SAND2022-14534C

Oxygen opacity experiments to advance our understanding of stellar interiors

Dan Mayes

University of Texas at Austin – Department of Astronomy

APS-DPP 2022

2022/10/18

Z Fundamental Science

NIF Discovery Science

National Nuclear Security Administration

WOOTTON CAPP

TEXAS The University of Texas at Austin

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

We have a growing collaboration across universities, national labs, and private industry, both domestic and international.

J.E. Bailey, T. Nagayama, G.P. Loisel, G.S. Dunham, S.B. Hansen, T.A. Gomez, G.A. Rochau, B.M. Jones, R.M. More
– **Sandia National Laboratories**, Albuquerque, NM

D.E. Winget, M.H. Montgomery, D.C. Mayes, M. Kao, B. Hobbs
– **University of Texas at Austin**, Austin, TX

T.S. Perry, H.M. Johns, H.F. Robey, E.S. Dodd, N.S. Krasheninnikova, C.J. Fontes, D.P. Kilcrease, J.P. Colgan, D. Saumon, T.H. Day, M. Sherrill
– **Los Alamos National Laboratory**, Los Alamos, NM

R.F. Heeter, Y.P. Opachich, R. Shepherd, C.A. Iglesias, D.A. Liedahl, B. Wilson
– **Lawrence Livermore National Laboratory**, Livermore, CA

M.S. Wallace, E.C. Dutra, R.A. Knight
– **Nevada National Security Site**, Las Vegas, NV

H. Huang, C. Monton, K. Sequoia
– **General Atomics**, La Jolla, CA

J.J. MacFarlane, I.E. Golovkin
– **Prism Computational Sciences**, Madison, WI

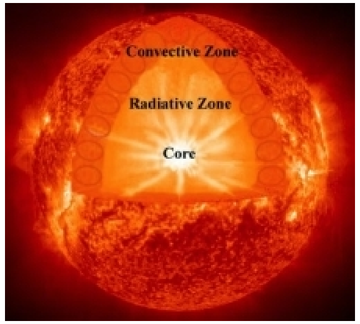
R.C. Mancini, E. Gallardo-Diaz
– **University of Nevada – Reno**, Reno, NV

C. Blancard, Ph. Cossé, G. Faussurier, F. Gilleron, J.-C. Pain
– **French Alternative Energies and Atomic Energy Commission (CEA)**, France

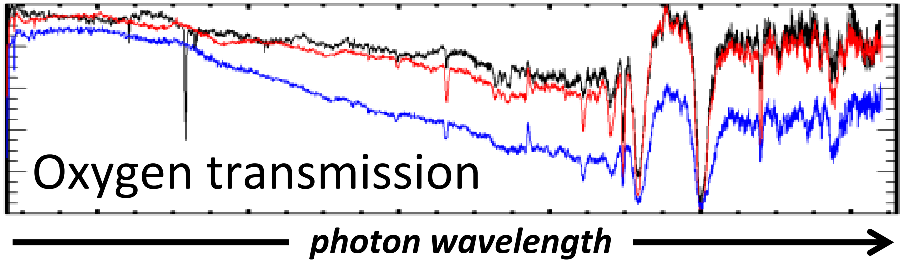
Y. Kurzweil and G. Hazak
– **Negev Nuclear Research Center**, Israel

This work was sponsored in part by the Wootton Center for Astrophysical Plasma Properties under U.S. Department of Energy cooperative agreement number DE-NA0003843, the Z Facility's Fundamental Science Program of Sandia National Laboratories, and the National Ignition Facility's Discovery Science Program of Lawrence Livermore National Laboratory.

Summary: Oxygen opacity experiments at Z and NIF address key challenges for resolving the solar problem



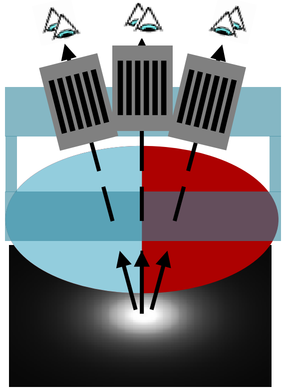
- Solar models and helioseismology disagree, and increased opacities could resolve the discrepancy.
- Oxygen is a major source of opacity at the solar convection zone base (CZB).
- Oxygen opacity measurements will test the treatment of density effects in modeled opacities.
- Cross-platform comparison (Z vs NIF) of results will increase confidence in the findings.

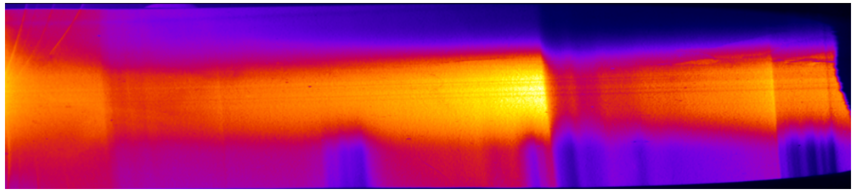


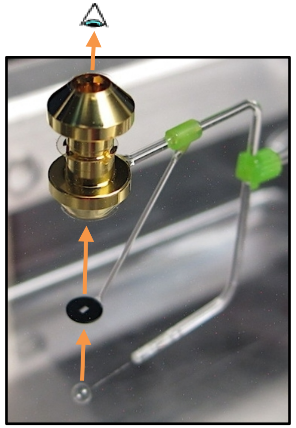
– Oxygen opacity was successfully measured at T_e~160 eV and n_e~8e21 e/cc.

– Preliminary model-data comparison already shows interesting disagreement.

– First measurements performed at higher T_e and n_e, closer to the solar interior.





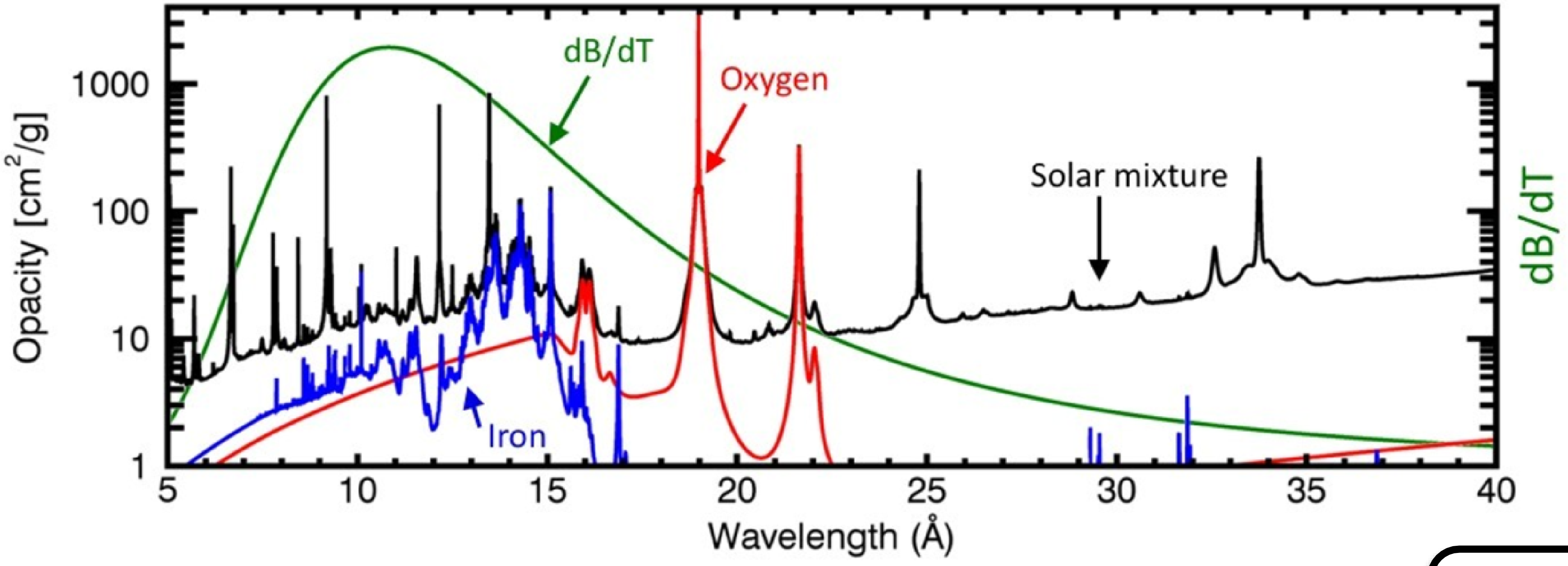


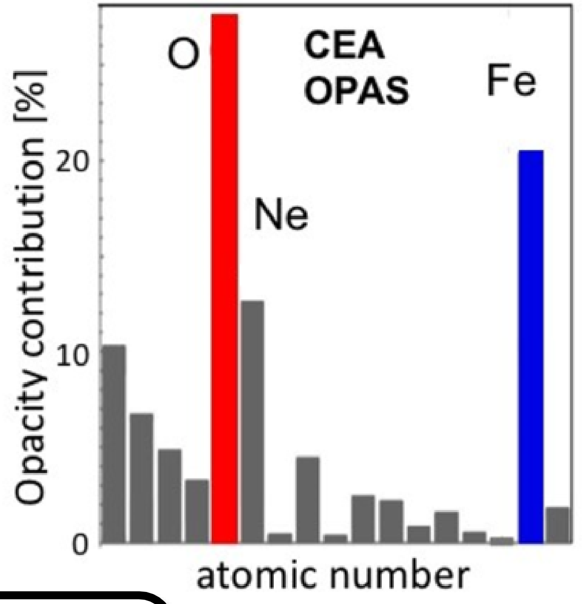
– Oxygen transmission measured at T_e~140 eV and N_e~2e22 e/cc.

– Preliminary model-data comparison shows interesting disagreement.

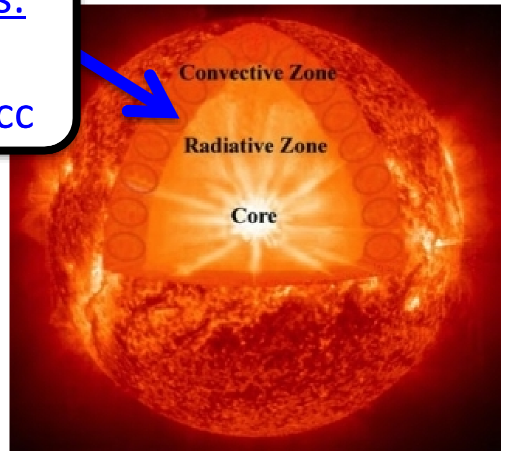
– Improvements to experiments:
  - Sample expansion measurement
  - Low-energy band spectrum

Oxygen opacity measurements are essential to resolve the solar problem





CZB conditions:
T_e ~ 185 eV
n_e ~ 9×10^{22} e$^-$/cc

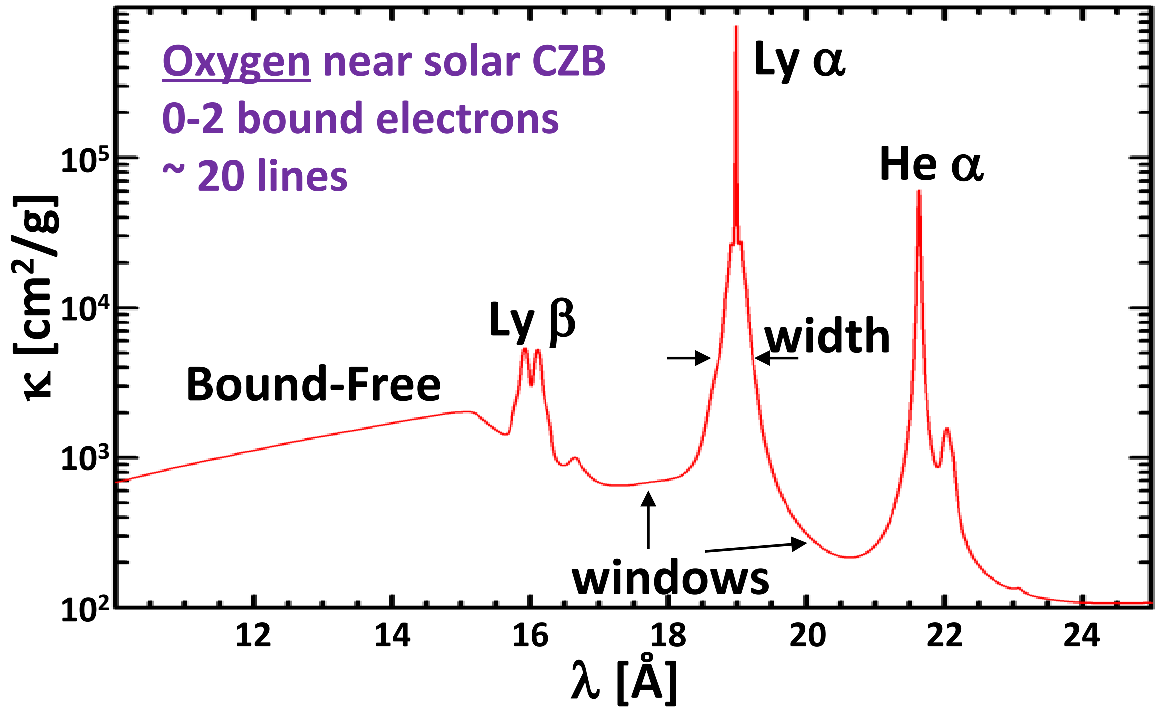


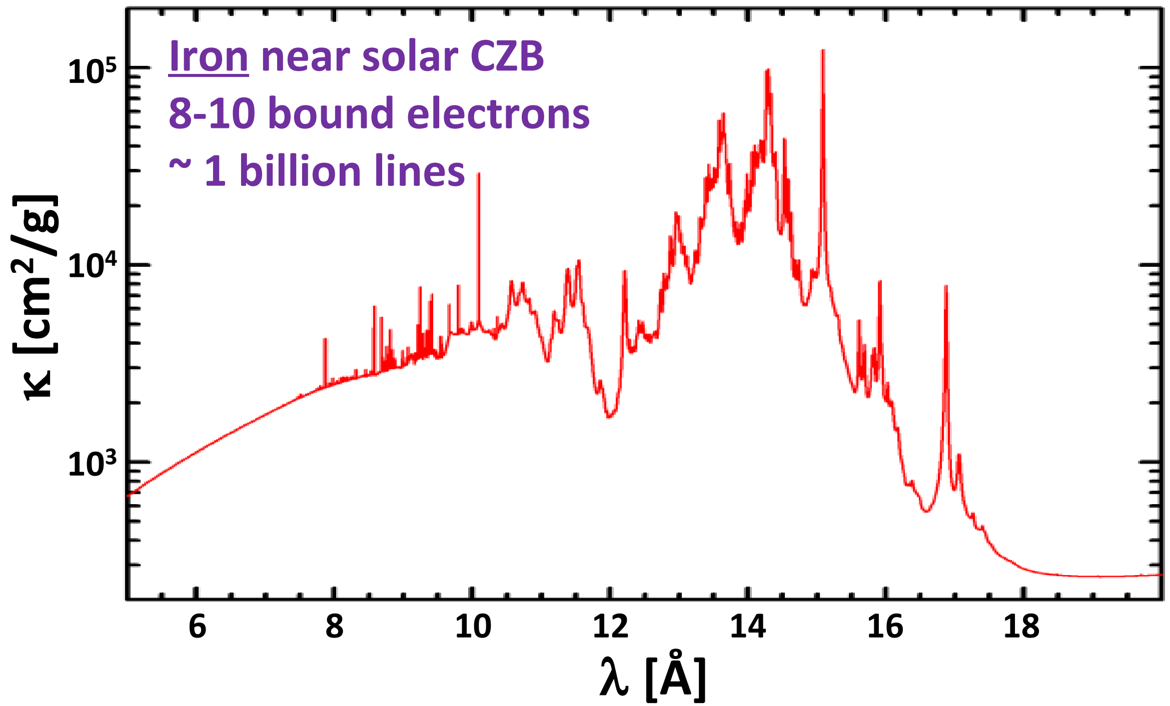
- Solar models disagree with precision helioseismic measurements.
- The discrepancy could be resolved if opacities are higher than models predict.
- O and Fe are dominant sources of opacity near the convection zone base (CZB).
  - Fe opacity measurements have revealed discrepancies with models at higher T_e and n_e.
  - If measured O opacity is also higher, it could further help resolve the solar problem.

Basu and Antia, *Phys Reports* (2008); Serenelli, *ApJ* (2009); Blancard, *ApJ* (2012); Seaton, *MNRAS* (1994); Bailey, *Nature* (2015)

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



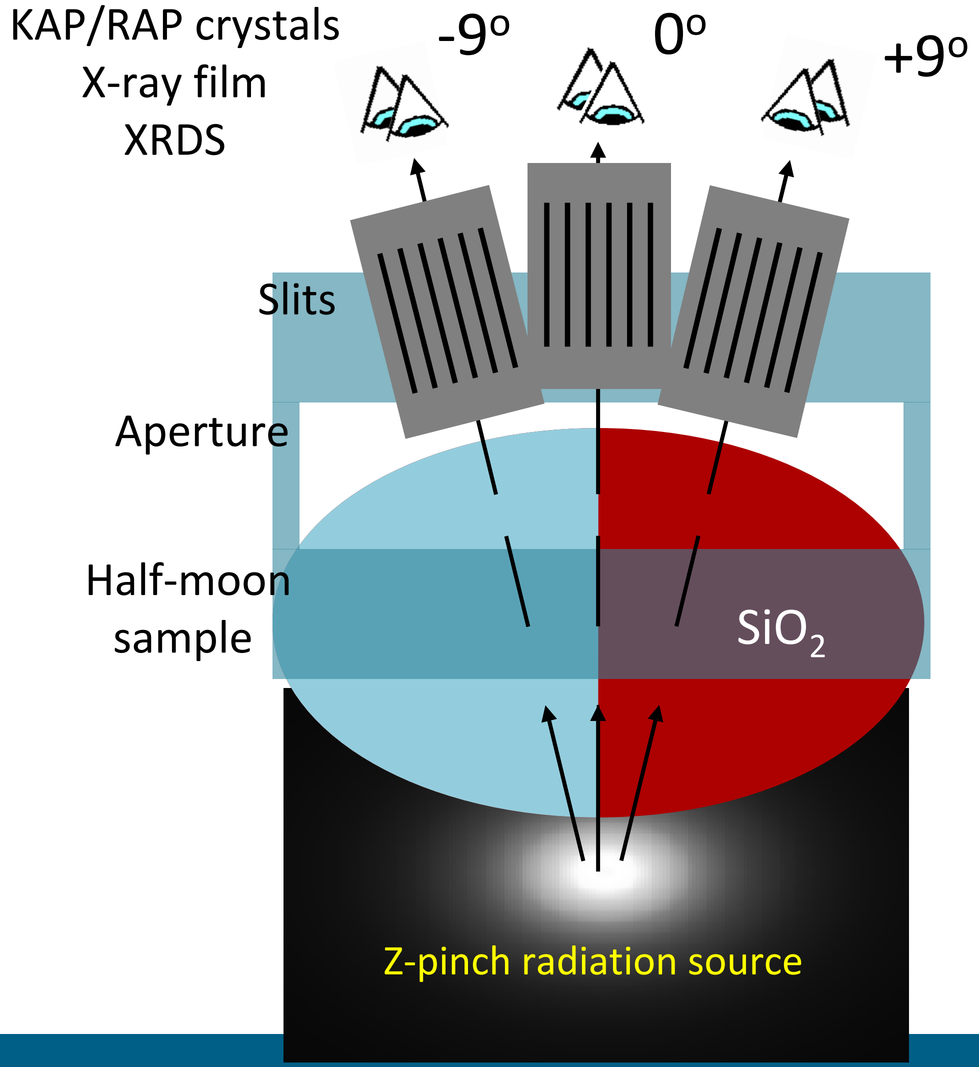


- Bare atoms do not have bound-bound or bound-free absorption.
  - ➢ ***Oxygen opacity is highly dependent on level of ionization.*** Iron is less affected by small ionization changes.
- Density effects: · · · · Affected features:

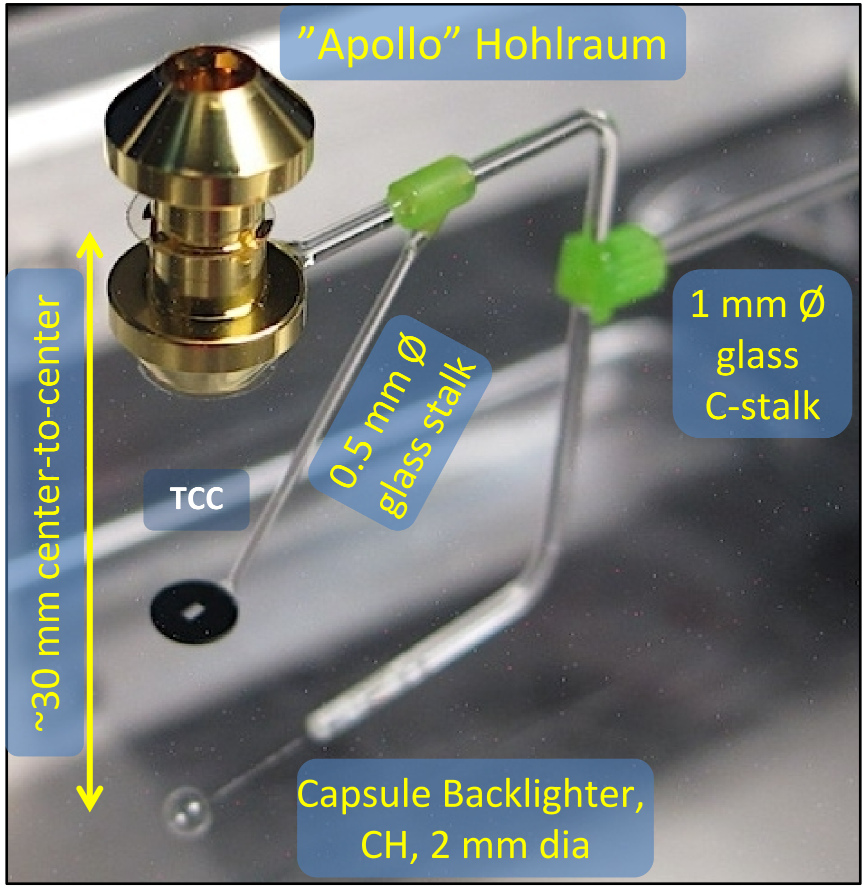
Density effects:		Affected features:
Line broadening	· · · · >	Opacity windows
Ionization potential depression	· · · · >	Bound-free absorption
Occupation probability	· · · · >	Ionization balance

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

Z Opacity Platform

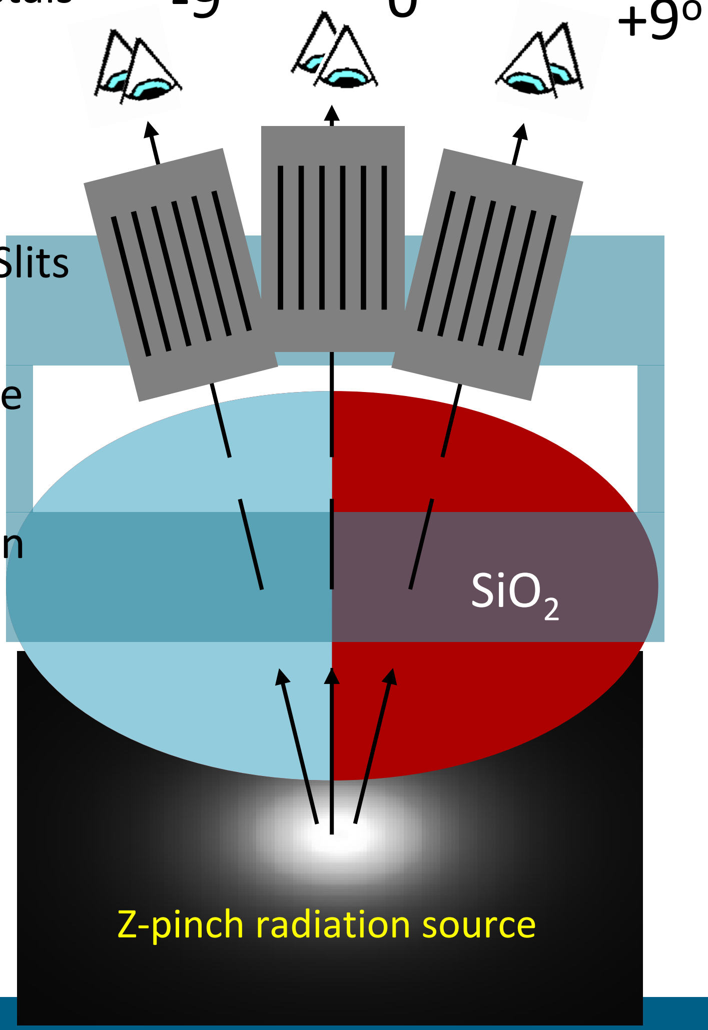


NIF Opacity Platform

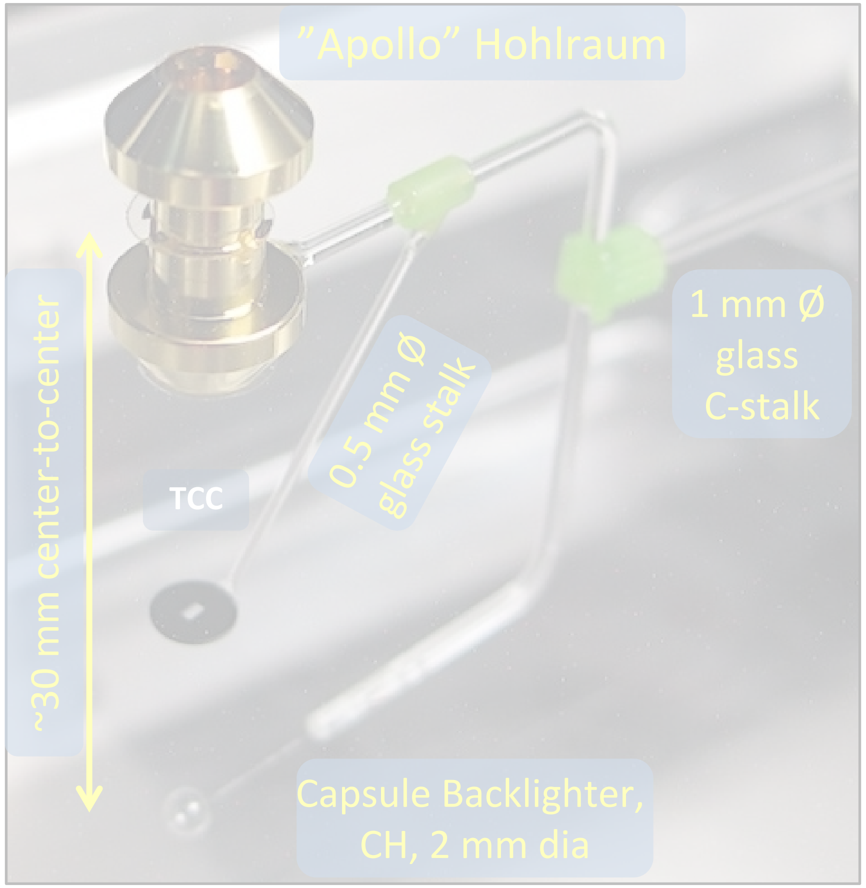


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

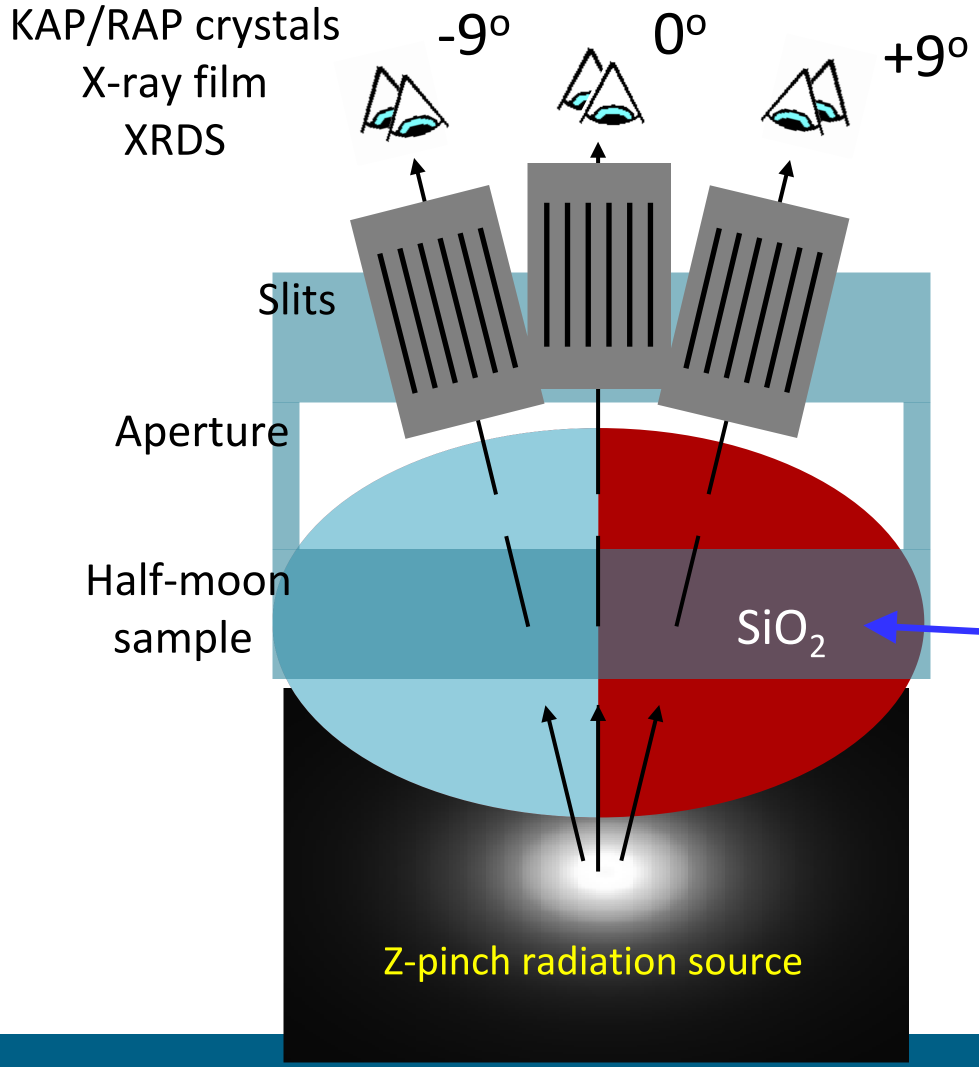


NIF Opacity Platform

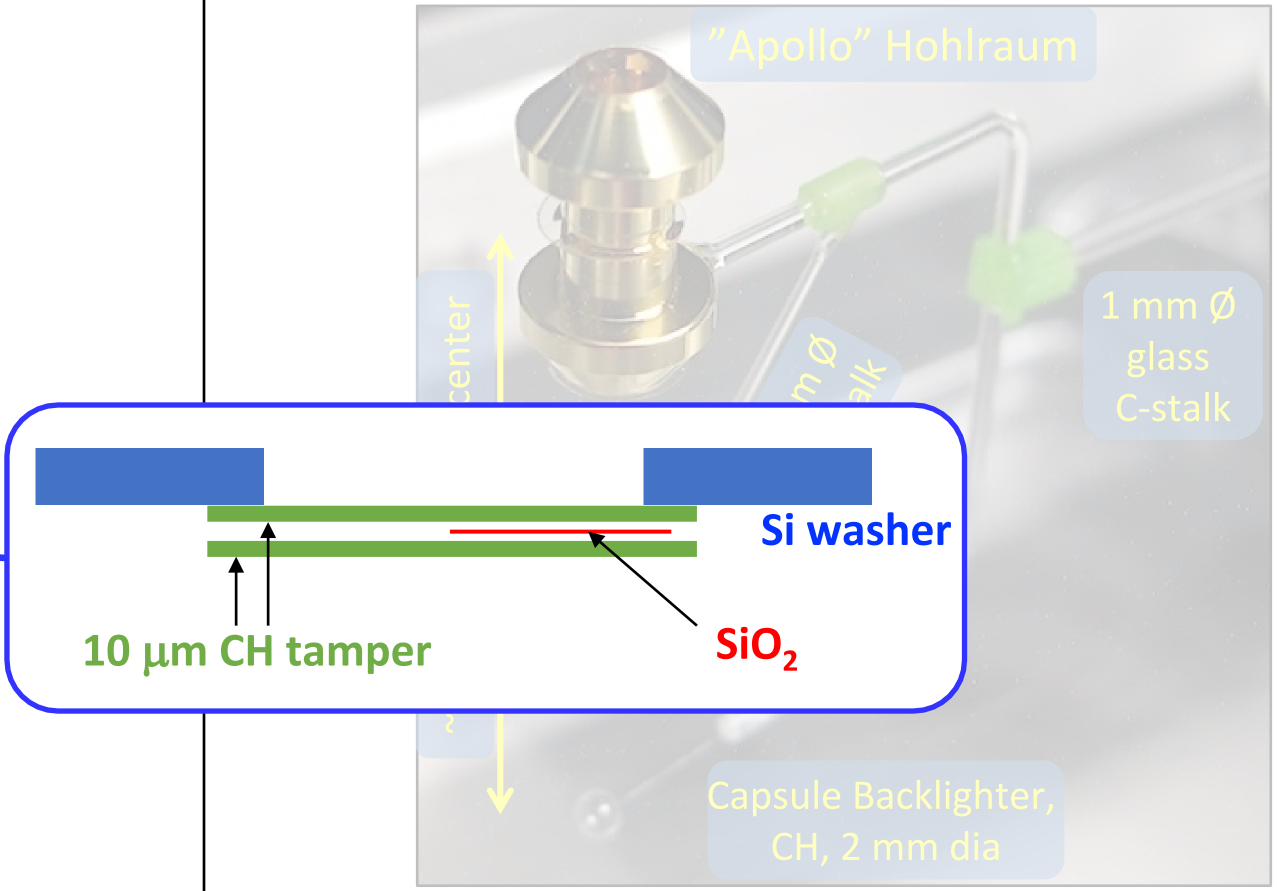


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

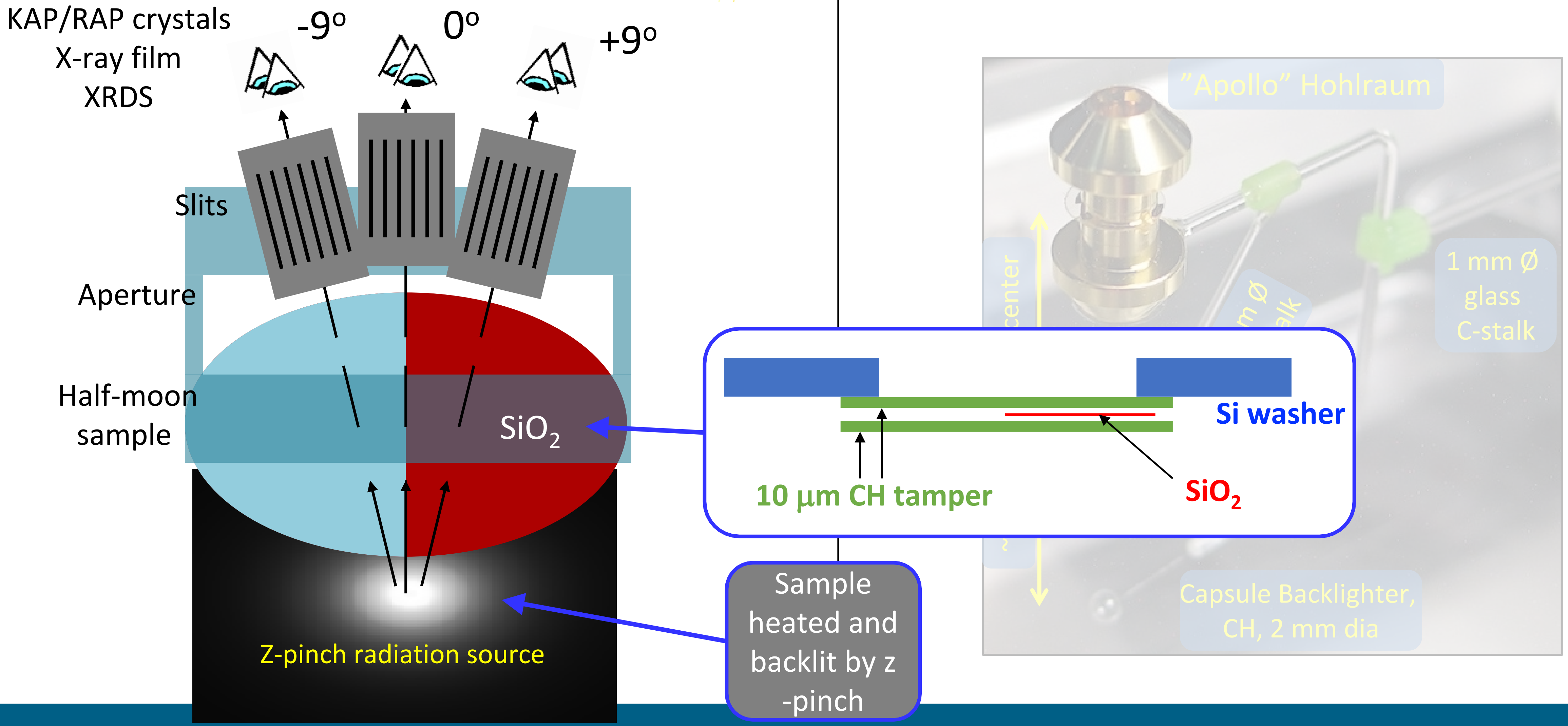


NIF Opacity Platform



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

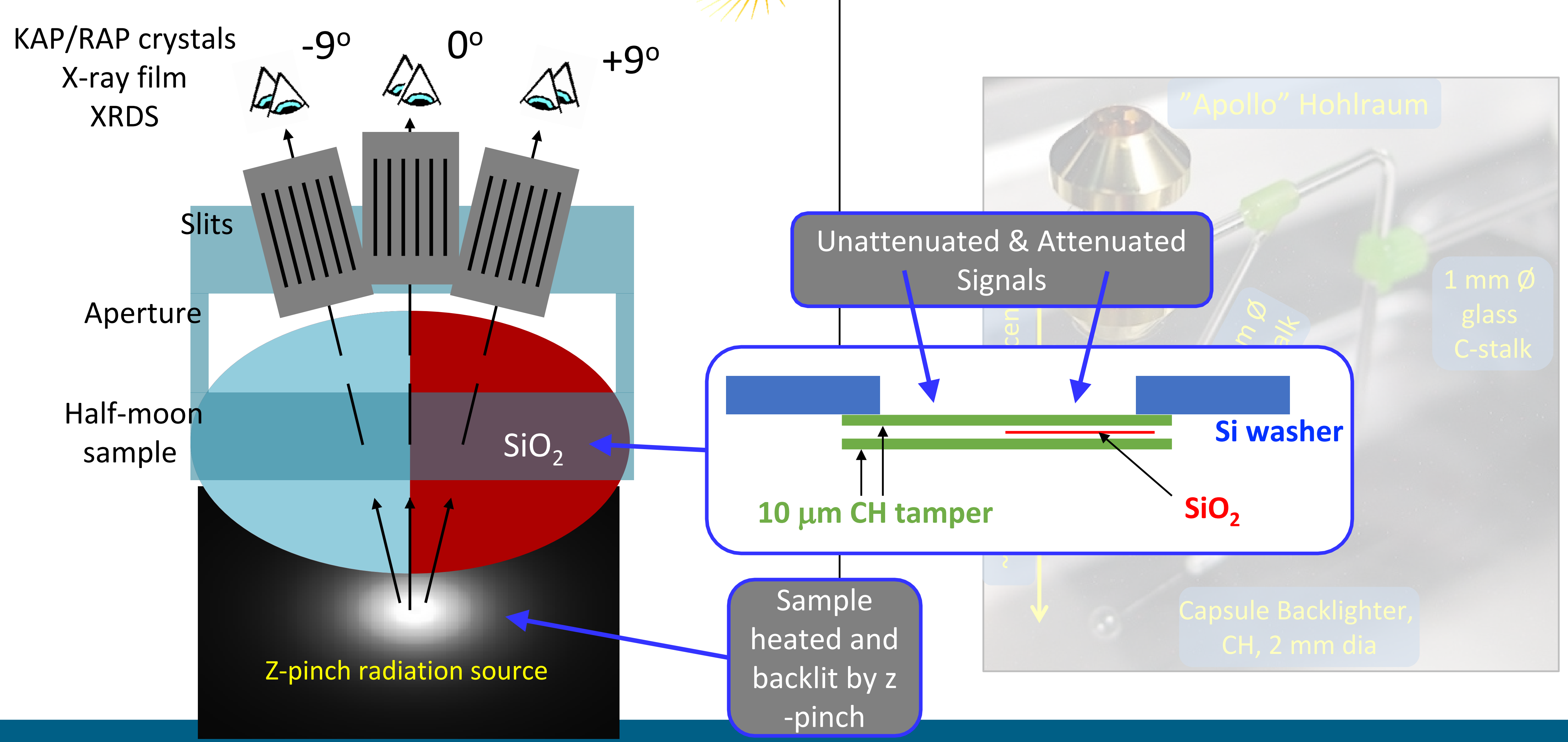
Z Opacity Platform | NIF Opacity Platform



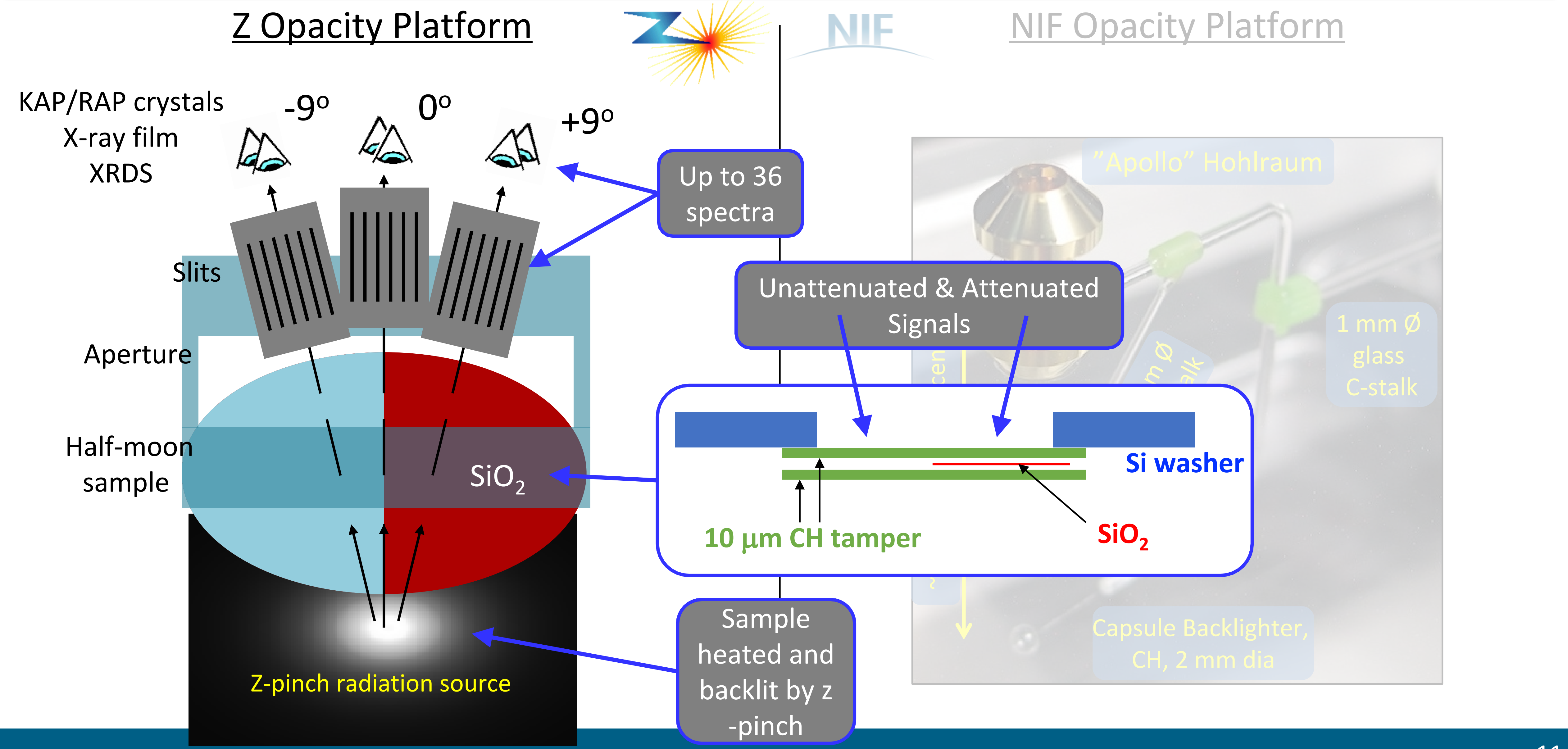
Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

NIF Opacity Platform

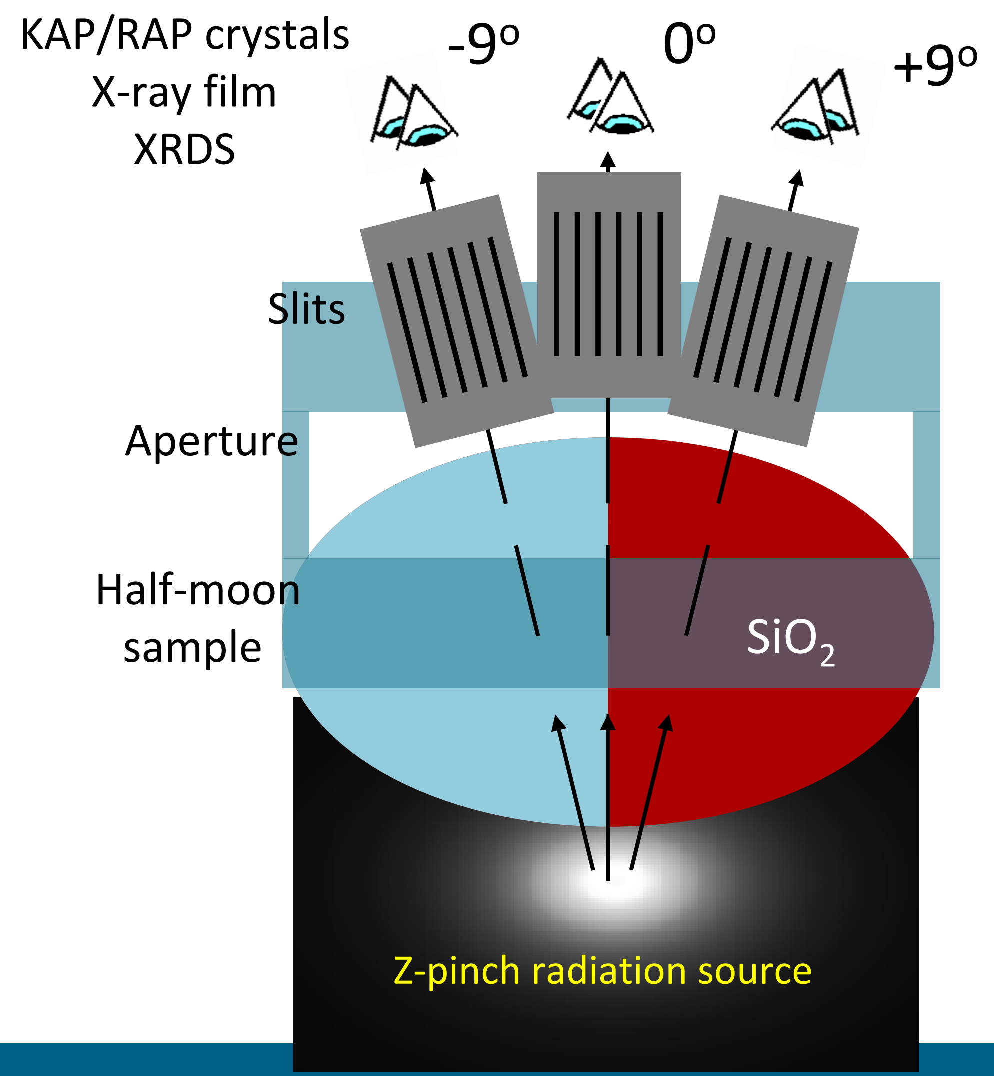


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

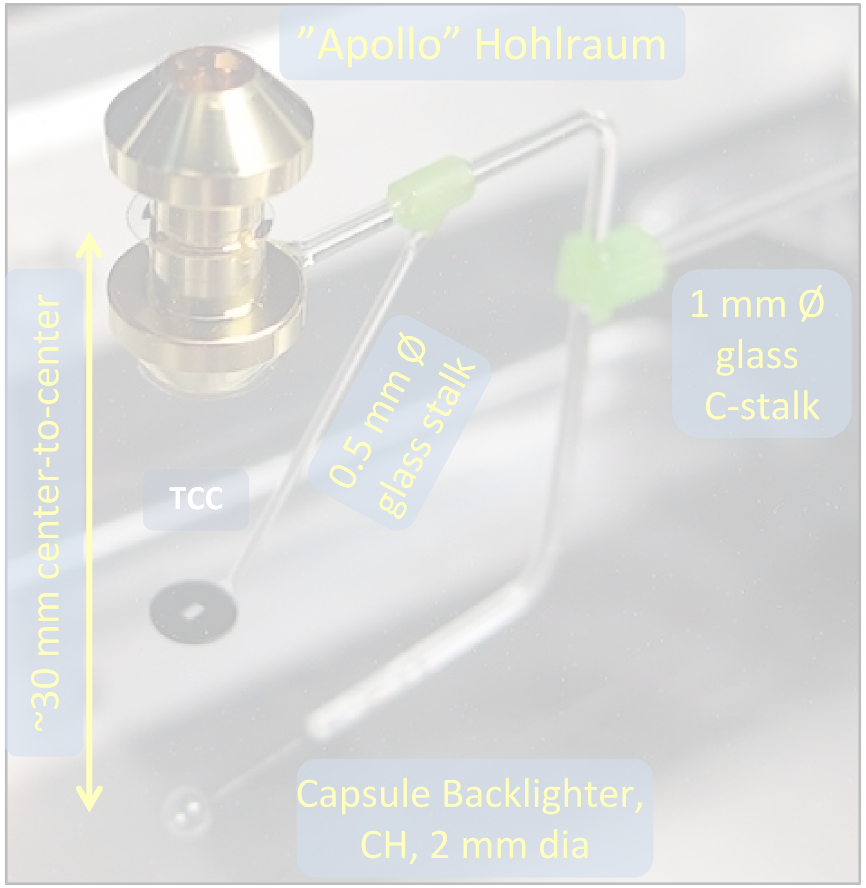


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

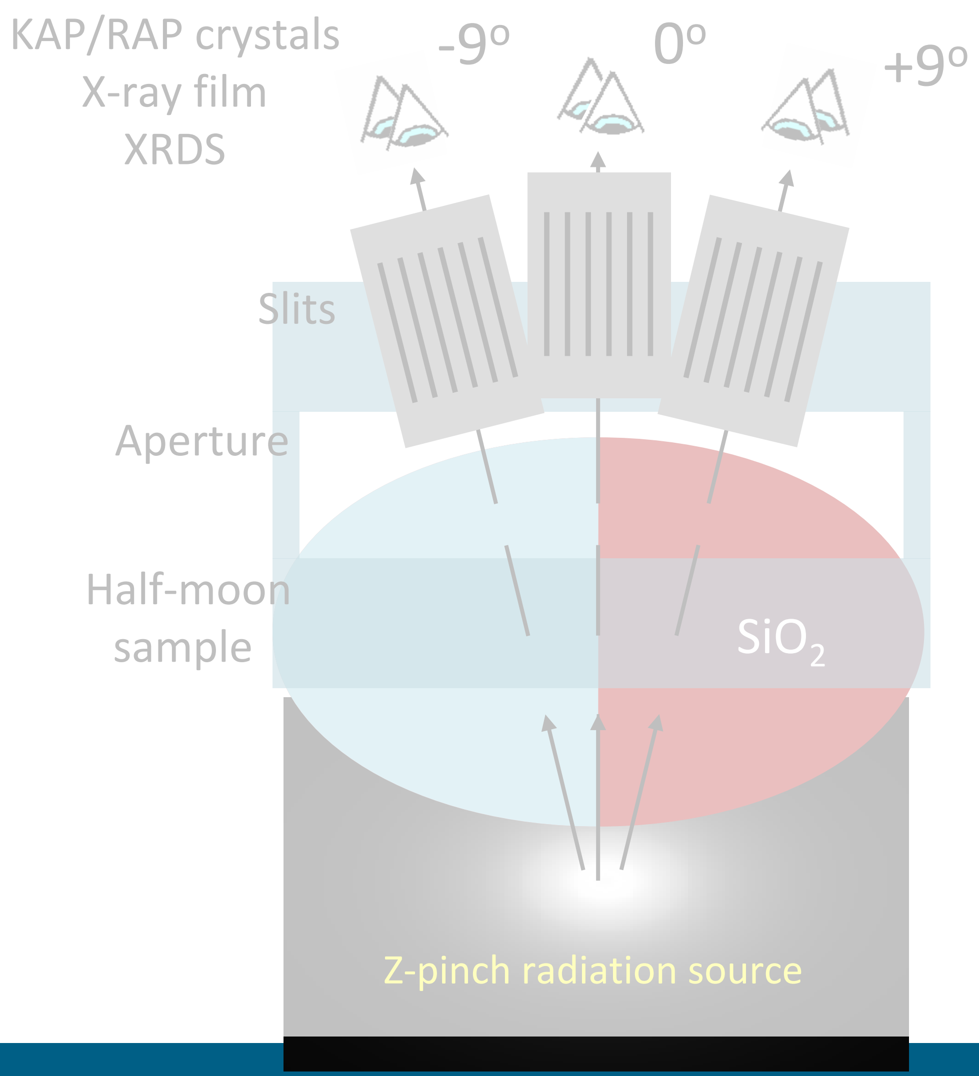


NIF Opacity Platform

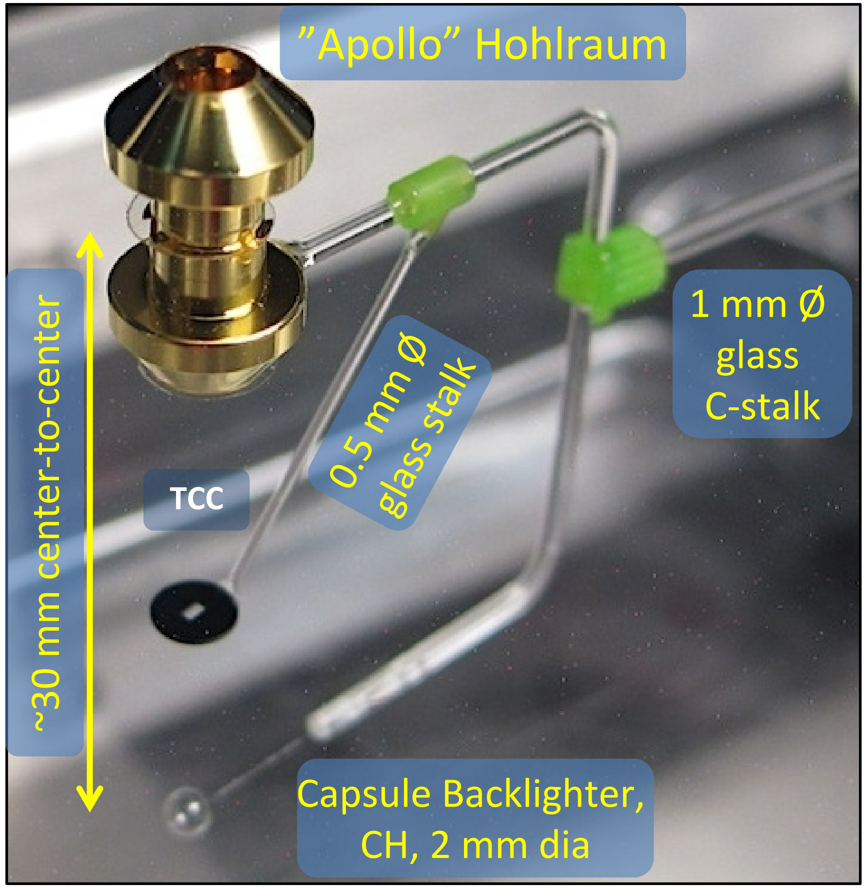


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

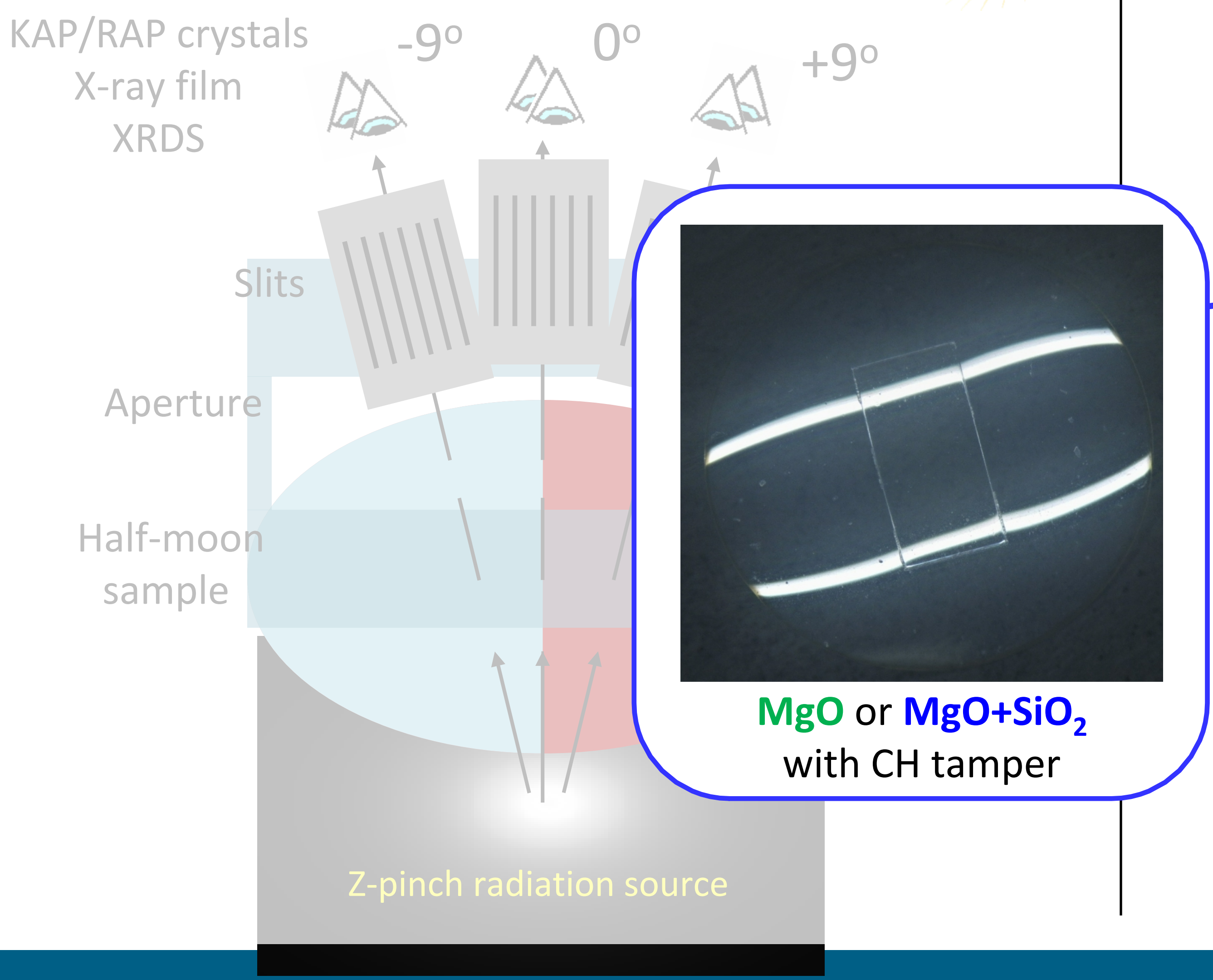


NIF Opacity Platform

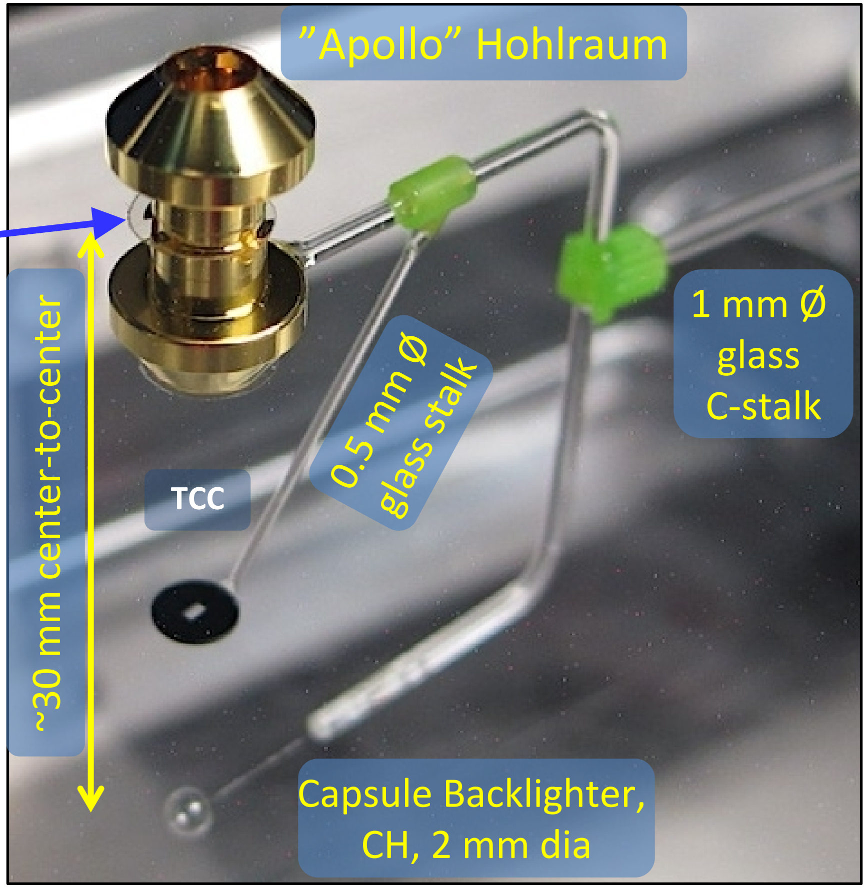


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

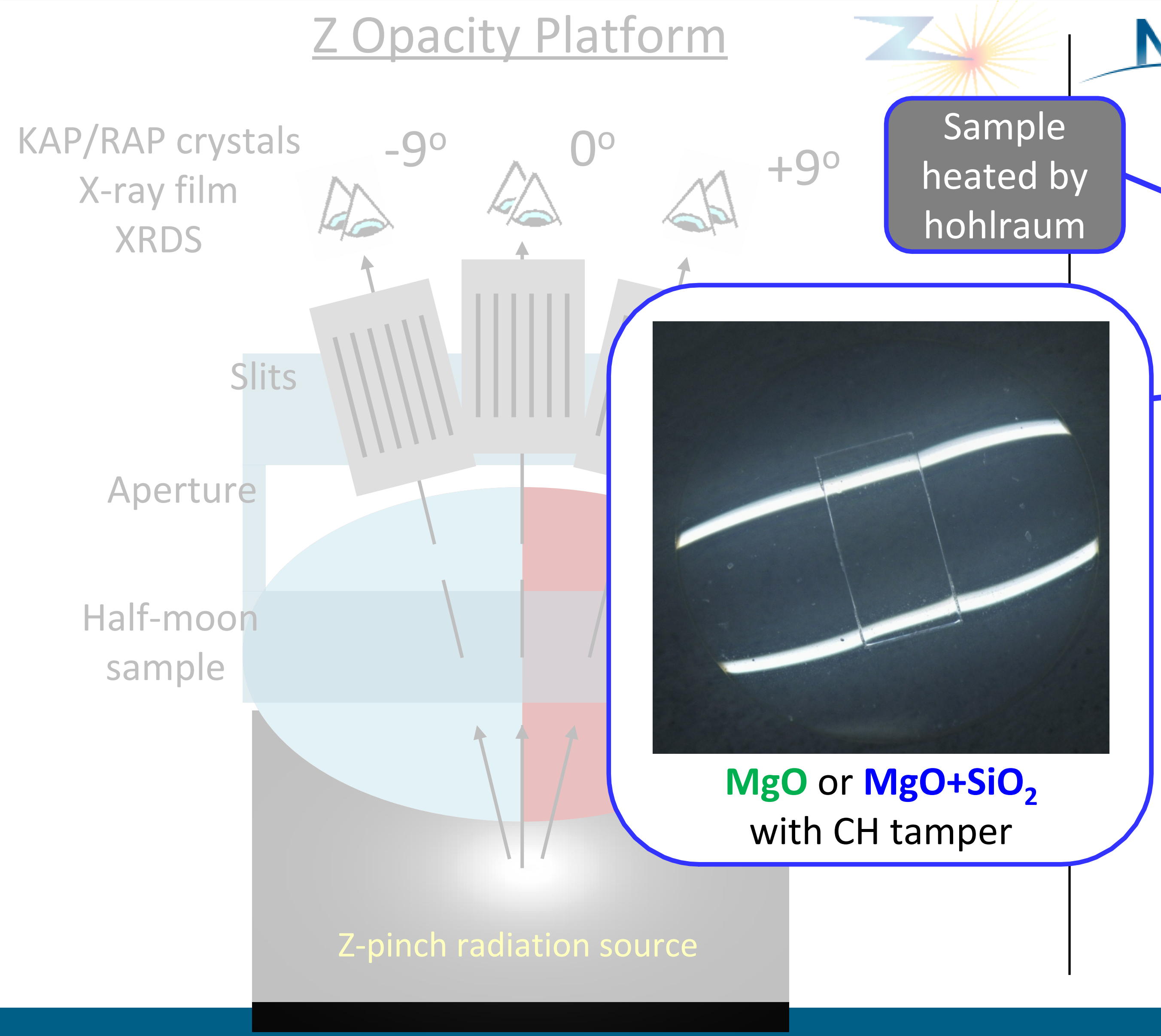
Z Opacity Platform

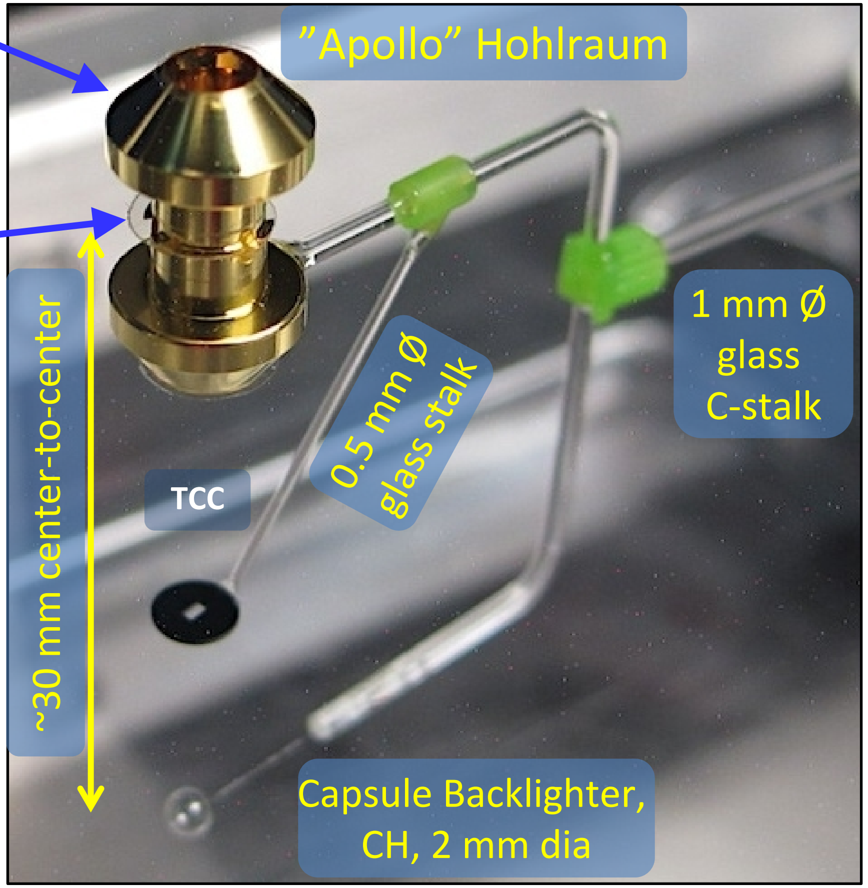


NIF Opacity Platform



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

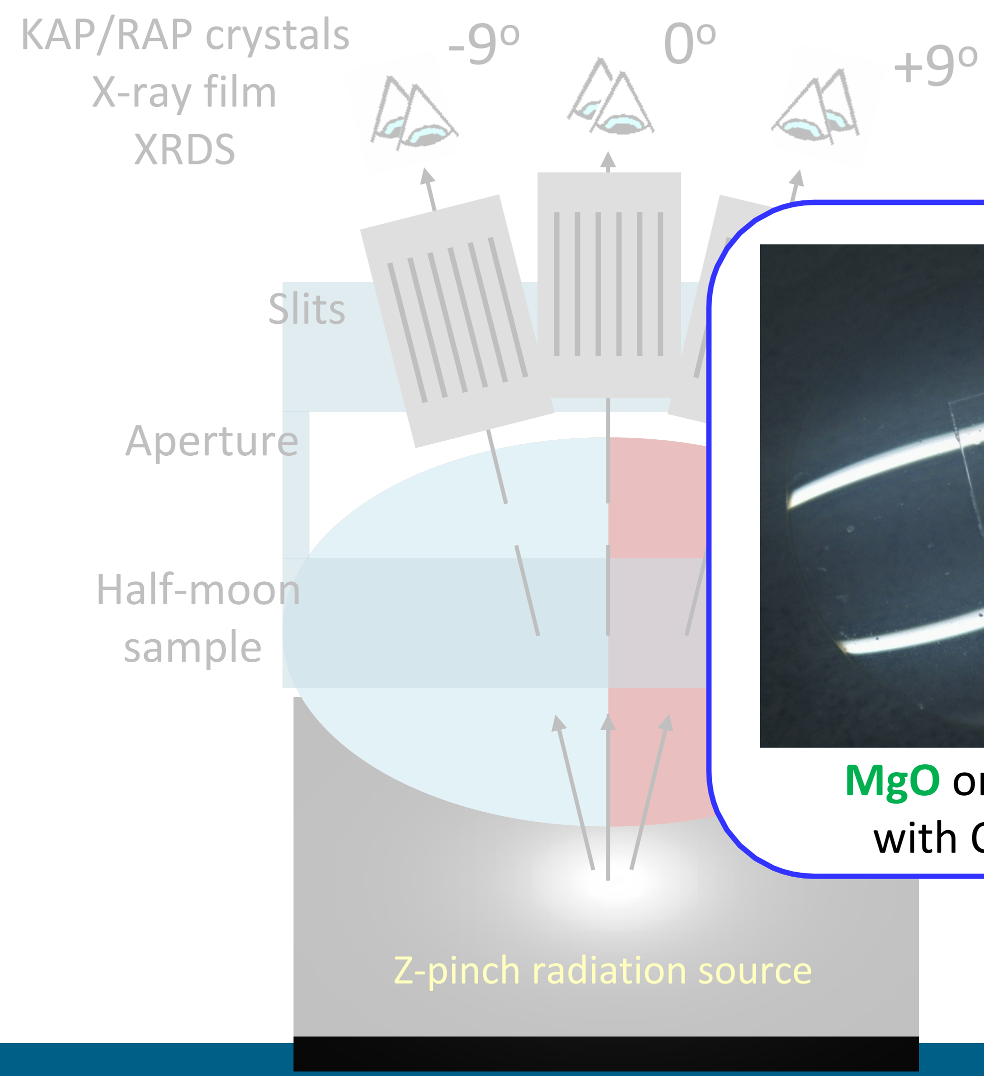




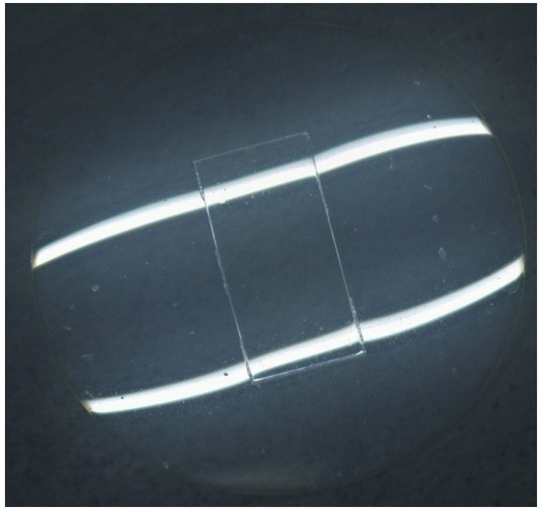
Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

NIF Opacity Platform

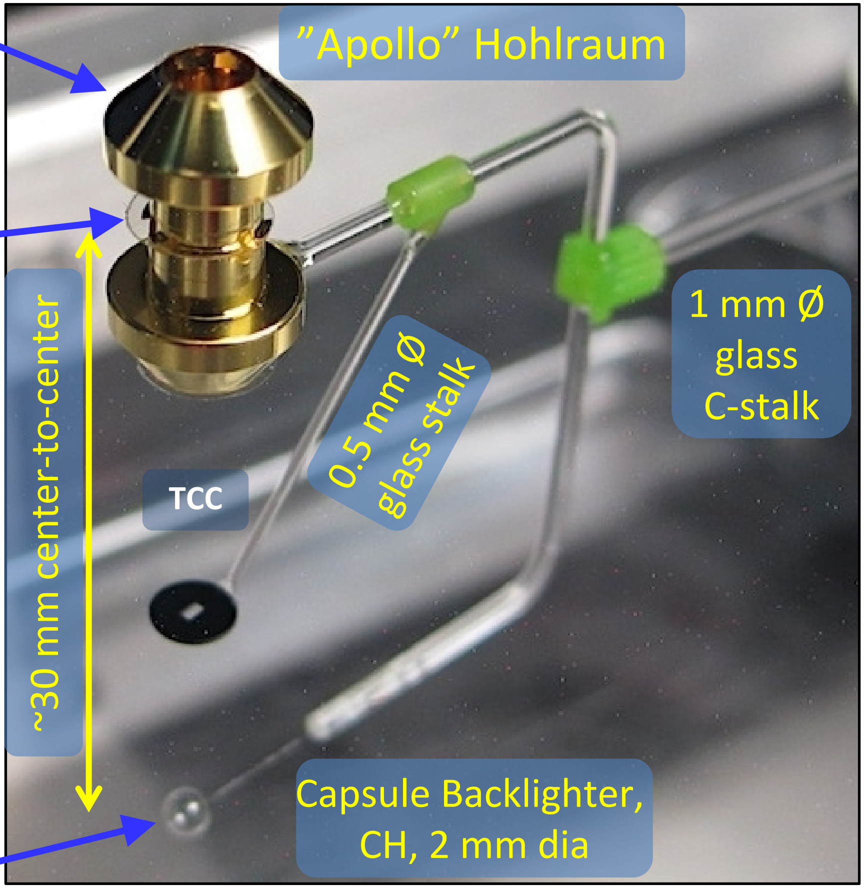


Sample heated by hohlraum

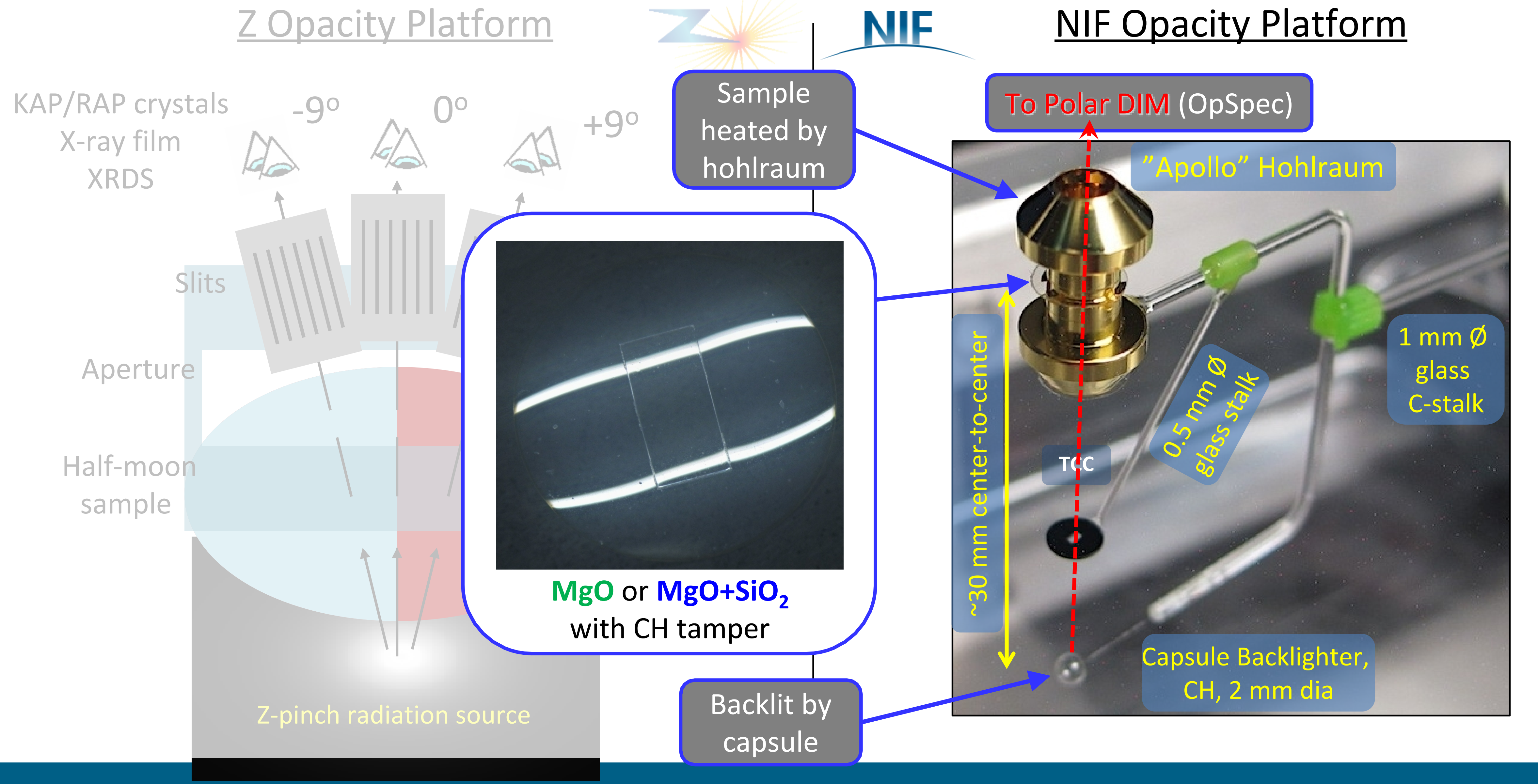


MgO or MgO+SiO_2
with CH tamper

Backlit by capsule

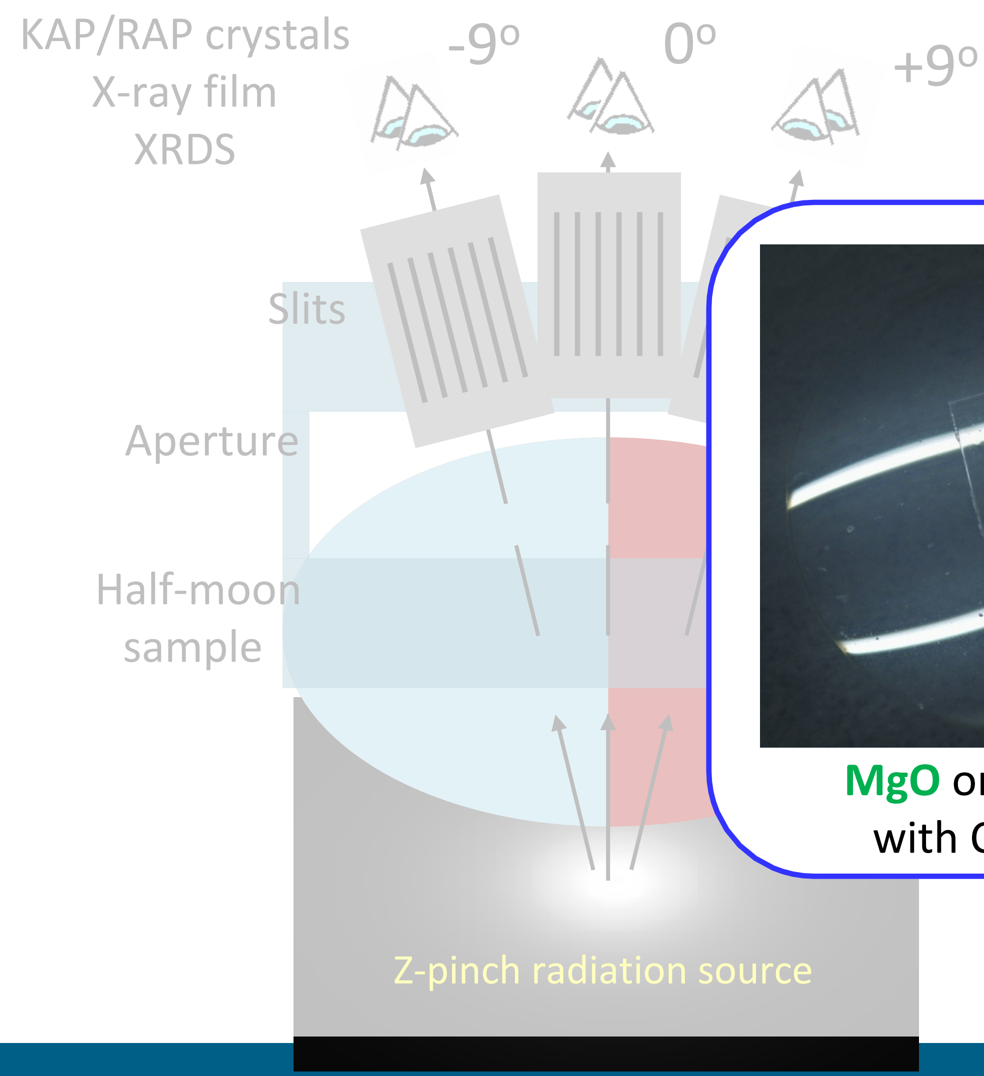


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

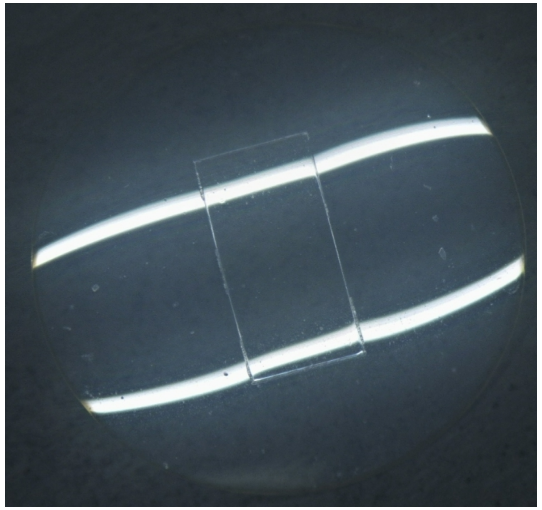


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform



Sample heated by hohlraum

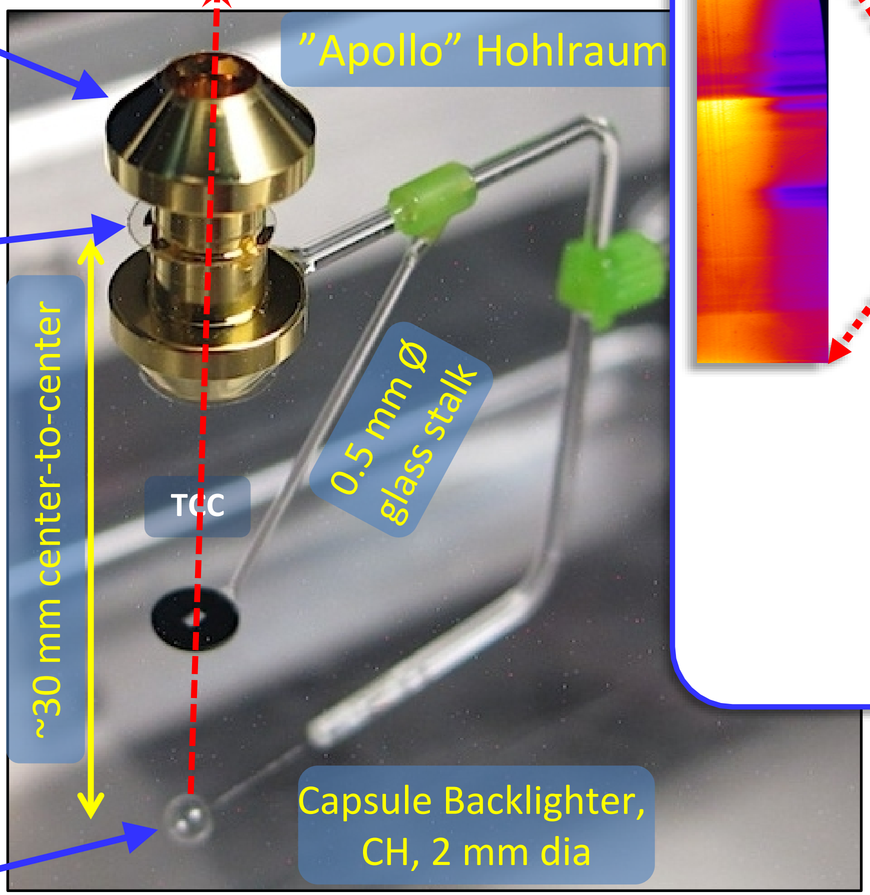


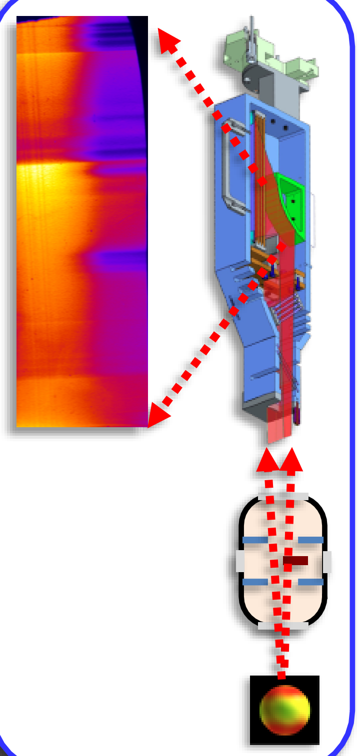
MgO or $MgO+SiO_2$ with CH tamper

Backlit by capsule

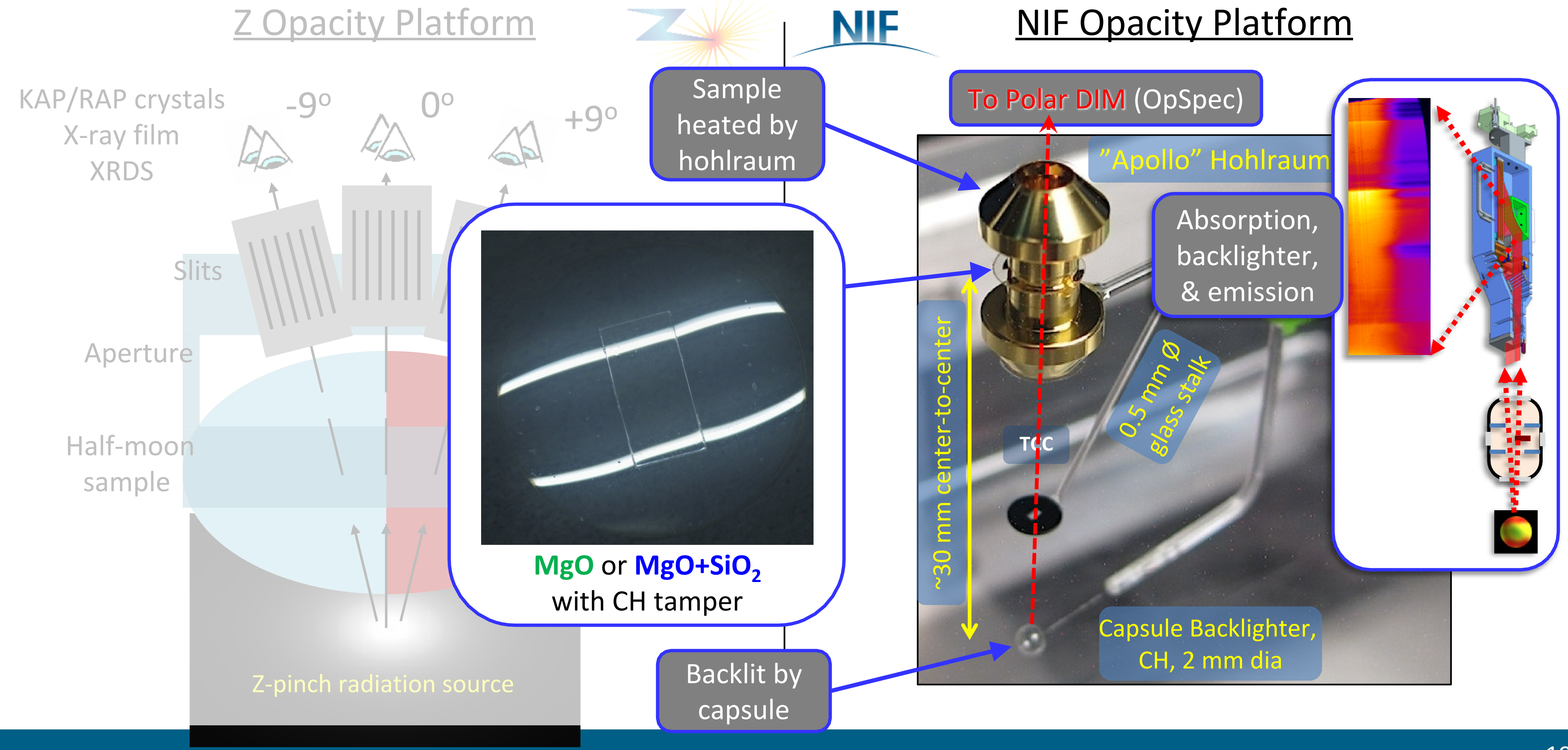
NIF Opacity Platform

To Polar DIM (OpSpec)

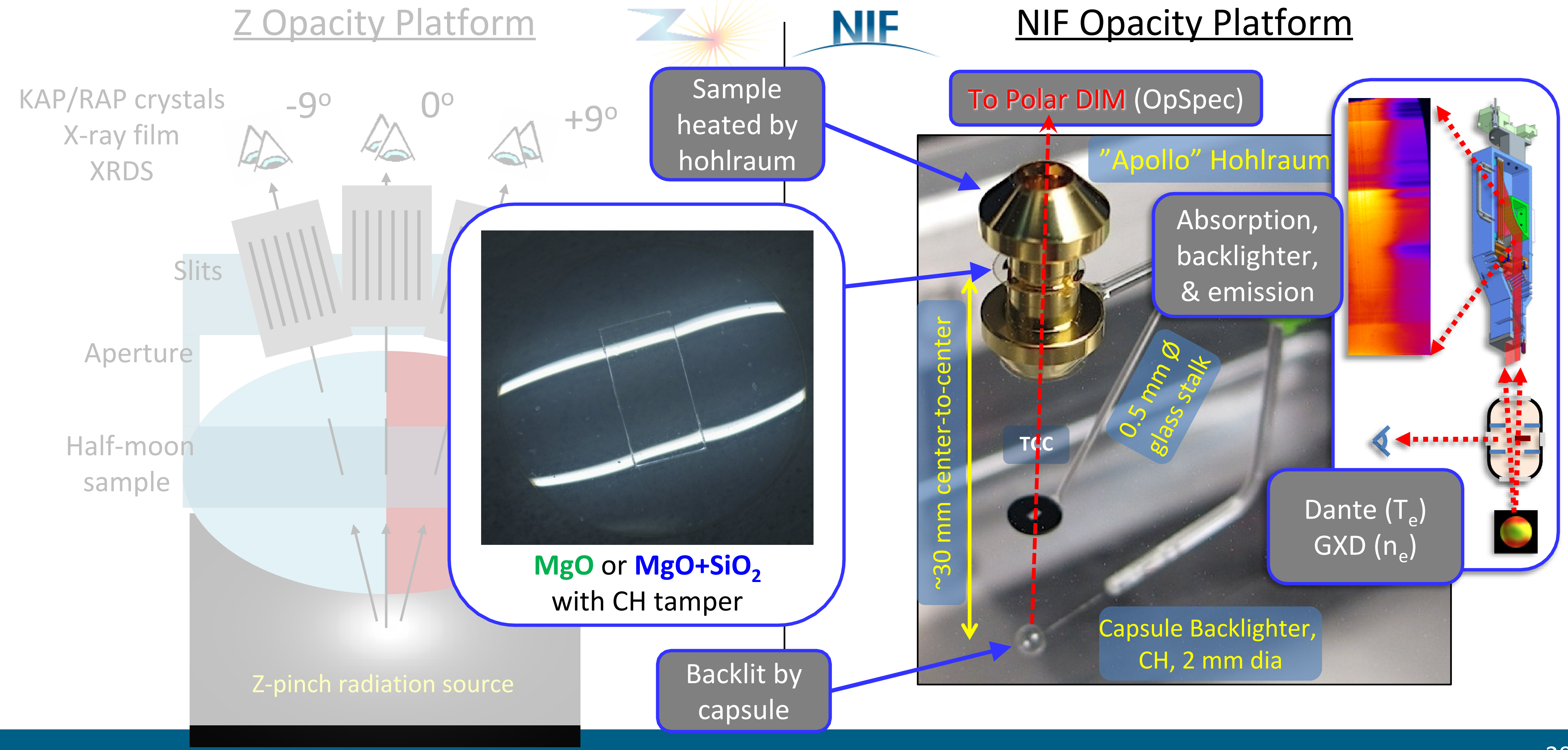




Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

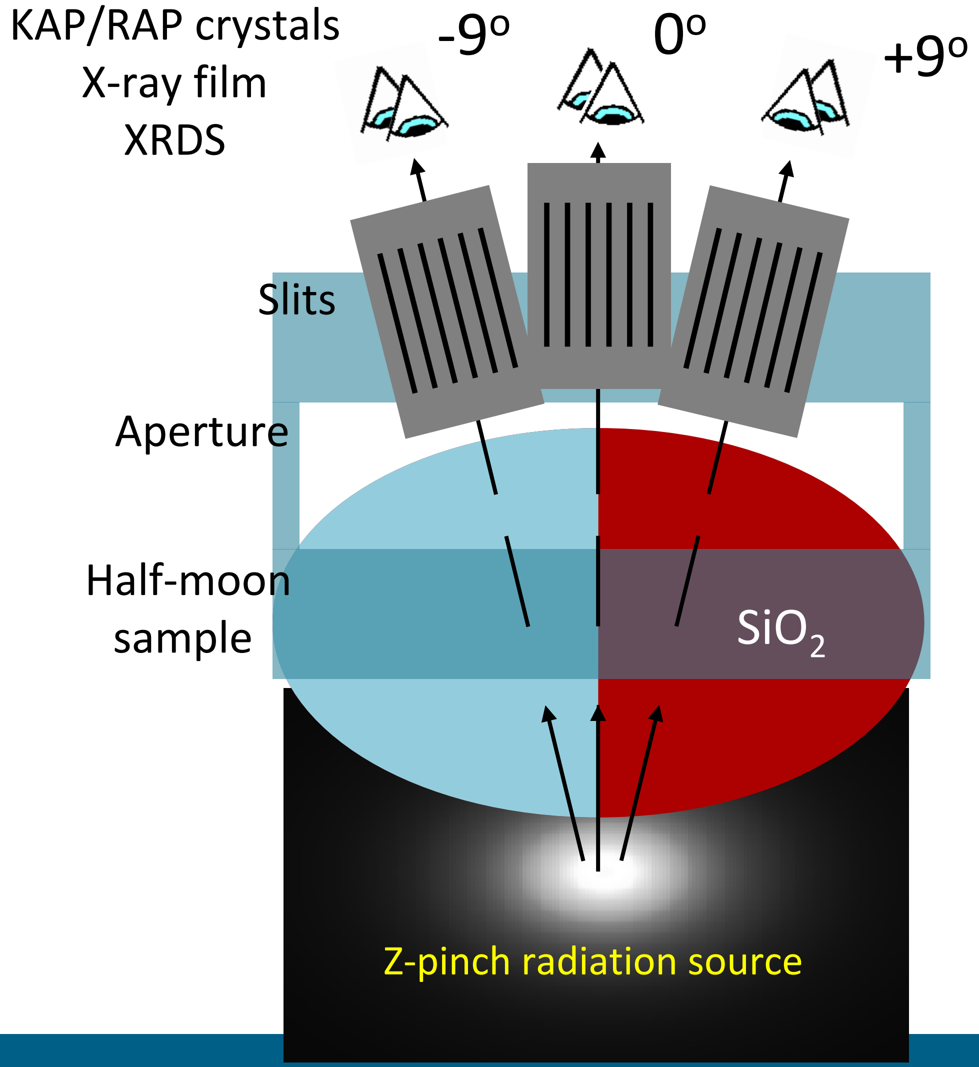


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

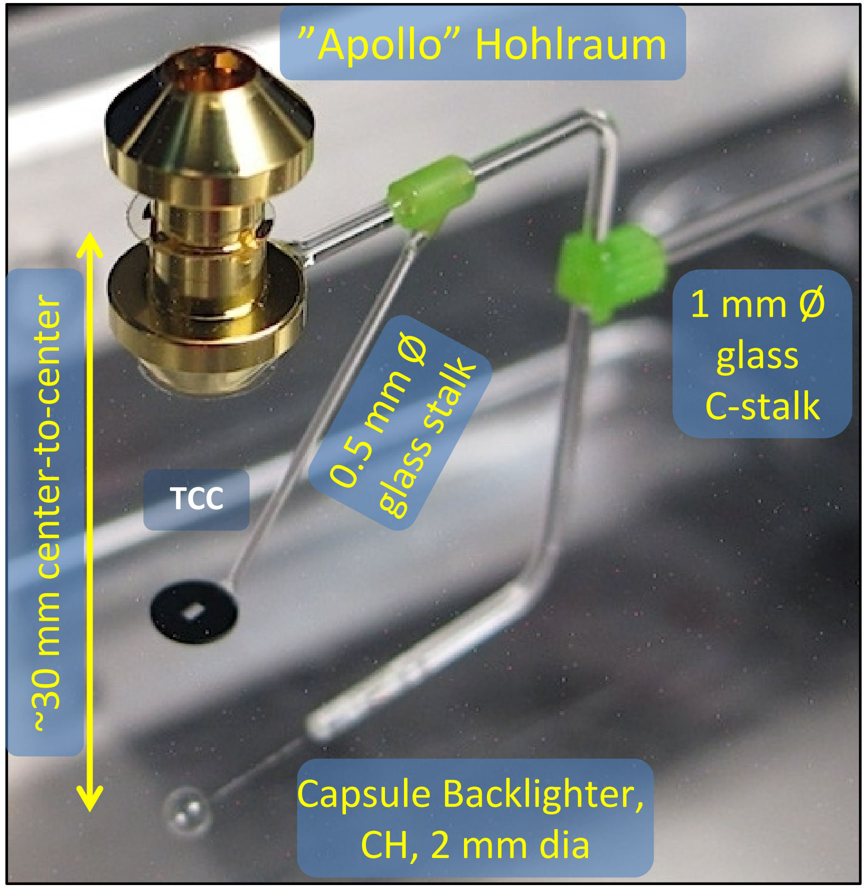


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

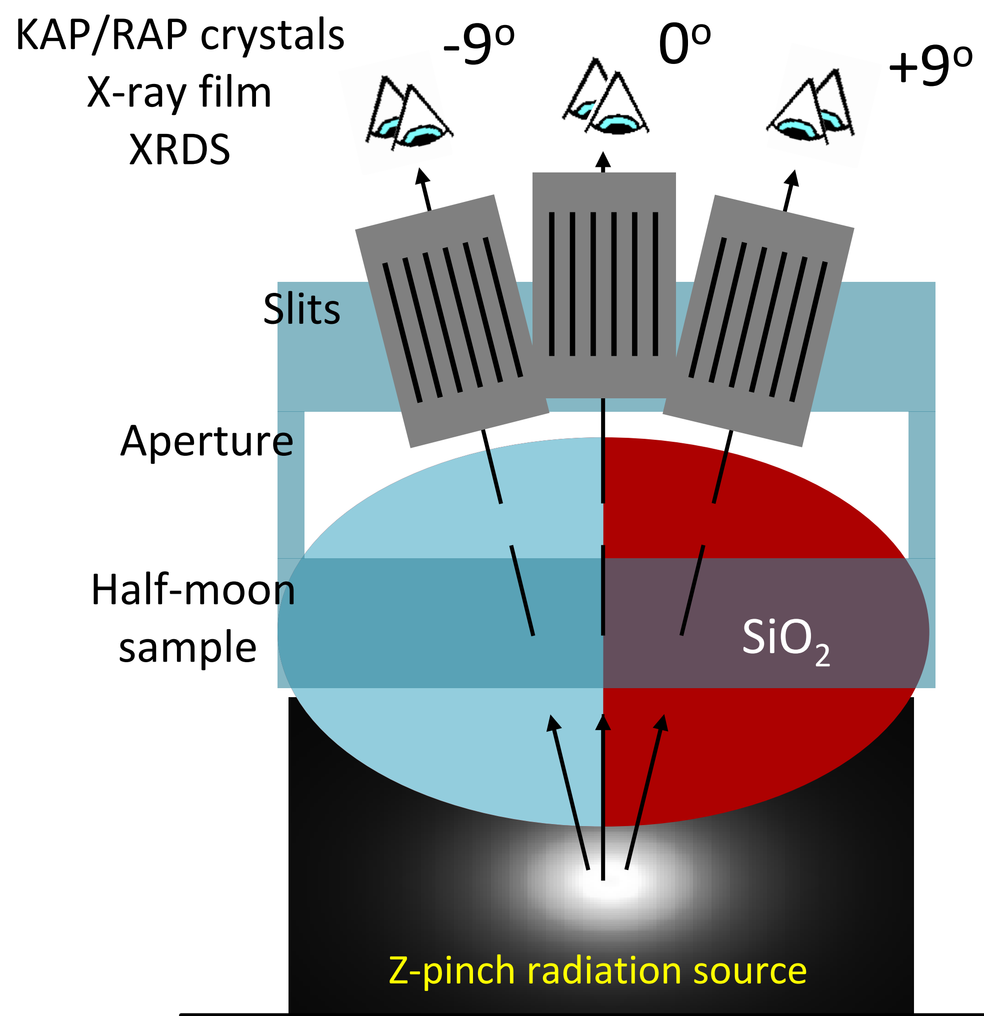


NIF Opacity Platform

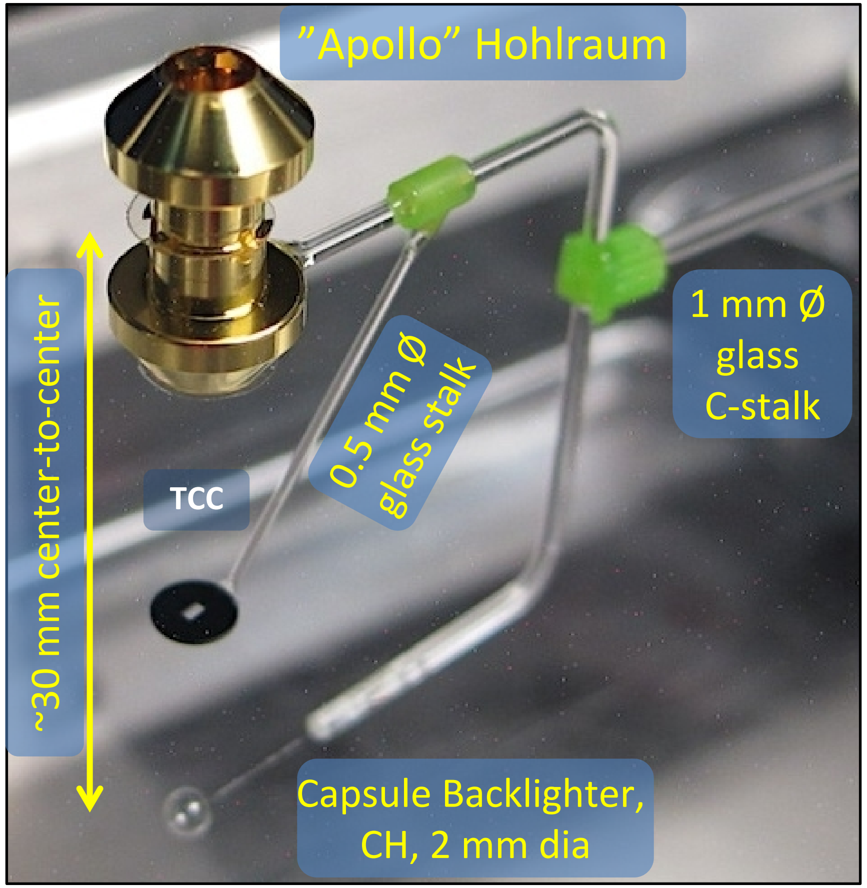


Oxygen opacity experiments relevant to stellar interiors are being done at both Z and NIF

Z Opacity Platform

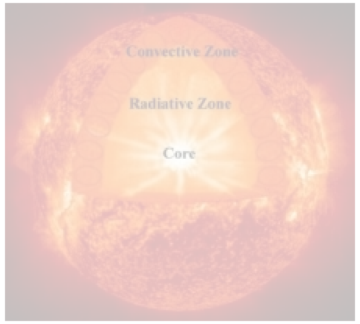


NIF Opacity Platform

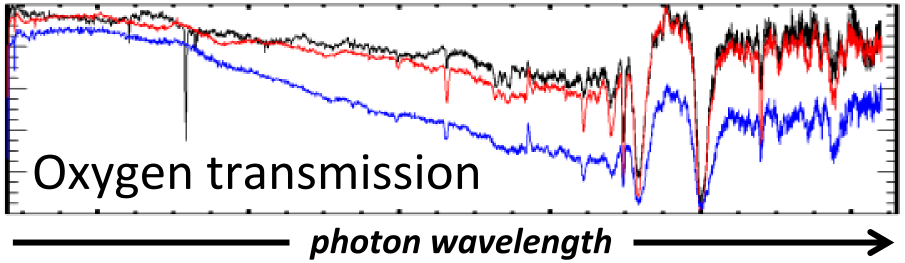


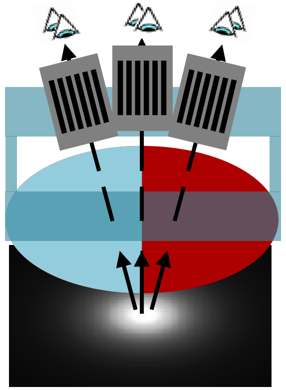
Complementary experiments permit cross-comparison to increase confidence in the results.

Summary: Oxygen opacity experiments at Z and NIF address key challenges for resolving the solar problem

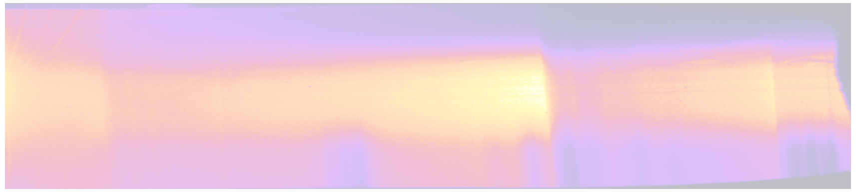


- Solar models and helioseismology disagree, and increased opacities could resolve the discrepancy.
- Oxygen is a major source of opacity at the solar convection zone base (CZB).
- Oxygen opacity measurements will test the treatment of density effects in modeled opacities.
- Cross-platform comparison (Z vs NIF) of results will increase confidence in the findings.



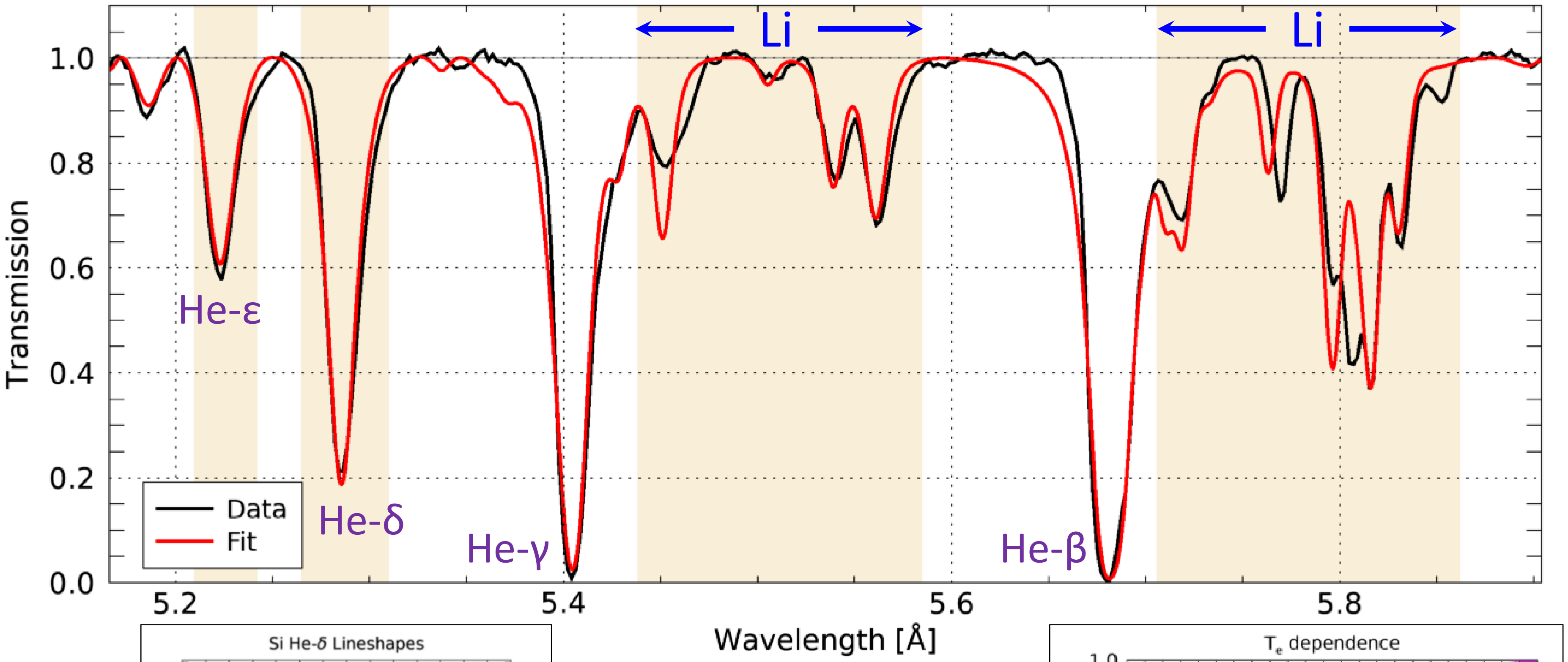


- Oxygen opacity was successfully measured at T_e~160 eV and n_e~8e21 e/cc.
- Preliminary model-data comparison already shows interesting disagreement.
- First measurements performed at higher T_e and n_e, closer to the solar interior.

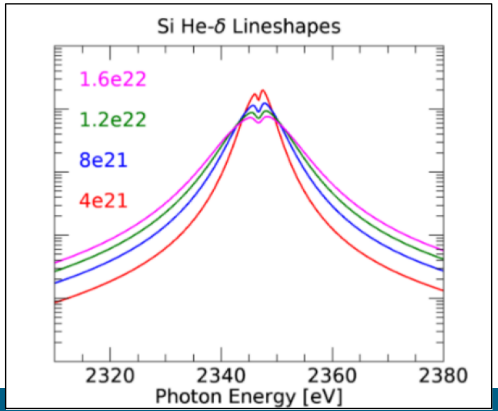


- Oxygen transmission measured at T_e~140 eV and N_e~2e22 e/cc.
- Preliminary model-data comparison shows interesting disagreement.
- Improvements to experiments:
  - Sample expansion measurement
  - Low-energy band spectrum

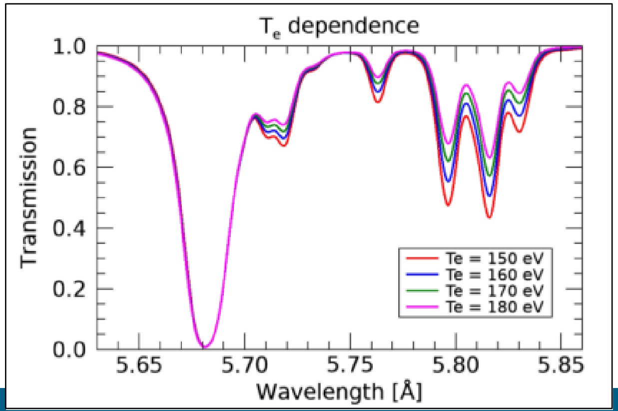
Silicon line transmission is used to diagnose the plasma conditions (T_e and n_e)



- Preliminary conditions: **T_e~160 eV, n_e~8e21 e/cc**
- Accurate conditions are required to produce reliable model-data comparisons.
- For O opacity known to 10%, we need to know:
  - n_e ~ 12%
  - T_e ~ 2%

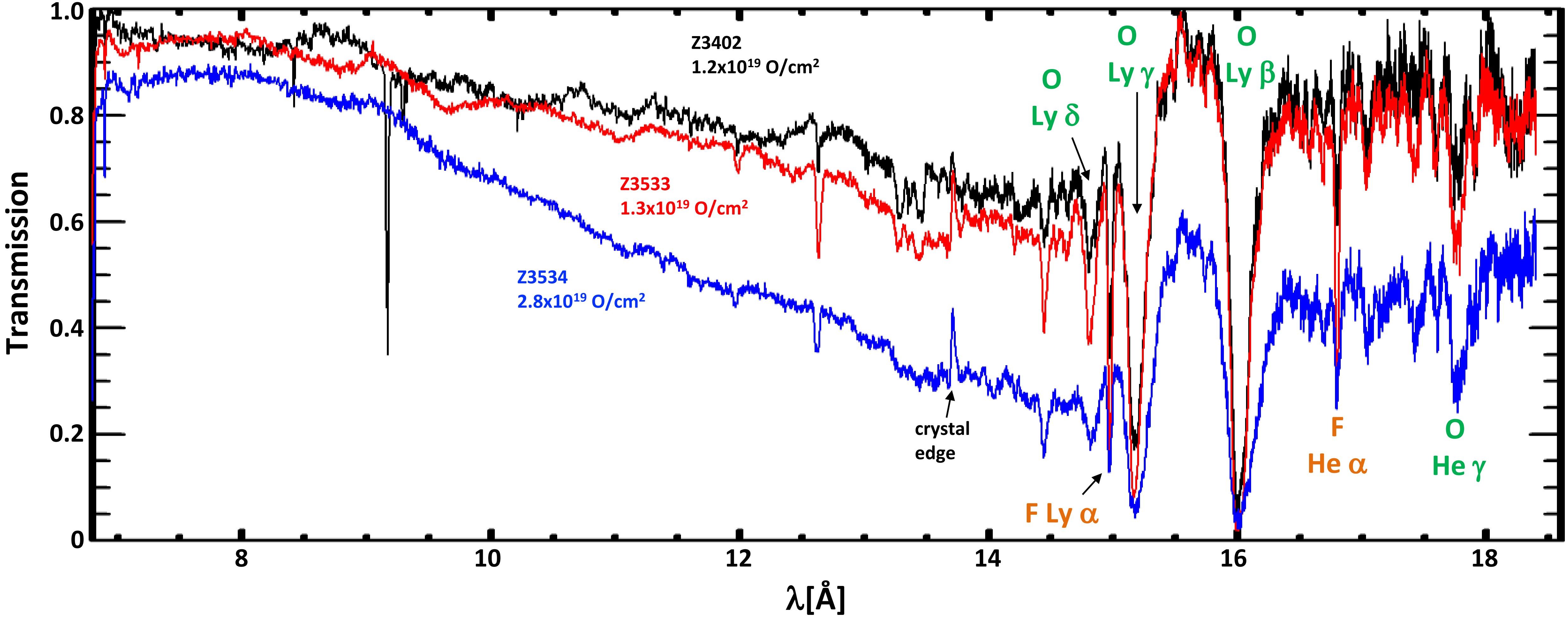


← ***n_e*** is constrained by line widths.



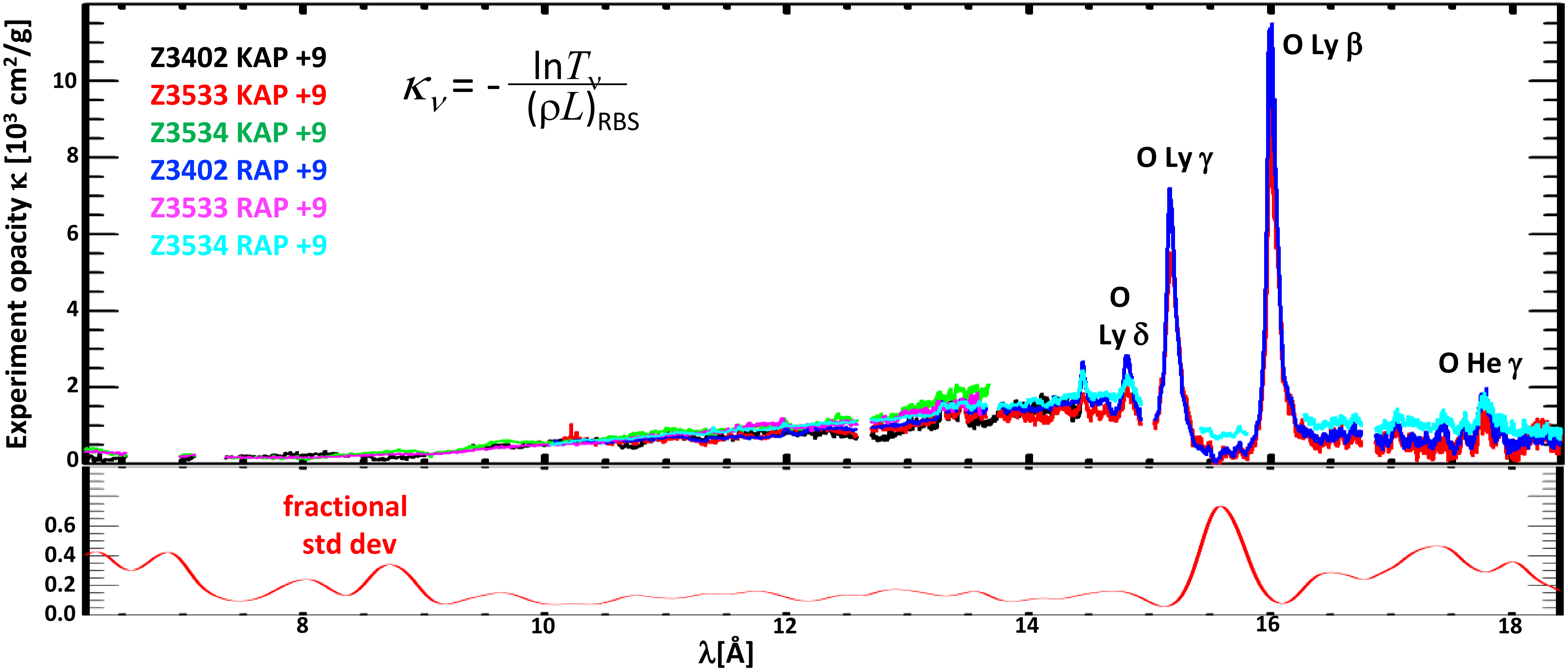
← ***T_e*** is inferred from ratio of Li-like to He-like lines.

Preliminary analysis provides transmission from three oxygen opacity experiments at two different areal densities



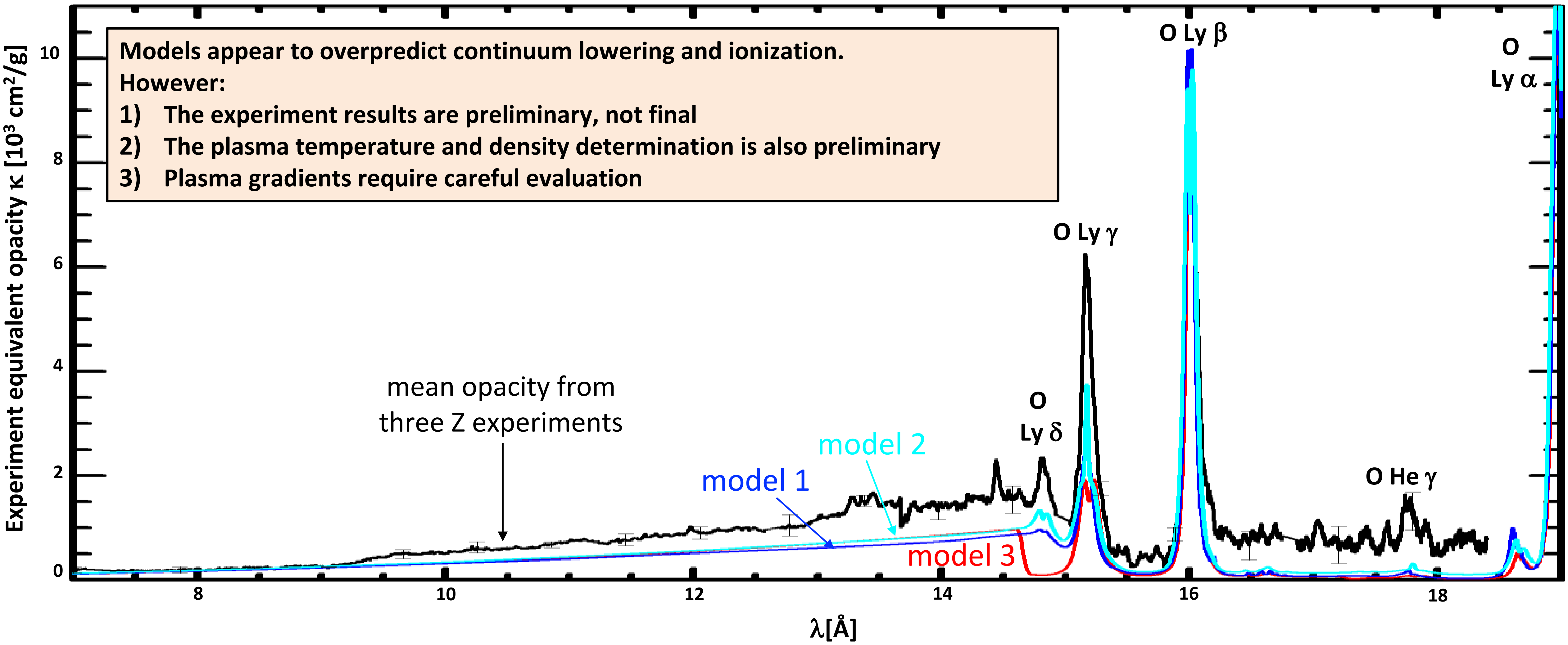
- Multiple experiments test reproducibility
- Different areal densities help assess accuracy and expand dynamic range

Preliminary oxygen opacity measurements are reproducible

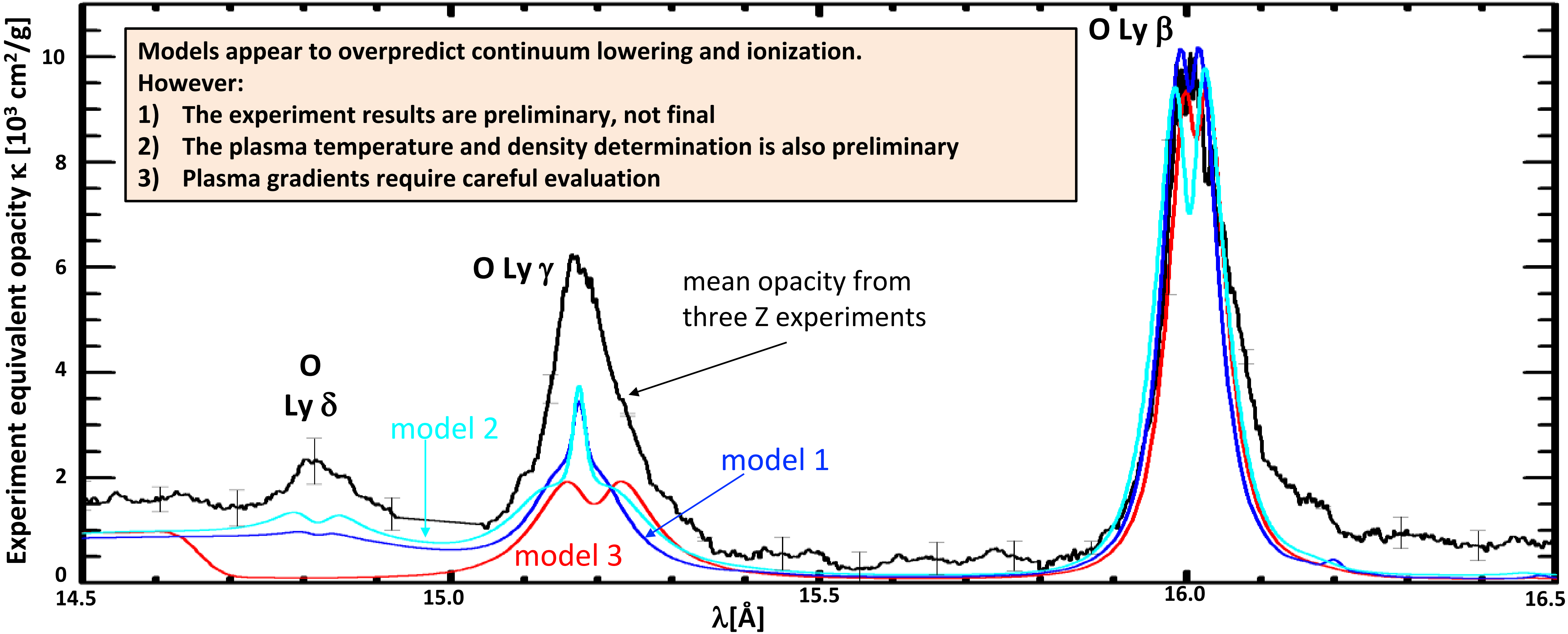


Preliminary reproducibility better than +/- 20% over 9-15 Angstroms
Refined analysis in progress
There are 12 more spectra to include from these three shots

Preliminary Z measurements provide the first tests of oxygen opacity models at high energy density conditions



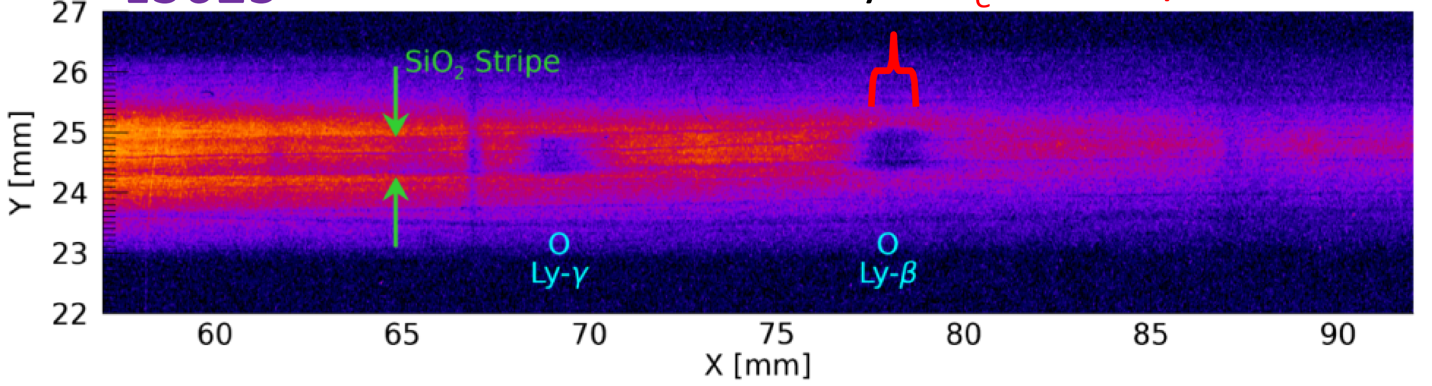
Preliminary Z measurements provide the first tests of oxygen opacity models at high energy density conditions



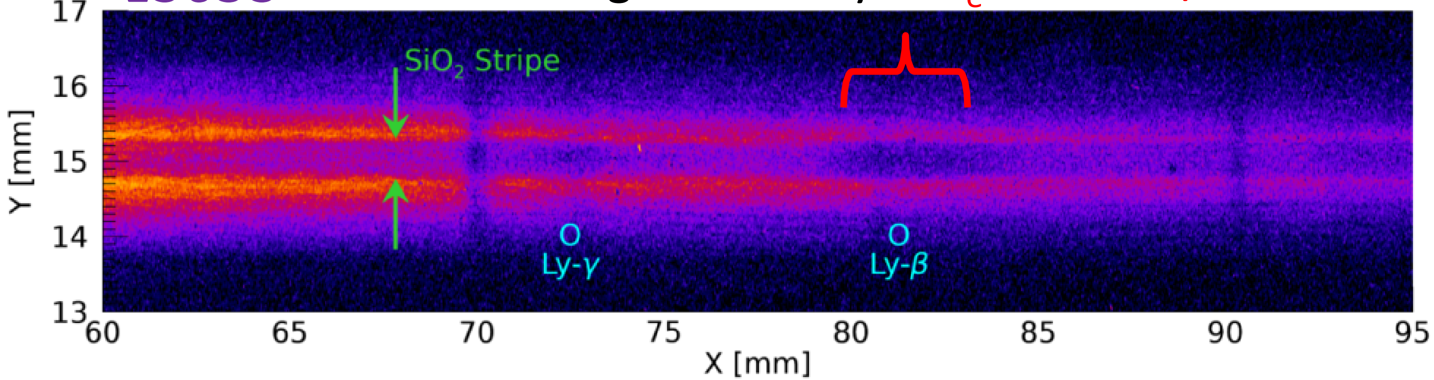
The models don't even agree with each other

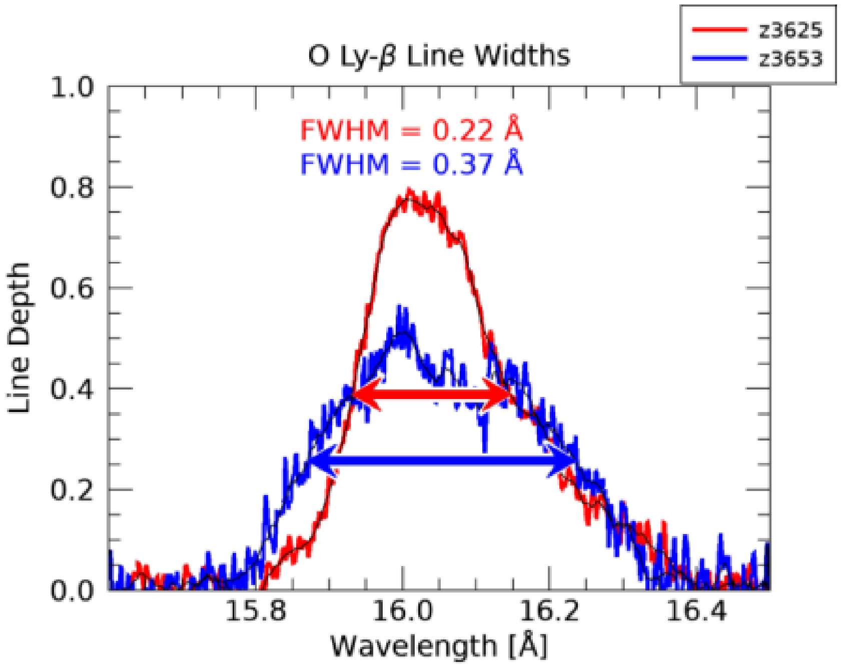
First measurements were obtained at conditions closer to solar CZB conditions

z3625 Lower density: T_e~160 eV, n_e~8e21 e/cc



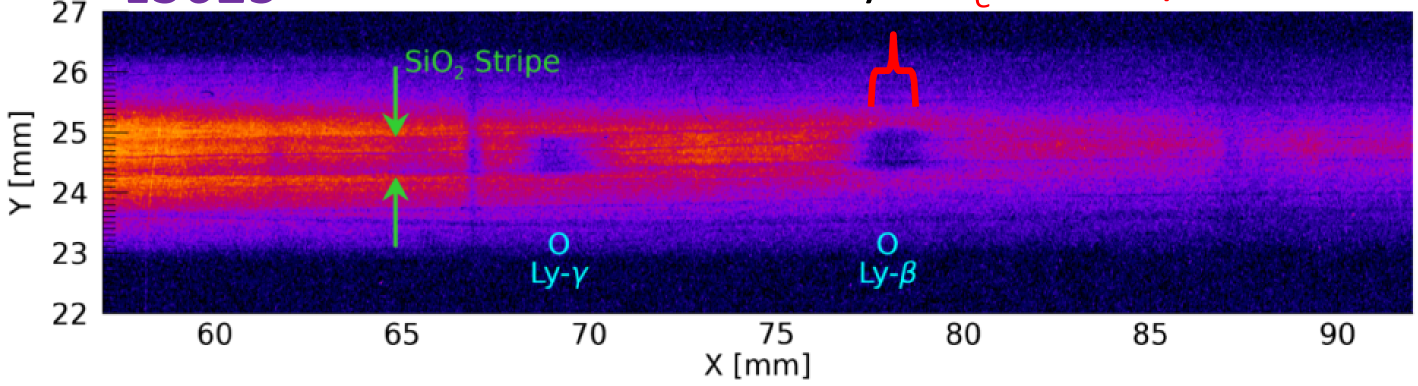
z3653 Higher density: T_e~170 eV, n_e~30e21 e/cc



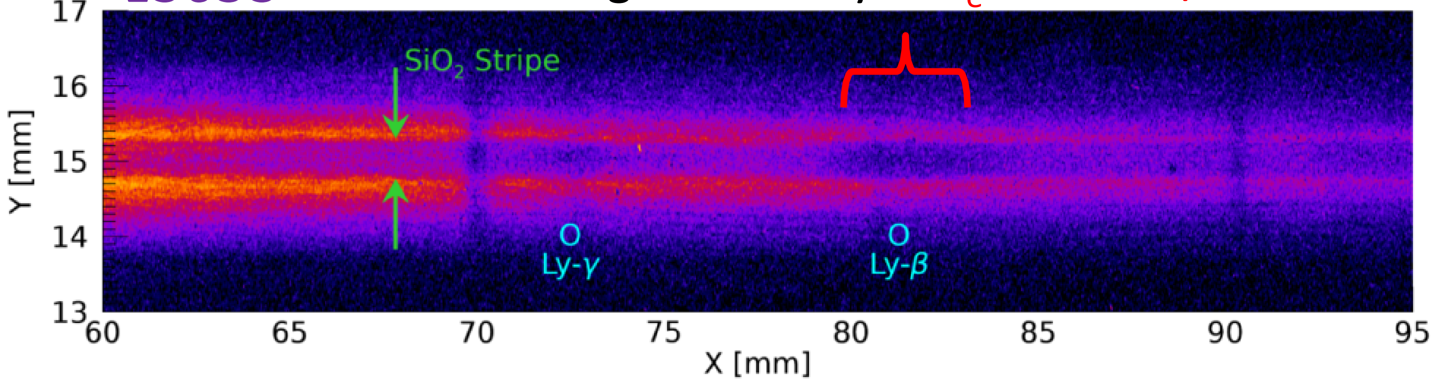


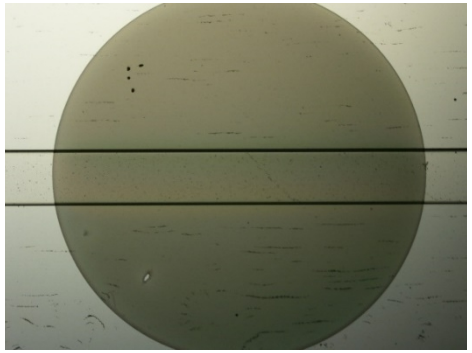
New stripe-style samples may help to better constrain the transmission

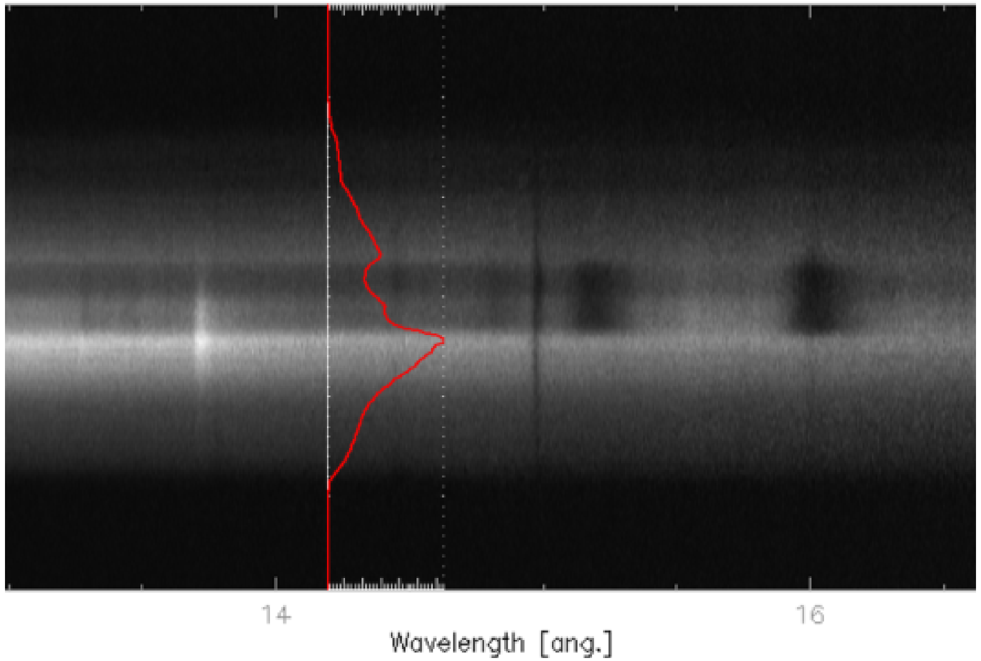
z3625 Lower density: T_e~160 eV n_e~8e21 e/cc



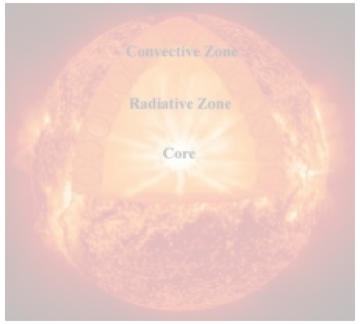
z3653 Higher density: T_e~170 eV n_e~30e21 e/cc



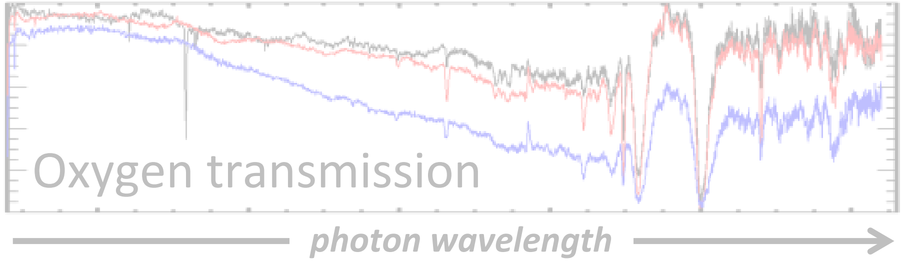


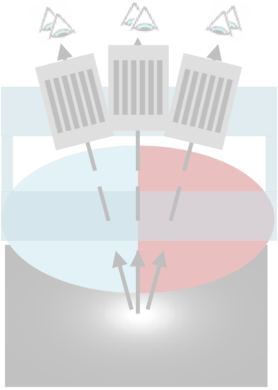


Summary: Oxygen opacity experiments at Z and NIF address key challenges for resolving the solar problem



- Solar models and helioseismology disagree, and increased opacities could resolve the discrepancy.
- Oxygen is a major source of opacity at the solar convection zone base (CZB).
- Oxygen opacity measurements will test the treatment of density effects in modeled opacities.
- Cross-platform comparison (Z vs NIF) of results will increase confidence in the findings.

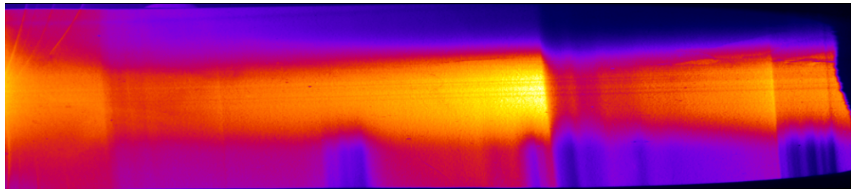


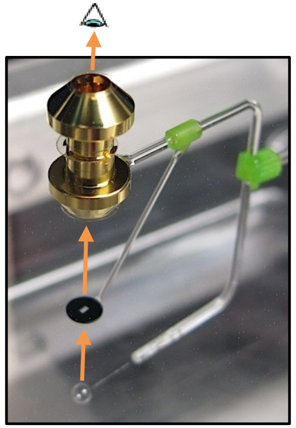


– Oxygen opacity was successfully measured at T_e~160 eV and n_e~8e21 e/cc.

– Preliminary model-data comparison already shows interesting disagreement.

– First measurements performed at higher T_e and n_e, closer to the solar interior.





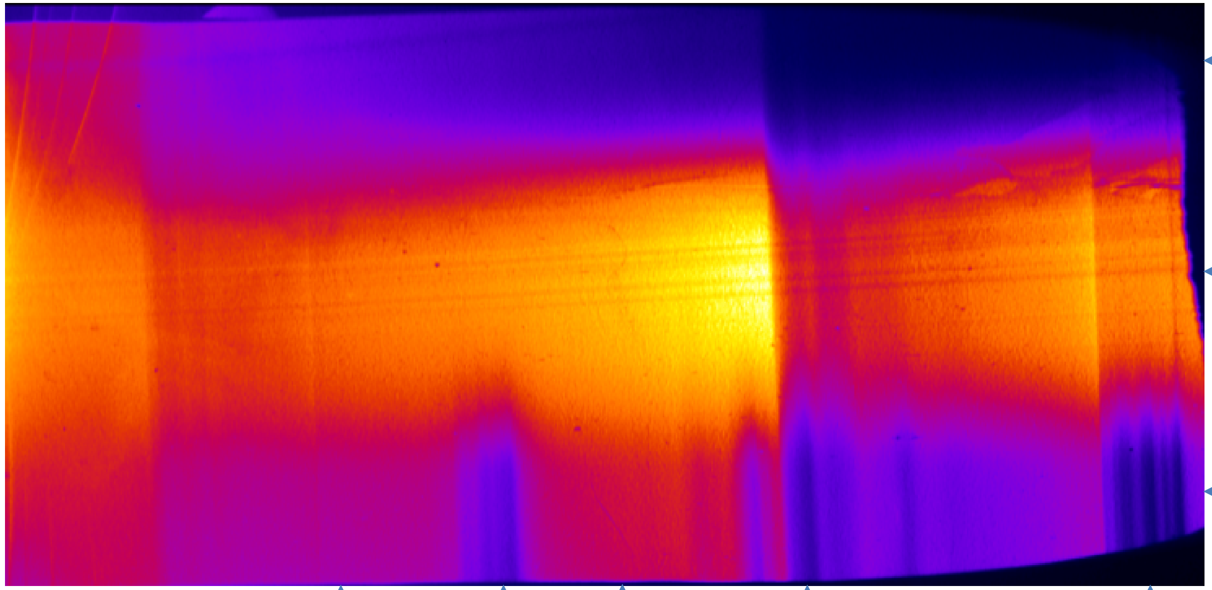
– Oxygen transmission measured at T_e~140 eV and N_e~2e22 e/cc.

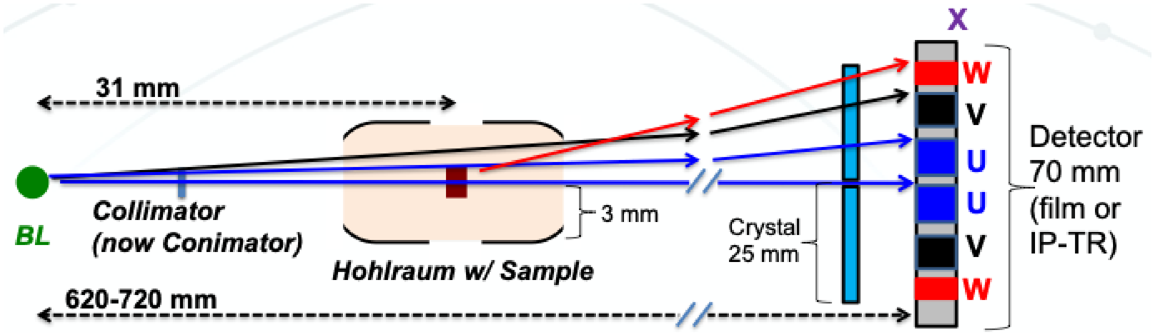
– Preliminary model-data comparison shows interesting disagreement.

– Improvements to experiments:
  - Sample expansion measurement
  - Low-energy band spectrum

At NIF, the spectrometer records absorption, backlight, and emission simultaneously

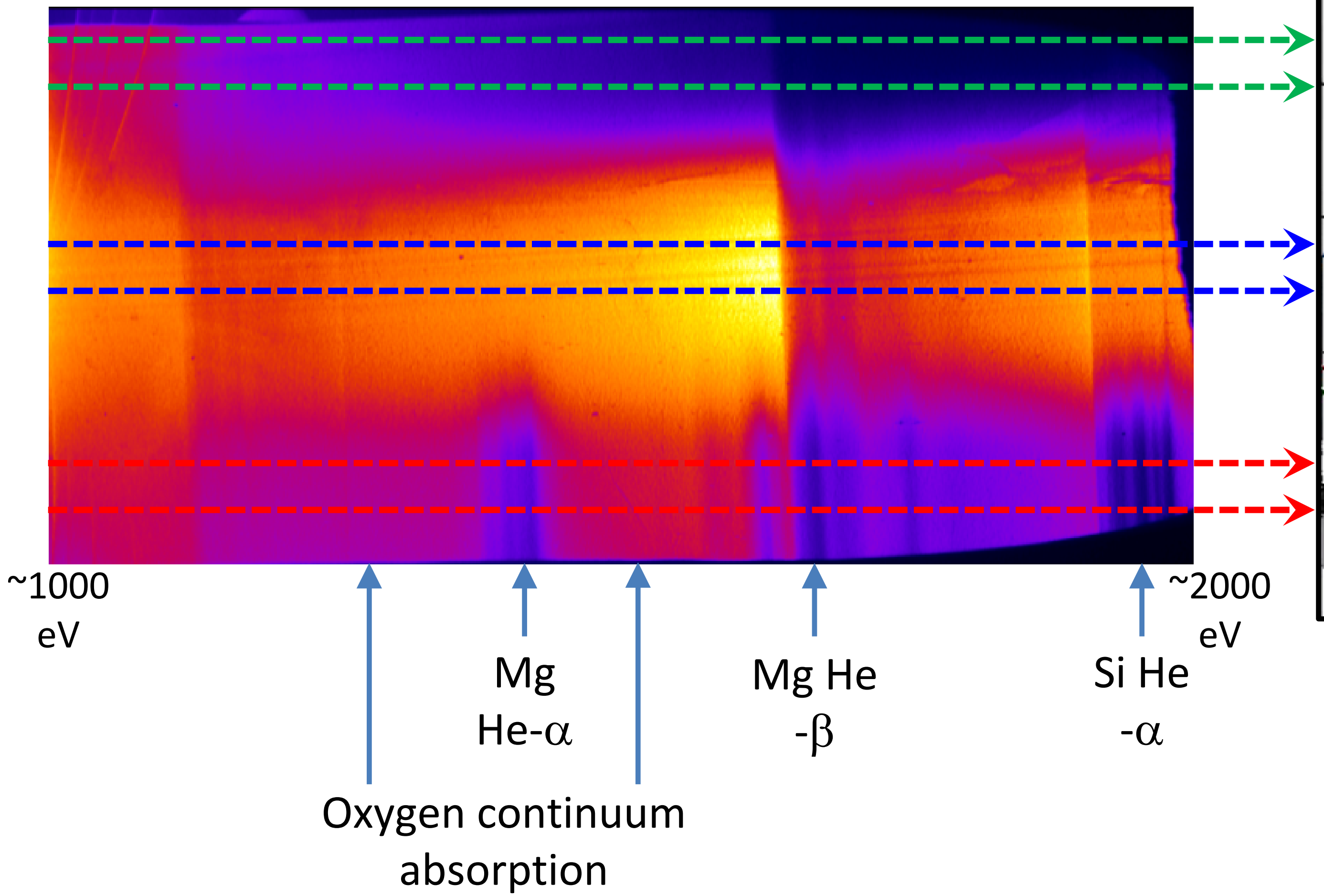
Sample: $MgO + SiO_2$ layers tamped with plastic

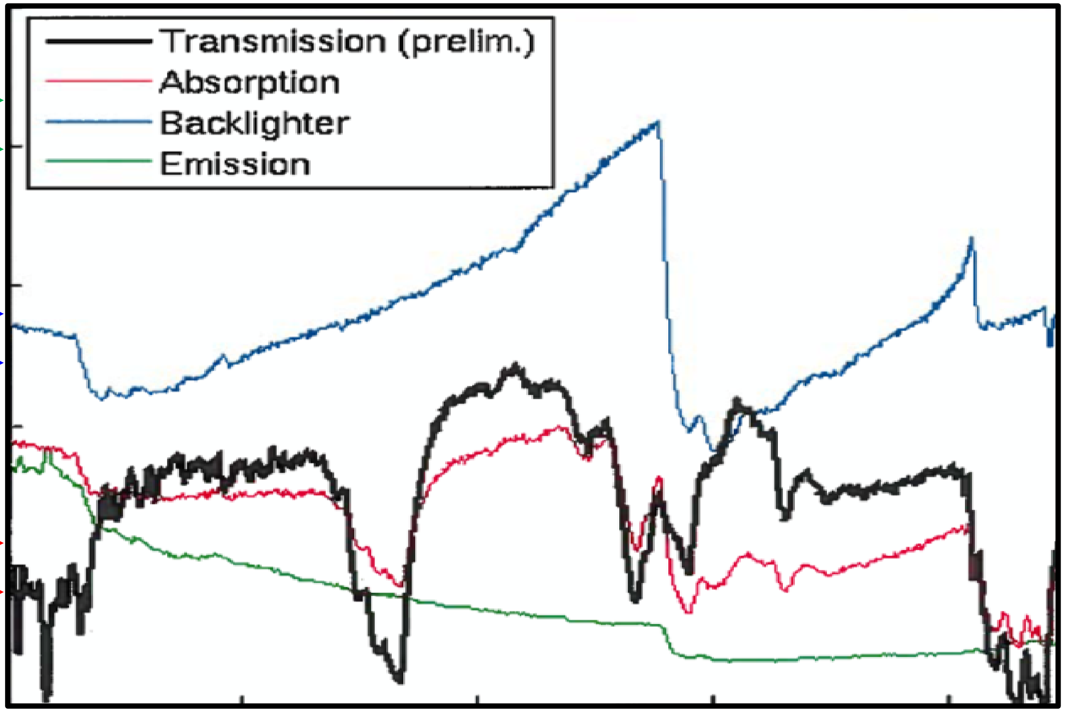




At NIF, the spectrometer records absorption, backlight, and emission simultaneously

Sample: $MgO + SiO_2$ layers tamped with plastic

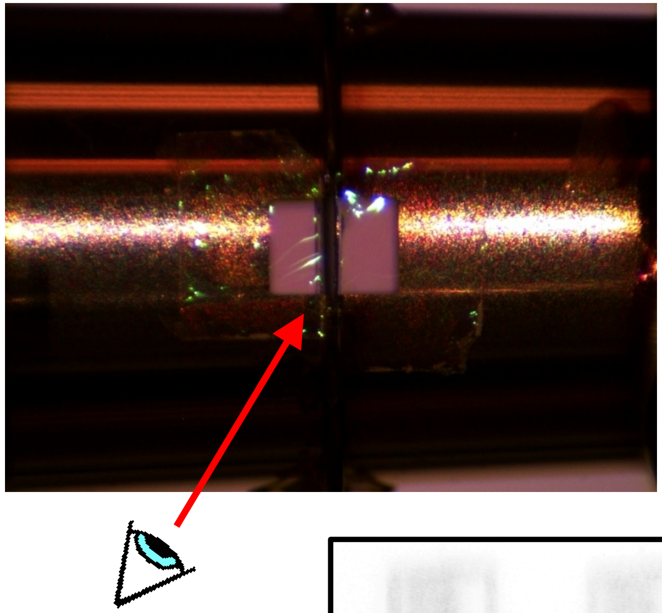


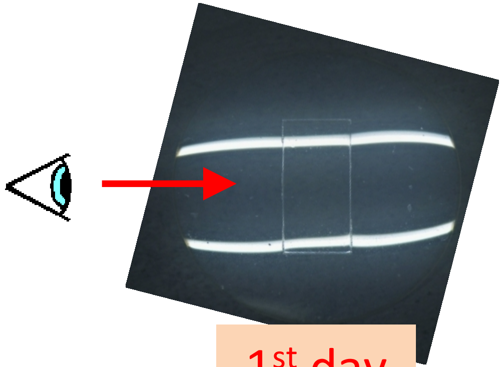


$$\text{Transmission} = \frac{\text{Absorption} - \text{Emission}}{\text{Backlighter} - \text{Emission}}$$

Plasma conditions are inferred from measurements viewed through a hohlraum side window

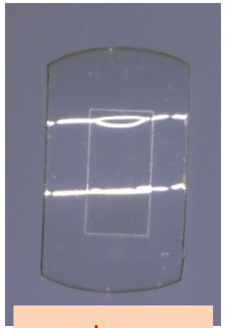
- Dante instrument monitors hohlraum inner wall emission.
  - ➢ Electron temperature (with simulation correction factor)
- Gated x-ray camera (GXD) views sample expansion.
  - ➢ Electron density
- Estimated plasma conditions:
  - 1st shot day: T_e ~ 125 eV and (n_e ~ 2x10^{22} e/cc) (from simulations)
  - 2nd shot day: T_e ~ 142 eV and n_e ~ 2.1x10^{22} e/cc



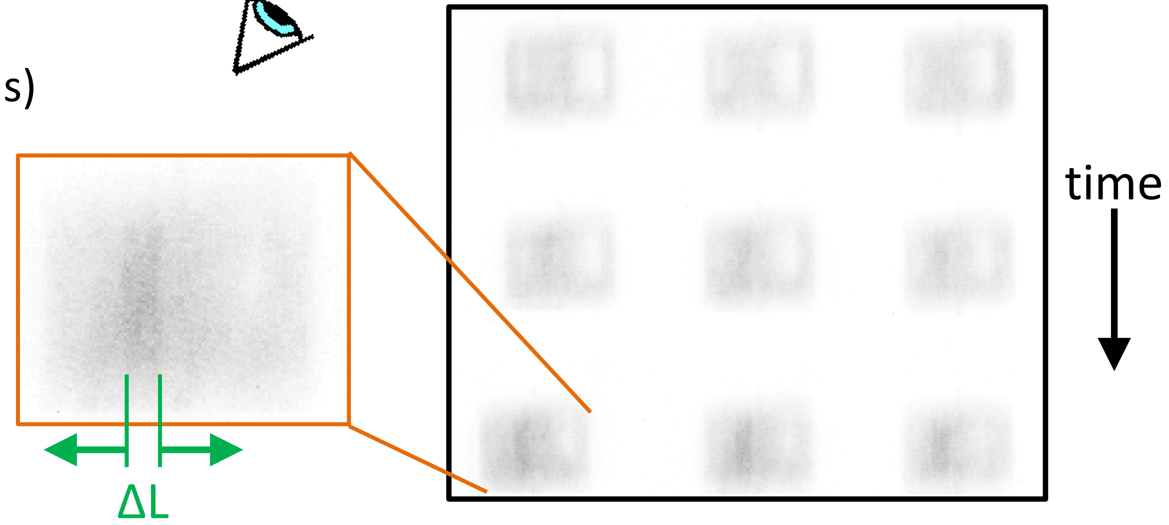


1st day

vs



2nd day

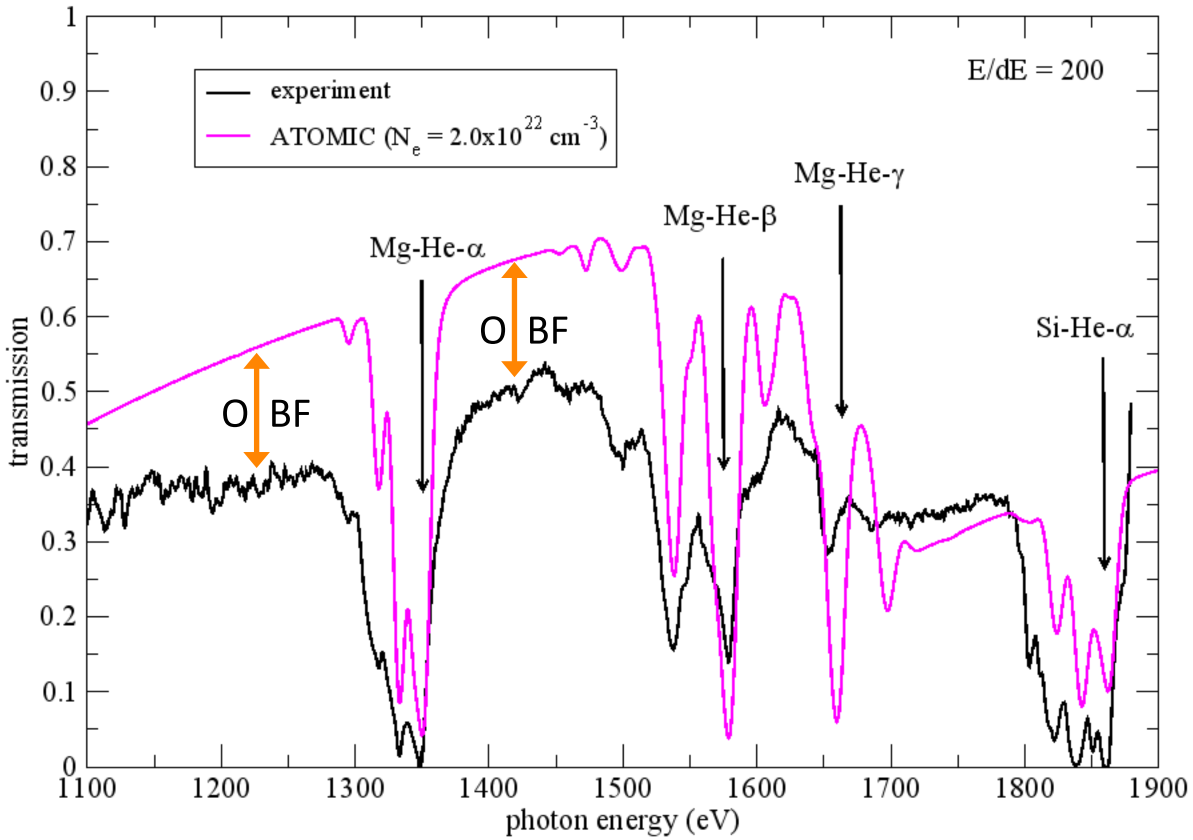


Preliminary analysis of experimental data shows possible disagreement with theory

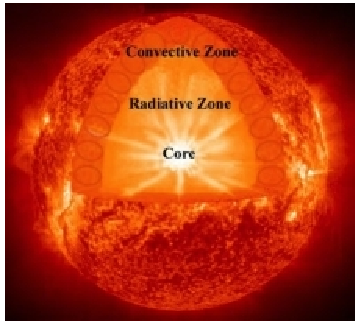
**** CAUTION! ****

- The oxygen bound-free opacity is very sensitive to plasma conditions
  - Preliminary: $T_e \sim 125$ eV and $n_e \sim 2\times10^{22}$ e/cc.
- Potential sources of uncertainty:
  - How well do we know the plasma conditions?
  - Have we correctly accounted for all background and self-emission?
  - How uniform is the plasma?
  - How large are temporal gradients?

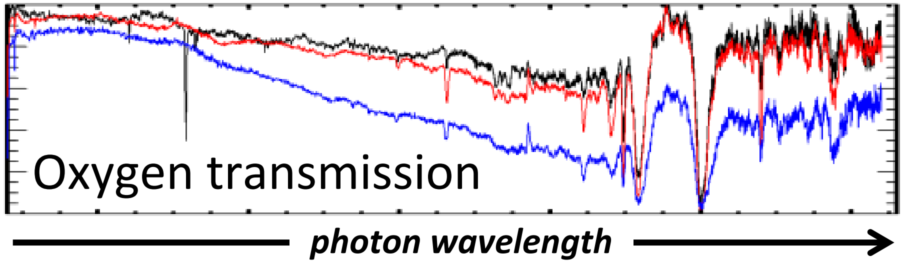
Si+O+Mg transmission



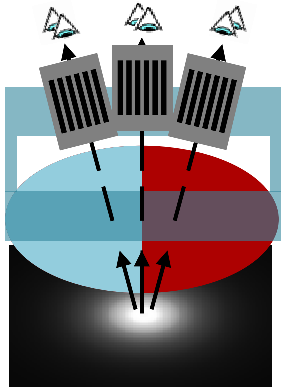
Summary: Oxygen opacity experiments at Z and NIF address key challenges for resolving the solar problem

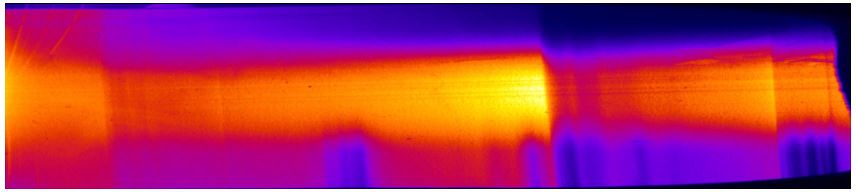


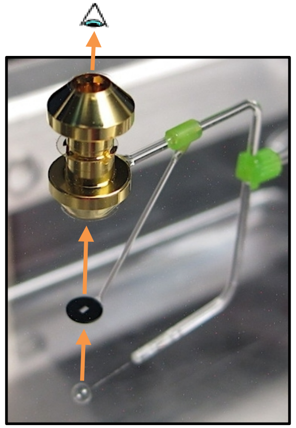
- Solar models and helioseismology disagree, and increased opacities could resolve the discrepancy.
- Oxygen is a major source of opacity at the solar convection zone base (CZB).
- Oxygen opacity measurements will test the treatment of density effects in modeled opacities.
- Cross-platform comparison (Z vs NIF) of results will increase confidence in the findings.



- Oxygen opacity was successfully measured at T_e~160 eV and n_e~8e21 e/cc.
- Preliminary model-data comparison already shows interesting disagreement.
- First measurements performed at higher T_e and n_e, closer to the solar interior.

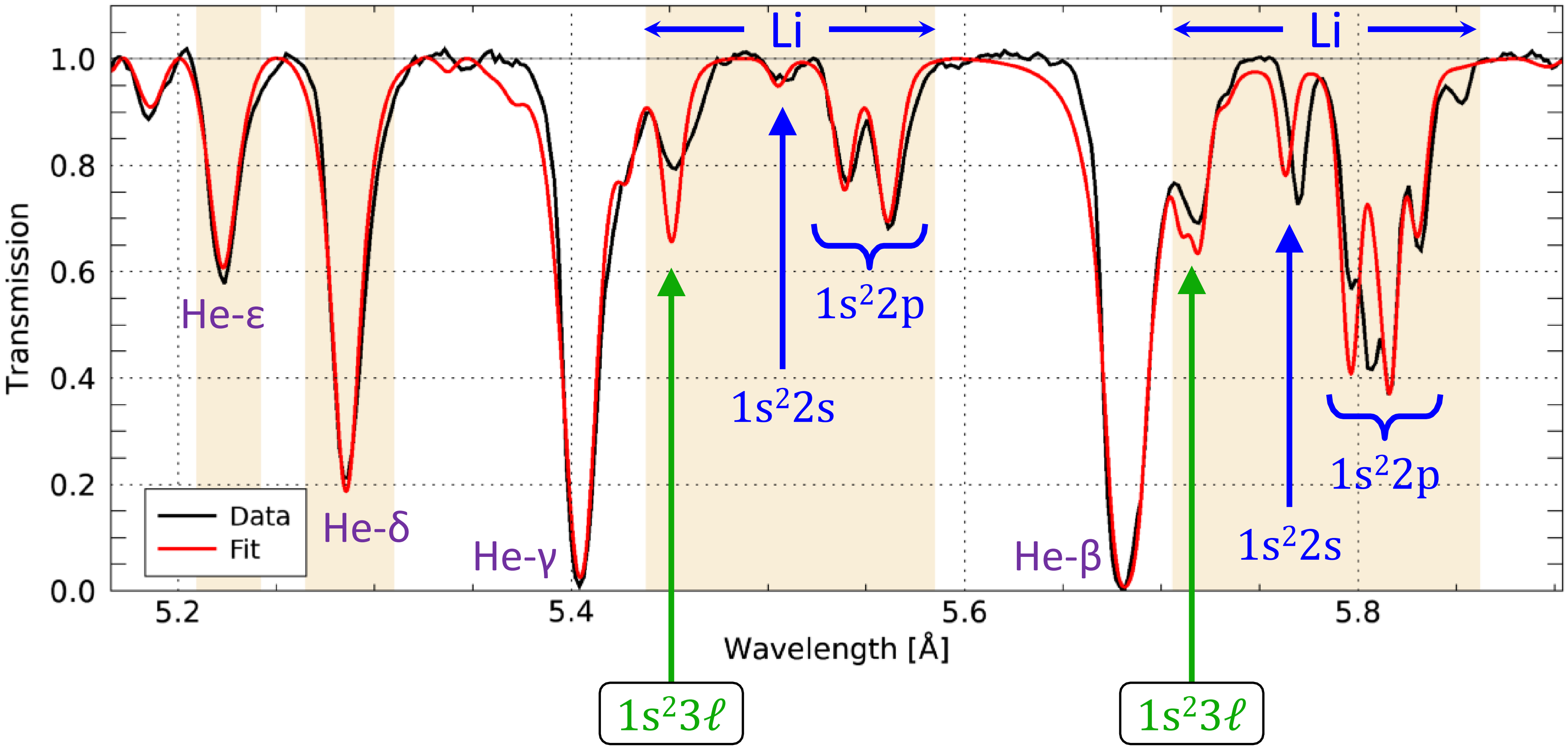


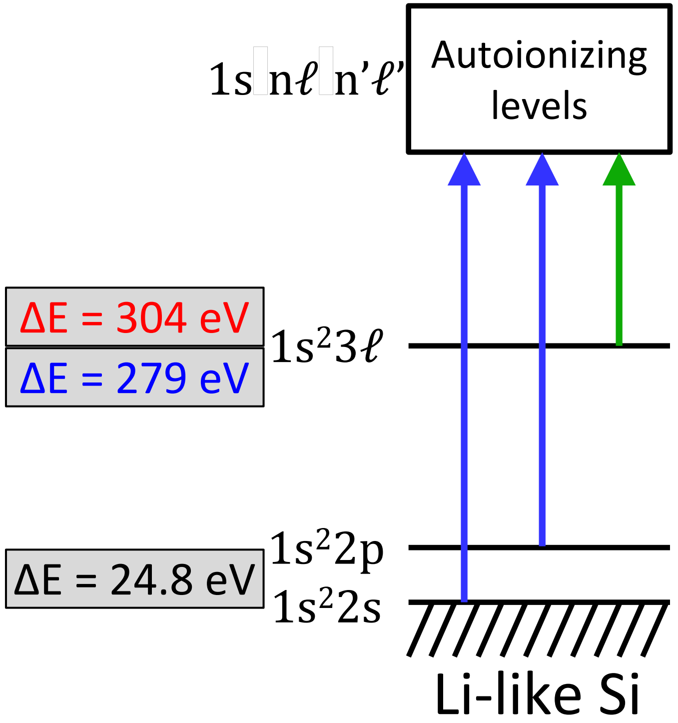


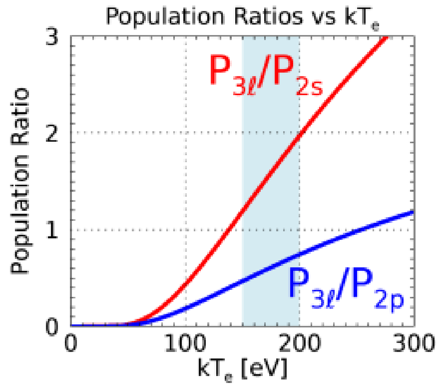


- Oxygen transmission measured at T_e~140 eV and N_e~2e22 e/cc.
- Preliminary model-data comparison shows interesting disagreement.
- Improvements to experiments:
  - Sample expansion measurement
  - Low-energy band spectrum

Novel method to infer temperature from population ratios of Li-like satellites.







- Measure the relative population in each Li-like configuration.
- The ratio of populations in different configurations depends on T_e.