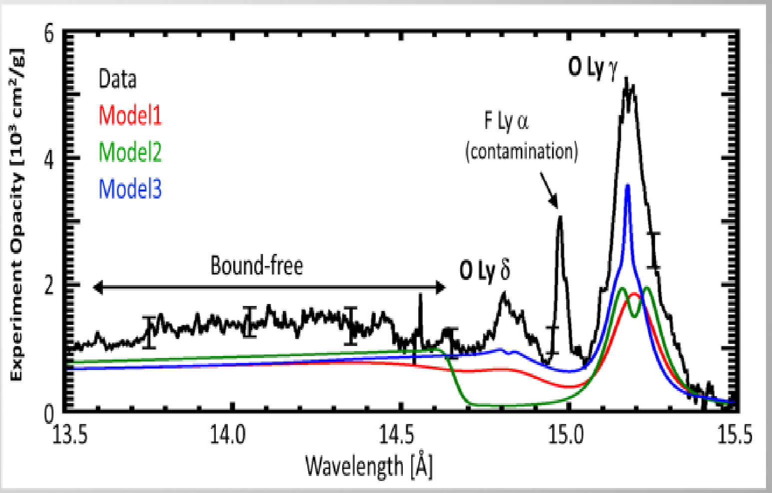


- Preliminary plasma conditions: T_e ~ 130 eV and n_e ~ 4×10^{22} e/cc.
- Electron temperature measured by Dante instrument.
- Electron density inferred from simulation results. We hope to use GXD imager in the future.
- An independent analysis based on spectroscopy of the Mg lines is underway.

Plans for continued progress on oxygen opacities and resolving the solar problem

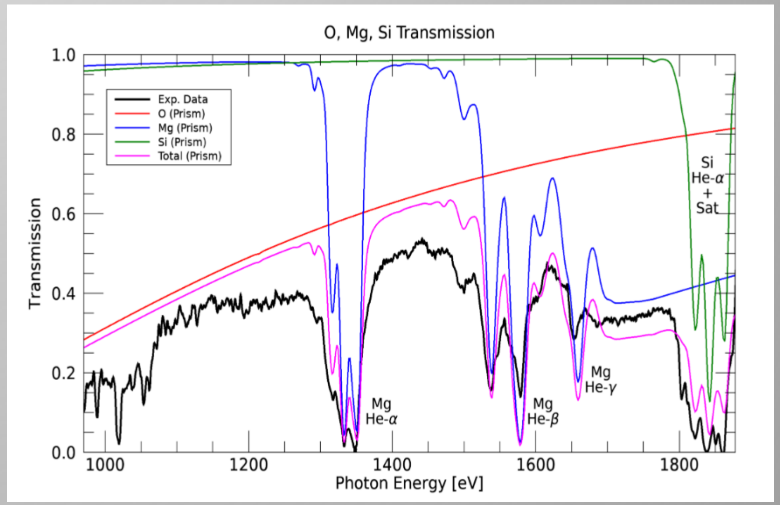
Z:

- Finalize oxygen opacity investigation at T_e~160 eV and N_e~8e21 e/cc.
  - Refining T_e and N_e analysis results.
  - Verify reproducibility and quantify uncertainties.
- Test oxygen opacity closer to solar CZB conditions (T_e~180 eV, N_e~3e22 e/cc).
- Test opacity models to quantify impact on solar models.



NIF:

- Analysis of present data set.
  - Spectral analysis to infer T_e and N_e.
  - Extraction of oxygen opacity.
- Further experiment developments/improvements.
  - Next samples will be "band-aid" style to help expansion measurement.
  - Improvements to spectrometer filtering to avoid breakage.
  - Next experiments will target higher temperature.



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