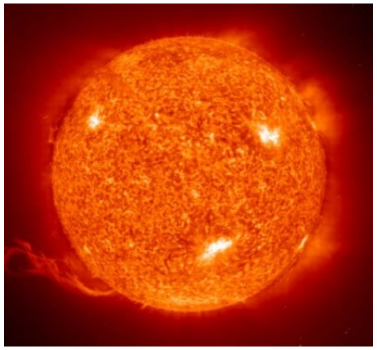
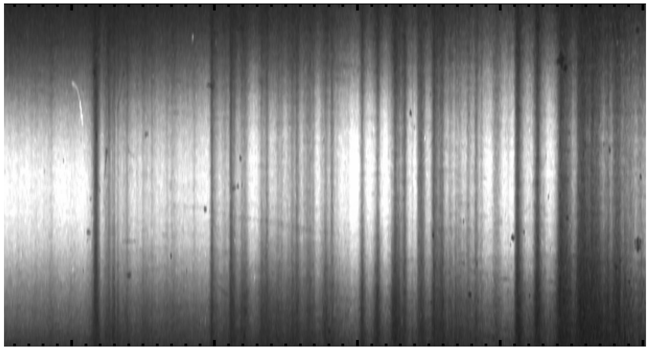
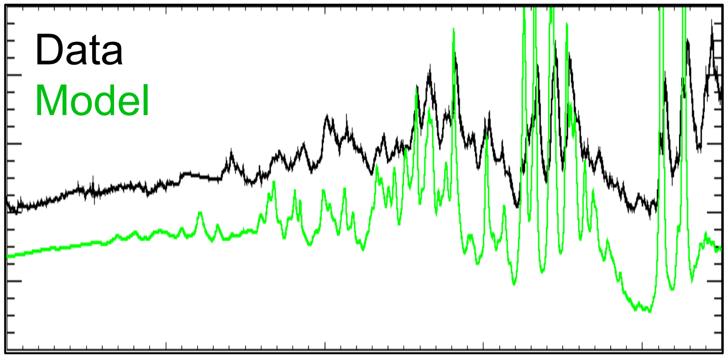
Exceptional service in the national interest

Sandia National Laboratories







Numerical scrutiny of SNL iron opacity experiments

Taisuke Nagayama
Sandia National Laboratories

National ICF Diagnostics Workshop, Los Alamos, October 6, 2015

The solar opacity collaboration involves universities, U.S. national labs, a private company, and the French CEA laboratory

J.E. Bailey, T. Nagayama, G. Loisel, G.A. Rochau, S.B. Hansen, C. Ball, M. Kernaghan, G.S. Dunham, and M.R. Gomez
Sandia National Laboratories, Albuquerque, NM, 87185-1196

A.K. Pradhan, C. Orban, M. Pinsonneault, and S.N. Nahar
Ohio State University, Columbus, Ohio, 43210

C. Blancard, Ph. Cosse, G. Faussurier, J.-C. Pain, and F. Gilleron
CEA, DAM, DIF, F-91297 Arpajon, France

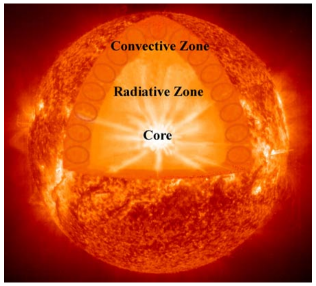
C.A. Iglesias and B. Wilson
Lawrence Livermore National Laboratory, Livermore, CA, 94550

J. Colgan, C.J. Fontes, D. Kilcrease, and M. Sherrill
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

J.J. MacFarlane and I. Golovkin
Prism Computational Sciences, Madison, WI

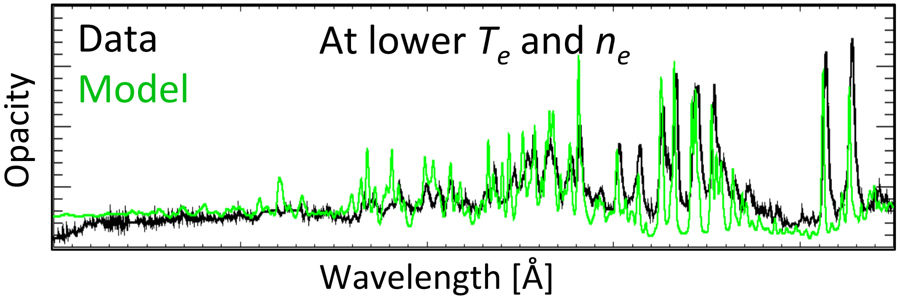
R.C. Mancini
University of Nevada, Reno, NV

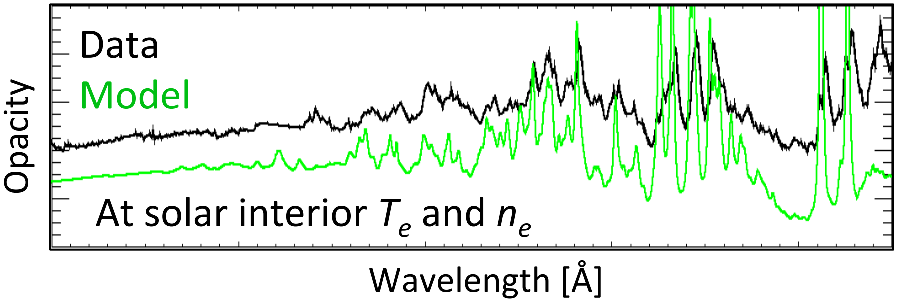
Numerical scrutiny verified the data interpretation of the SNL iron opacity measurements



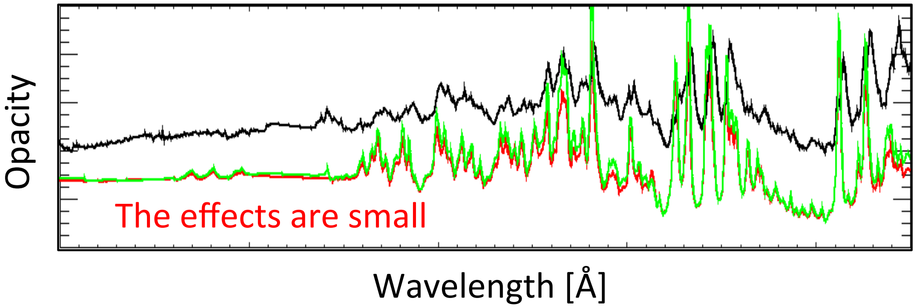
- Solar models disagree with observations.
  → Is iron opacity underestimated?

- Fe opacity is measured at SNL Z-machine
  → Modeled opacity disagrees at solar interior conditions





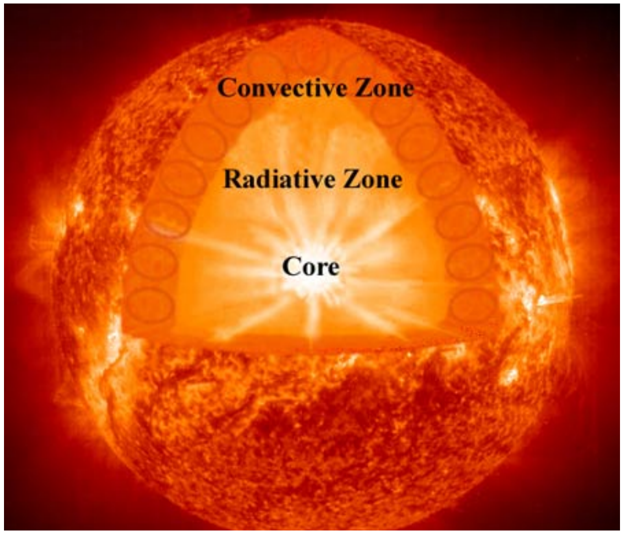
- Experiments and the data interpretation are scrutinized with simulations.
  - Self-emission
  - Tamping material
  - Time- and space-integration effects

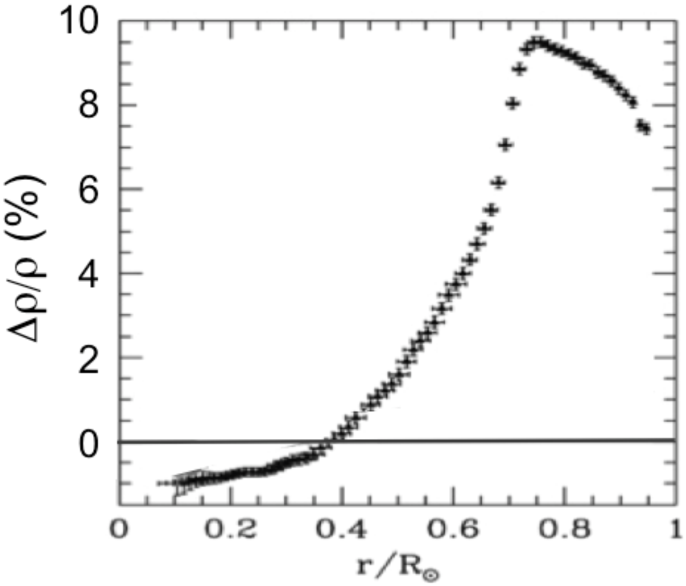


- **One source of systematic uncertainty is always the data interpretation**
- **Forward calculation helps investigate the validity of the data interpretation**

J. E. Bailey et al, Nature 517, 56 (2015).

Simulated solar structure disagree with observations, 15% mean opacity increase is needed



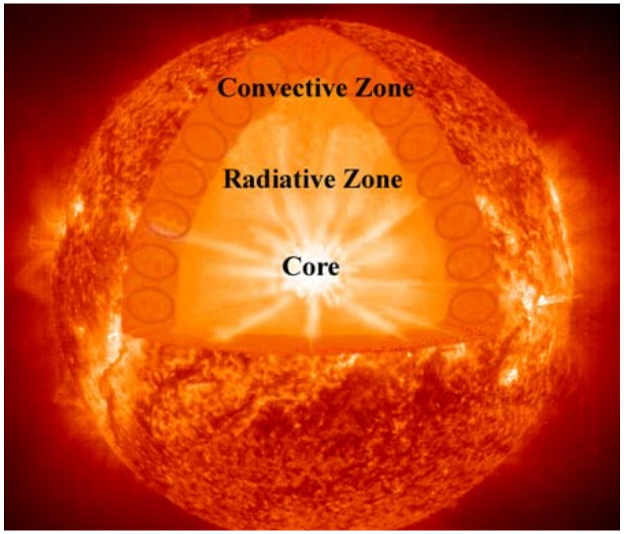


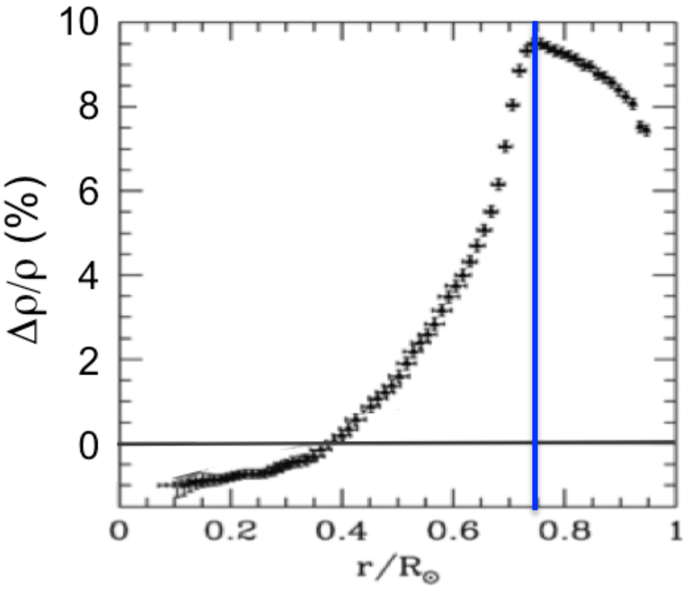
Opacity: κ_ν

- Quantifies radiation absorption
- $\kappa_\nu(T_e, n_e)$ … input for solar models
- Opacity models have never been tested

S. Basu et al, Physics Reports 457, 217 (2008).

Simulated solar structure disagree with observations, 15% mean opacity increase is needed





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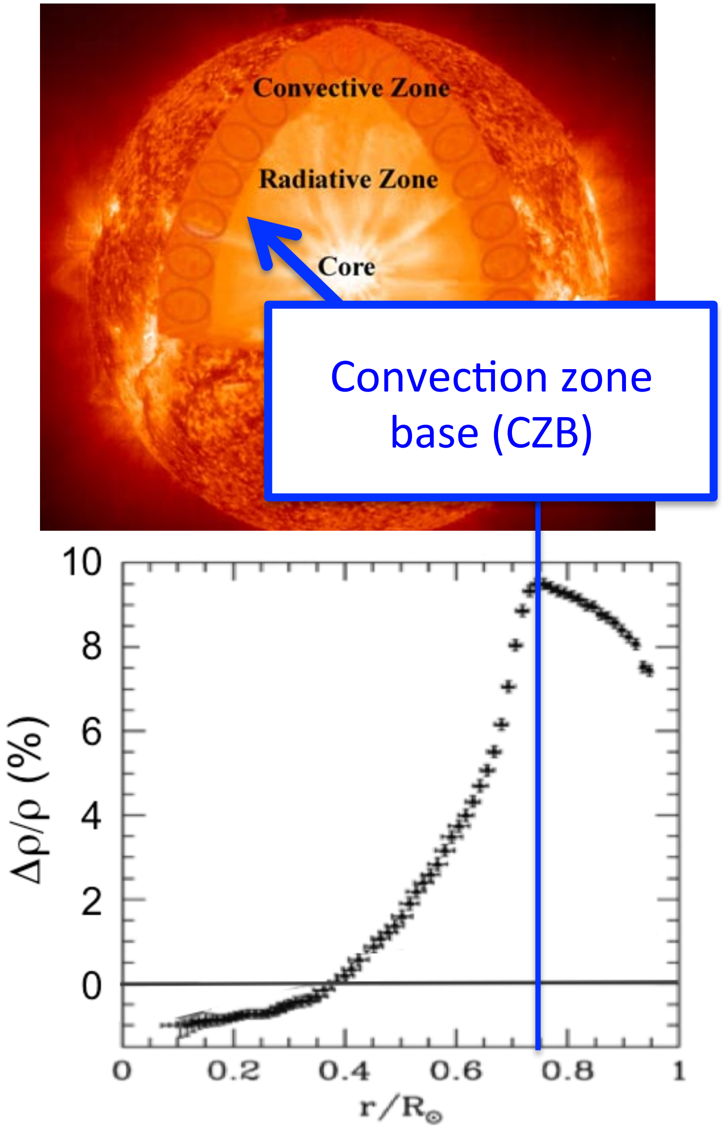

Convection zone base (CZB)

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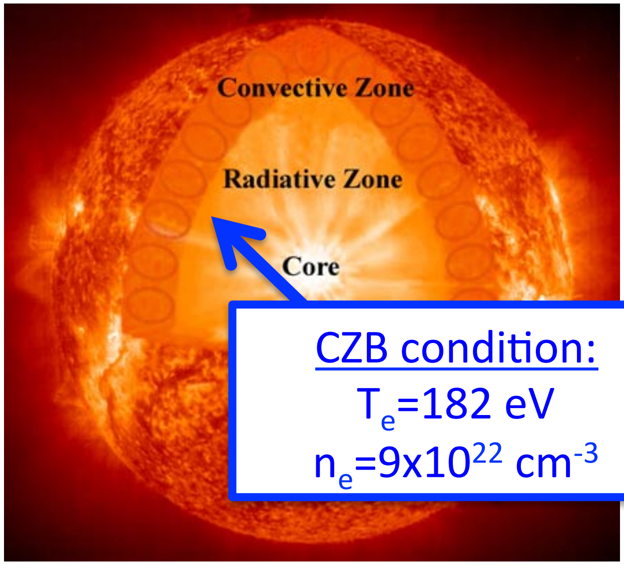
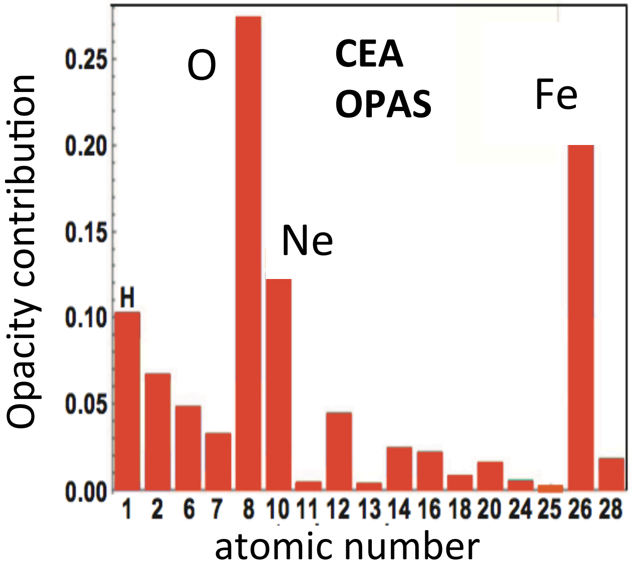


CZB condition:
T_e=182 eV
n_e=9x10^{22} cm^{-3}



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C. Blancard et al, The Astrophysical Journal 745, 10 (2012)

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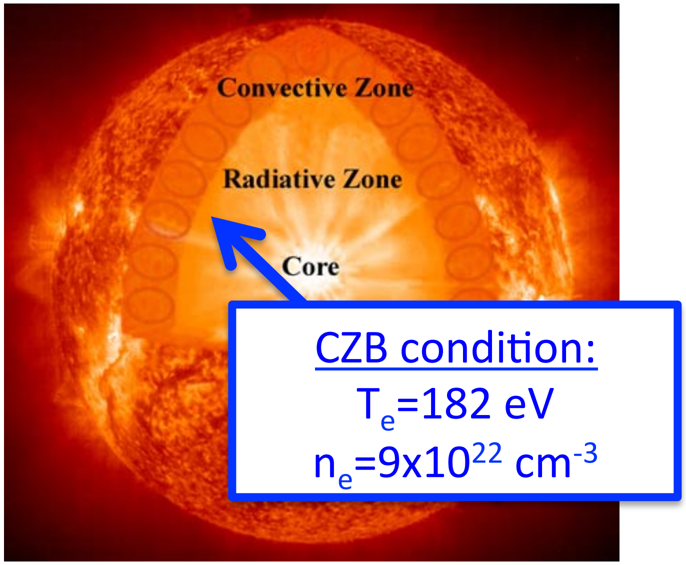

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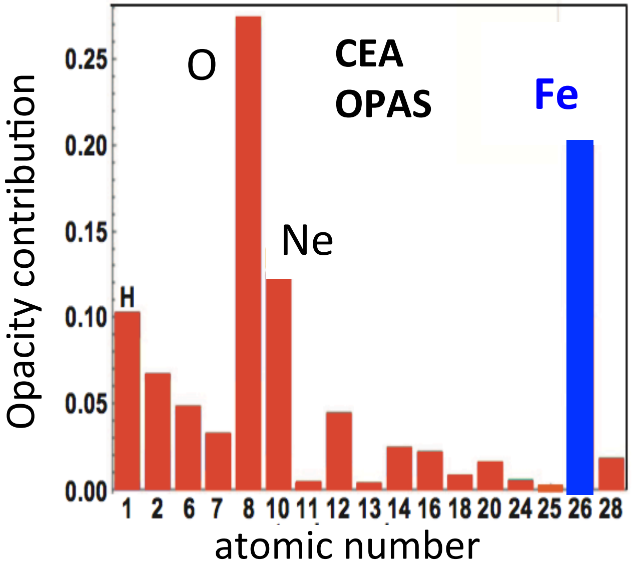

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If opacity is wrong, Fe is a likely suspect:

- 2nd largest contribution
- Most difficult to model

C. Blancard et al, The Astrophysical Journal 745, 10 (2012)

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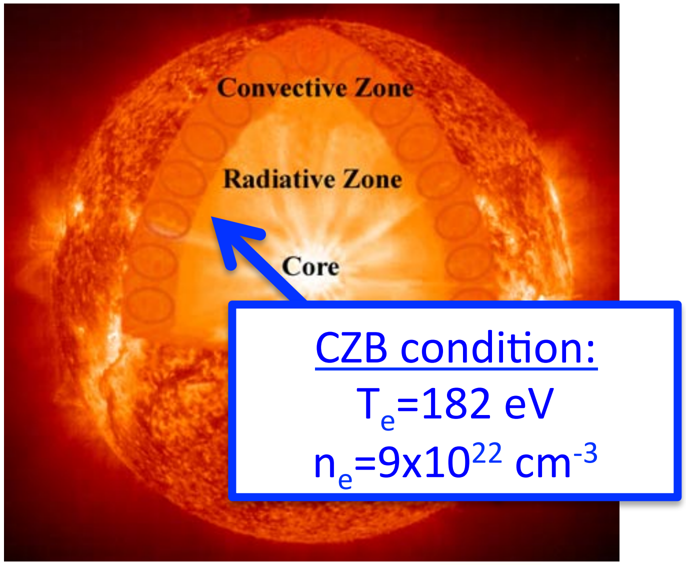

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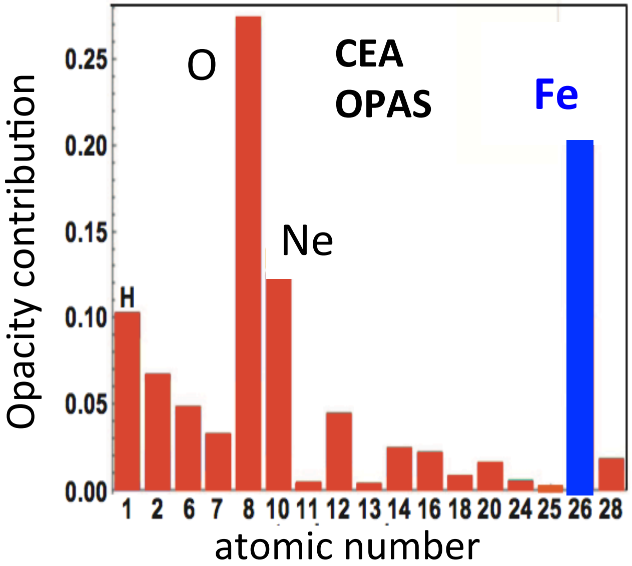

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Let's measure Fe opacity:

- CZB conditions
- l: 8-12 Å

C. Blancard et al, The Astrophysical Journal 745, 10 (2012)

Above 150 eV Fe opacities are measured using the Z-Pinch dynamic hohlraum (ZPDH) opacity science platform

Z-pinch dynamic hohlraum

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009).

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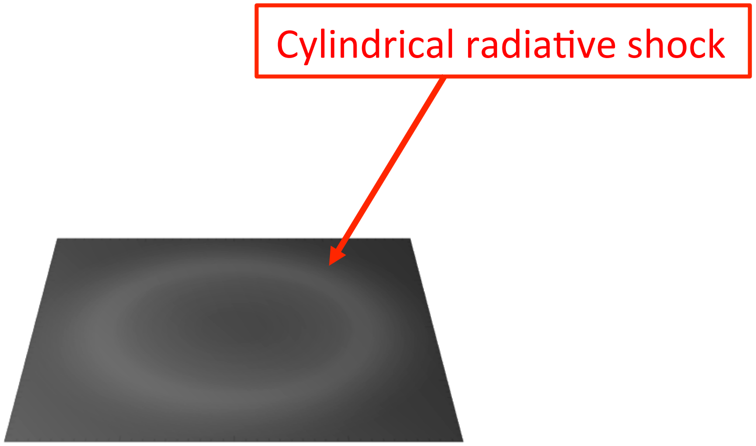

Cylindrical radiative shock

Z-pinch dynamic hohlraum

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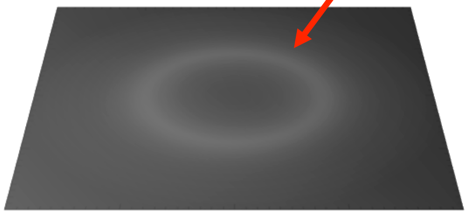

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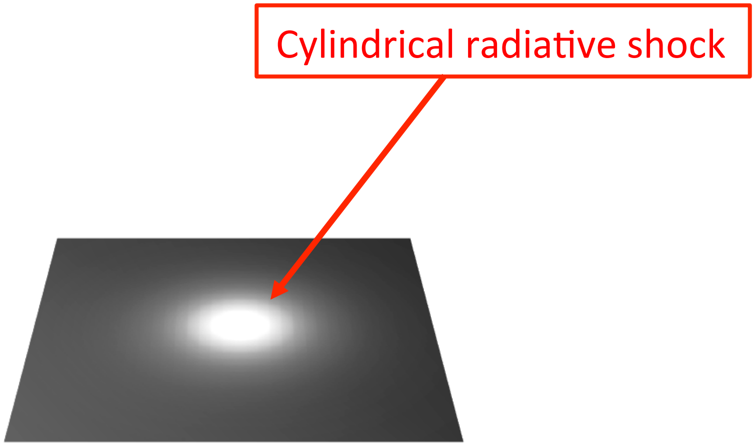
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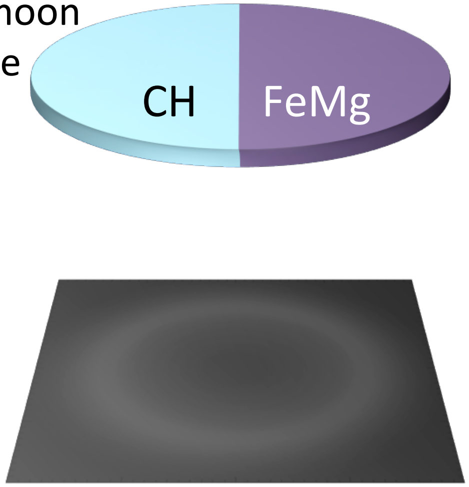

Half-moon sample

CH

FeMg

Z-pinch dynamic hohlraum

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009).

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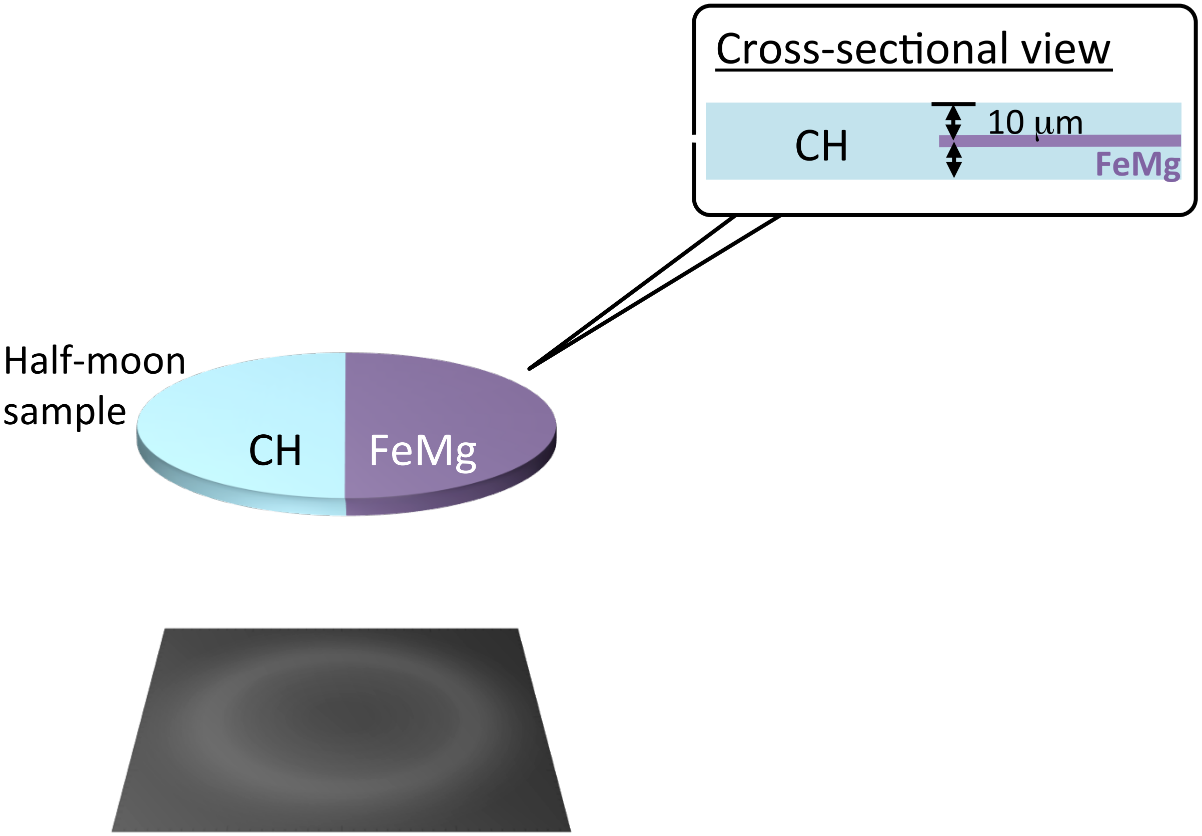

Cross-sectional view

CH

10 μm

FeMg

Half-moon sample

CH

FeMg

Z-pinch dynamic hohlraum

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009).

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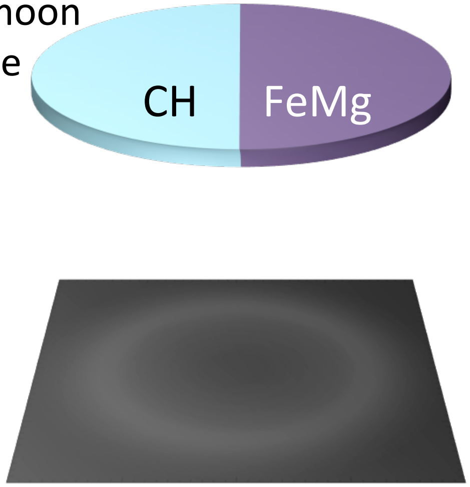

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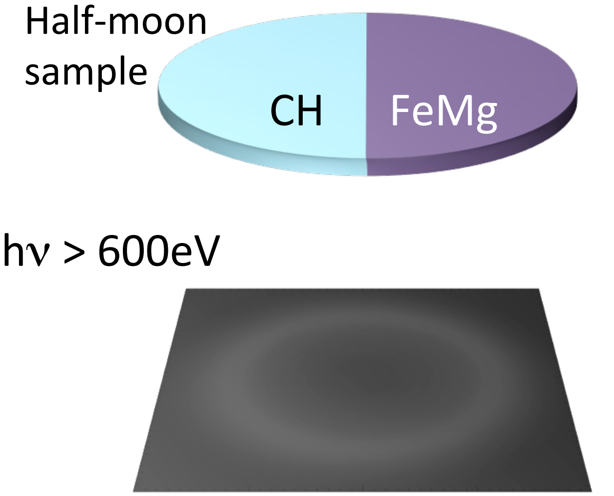

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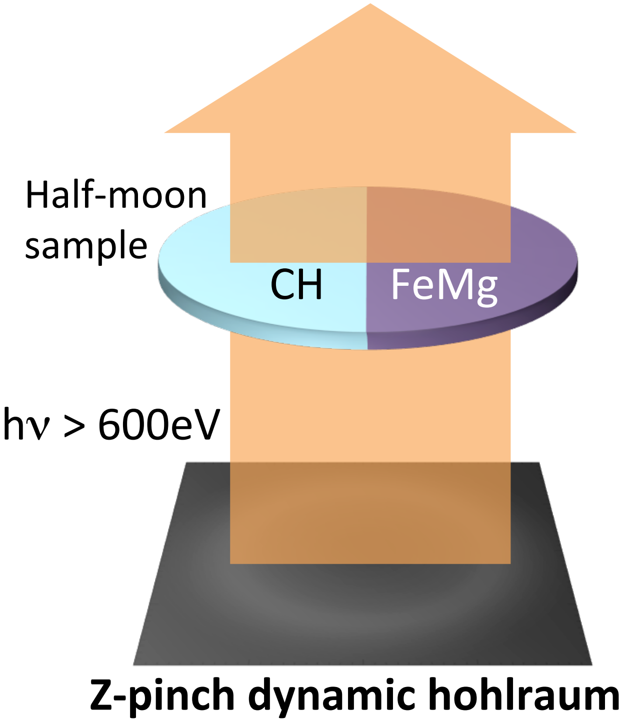

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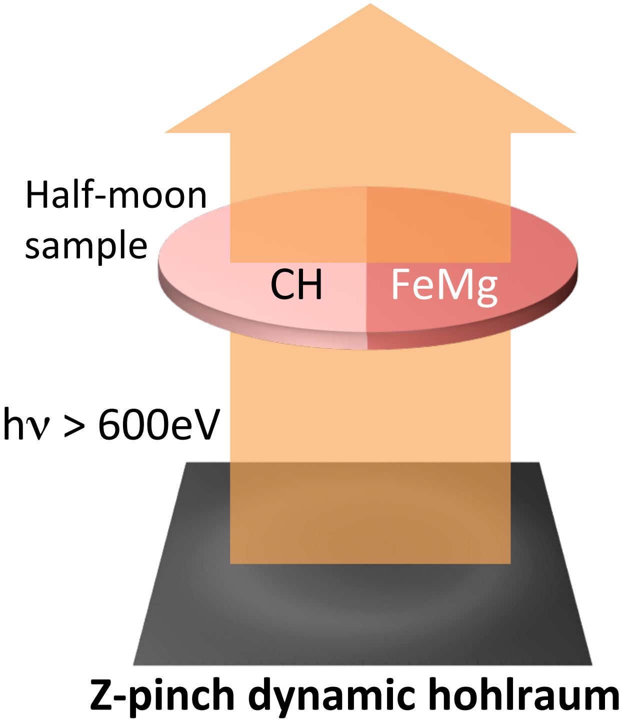

- Heating to uniform conditions:

  ZPDH radiation

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009).

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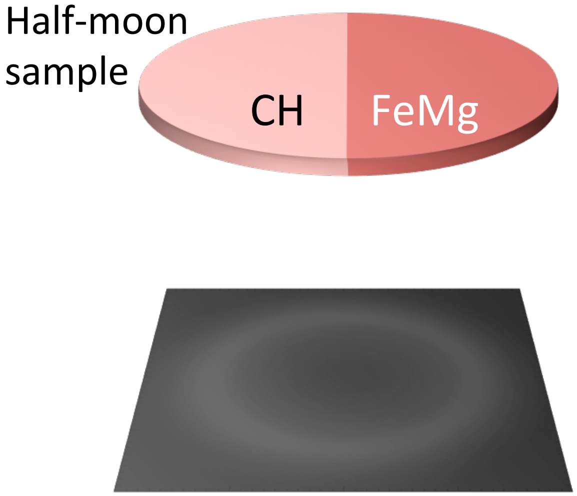

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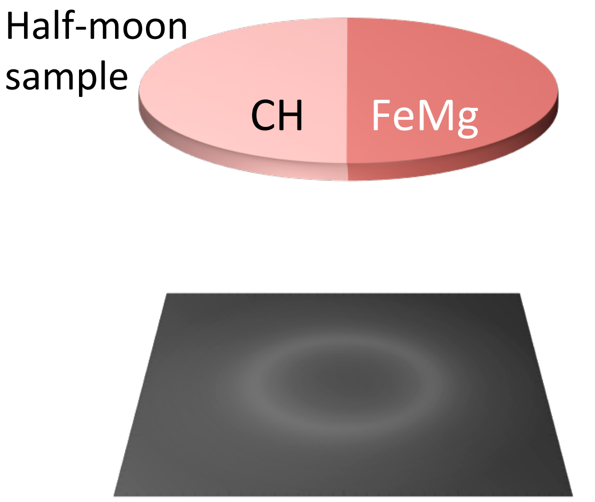

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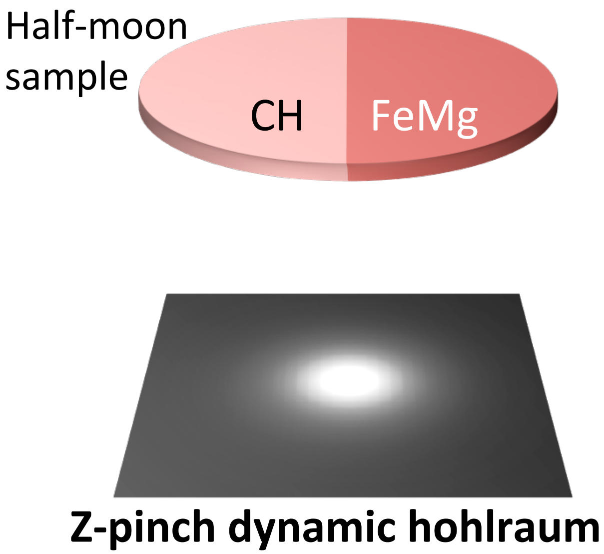

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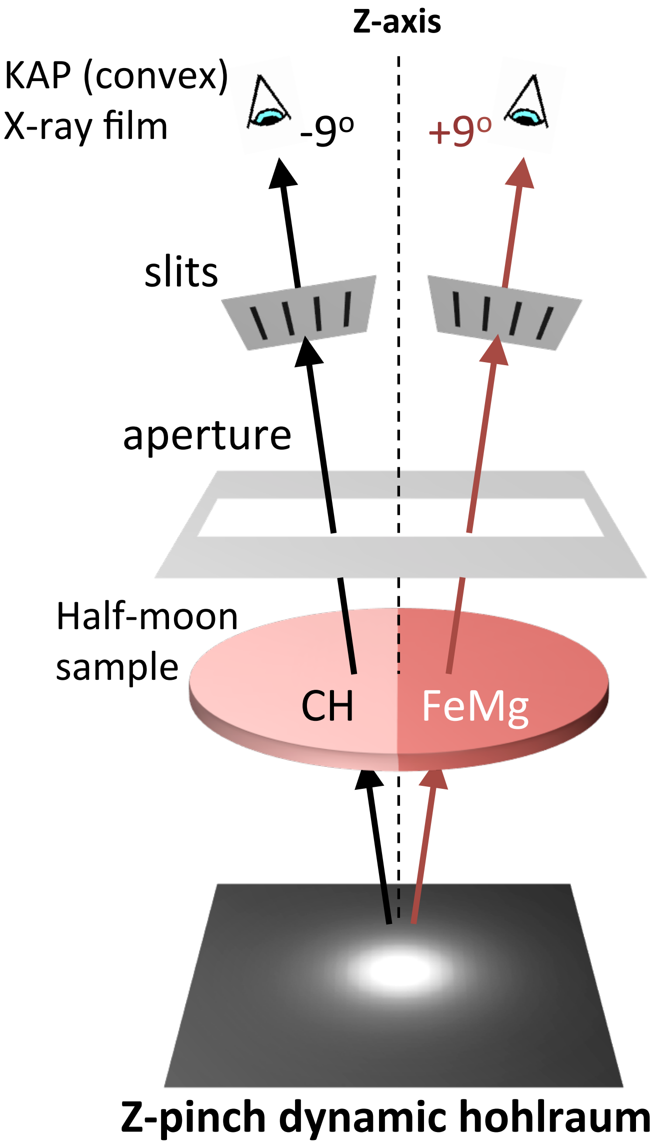

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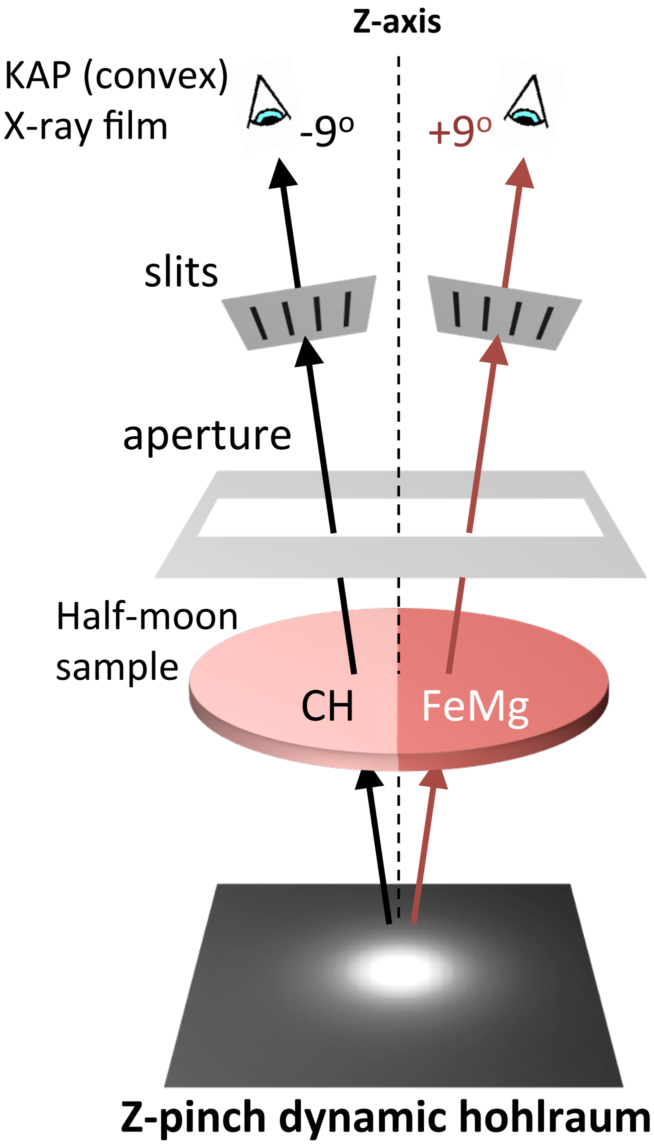

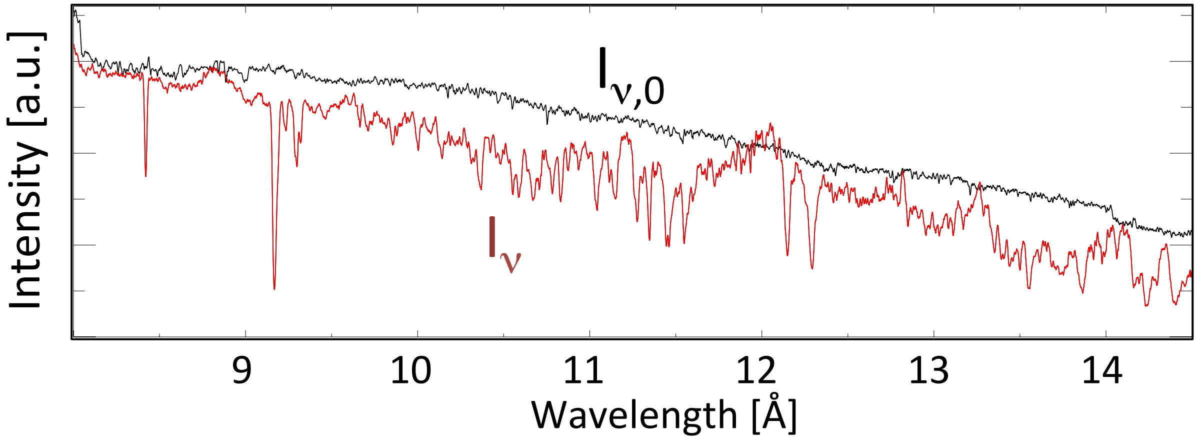

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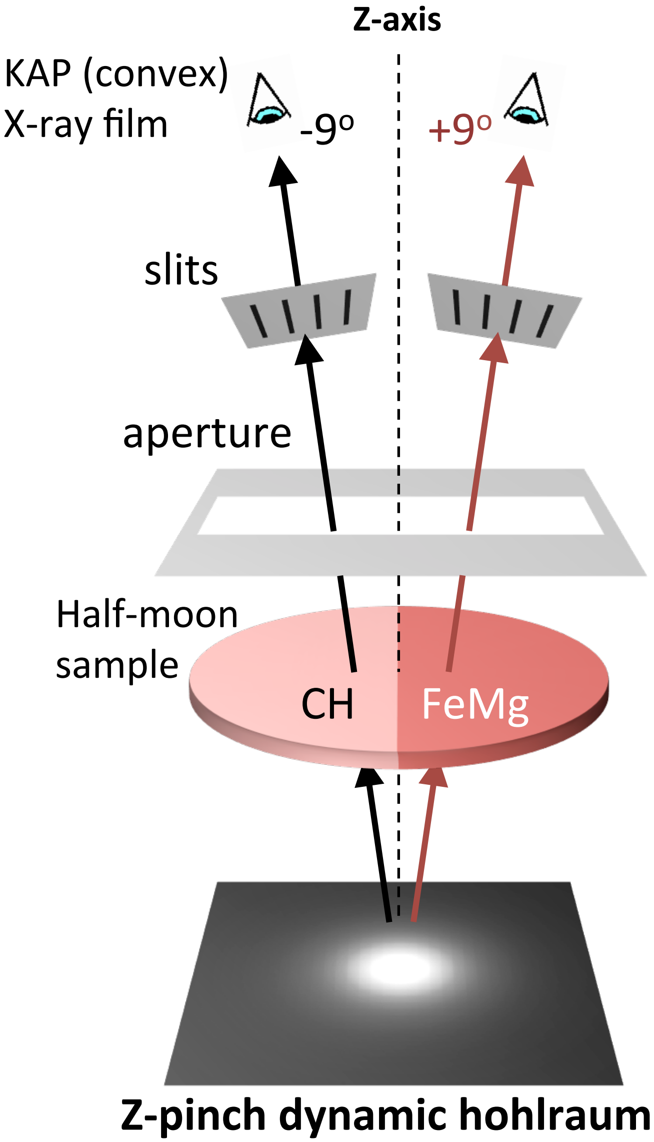
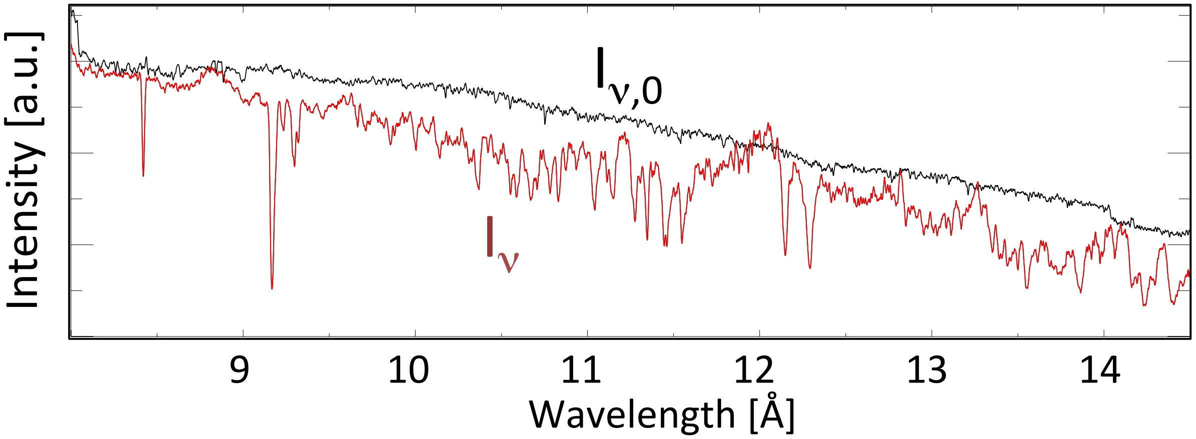


Z-pinch dynamic hohlraum



- Heating to uniform conditions:

  ZPDH radiation

- Transmission:

  $T_\nu = I_\nu / I_{\nu,0}$

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009).

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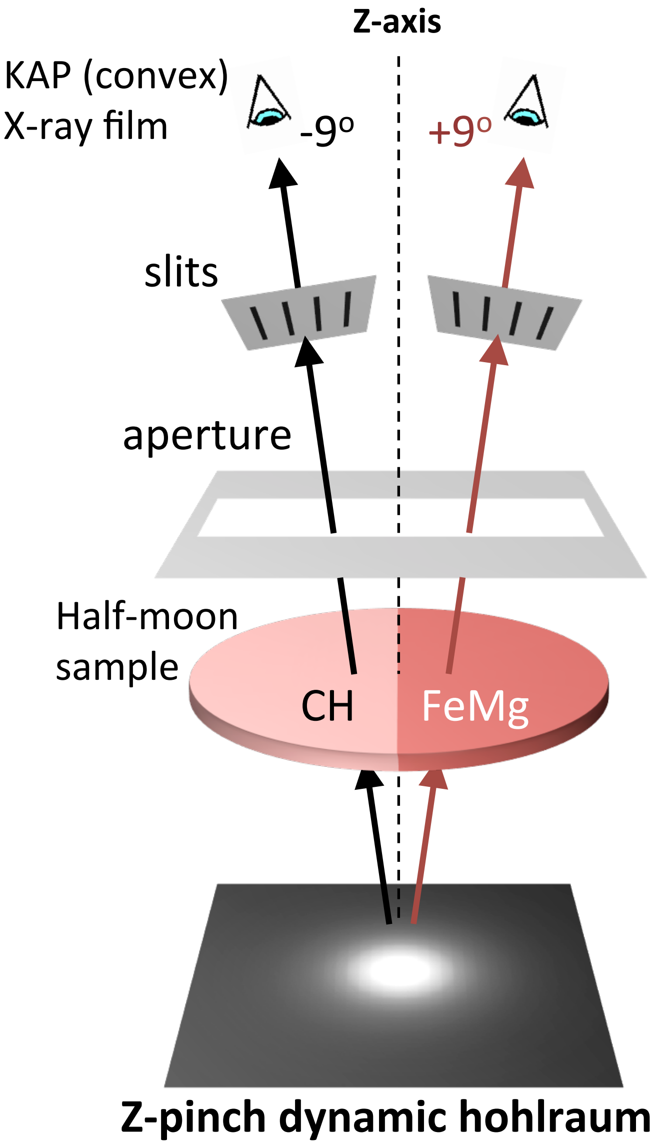


Z-axis

KAP (convex)
X-ray film

-9°

+9°

slits

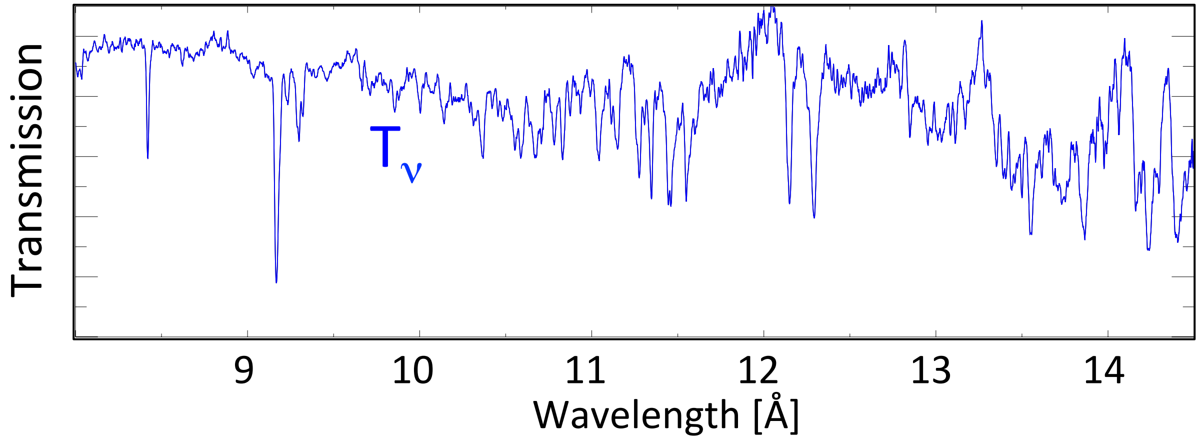
aperture

Half-moon
sample

CH

FeMg

Z-pinch dynamic hohlraum



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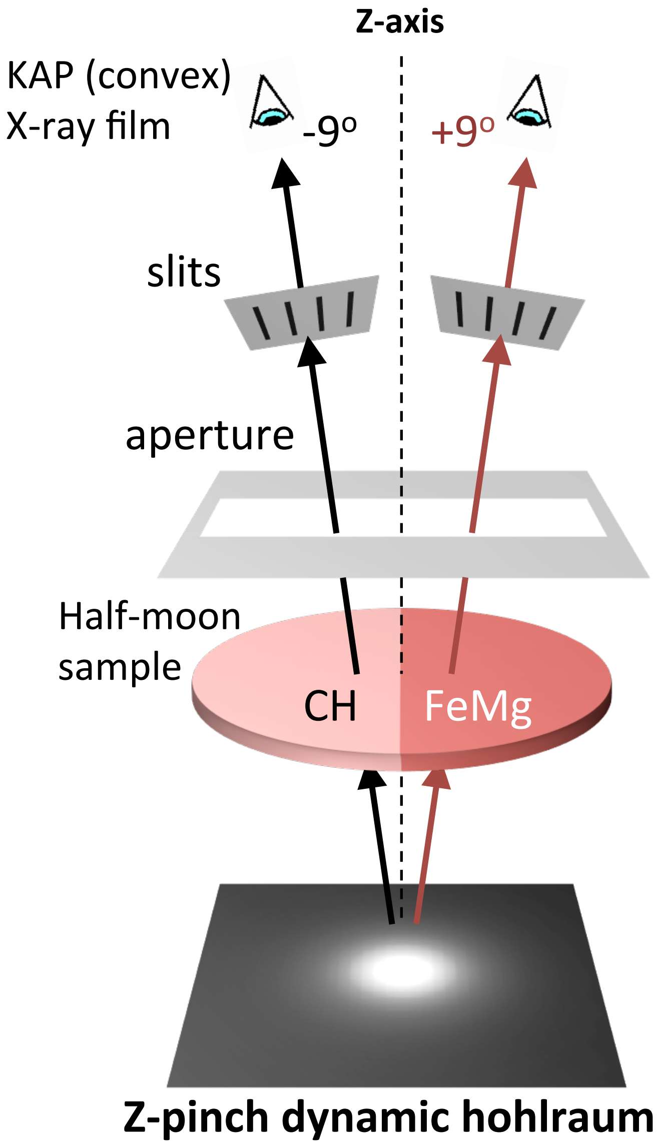

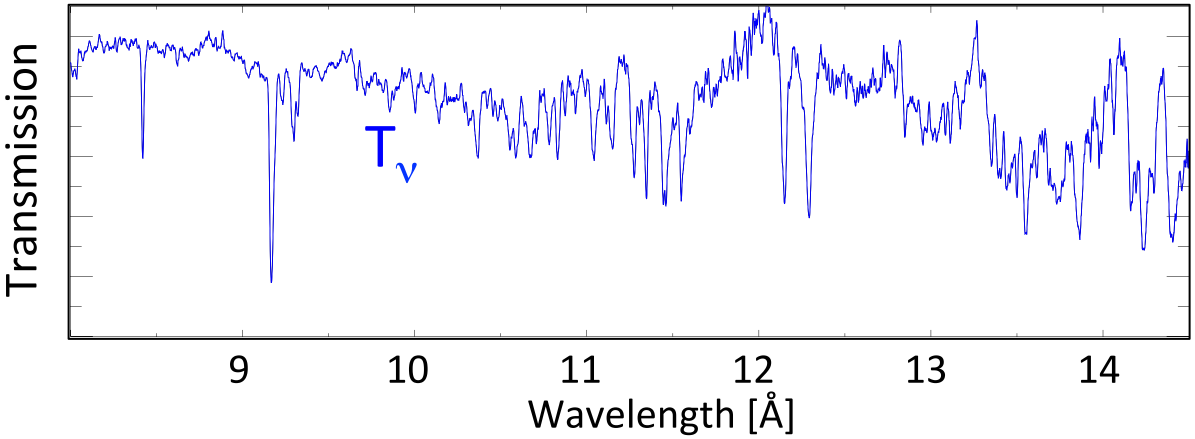

- Heating to uniform conditions:

  ZPDH radiation

- Transmission:

  $T_\nu = I_\nu / I_{\nu,0}$

- Opacity:

  $\kappa_\nu = -\ln(T_\nu)/\rho L$

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009).

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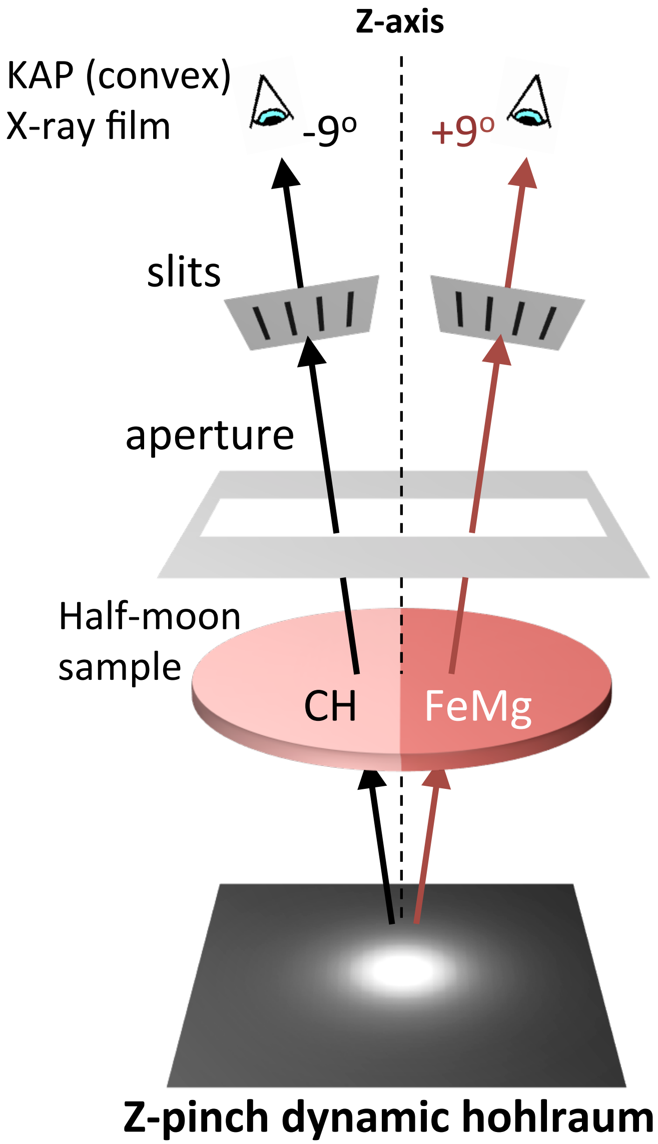

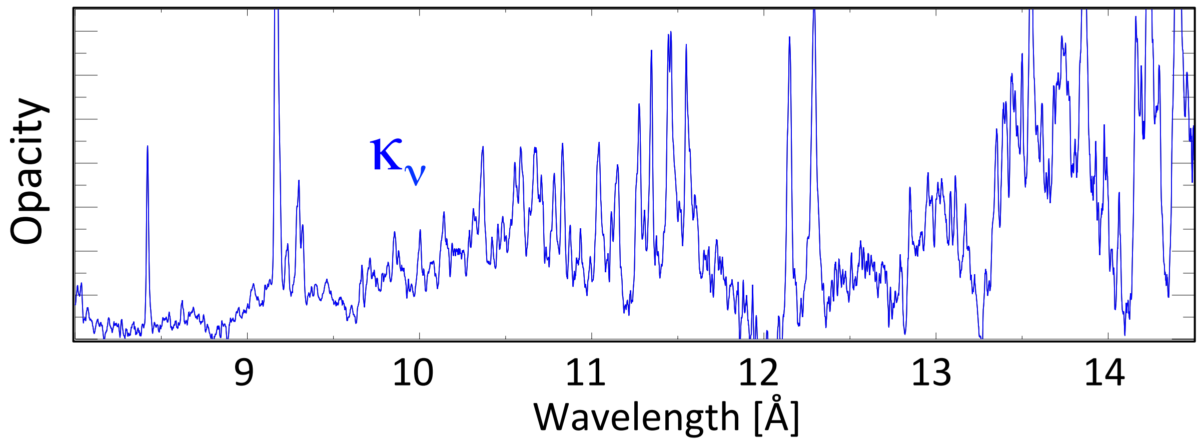

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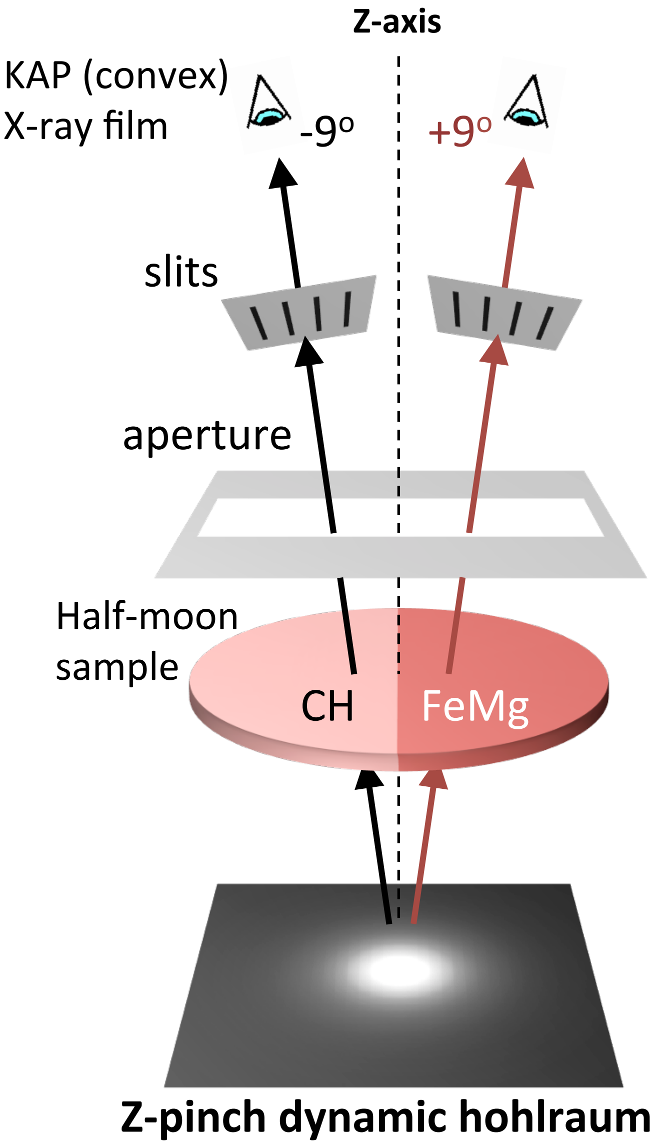

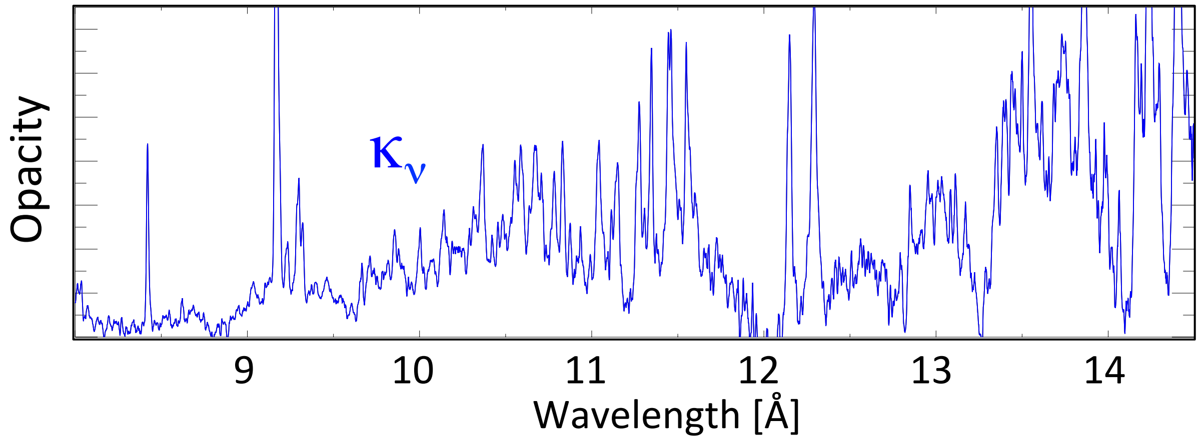

- <u>Heating to uniform conditions:</u>

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- <u>Transmission:</u>

  $T_{\nu} = I_{\nu} / I_{\nu,0}$

- <u>Opacity:</u>

  $\kappa_{\nu} = -\ln(T_{\nu})/\rho L$

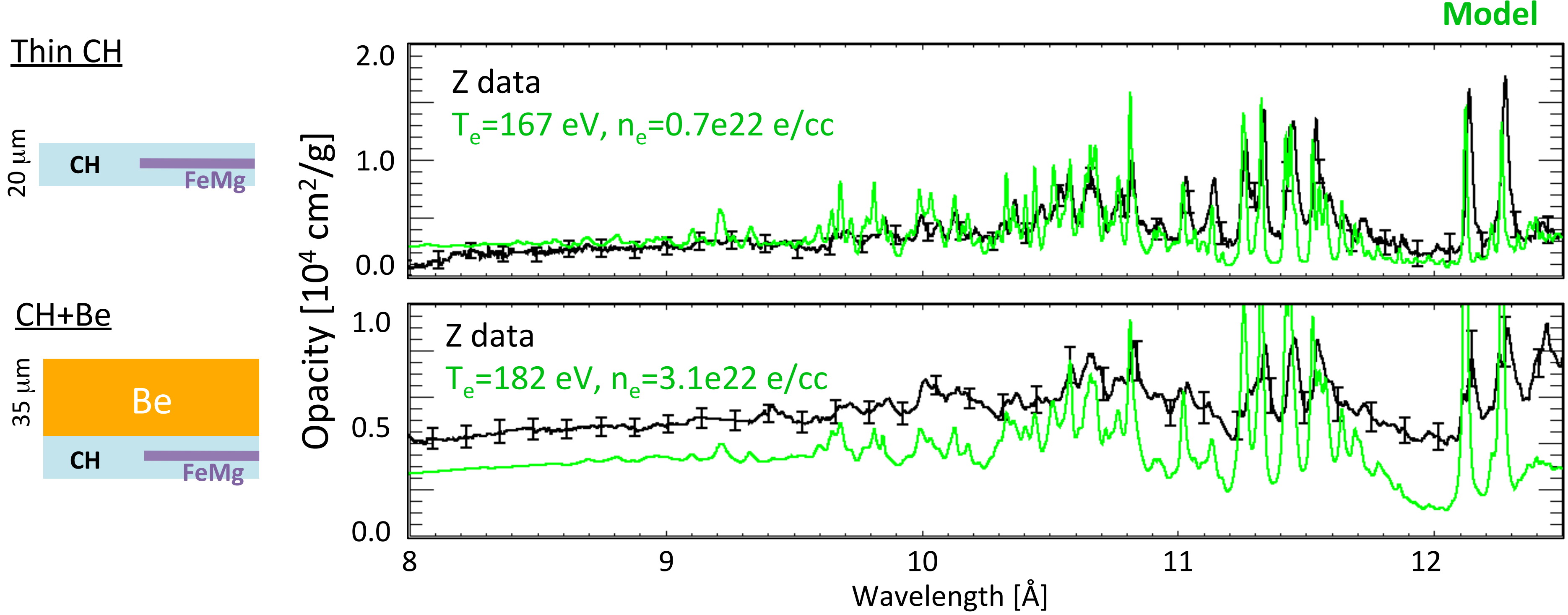
- <u>Plasma conditions:</u>

  Mg K-shell spectroscopy

J.E. Bailey et al, Physics of Plasmas 16, 058101 (2009). T. Nagayama et al, Phys Plasmas 21, 056502 (2014)

Iron opacity measurements indicate modeled iron opacity is underestimated as approaching the CZB conditions

(Convection Zone Base: T_e=182 eV, n_e=9x10^{22} cm^{-3})

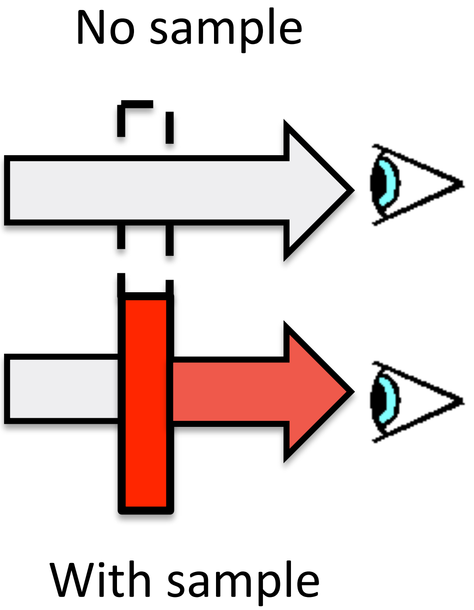


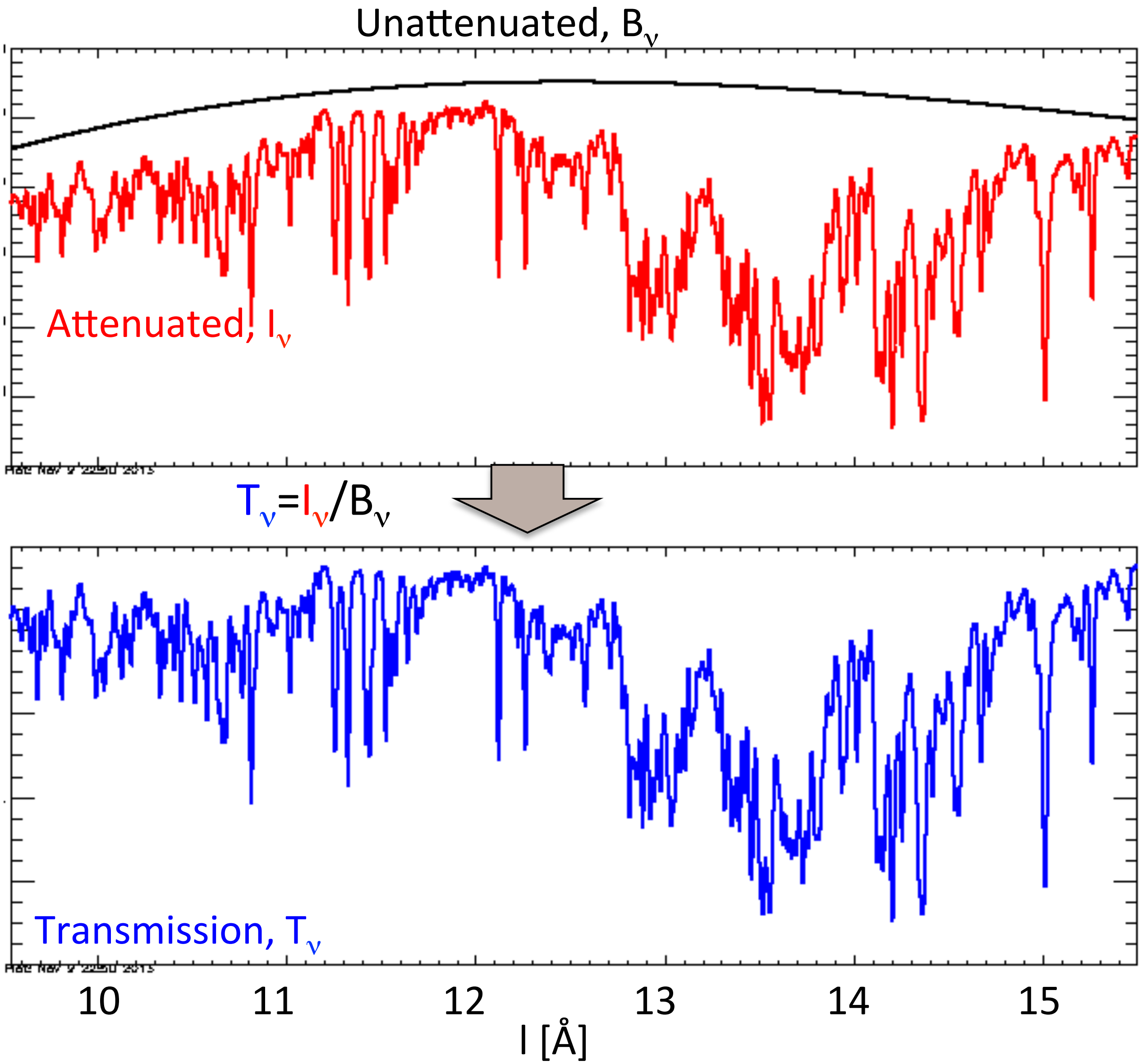
- Solar-mixture mean opacity increase = 7%
- The discrepancy has an impact on:
  - Astrophysics
  - Atomic physics
  - High energy density physics

Need to make sure that the discrepancies are not caused by experimental flaws

J.E. Bailey et al., Nature 517, 56 (2014) **T. Nagayama et al, Phys Plasmas 21, 056502 (2014)**

Concern 1: Plasma self-emission





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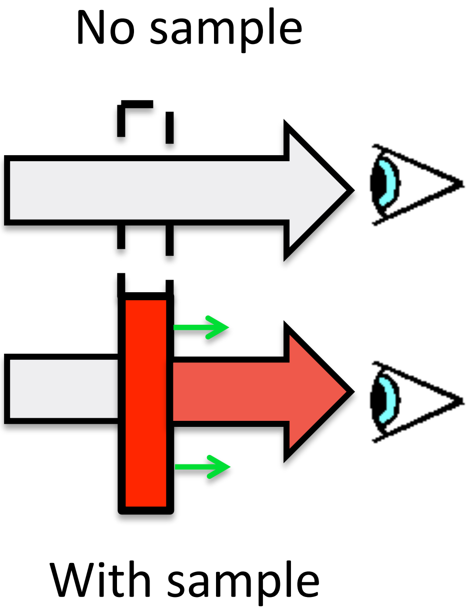
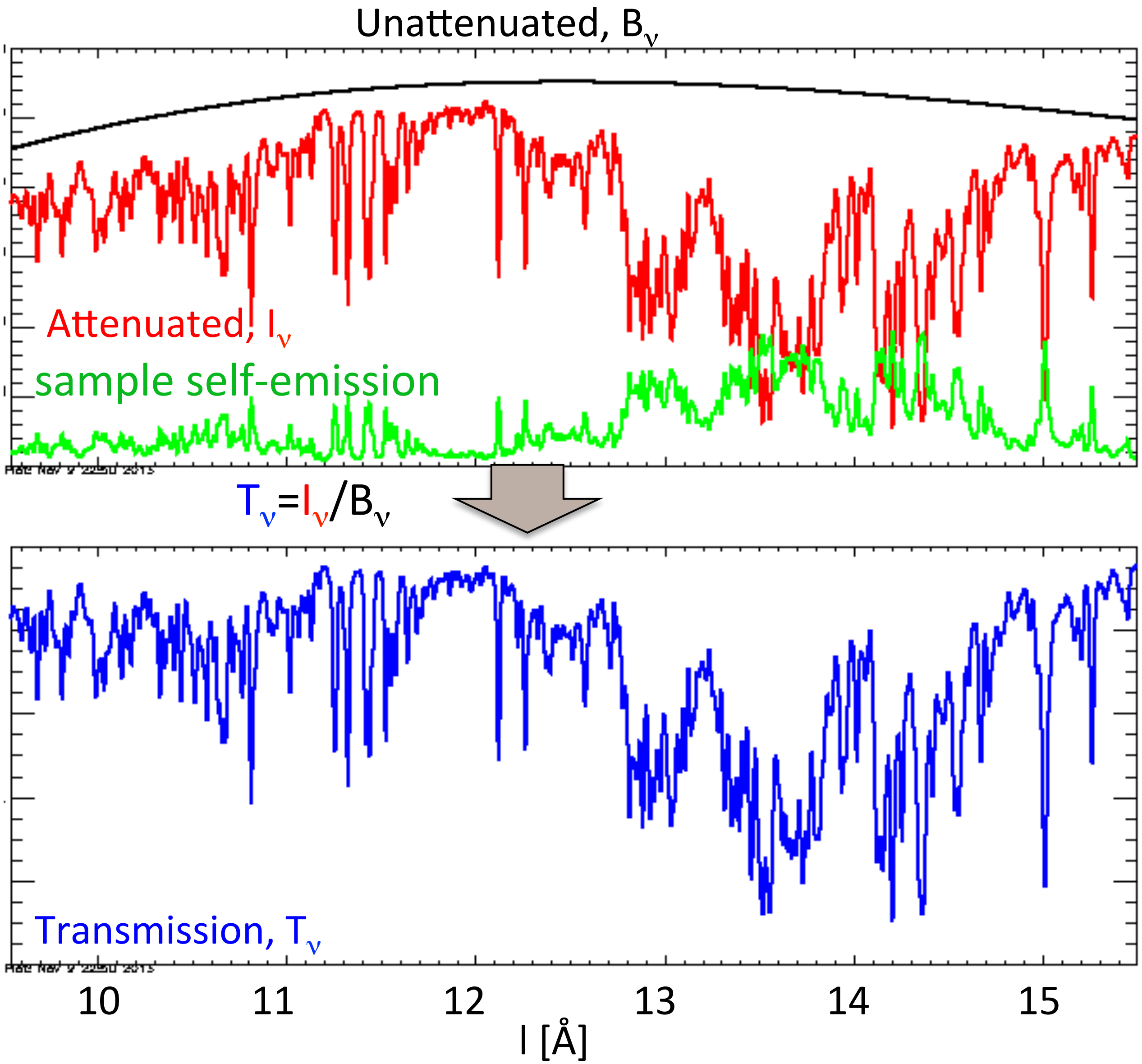
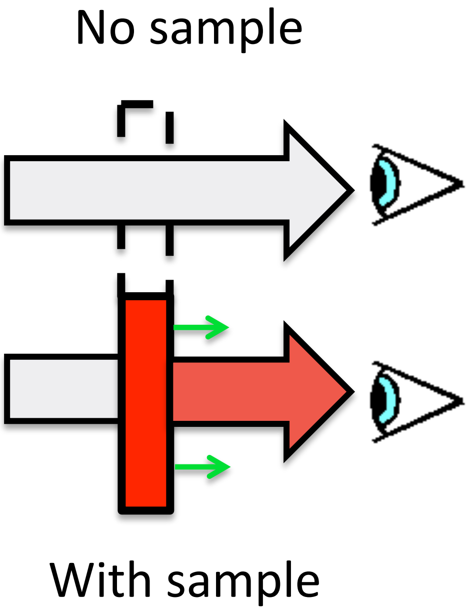
Concern 1: Plasma self-emission





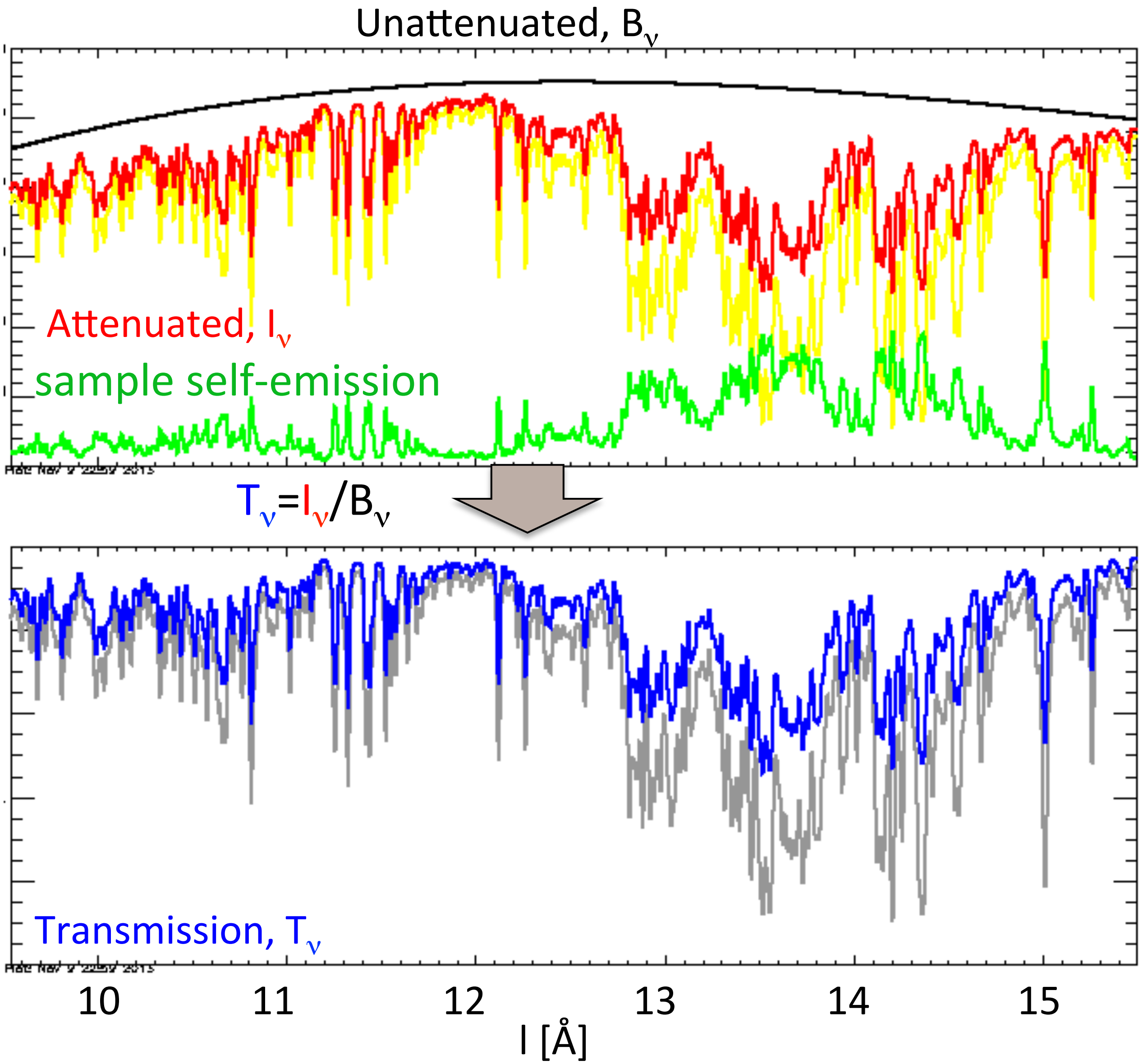
J.E. Bailey et al, Phys. Plasmas 16, 058101 (2009).

Concern 1: Plasma self-emission



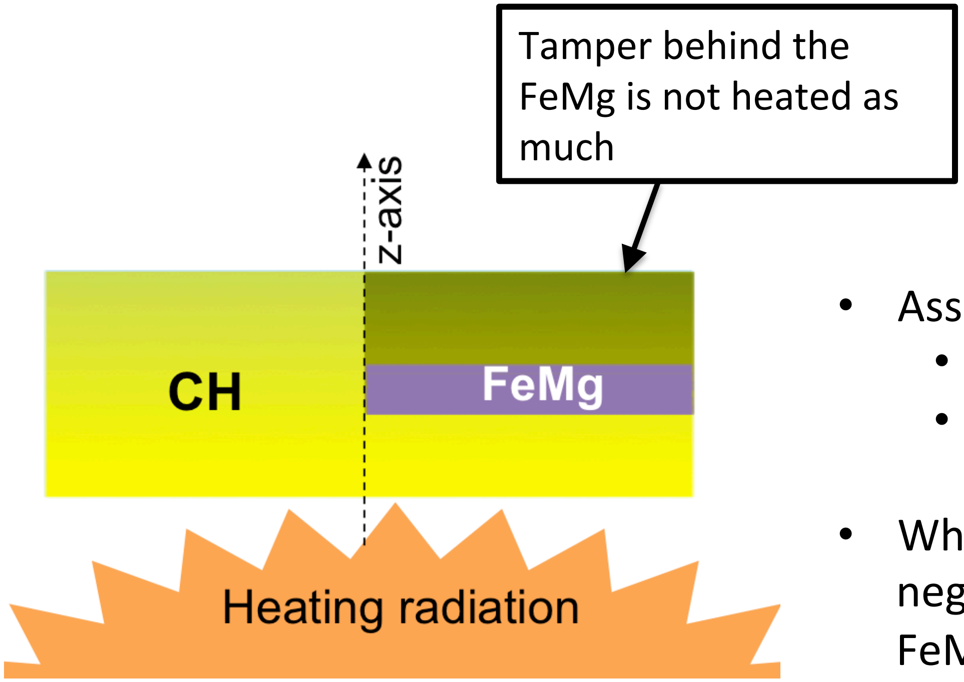
No sample

With sample



J.E. Bailey et al, Phys. Plasmas 16, 058101 (2009).

Concern 2: Tamper transmission difference


Tamper behind the FeMg is not heated as much

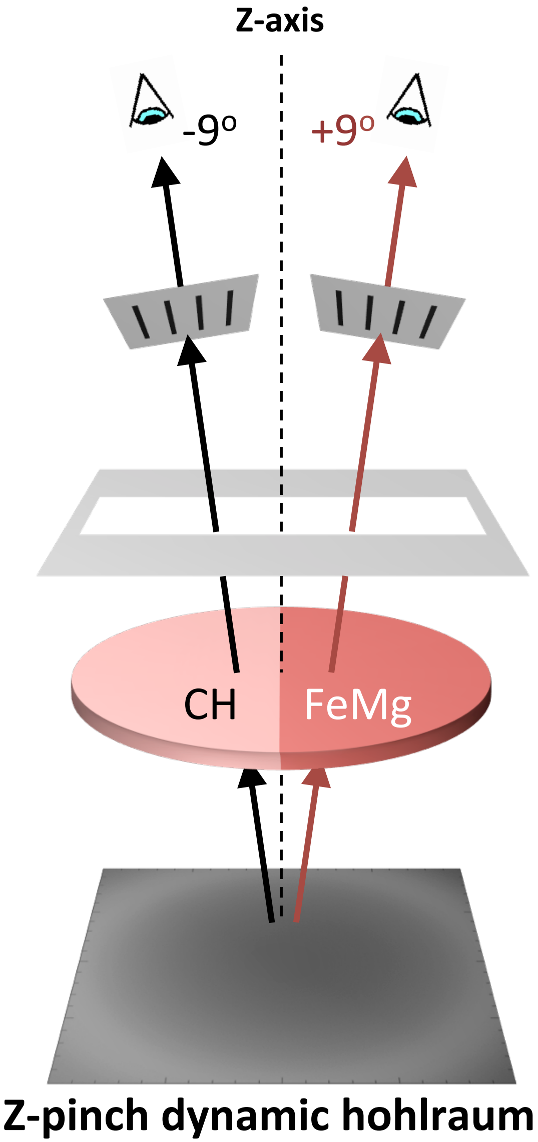
$$T_\nu^{FeMg}=I_\nu/I_{\nu,0}$$

- Assuming tamper transmission is
  - Negligible, or
  - The same on both sides
- What if tamper transmission is not negligible and different with/without FeMg?

Concern 3: Time- and space-integration effects

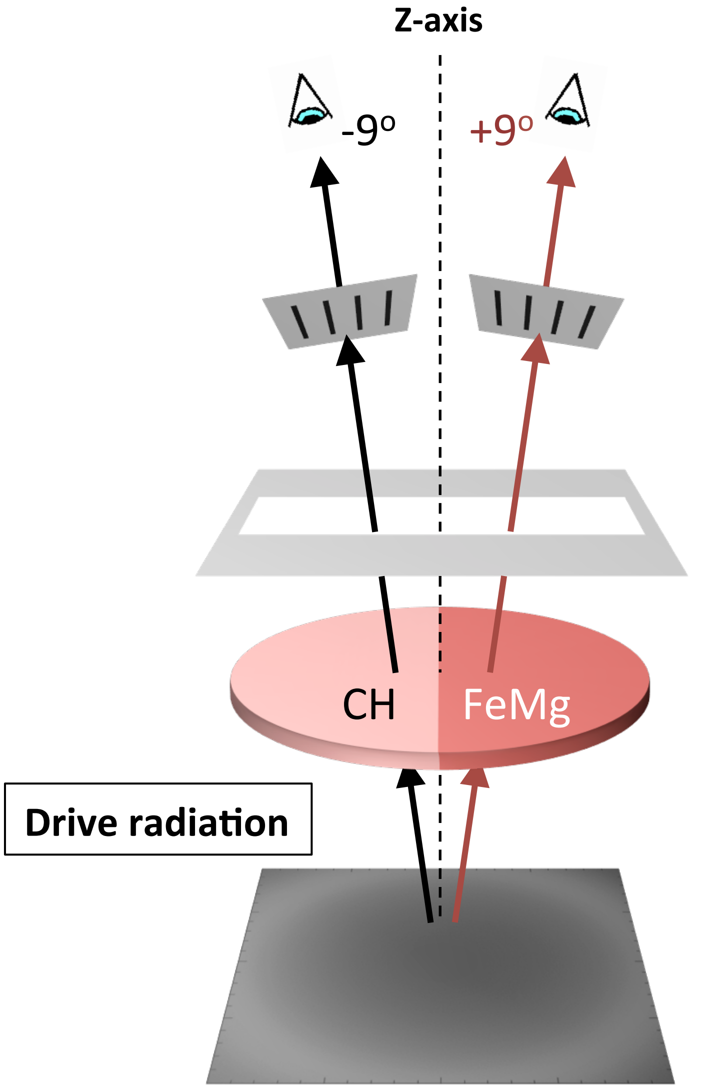
- The data are analyzed assuming static-uniform-plasma
- What if time- and space-integration effects are not negligible?

Systematic uncertainties associated with the concerns are numerically investigated



- Concerns
    - Self-emission effects
    - Tamper effects
    - Time- and space-integration effects

Systematic uncertainties associated with the concerns are numerically investigated

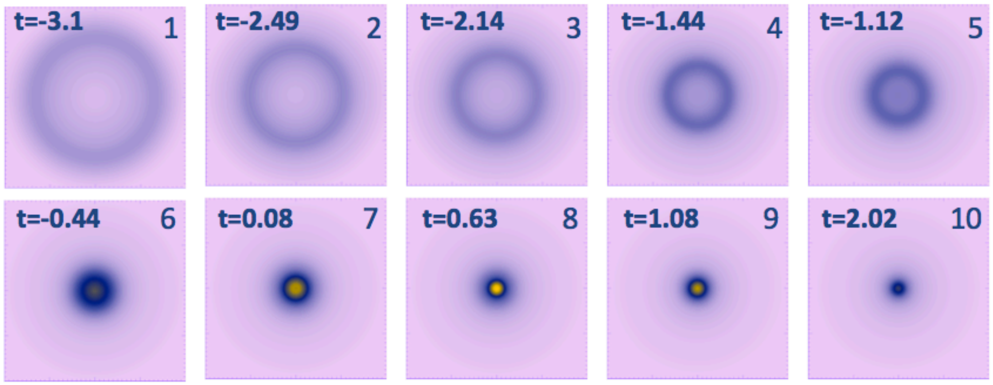


Z-pinch dynamic hohlraum

- Concerns
  - Self-emission effects
  - Tamper effects
  - Time- and space-integration effects

Drive radiation: VISRAD

- 3D view factor code, VISRAD
- Gated pinhole images of ZPDH



VISRAD: J.J. MacFarlane, J Quant Spectr Radiative Transfer 81, 287 (2003).

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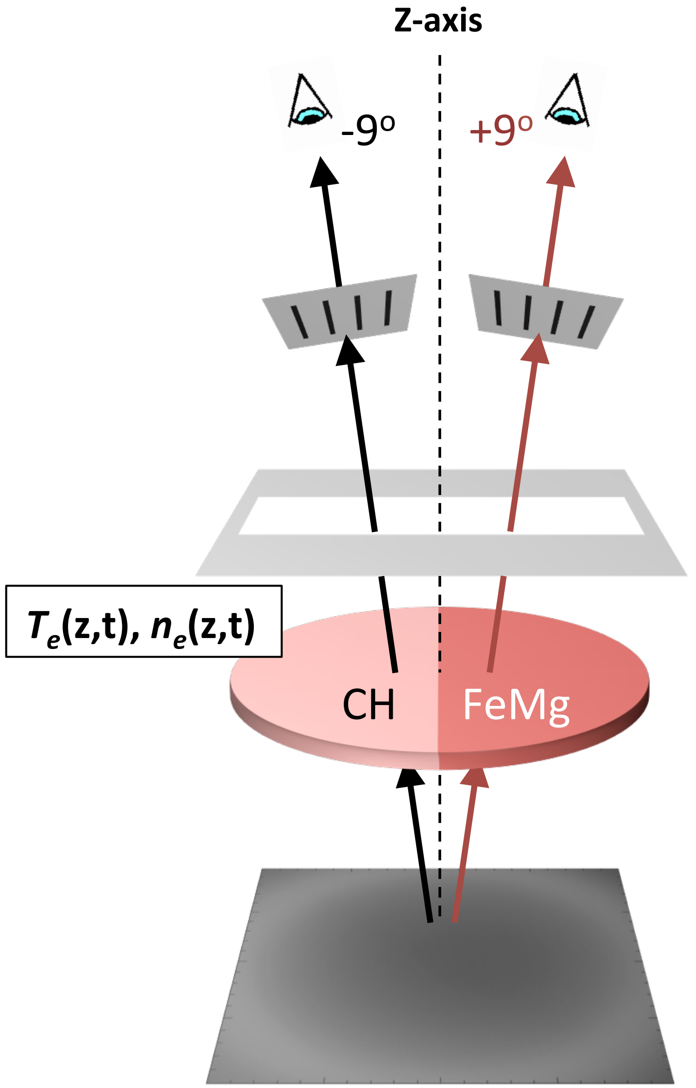
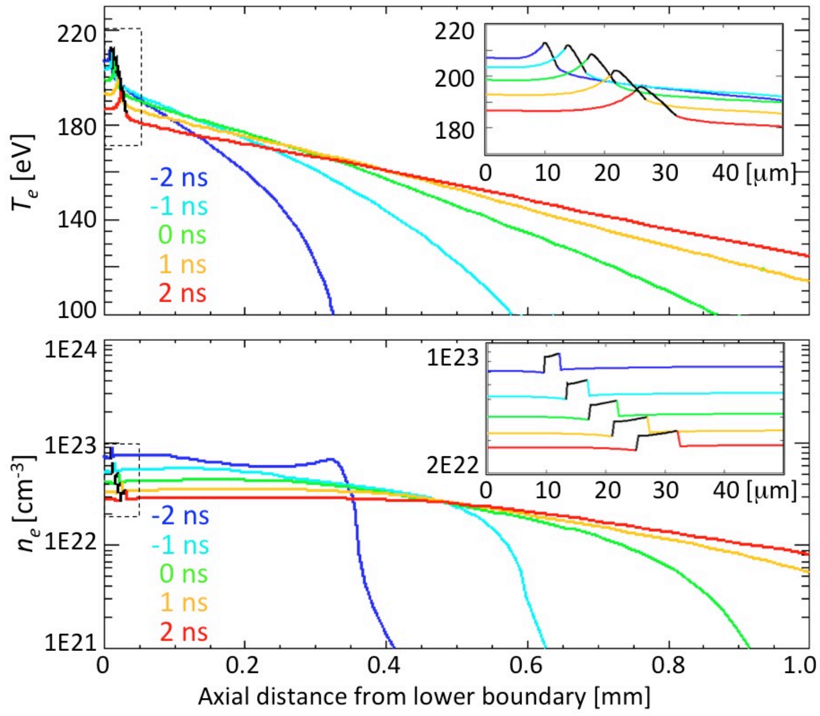


Z-pinch dynamic hohlraum

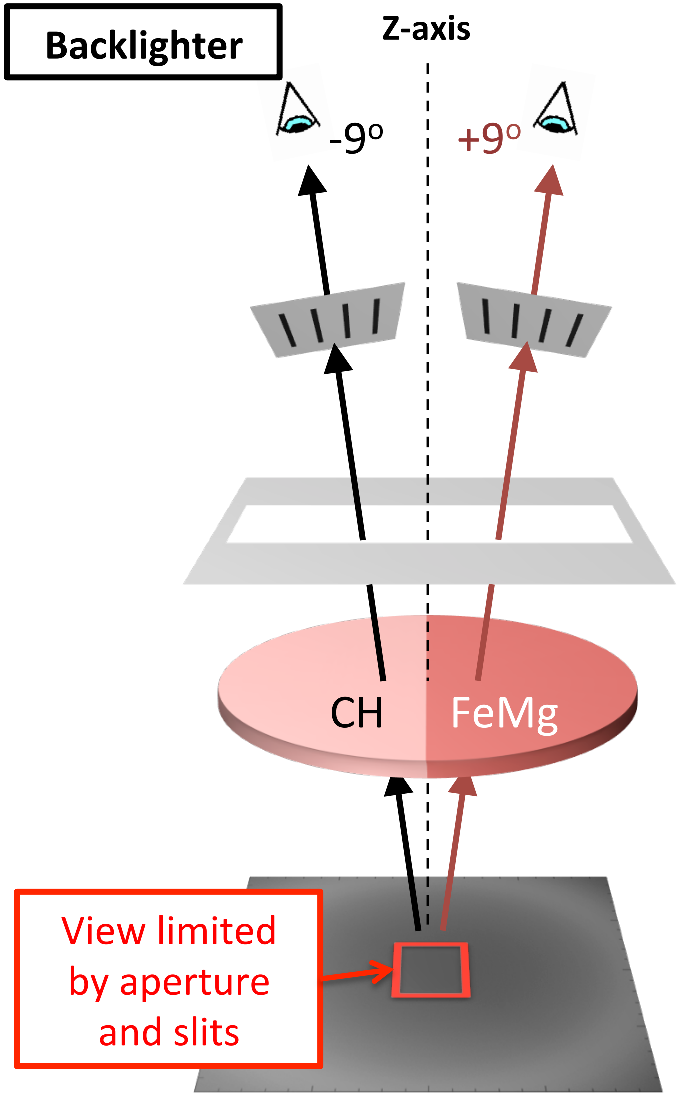
- Concerns
  - Self-emission effects
  - Tamper effects
  - Time- and space-integration effects

Hydrodynamics: 1D Lagrangian, HELIOS



HELIOS: J. MacFarlane et al, Phys. Rev. E 72, 066403 (2005).

Systematic uncertainties associated with the concerns are numerically investigated

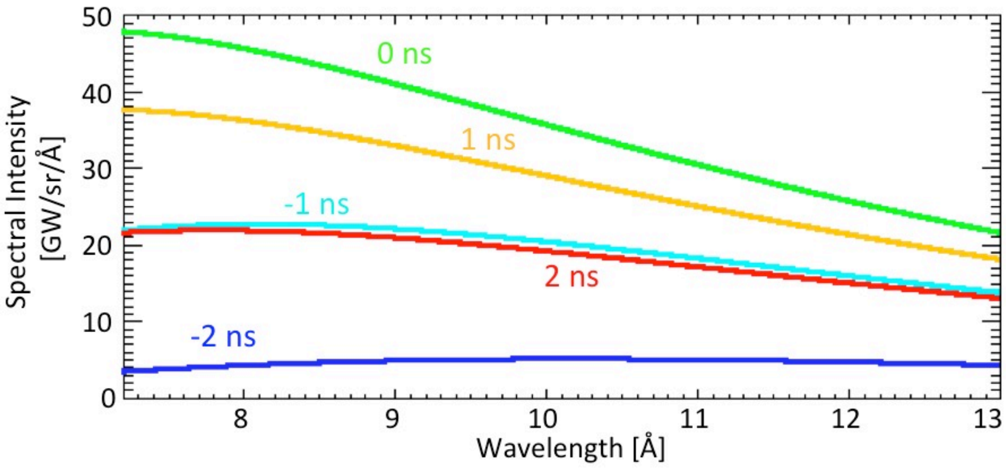


Z-pinch dynamic hohlraum

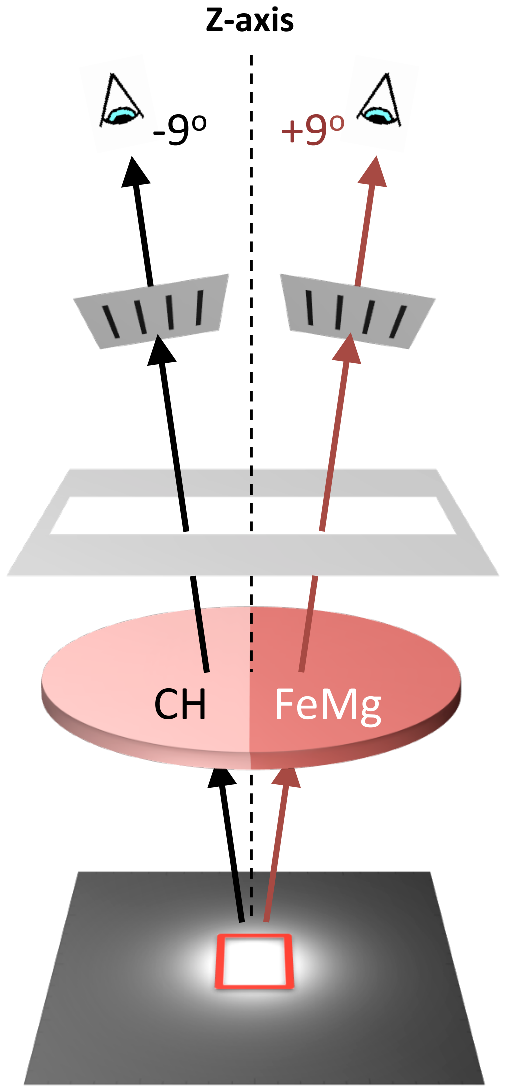
- Concerns
  - Self-emission effects
  - Tamper effects
  - Time- and space-integration effects

Backlight radiation

- Gated pinhole images of ZPDH
- Effects of aperture and slit



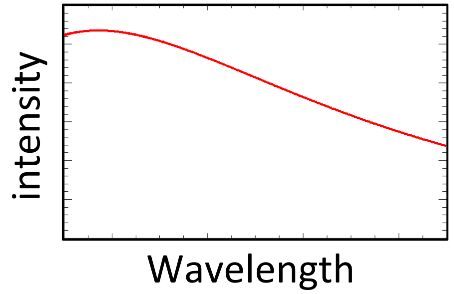
Systematic uncertainties associated with the concerns are numerically investigated



Z-pinch dynamic hohlraum

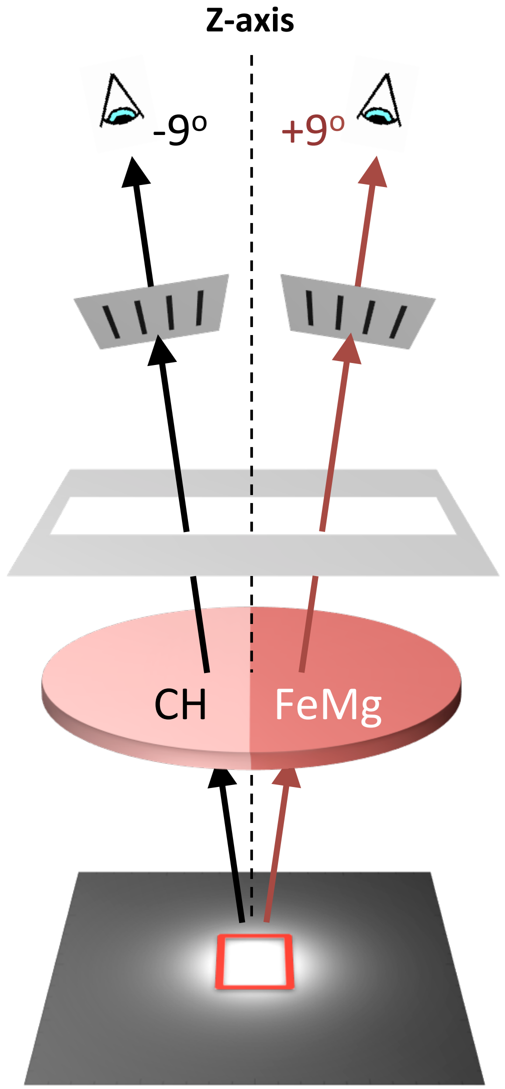
- Concerns
  - Self-emission effects
  - Tamper effects
  - Time- and space-integration effects

Radiation Transport



T. Nagayama et al, Phys Plasmas 21, 056502 (2014)

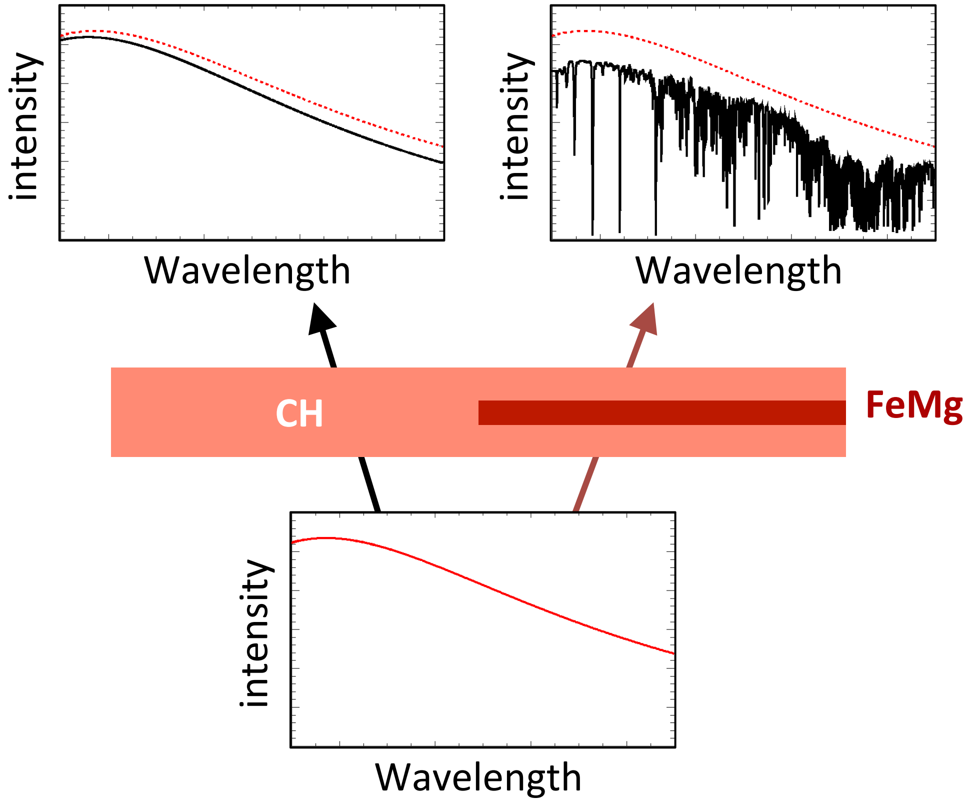
Systematic uncertainties associated with the concerns are numerically investigated



Z-pinch dynamic hohlraum

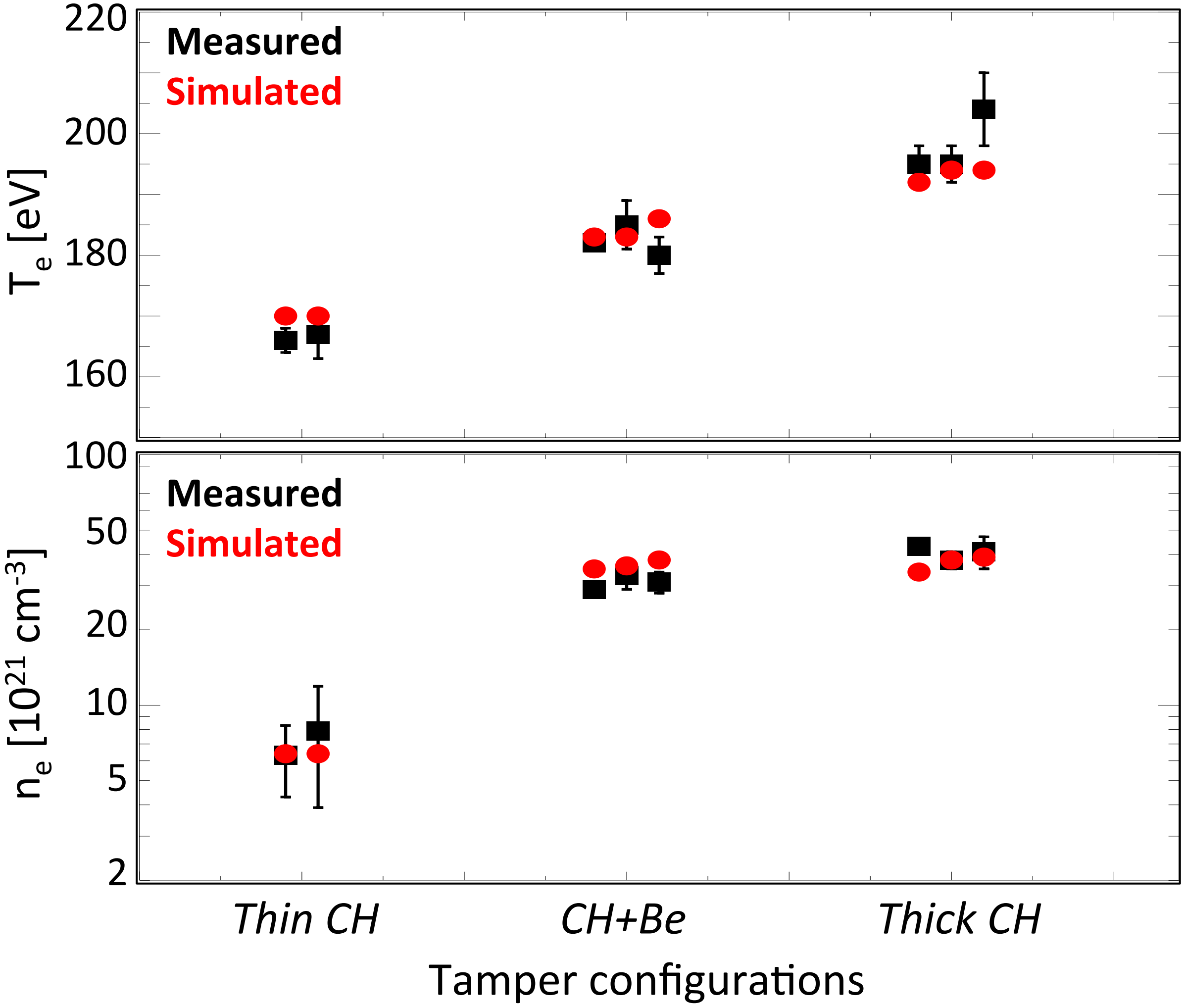
- Concerns
  - Self-emission effects
  - Tamper effects
  - Time- and space-integration effects

Radiation Transport

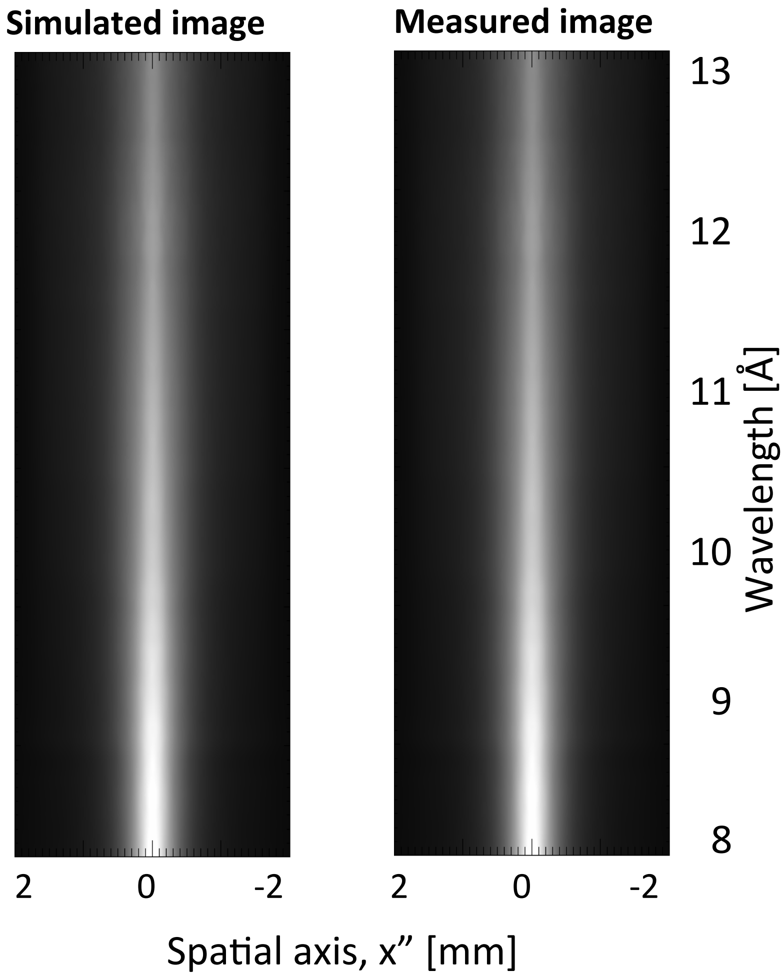


T. Nagayama et al, Phys Plasmas 21, 056502 (2014)

Simulated experiments reproduced the measured conditions for eight iron opacity experiments

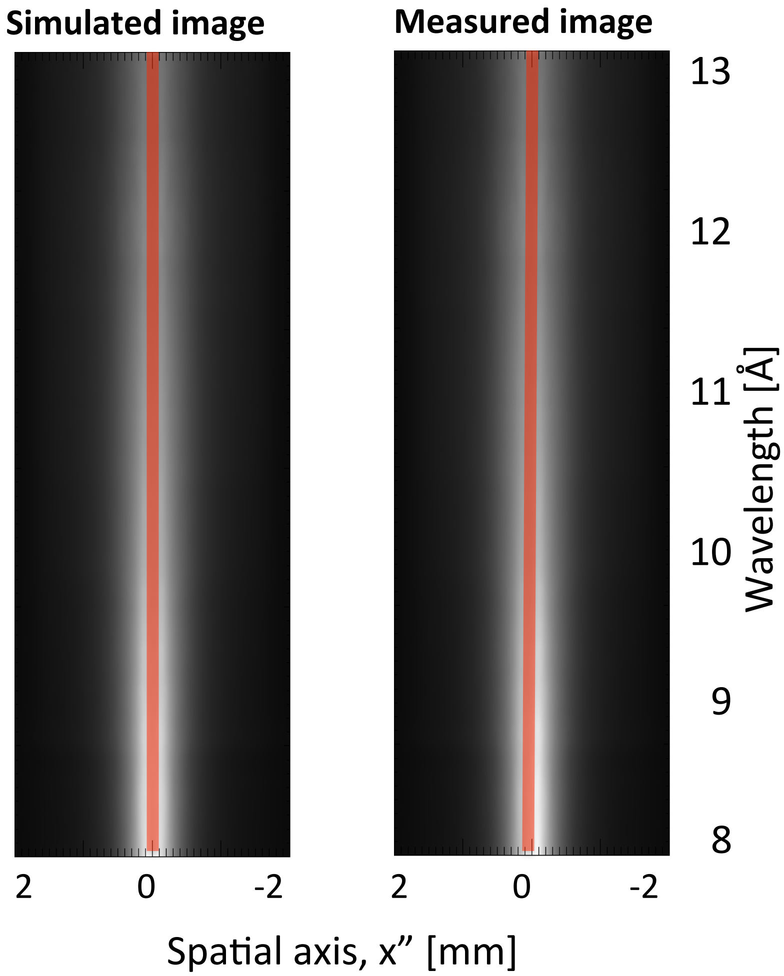


Simulated experiments reproduced the measured backlighter spectral image



- Measured image is the image averaged over 5 experiments

Simulated experiments reproduced the measured backlighter spectral image



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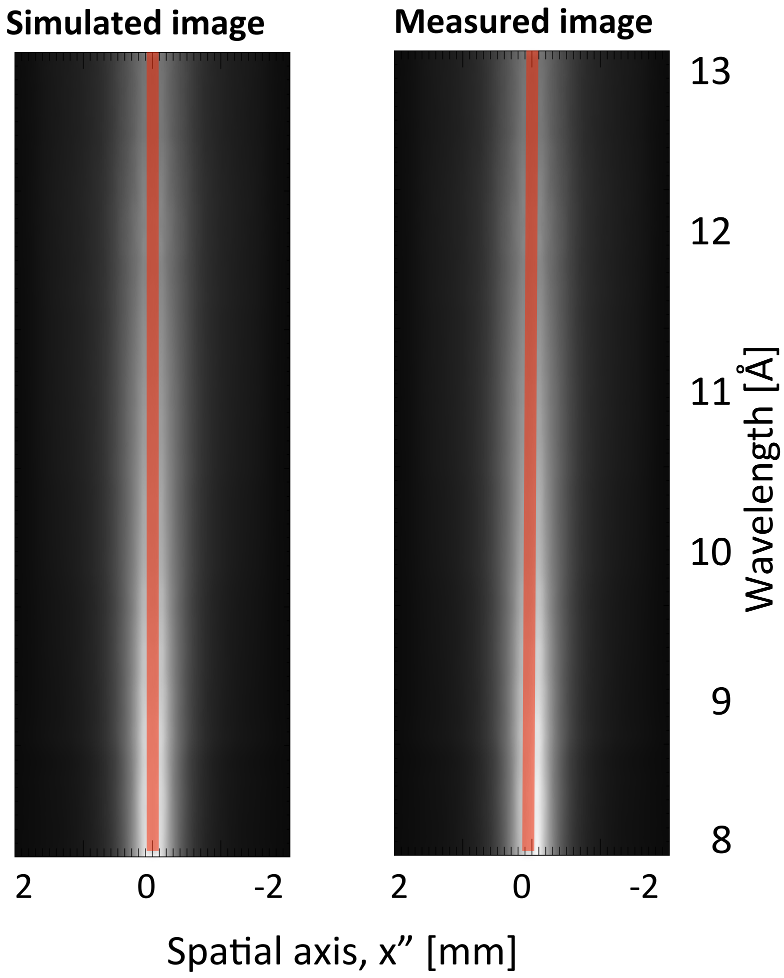
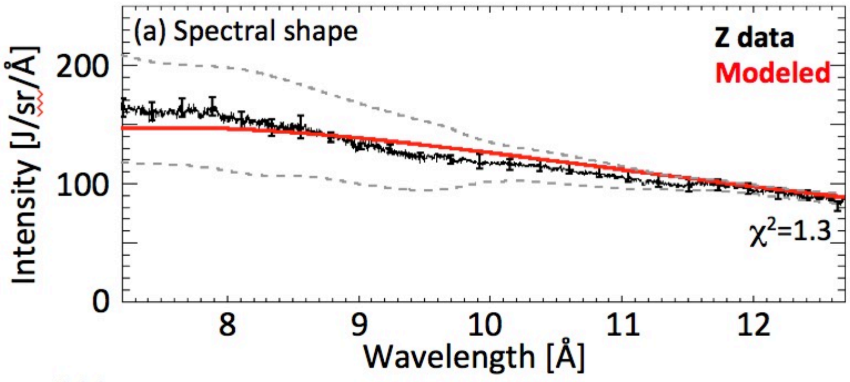
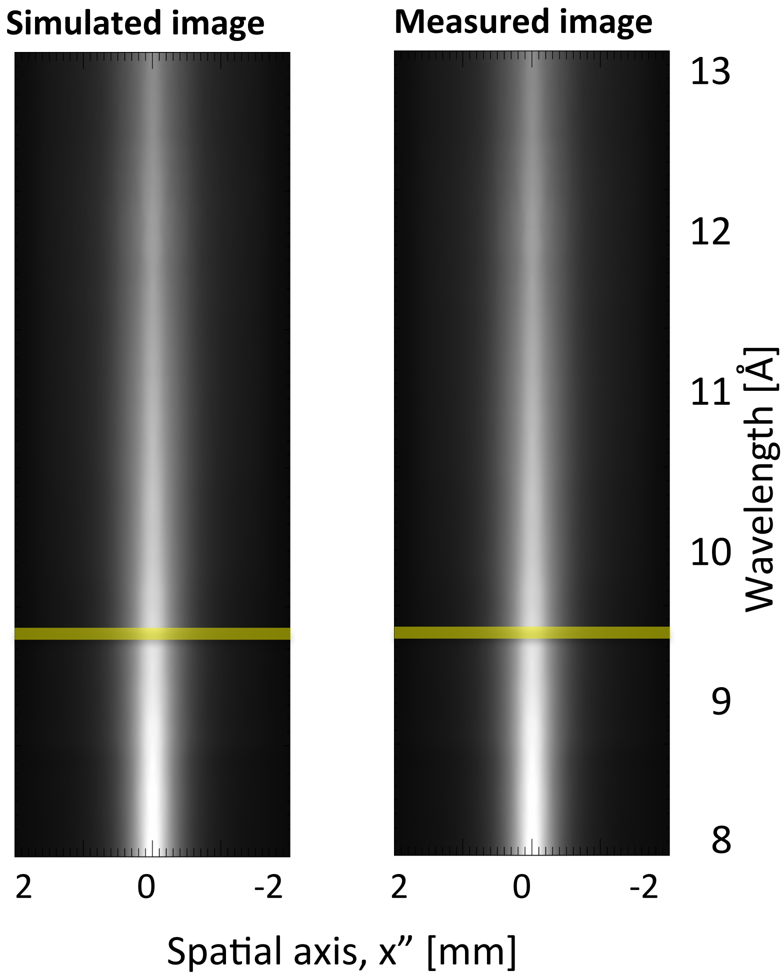
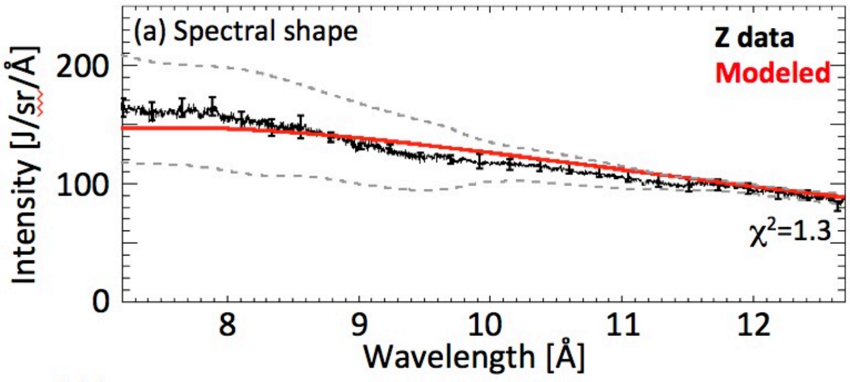




- Measured image is the image averaged over 5 experiments
- The simulated data agrees both in absolute value and in relative shape

Simulated experiments reproduced the measured backlighter spectral image





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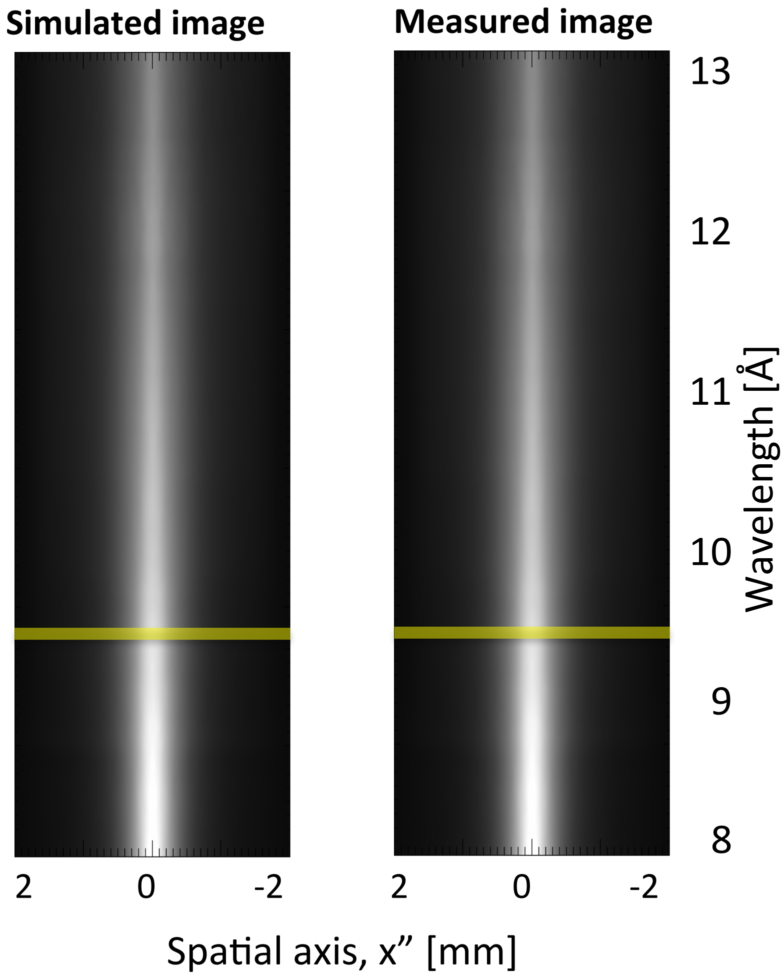
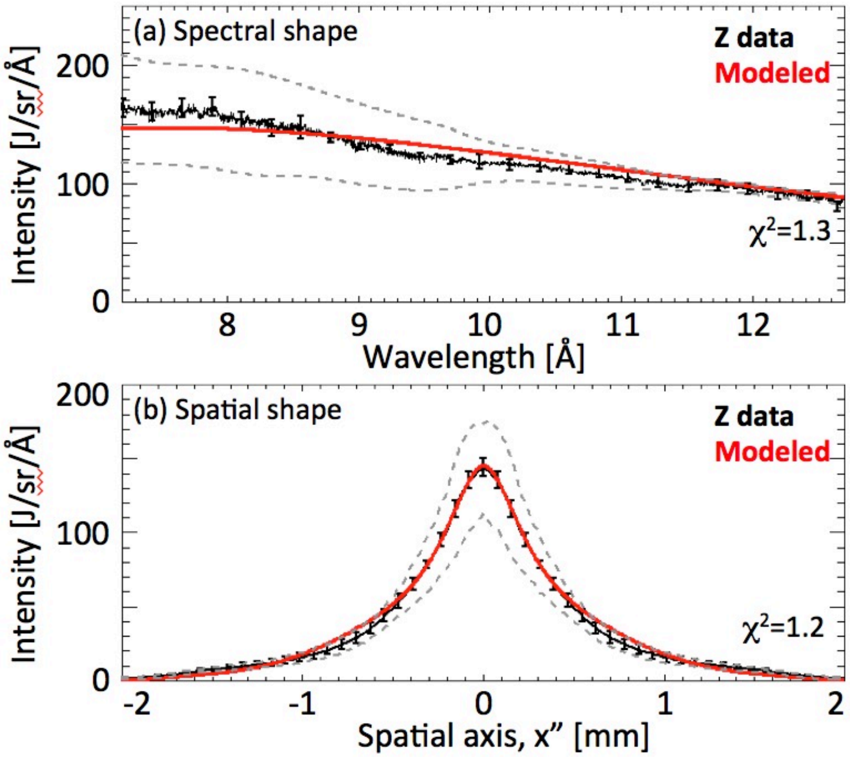
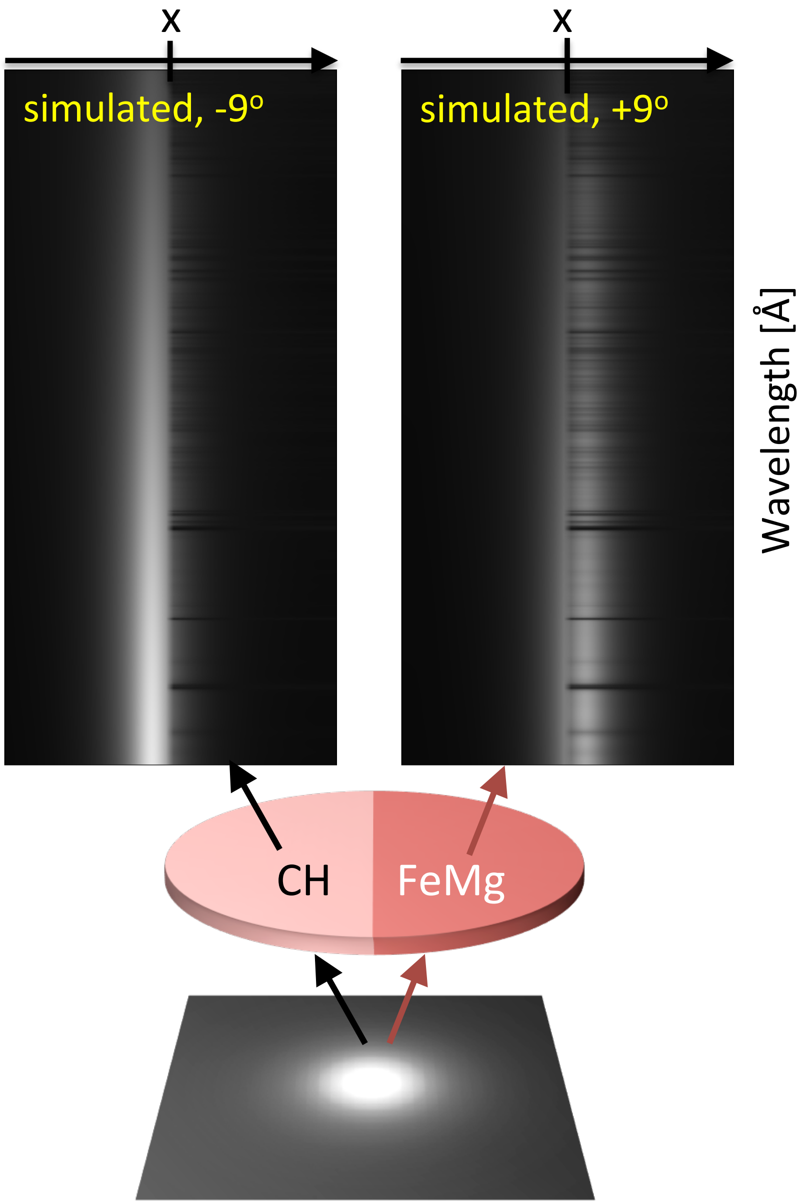
Simulated experiments reproduced the measured backlighter spectral image





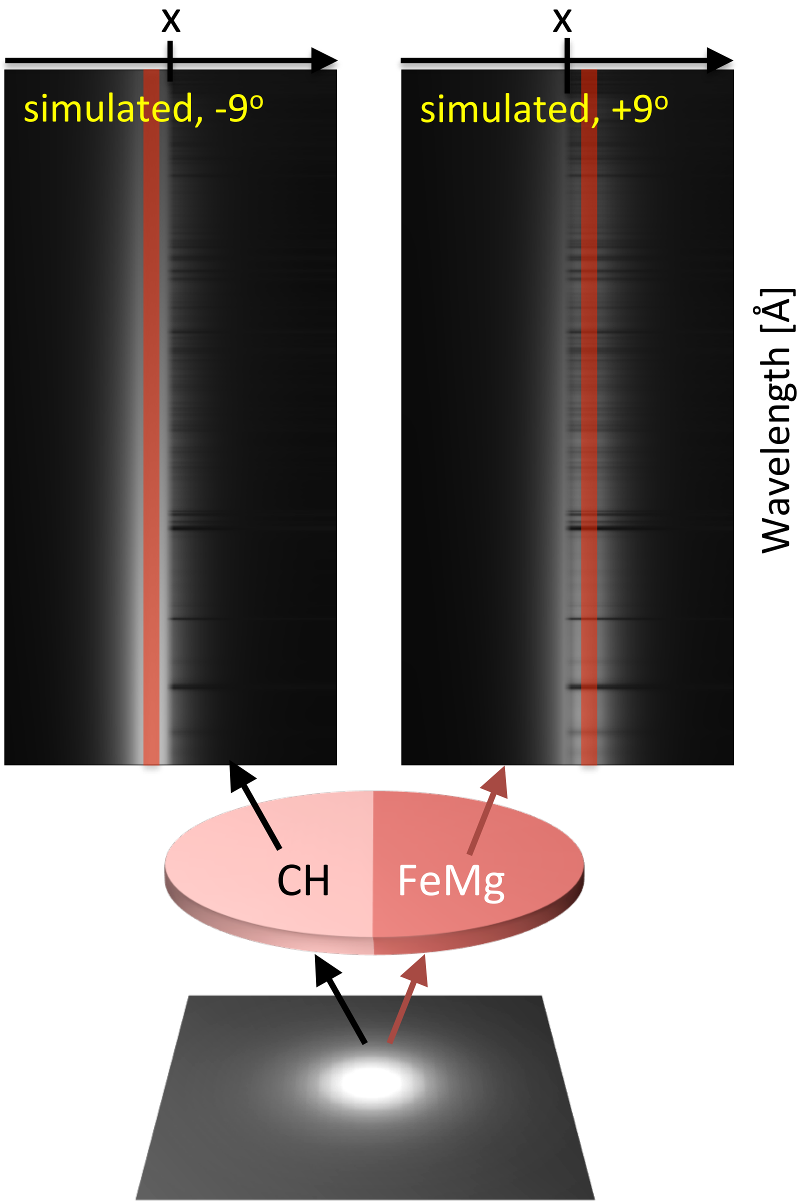
- Measured image is the image averaged over 5 experiments
- The simulated data agrees both in absolute value and in relative shape

The simulated data are analyzed in the same way



- Data are simulated for ±9º
- Backlight radiation is shifted with respect to sample boundary
- FeMg-attenuated and -unattenuated spectra are extracted

The simulated data are analyzed in the same way



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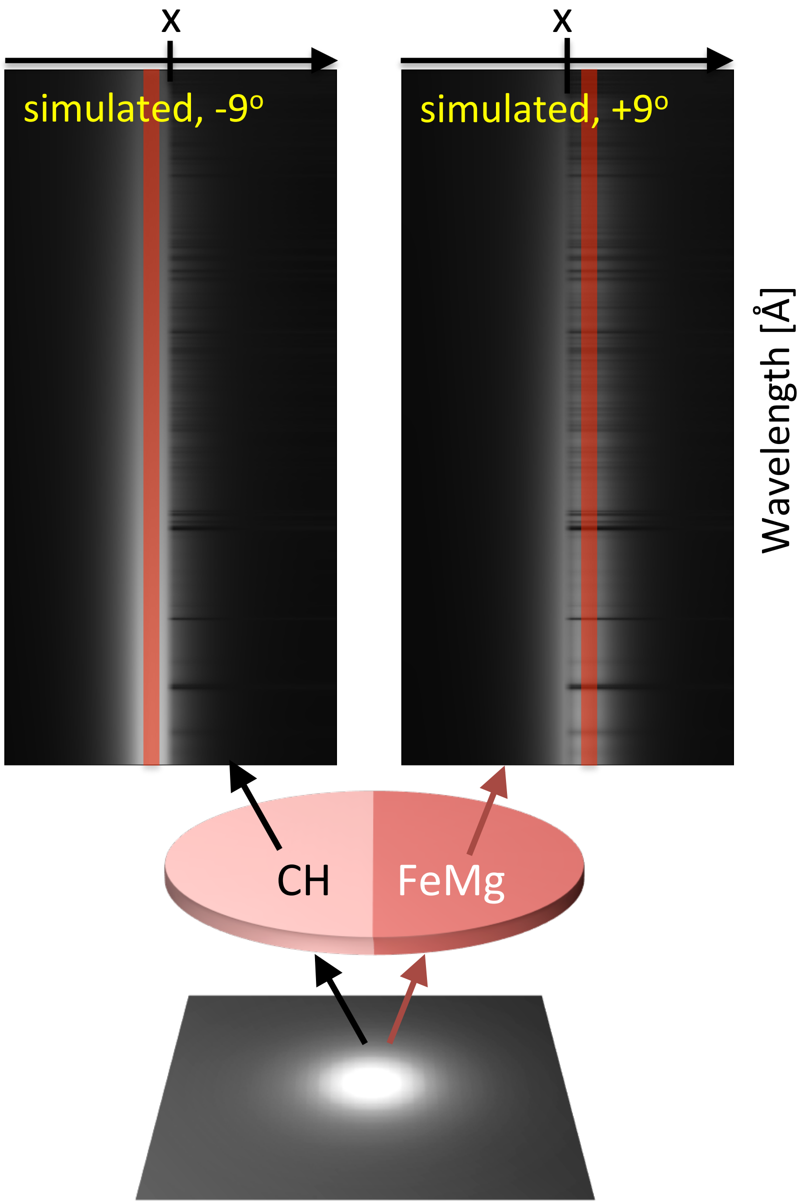

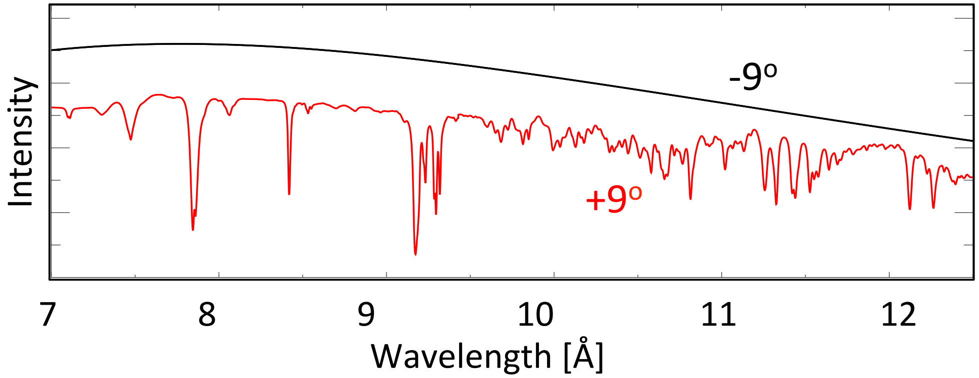

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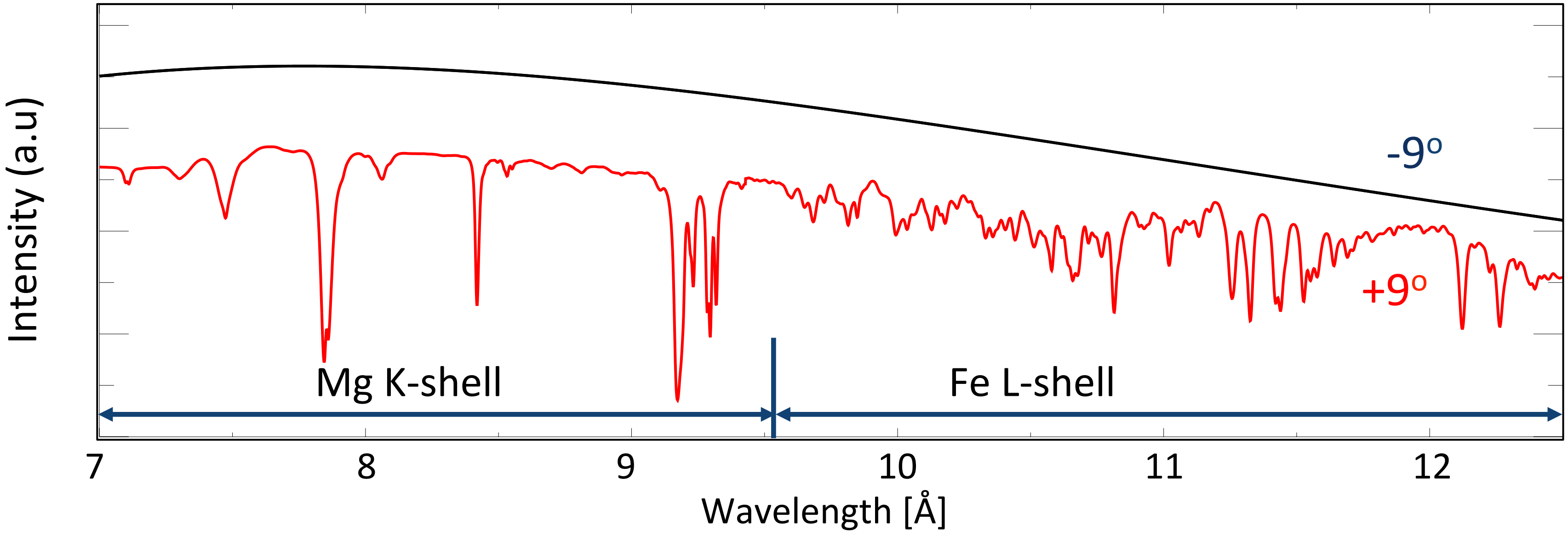
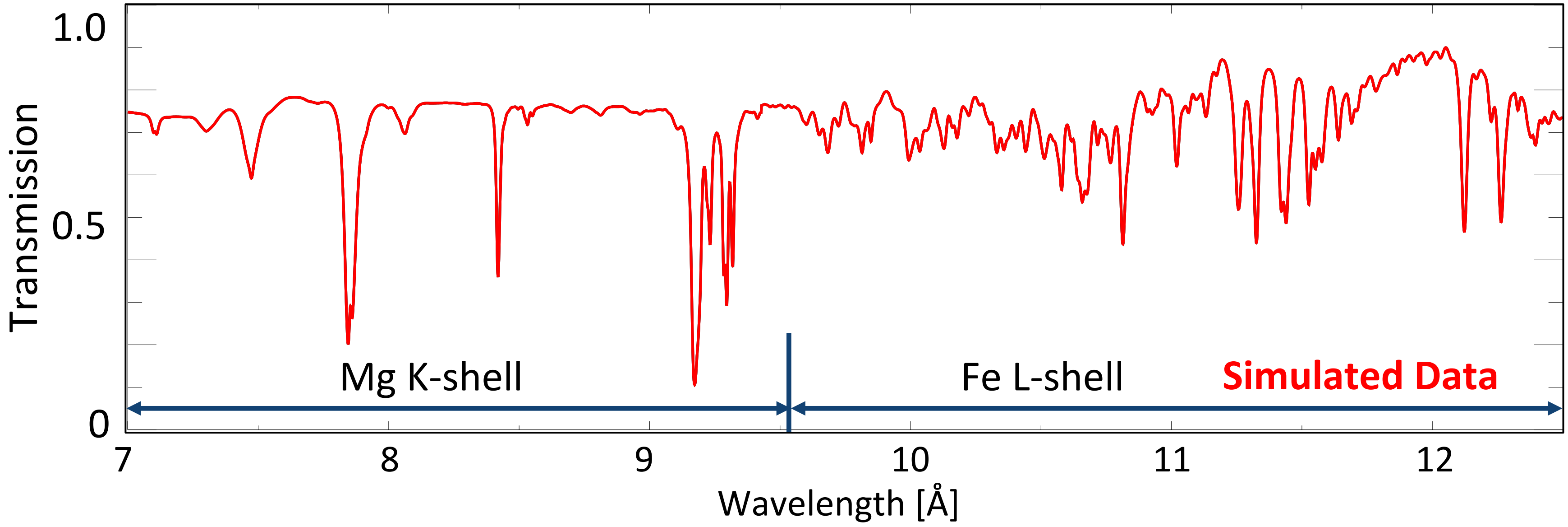


Simulated data are analyzed as follows:

1. Compute transmission: $T_\nu = I_\nu^{+9}/I_\nu^{-9}$
2. Infer T_e^{eff} and n_e^{eff} from Mg spectra
3. Model Fe transmission
4. Convert them to opacity
5. Remove Mg lines

The simulated data are analyzed in the same way



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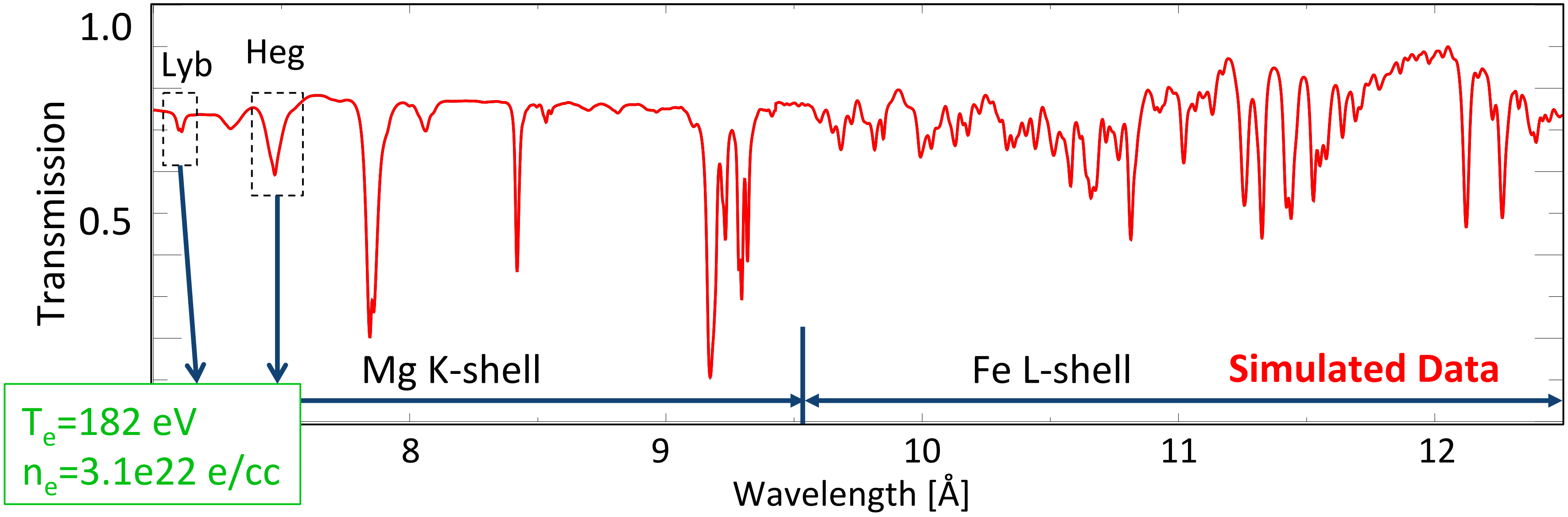

T_e=182 eV
n_e=3.1e22 e/cc

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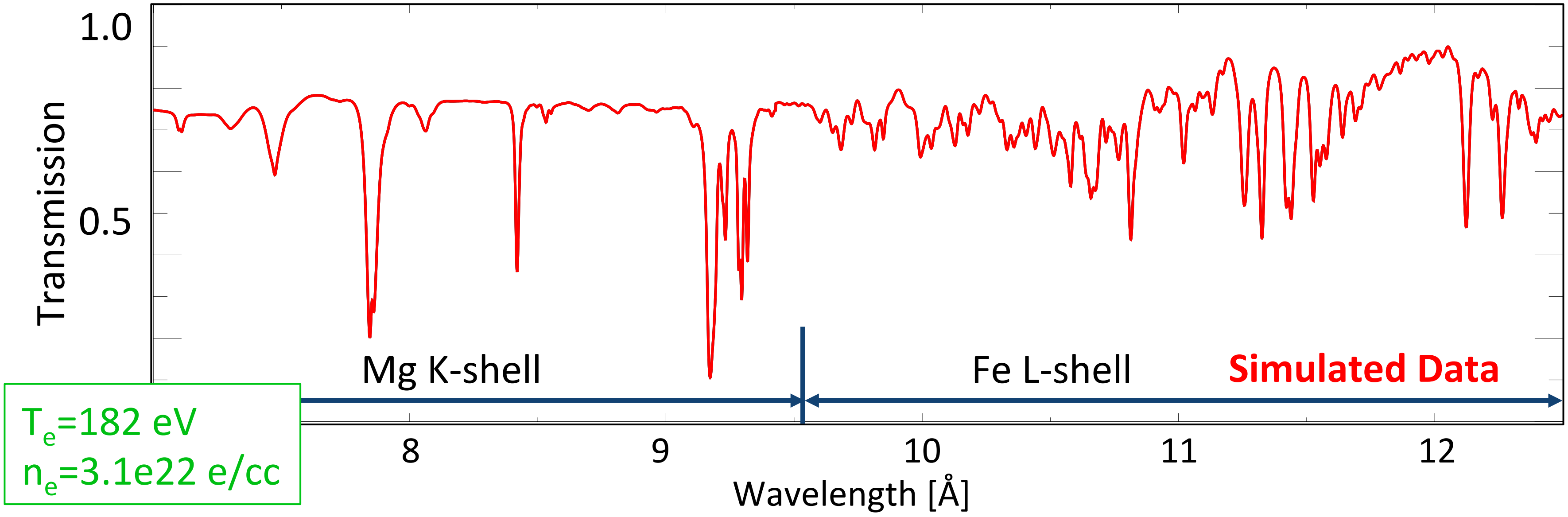

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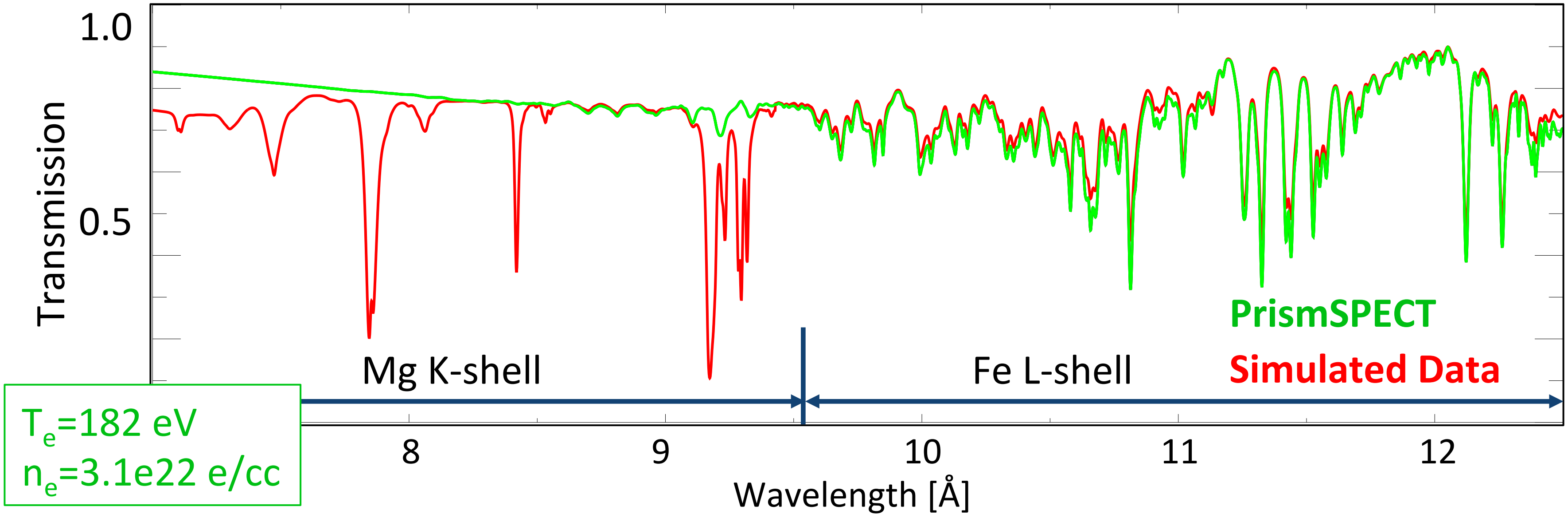

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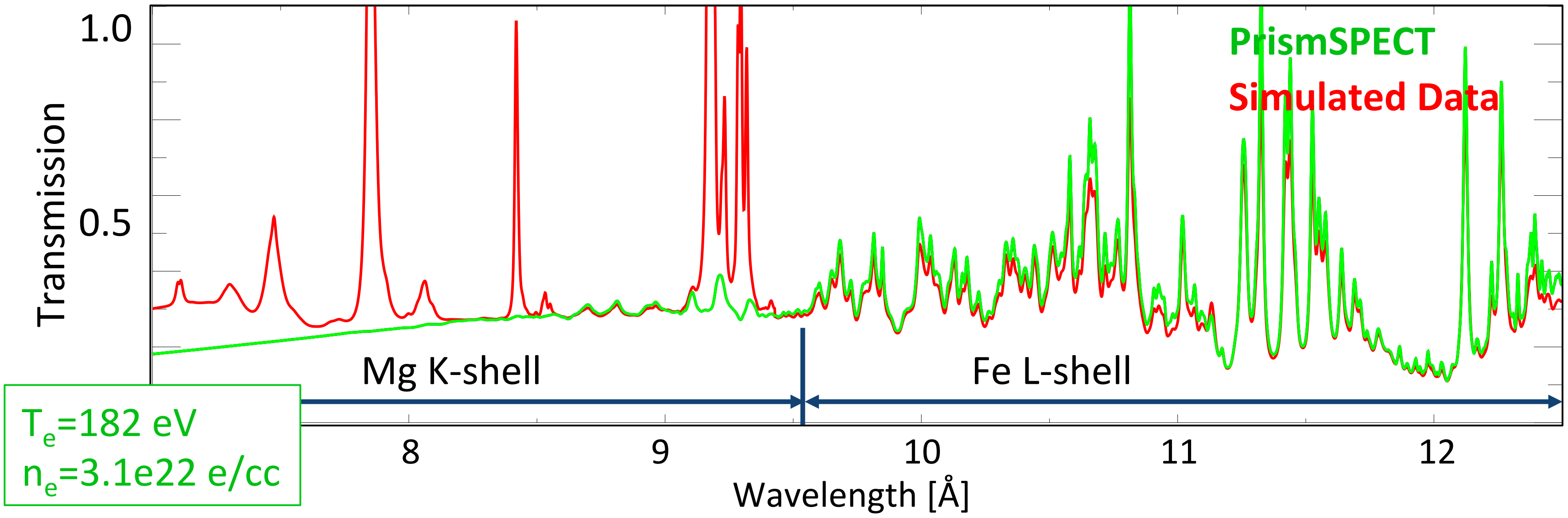

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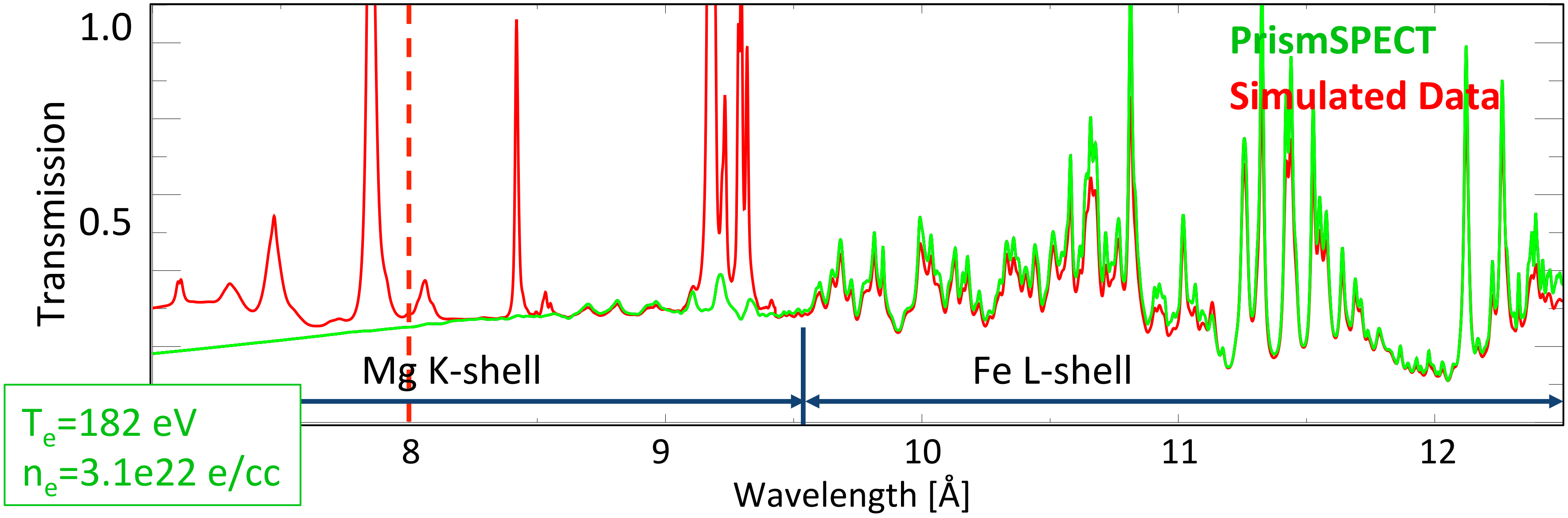

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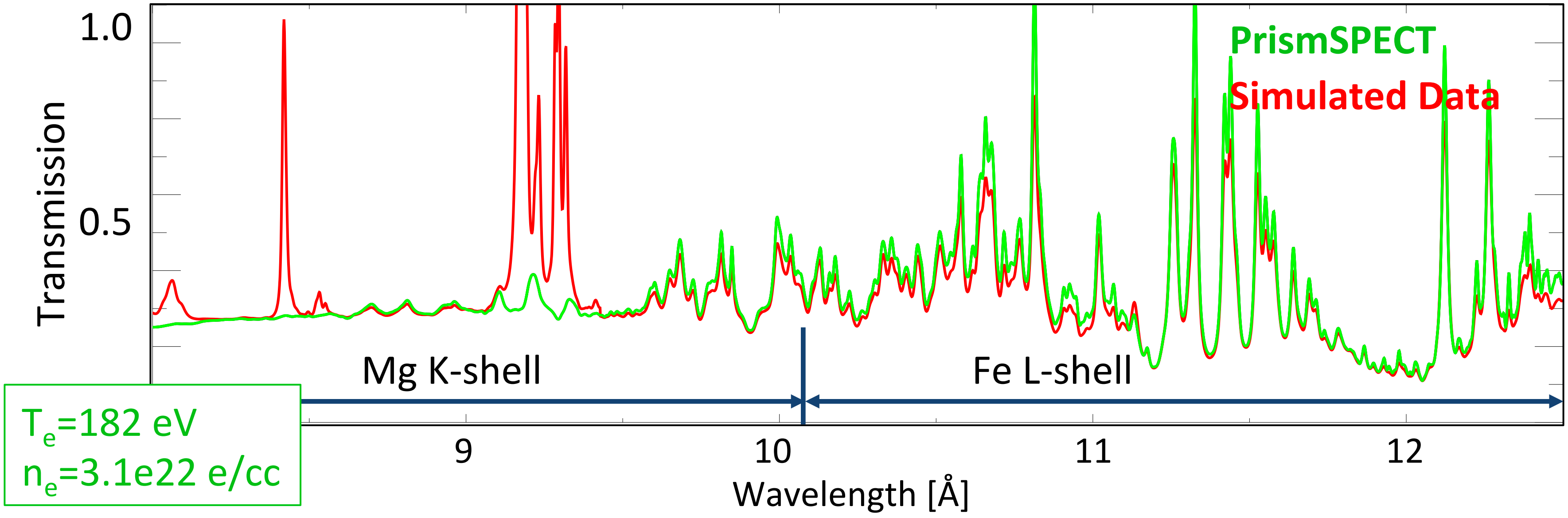

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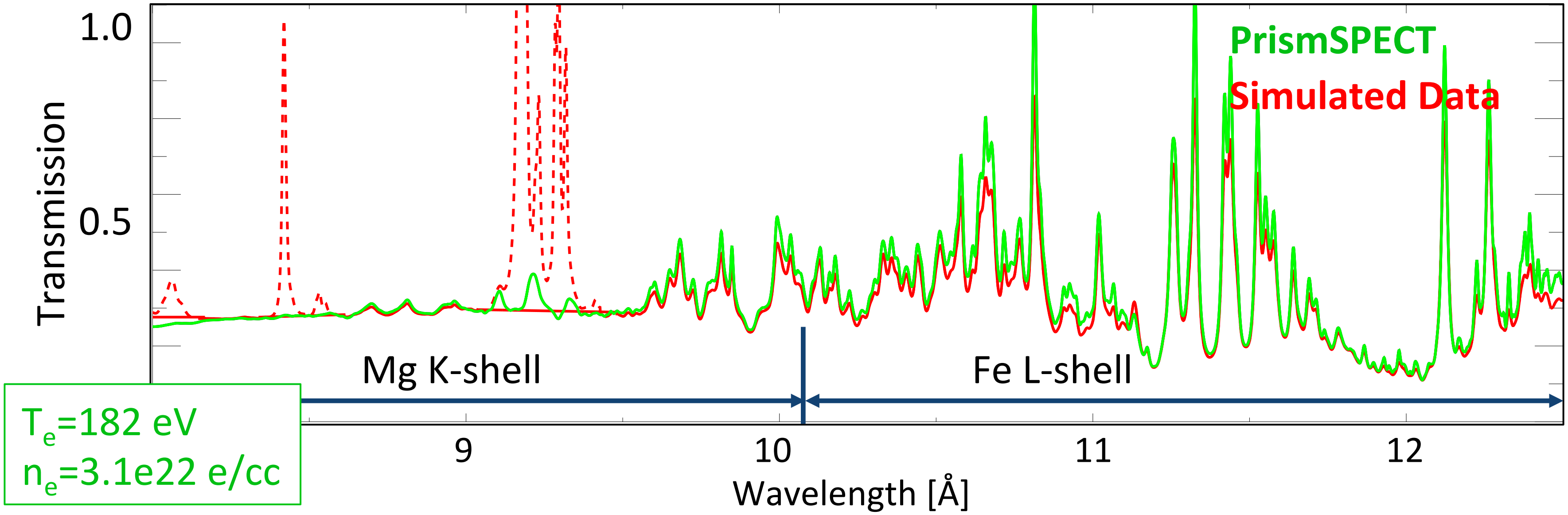

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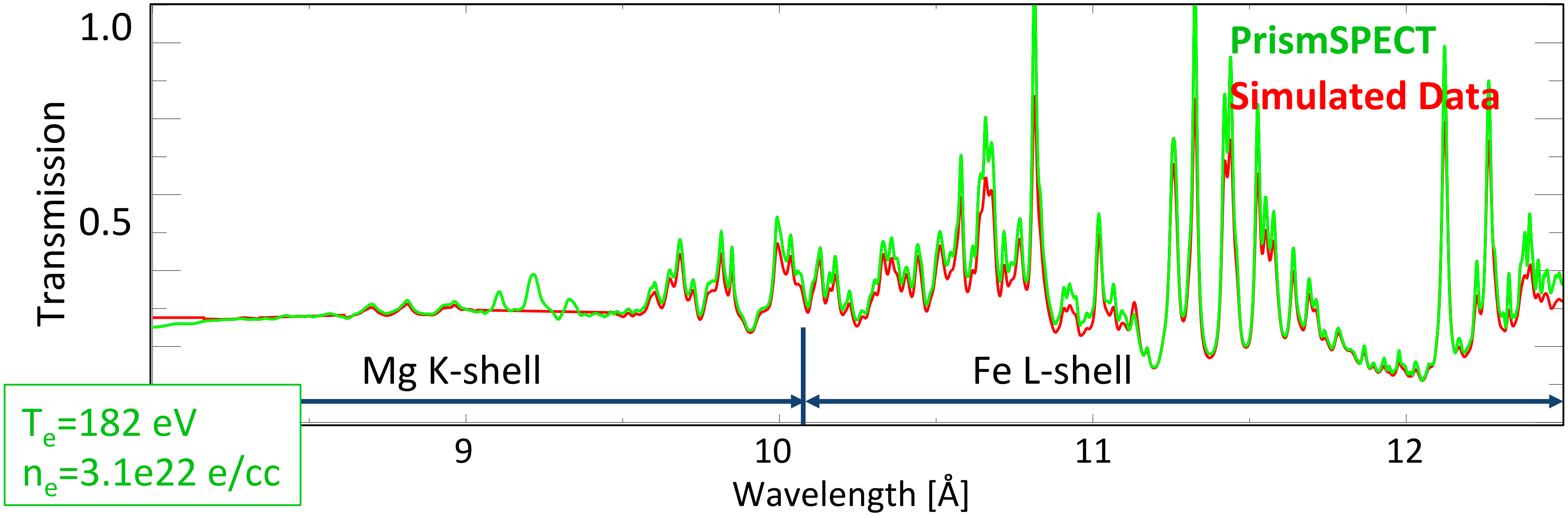

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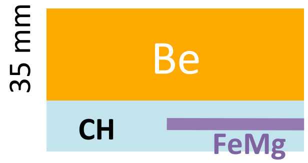
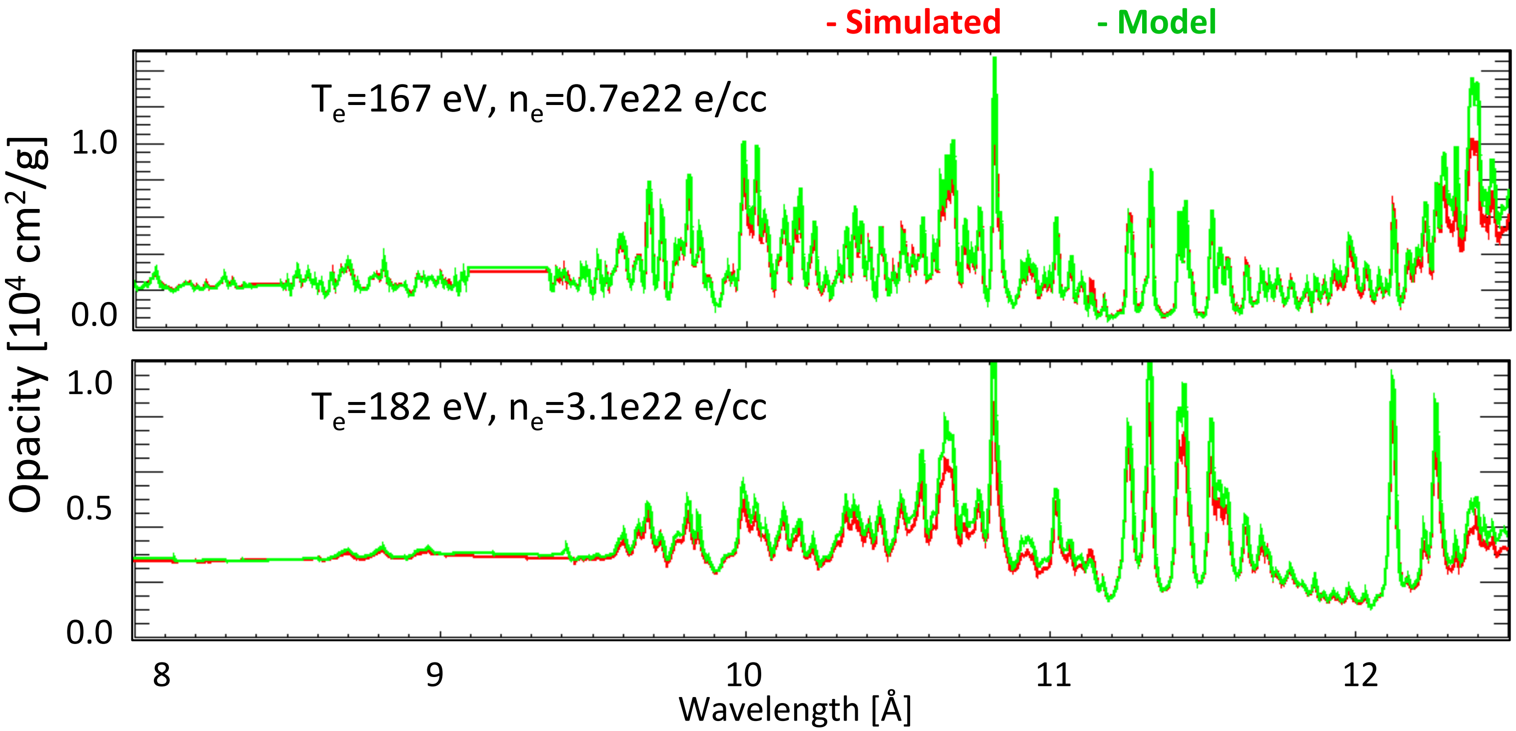
2. Infer T_e^{eff} and n_e^{eff} from Mg spectra
3. Model Fe transmission
4. Convert them to opacity
5. Remove Mg lines

The observed severe discrepancies are not explained by self-emission, tamper effect, and integration effects

Thin CH

CH+Be

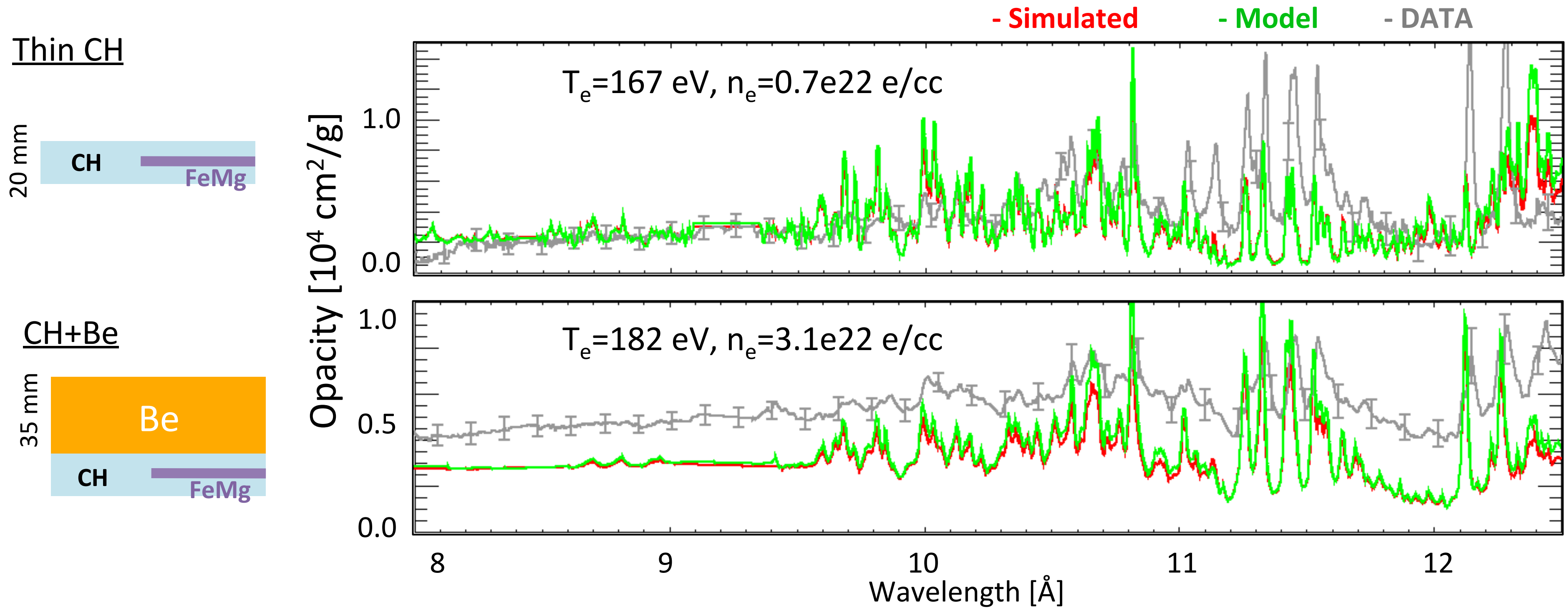




Simulated data include:

- FeMg emission
- Tamping material:
  - Tamper emission/absorption
  - Tamper condition difference
- Time- and space-integration effects
  - $T_e(t,z)$ and $n_e(t,z)$
  - $B_\nu(t,x,y)$
  - Radiation transport through the gradient
  - Emergent spectra integrated over time

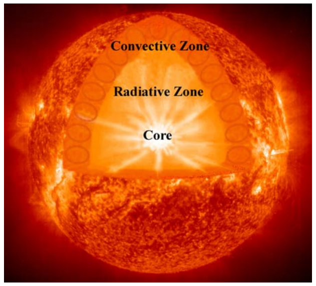
The observed severe discrepancies are not explained by self-emission, tamper effect, and integration effects



<u>Simulated data include:</u>

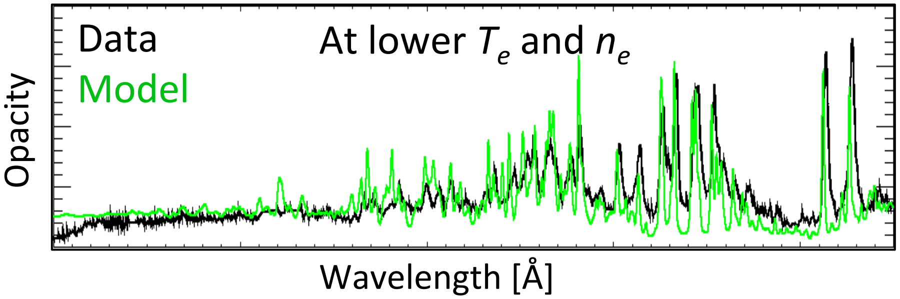
- FeMg emission
- Tamping material:
  - Tamper emission/absorption
  - Tamper condition difference
- Time- and space-integration effects
  - $T_e(t,z)$ and $n_e(t,z)$
  - $B_\nu(t,x,y)$
  - Radiation transport through the gradient
  - Emergent spectra integrated over time

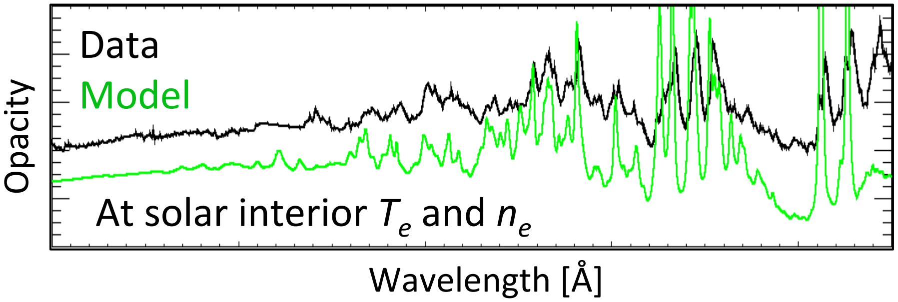
Numerical scrutiny verified the data interpretation of the SNL iron opacity measurements



- Solar models disagree with observations.
  → Is iron opacity underestimated?

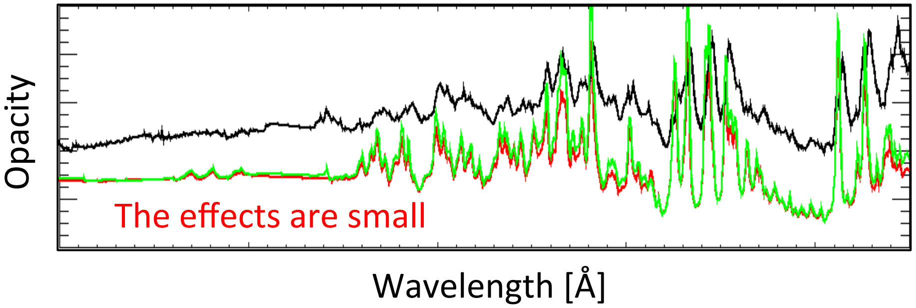
- Fe opacity is measured at SNL Z-machine
  → Modeled opacity disagrees at solar interior conditions





- Experiments and the data interpretation are scrutinized with simulations.

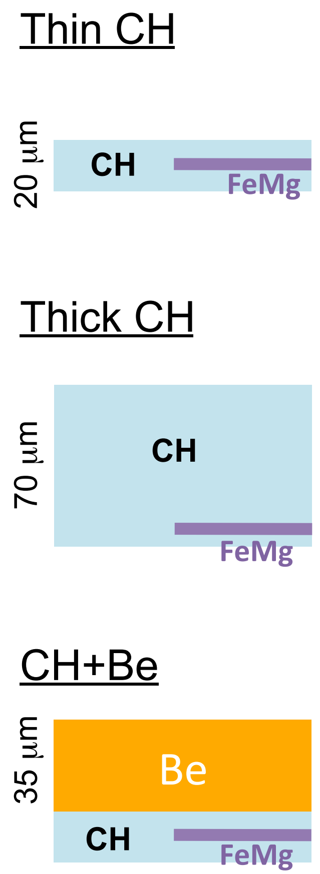
  - Self-emission
  - Tamping material
  - Time- and space-integration effects

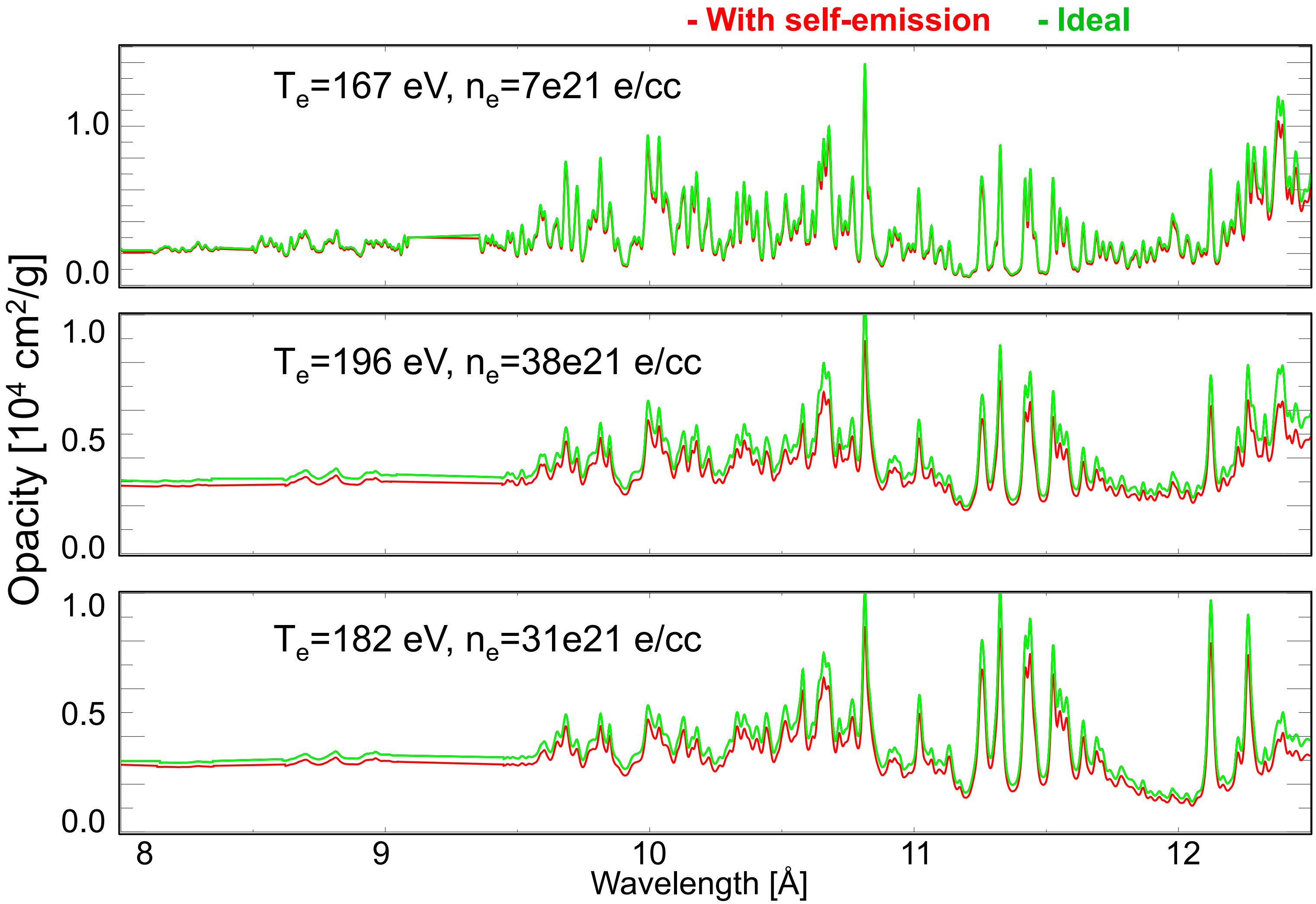


- **One source of systematic uncertainty is always the data interpretation**
- **Forward calculation helps investigate the validity of the data interpretation**

J. E. Bailey et al, Nature 517, 56 (2015).

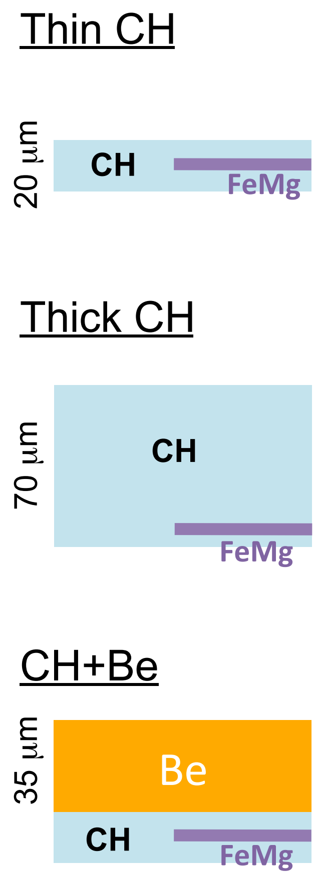
Concern 1: Self-emission is unimportant at λ < 12.5 Å

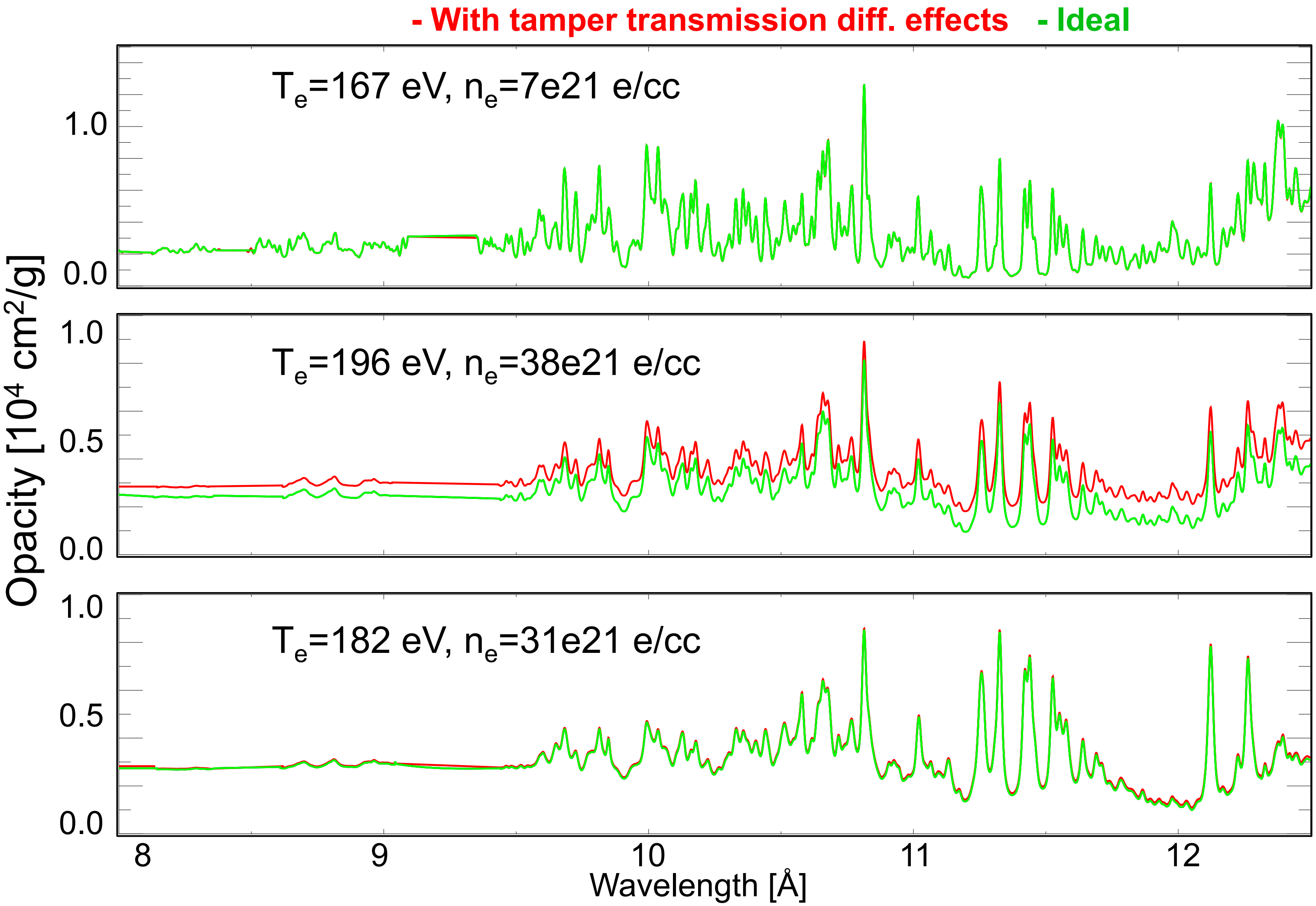




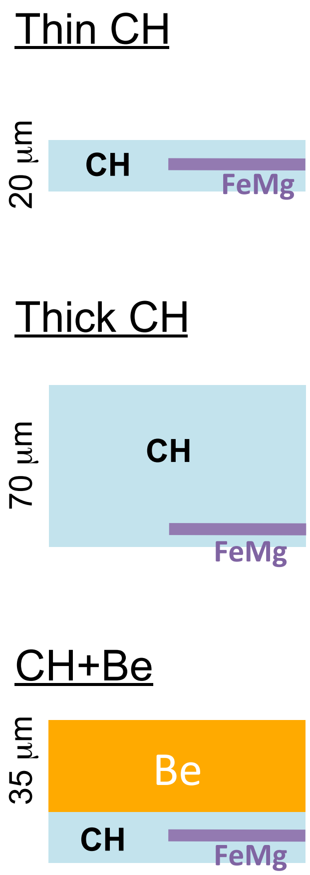
- Self-emission is negligible for Thin CH due to its lower T_e
- Accounting for self-emission would make the discrepancy worse

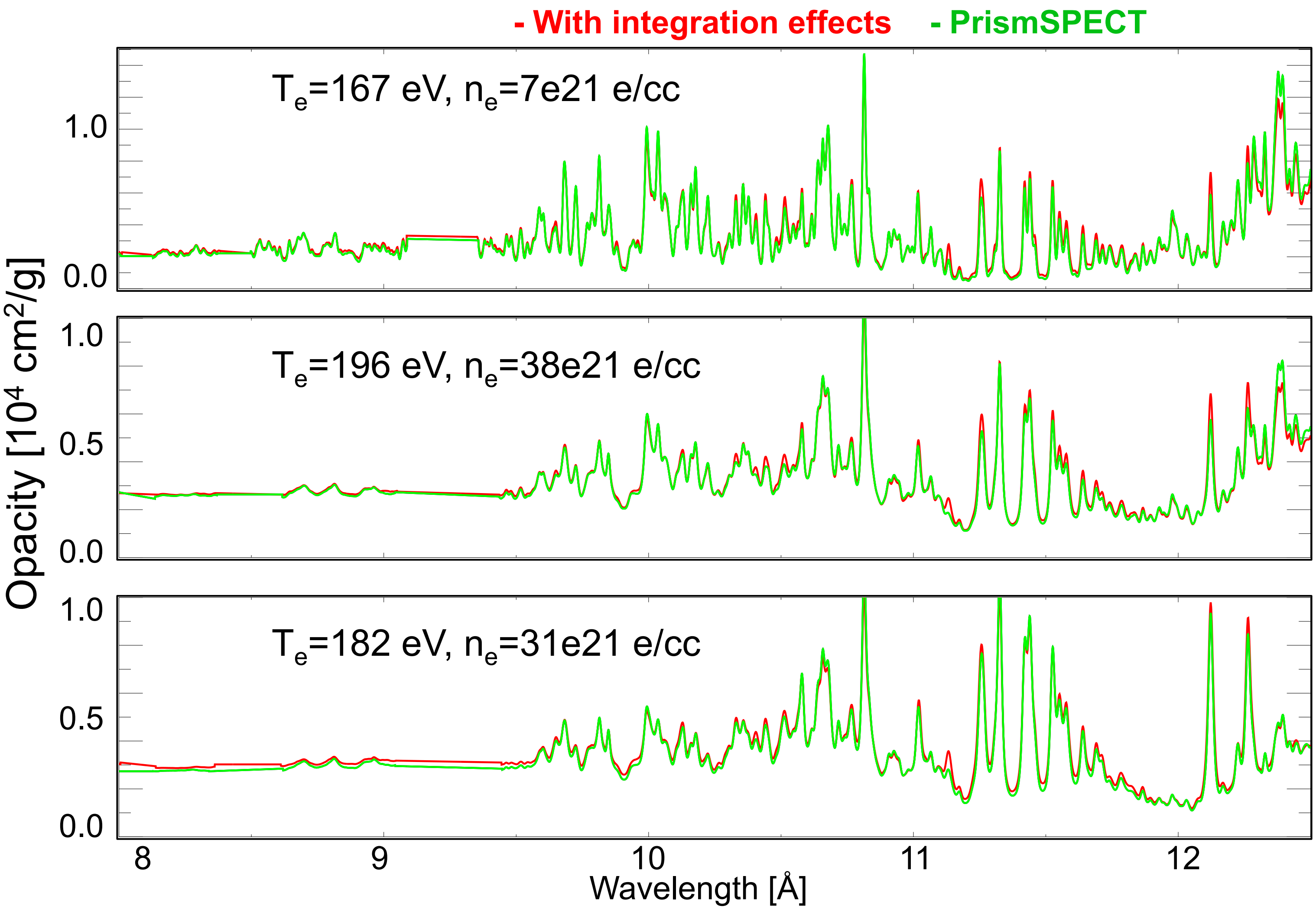
Concern 2: Tamper transmission difference effects are important for Thick CH case



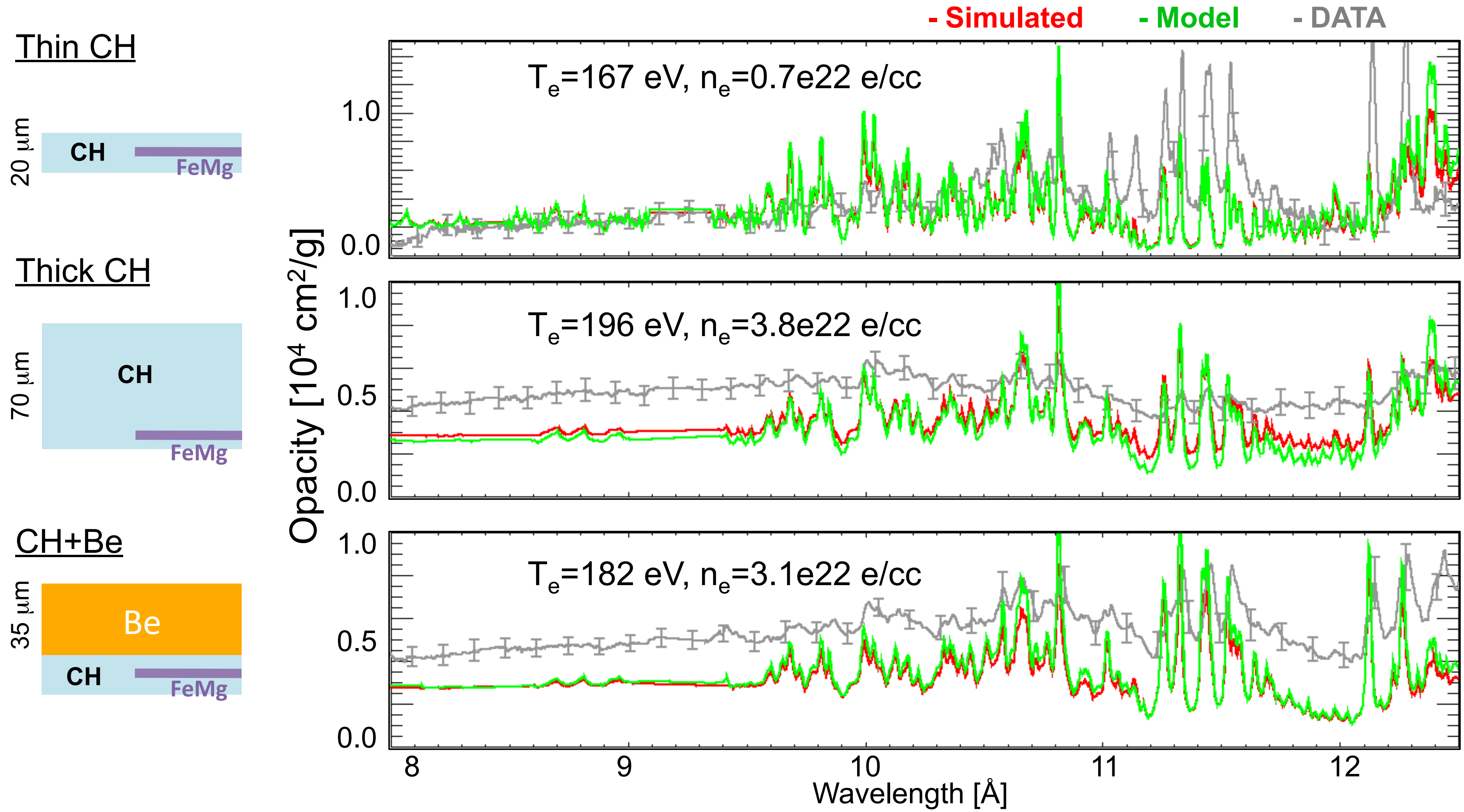


Concern 3: Time- and space-integration effects on the absorption features are negligible





Investigated concerns do not explain the observed discrepancies



Self-emission effects, tamper effects, and time- and space-integration effects do not explain the observed discrepancies

List of potential systematic errors

- Raise measured opacity
  - Sample contamination → RBS measurements, Thin CH data
  - Tamper shadowing → CH+Be data, simulation
- Lower measured opacity → do not explain the observed descrepancies
  - Extraneous background → Beer's law test
  - Tamper self-emission → Beer's law test, comparison of Thick CH and CH+Be, simulation
  - FeMg self-emission → -9^{o} data, simulation
- Random over experiments → included in the reported uncertainties
  - Sample areal density errors → RBS measurements, Thin CH data
  - Transmission errors → Beer's law test, Thin CH data
  - Spatial non-uniformities → Simulations, spectroscopic measurement
  - Temporal non-uniformities → Simulations, Thin CH data
  - Deviation from LTE → Simulations
  - Plasma diagnostics errors → Model uncertainty investigated, modeled opacity disagree with the data at any conditions