SAND2013-1970C

Determination of Plasma Temperature, Density, and Uniformity in Iron Opacity Experiments at Conditions Approaching the Base of the Solar Convection Zone

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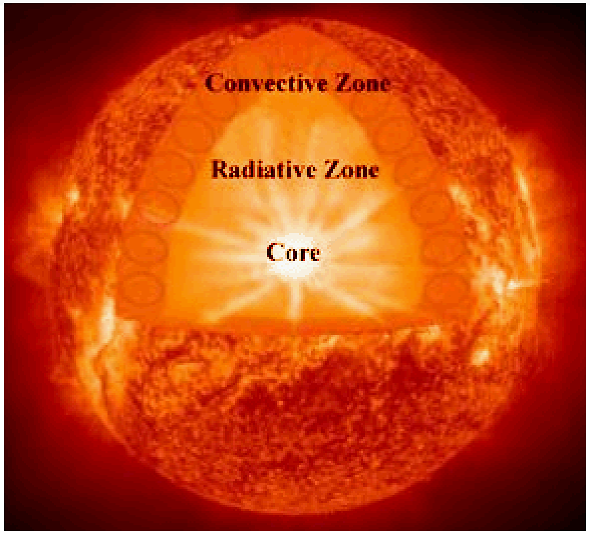
Two ways to study the solar structure

- Standard solar model (simulation)
  - Hydrostatic model
  - Inputs
    - Abundance
    - Opacity
    - EOS
    - Nuclear reaction rate
    - Diffusion rate



- Helioseismology (measurements)
  - Seismic study of acoustic pressure oscillation
  - From space-resolved solar pulsation

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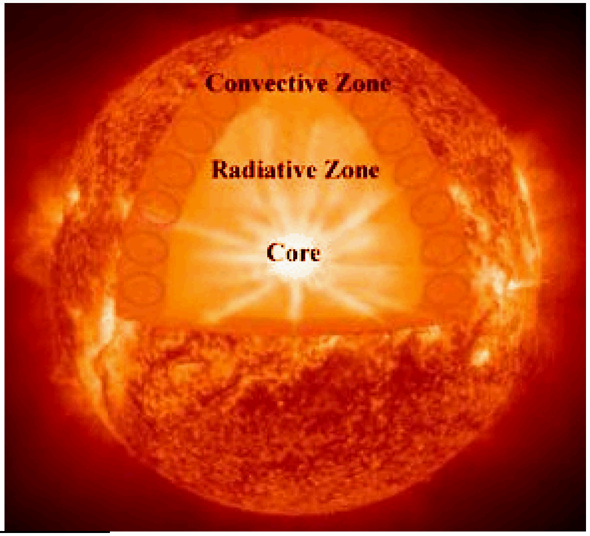
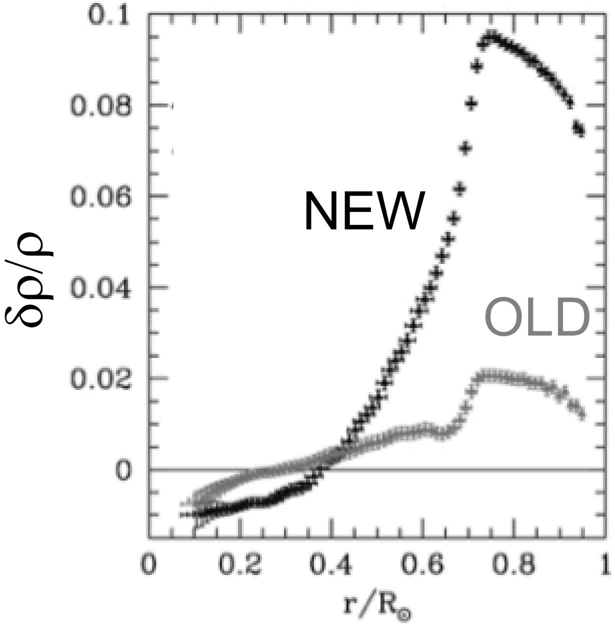
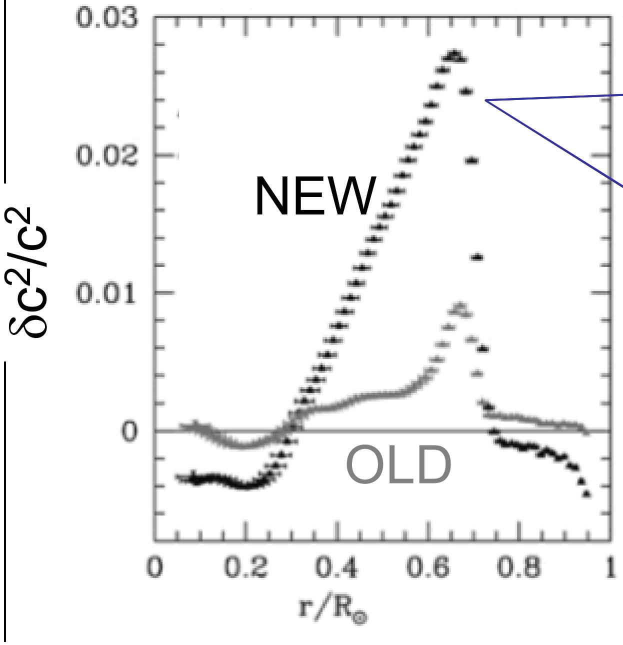
After solar abundance revision, simulation disagrees measurements

- In 2005, Asplund improved solar abundance by including
  - NLTE effects
  - 3D convection effects

→ Reduces abundances of metals (=elements heavier than He)







New abundance increases the discrepancies w/ Helioseismolgy

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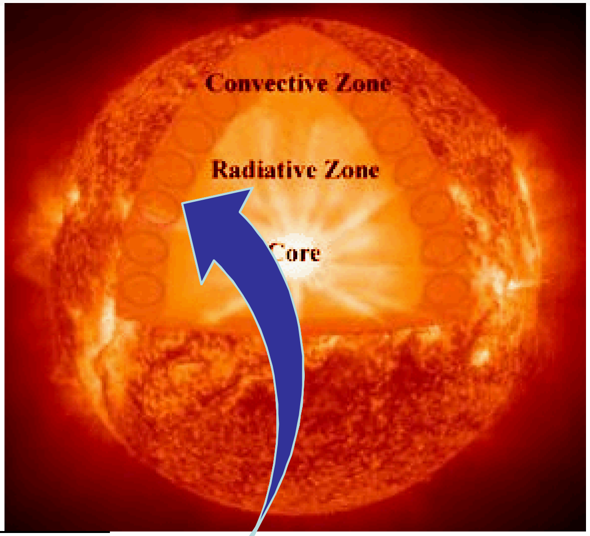
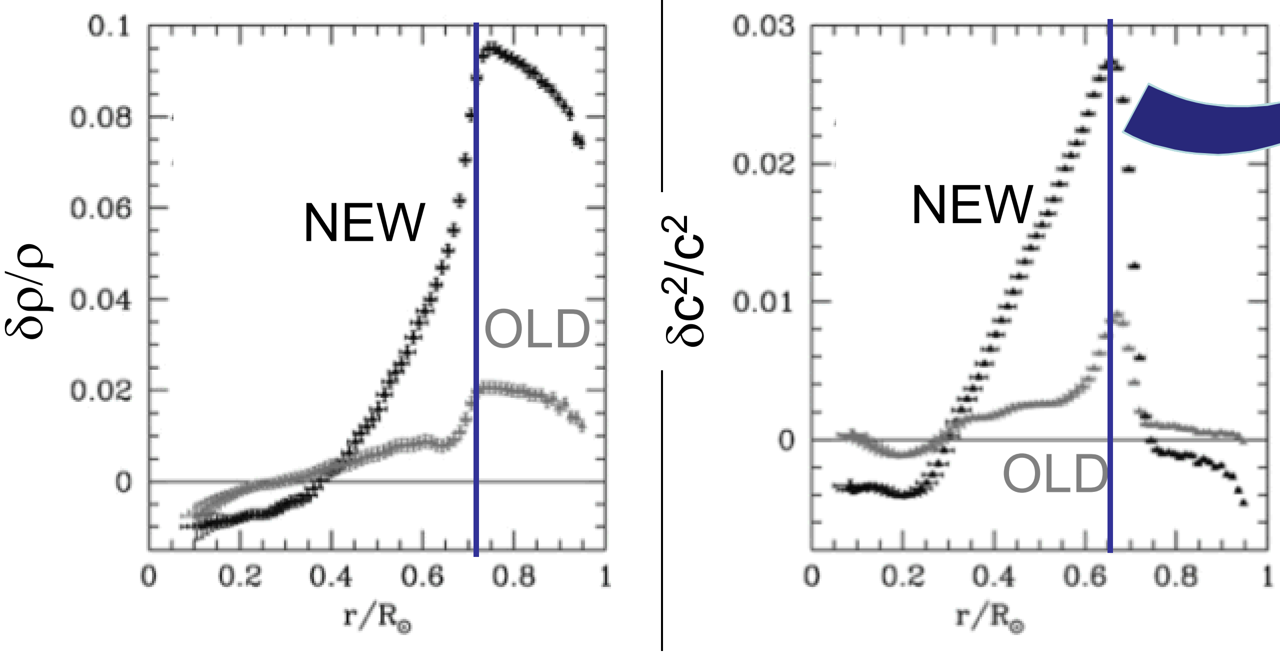
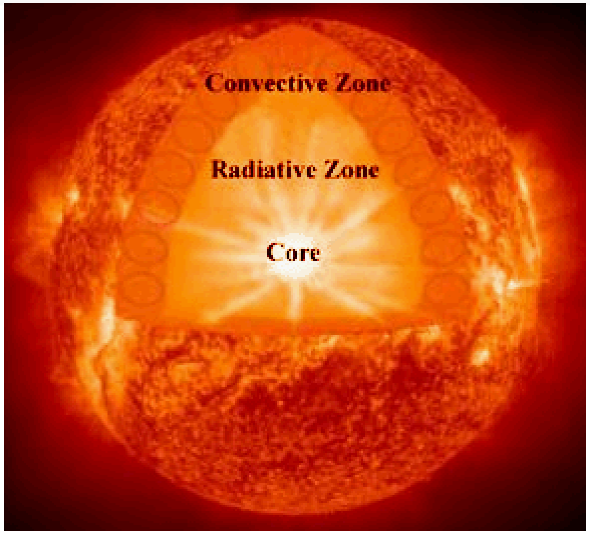




Discrepancy in convection zone (CZ) base location became larger too !!

New model does not have enough opacity around CZ base

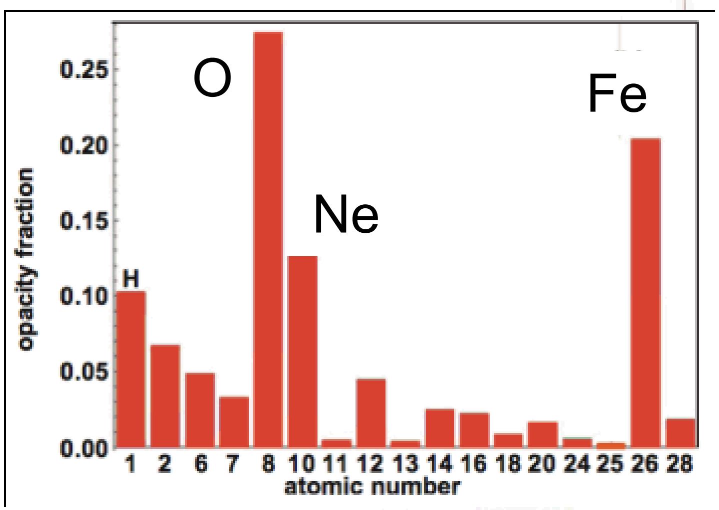


“The base of the convection zone occurs at a point where opacity is just small enough to allow the entire heat flux to be transported by radiation.” (Basu Phys. Rep. 2008)

What happens when heavy element abundance is lowered?

→Total opacity decreased

→CZ base location moves outward



Maybe input opacity should be higher.
Fe opacity is most likely suspect.

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Opacity is important input for HED plasma simulation

- Opacity = determines how energy is transferred by radiation
- Applications
  - Standard solar model
  - Inertial confinement fusion
  - Z-pinch

Opacity is difficult

- Theory becomes difficult when
  - Atomic number (Z) increases
  - # of bound electrons increase
- Measurement becomes difficult at high T
  - Self-emission becomes stronger

➔Modeled opacity is challenging but used without being benchmarked for

- mid-/high-Z (Fe: 26)
- Large # of bound electrons (Fe at CZB: ~9-10)
- High temperature (Fe at CZB: ~190 eV)

Let's benchmark modeled Fe opacity at CZB condition (T_e=190 eV, n_e=1x10^{23}cm^{-3})

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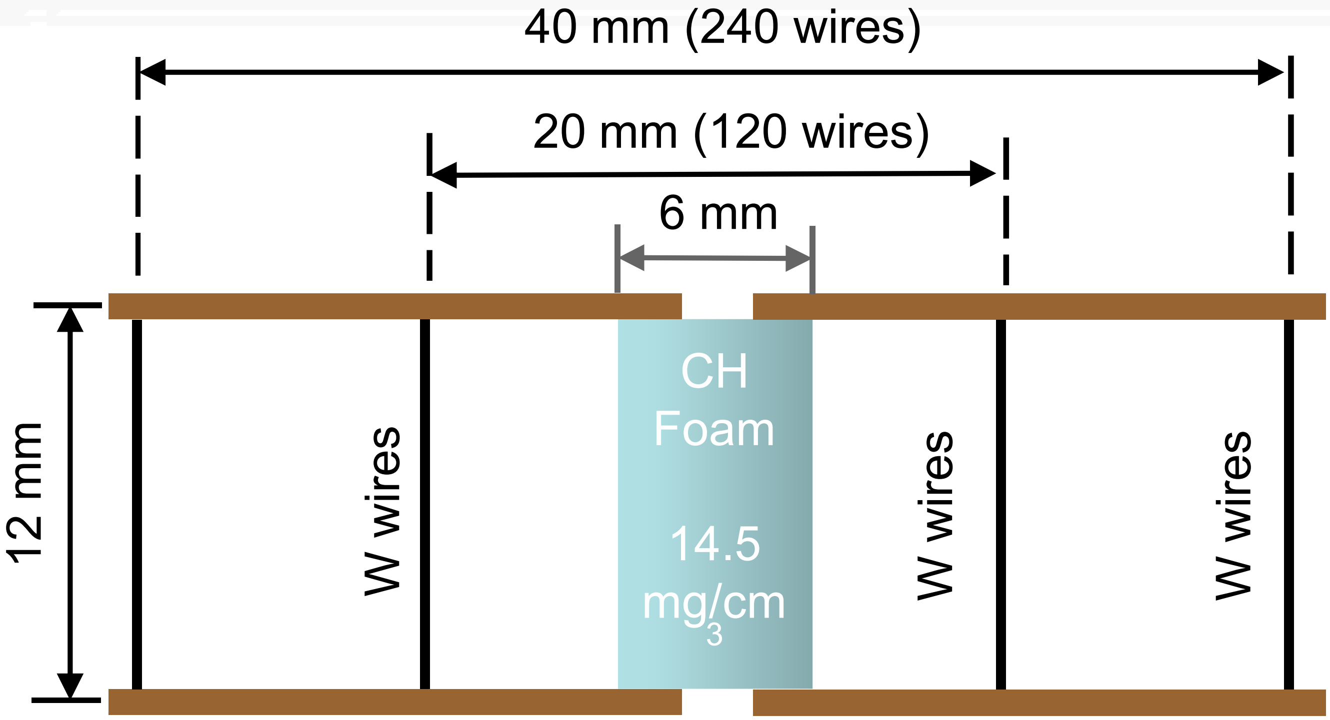
Three requirements for reliable opacity experiments

- Steps
  - Make Fe plasma to unif
    to CZB
  - Provide a backlighter to
    transmission
  - Compute the Fe opacity and compare with data → need to know the exact condition
- Requirements
  1. Strong and smooth backlighter
  2. Sample uniformity
  3. Independent Te and ne measurement

A little animation to show how each step is done helps

Z-pinch dynamic hohlraum satisfies these

Z Pinch Dynamic Hohlraum



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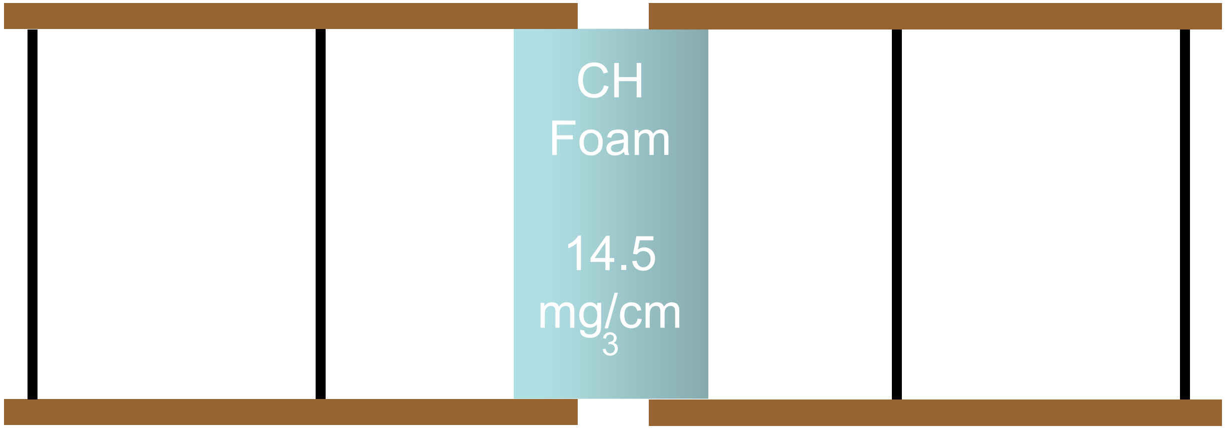

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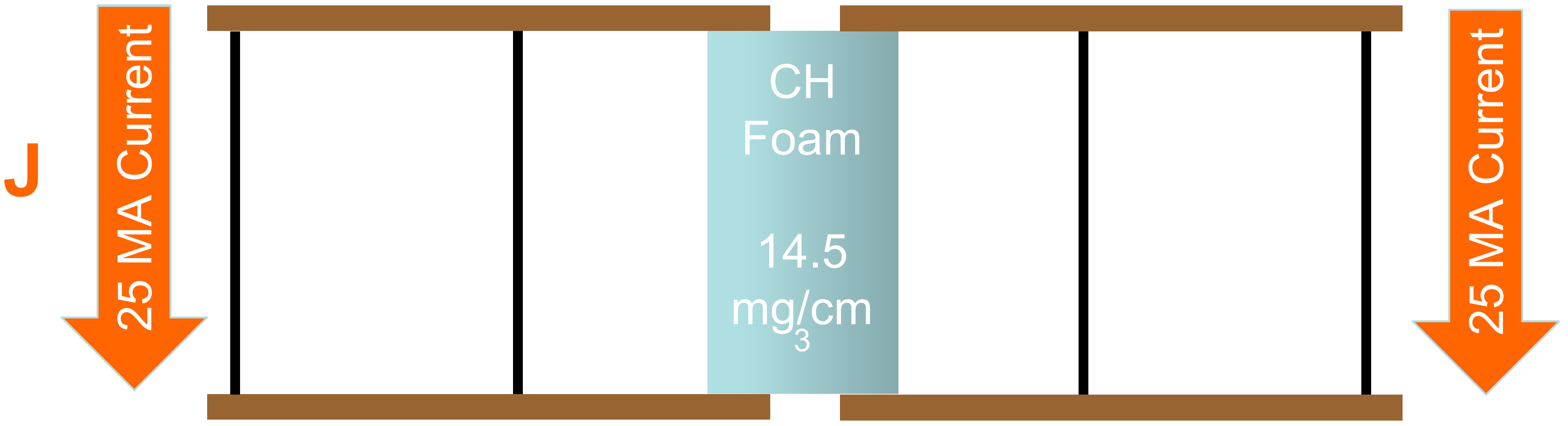

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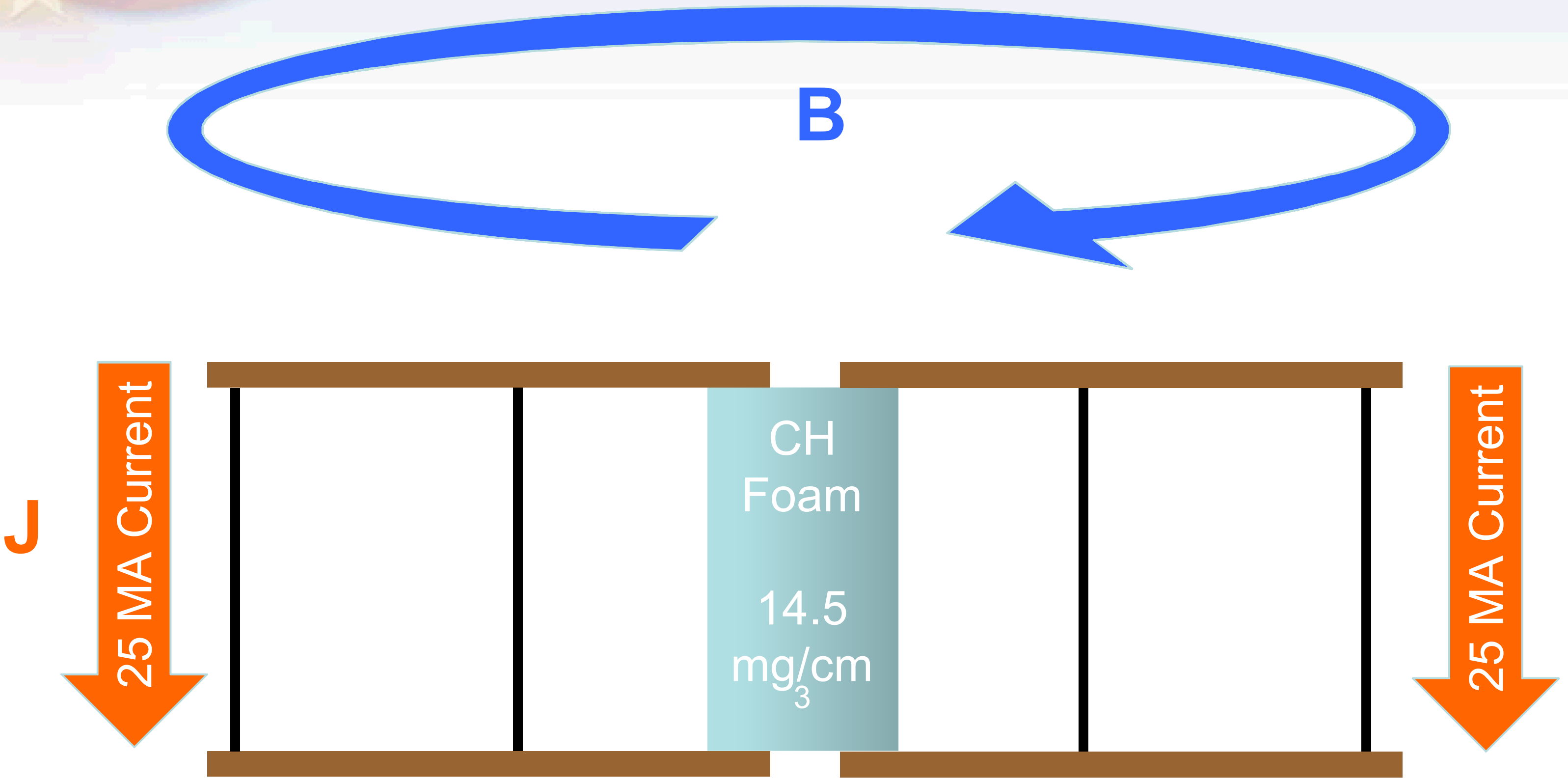

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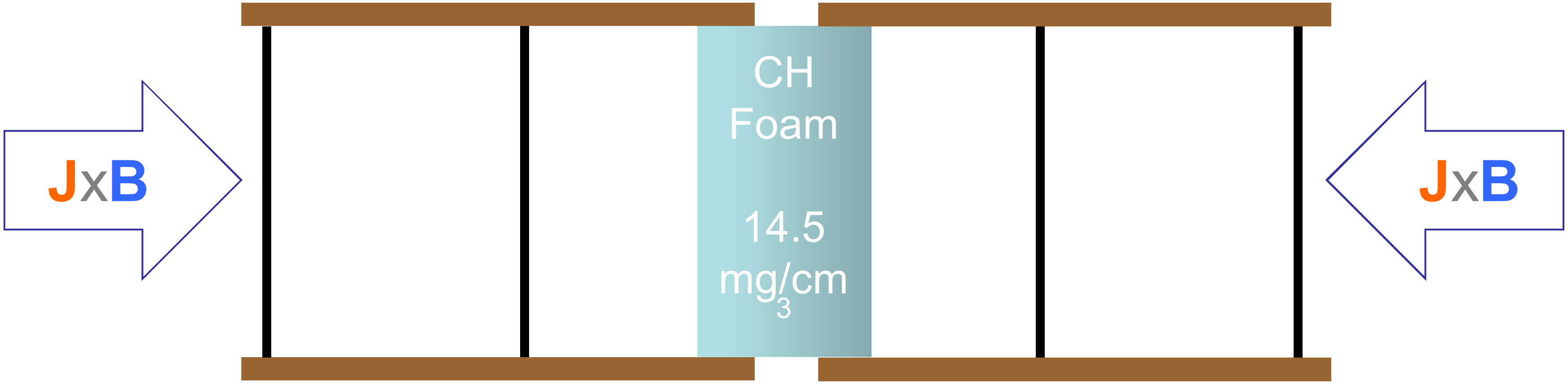

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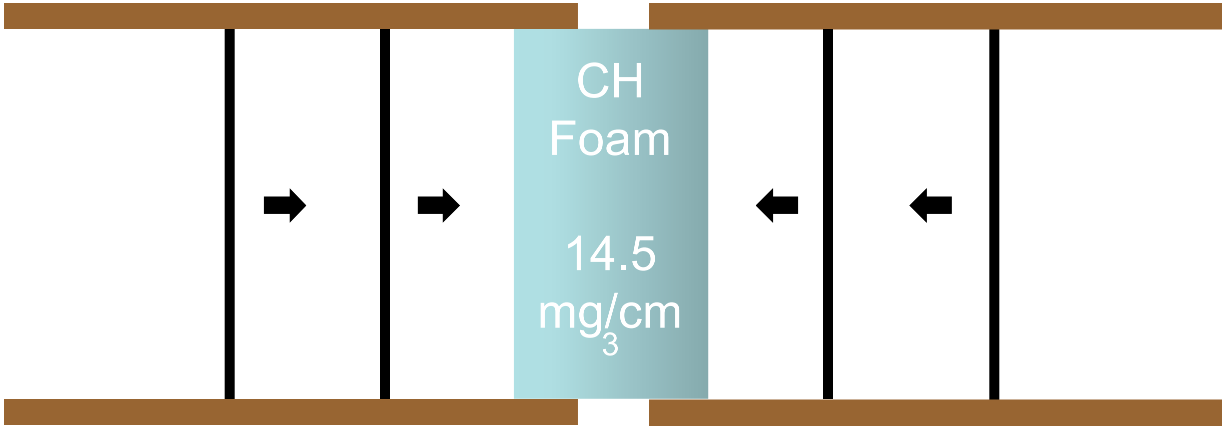

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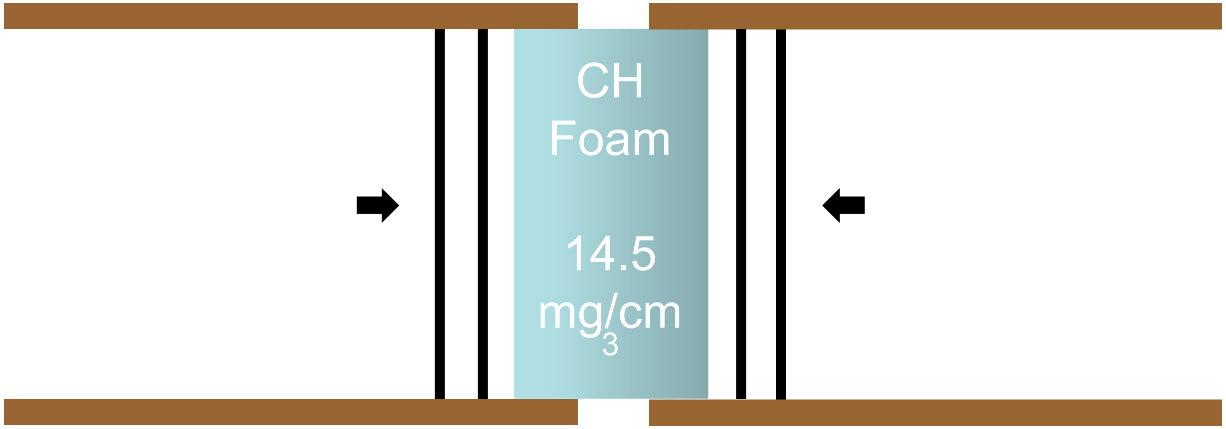

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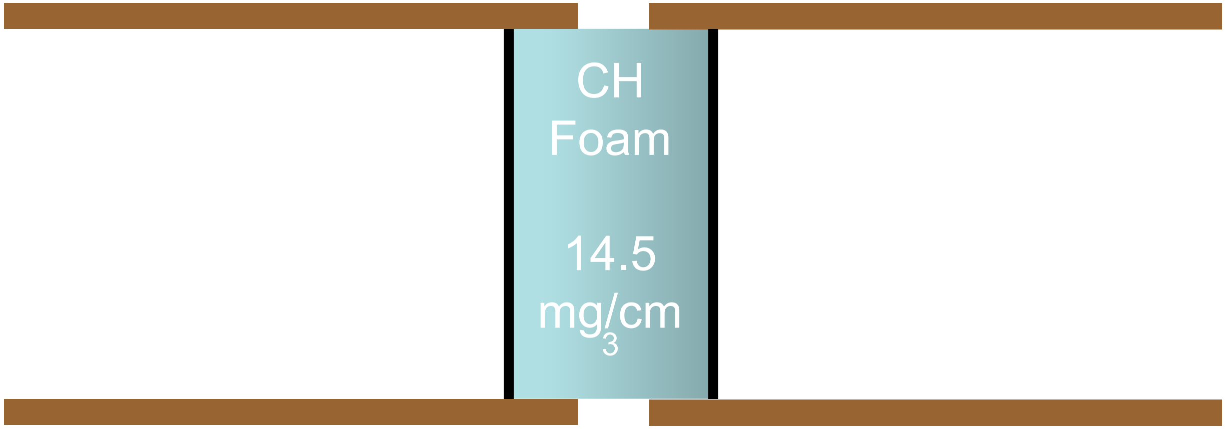

- W plasma collide with CH foam, and generates radiative shock
- Radiation is trapped inside W plasma due to high W opacity

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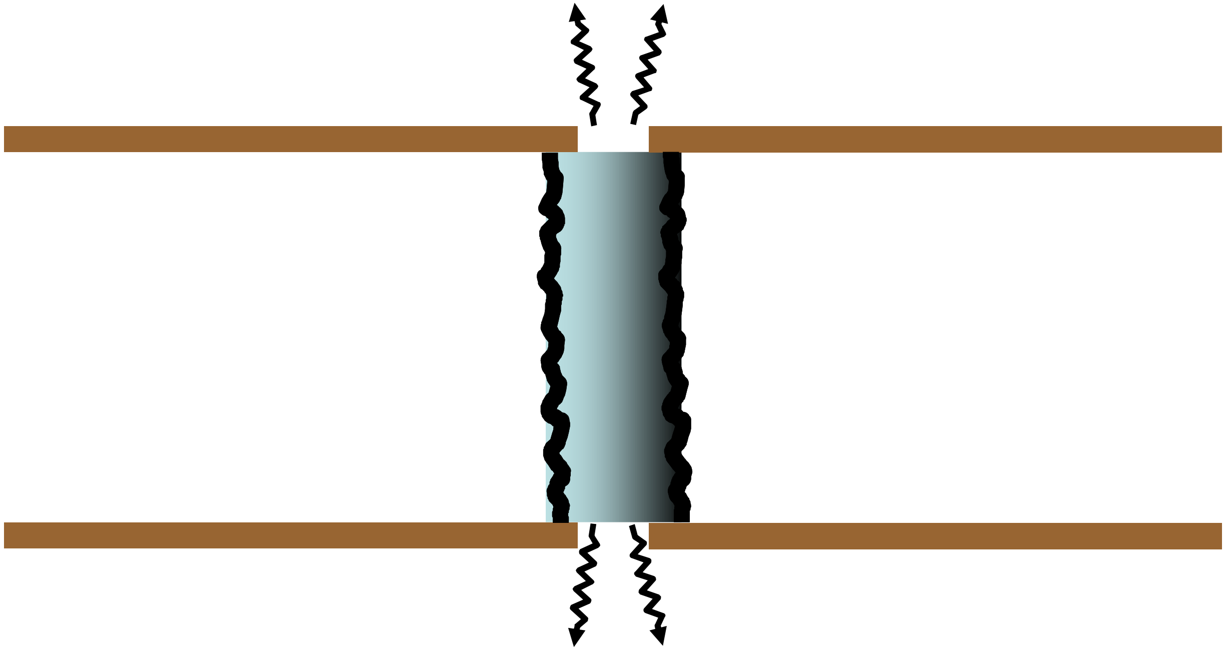

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- Some radiation are leaked from the top/bottom wholes

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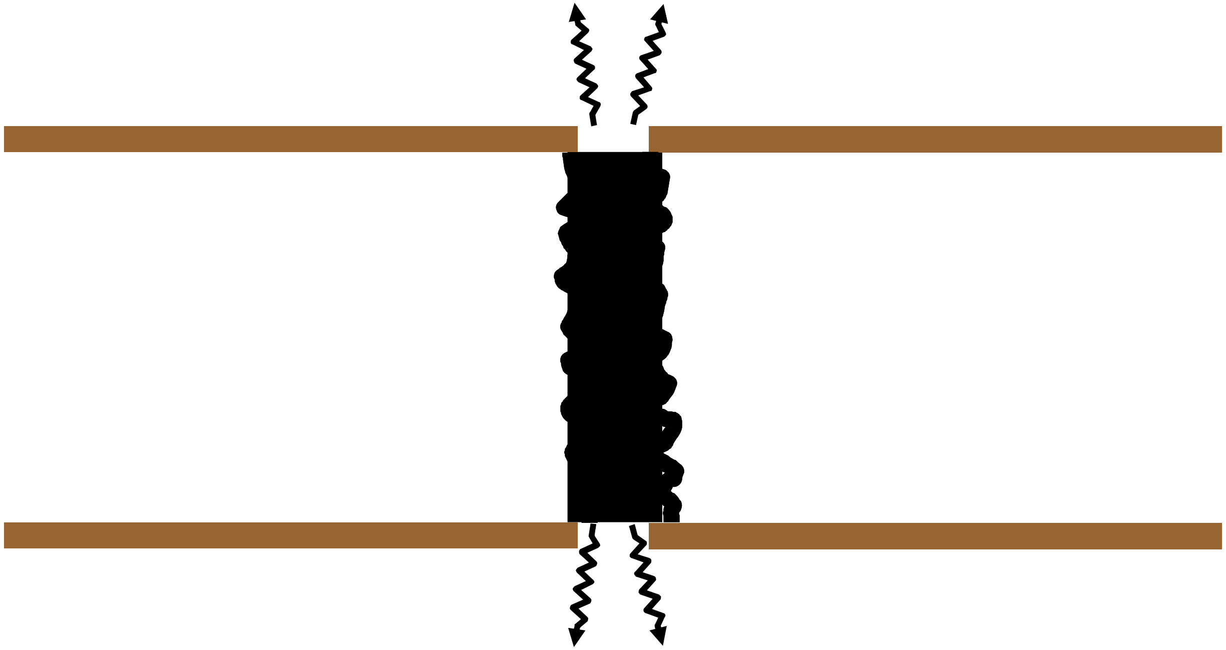

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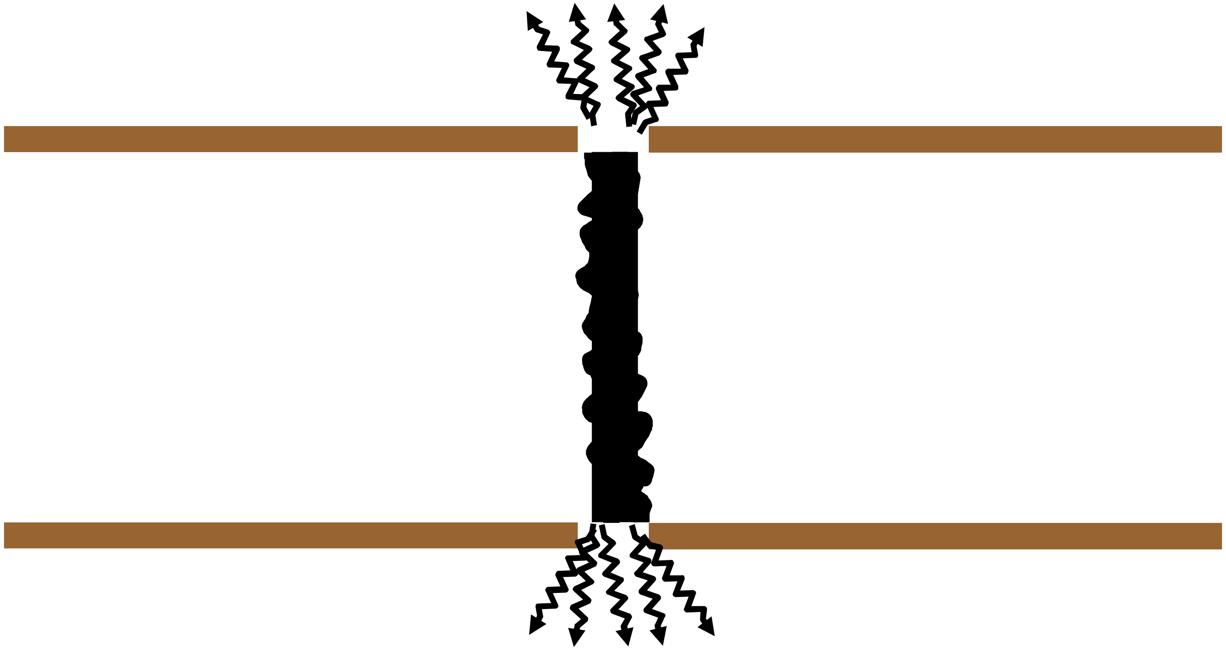

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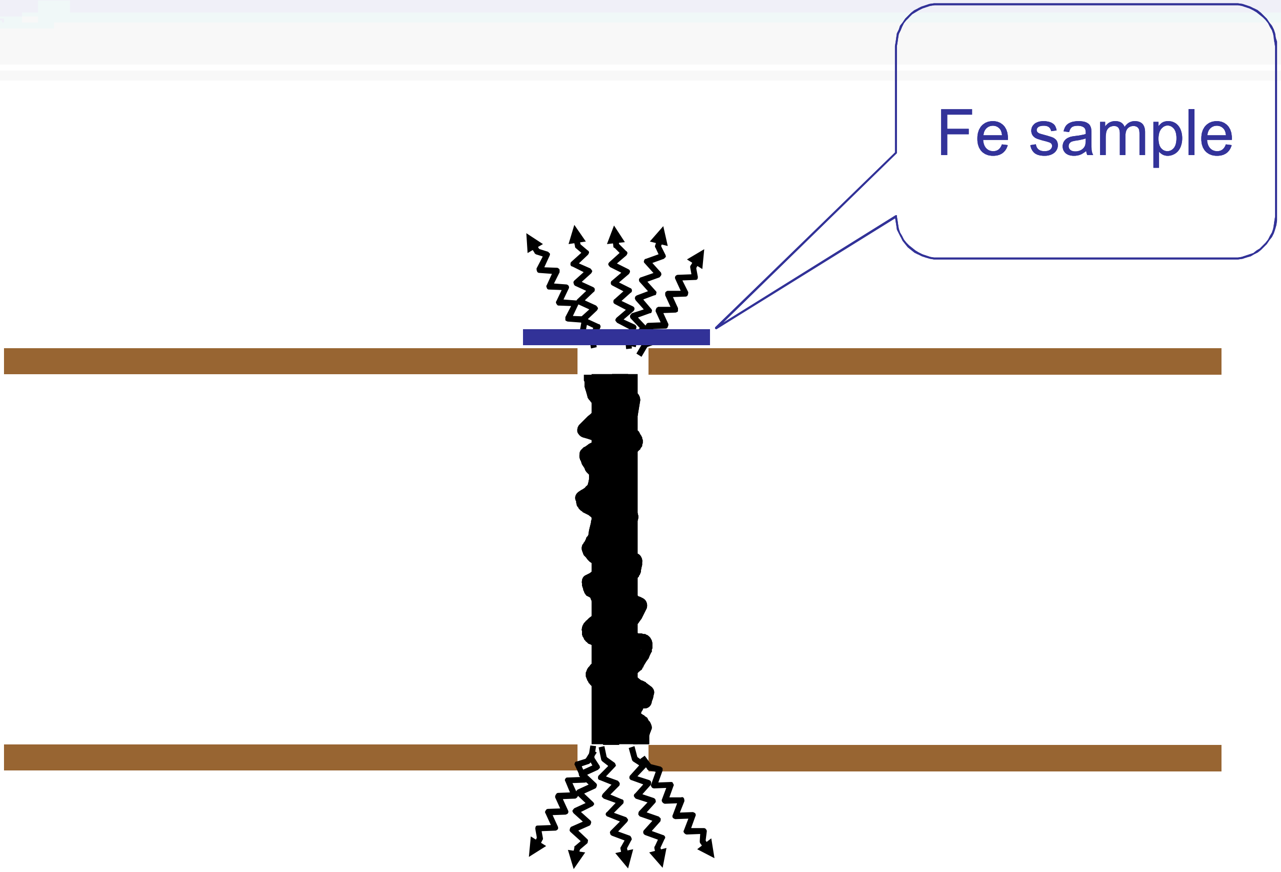

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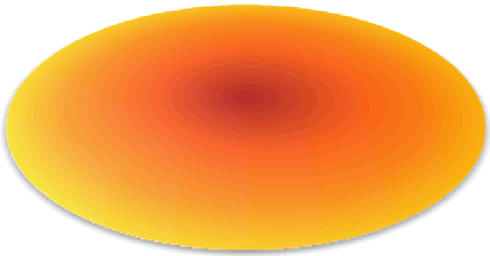

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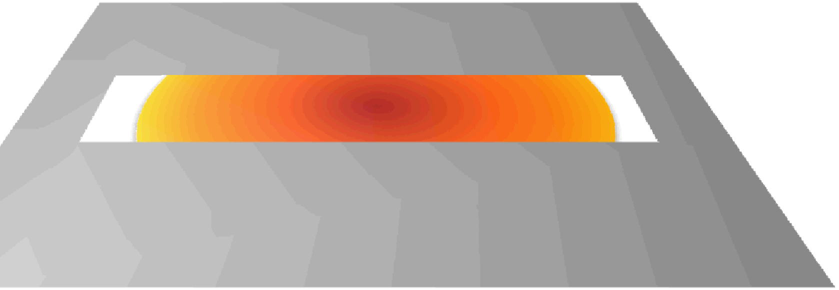

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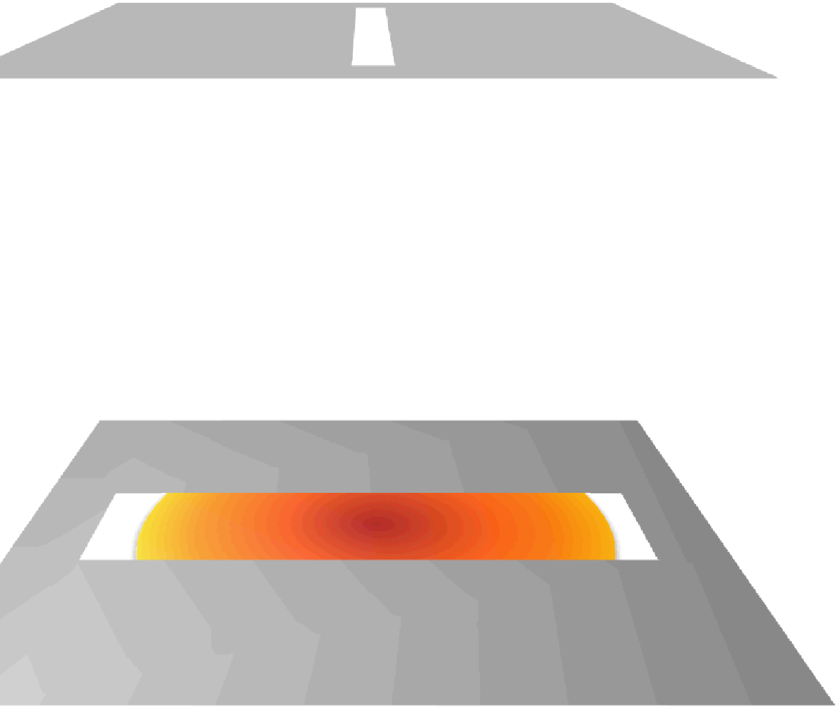

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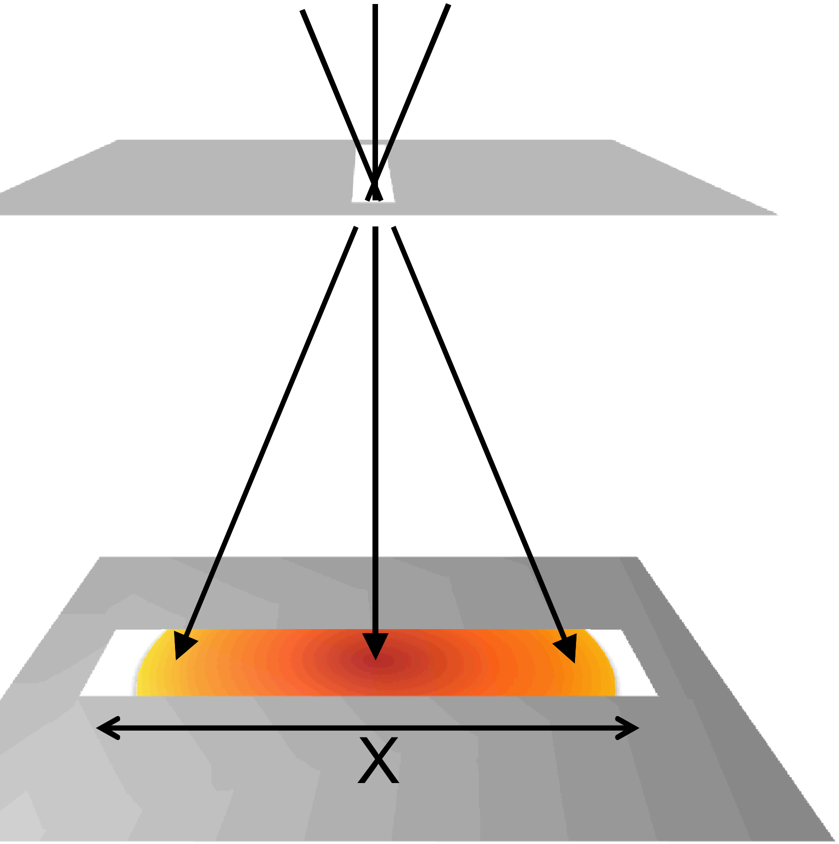

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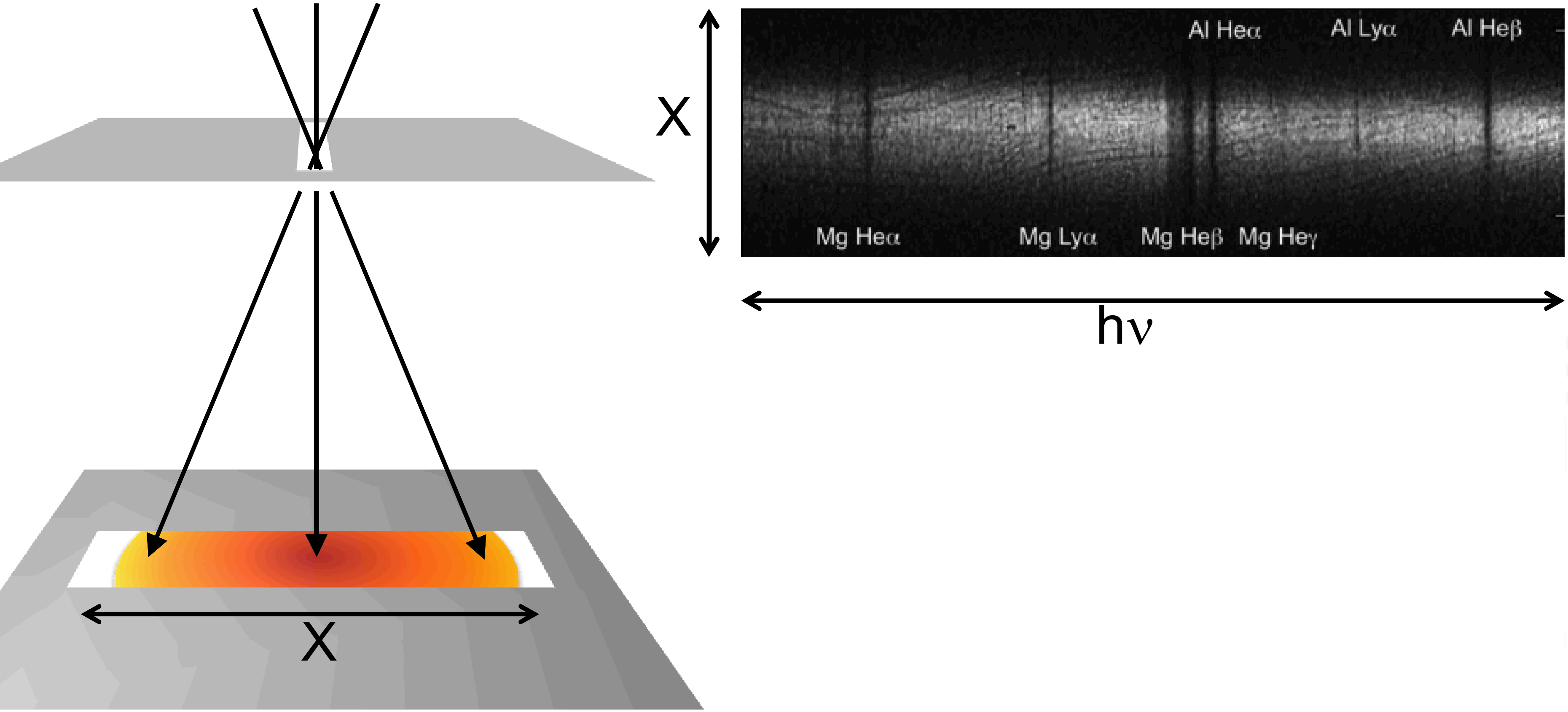

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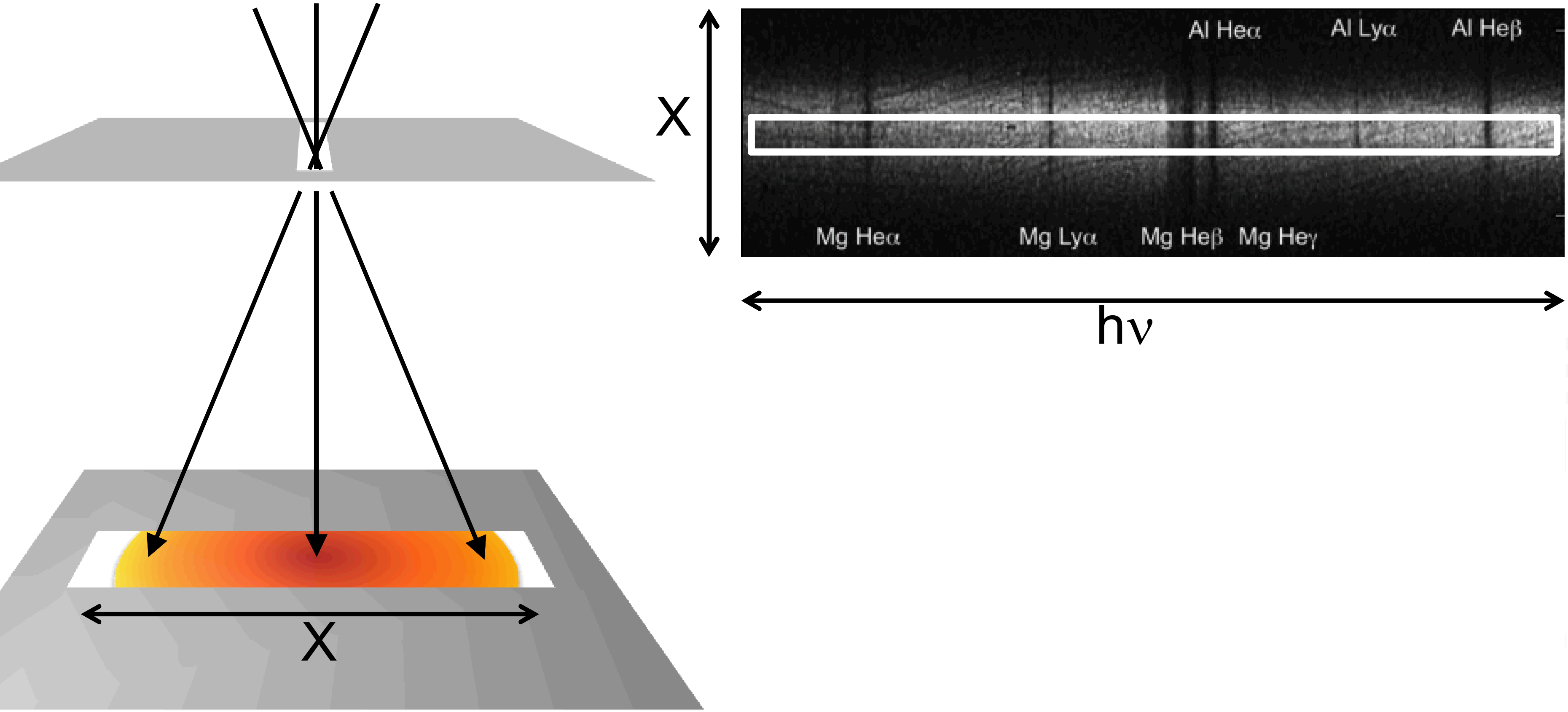

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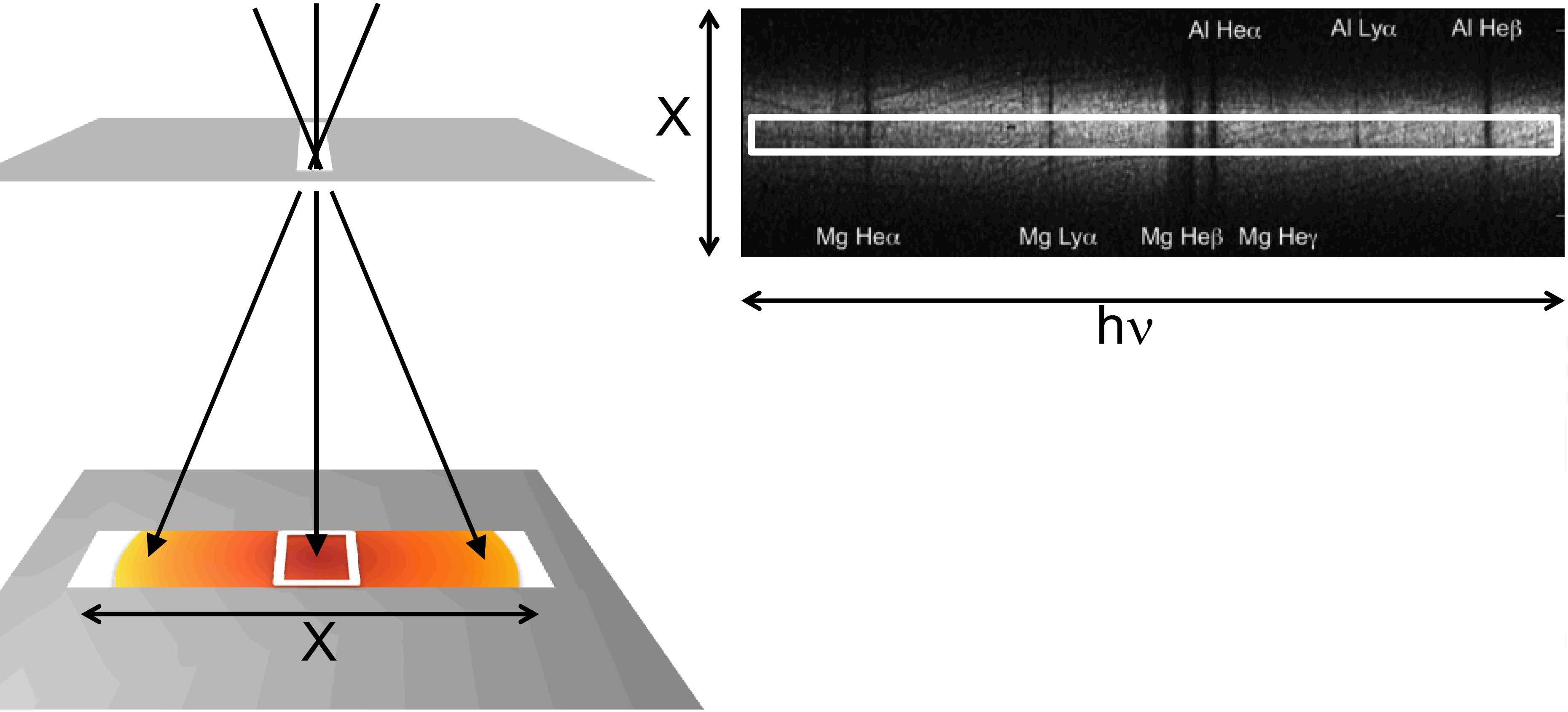

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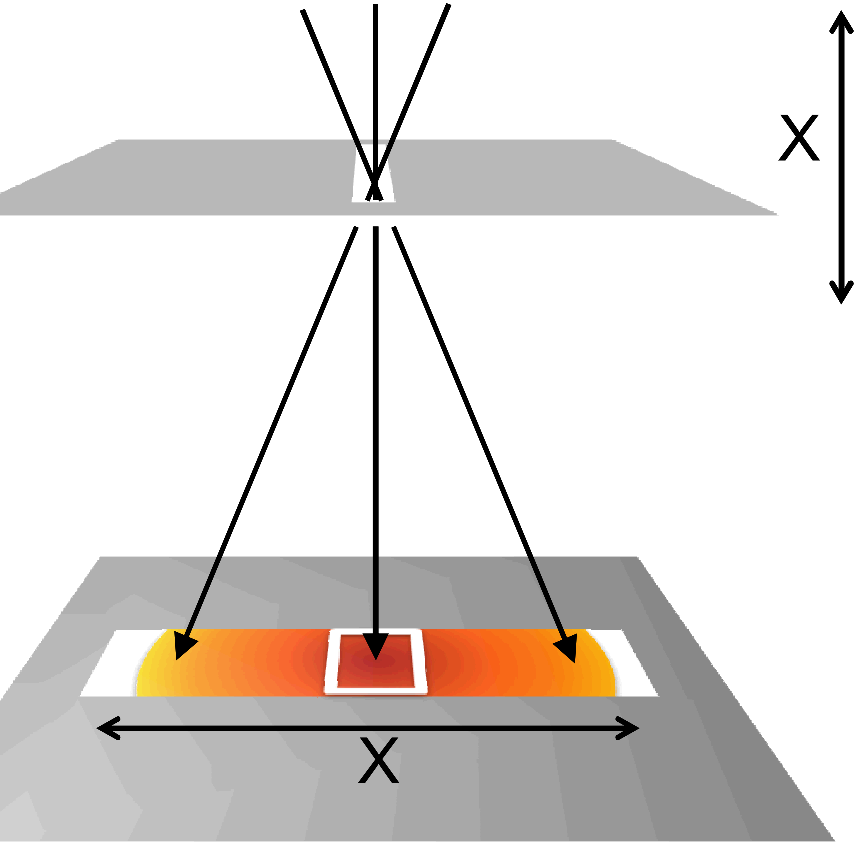

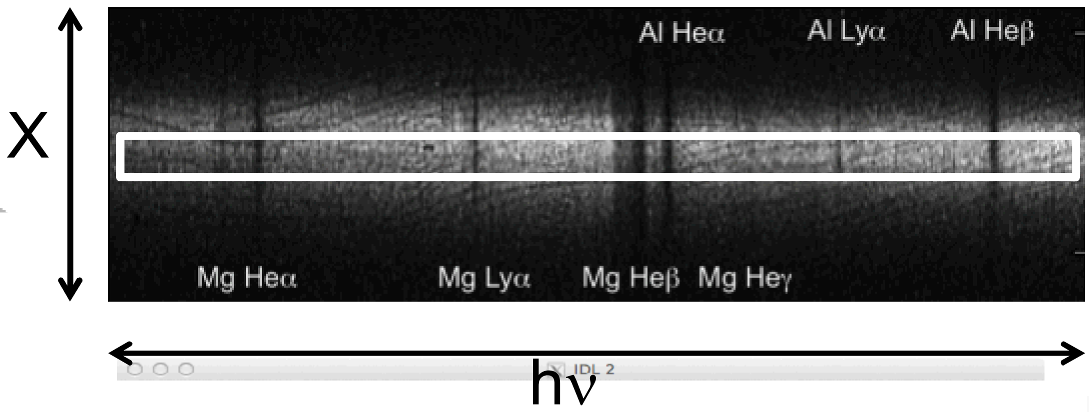

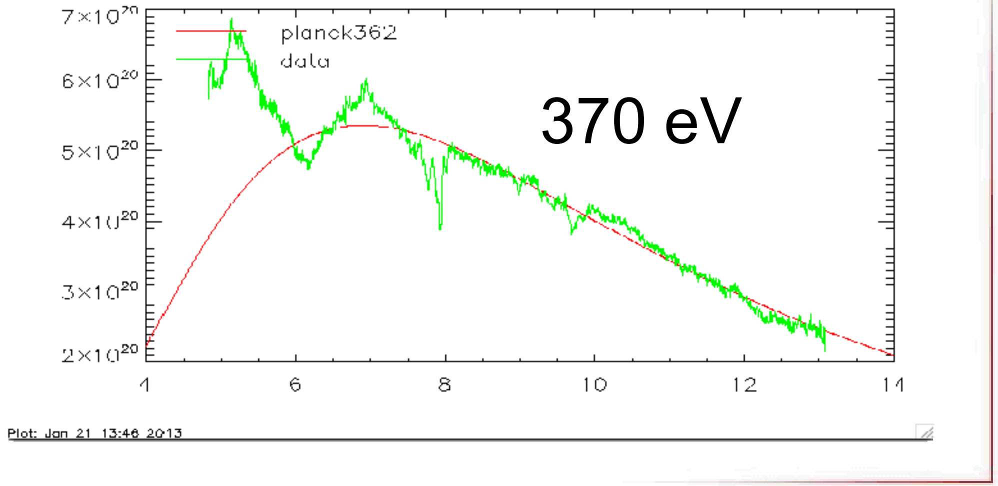

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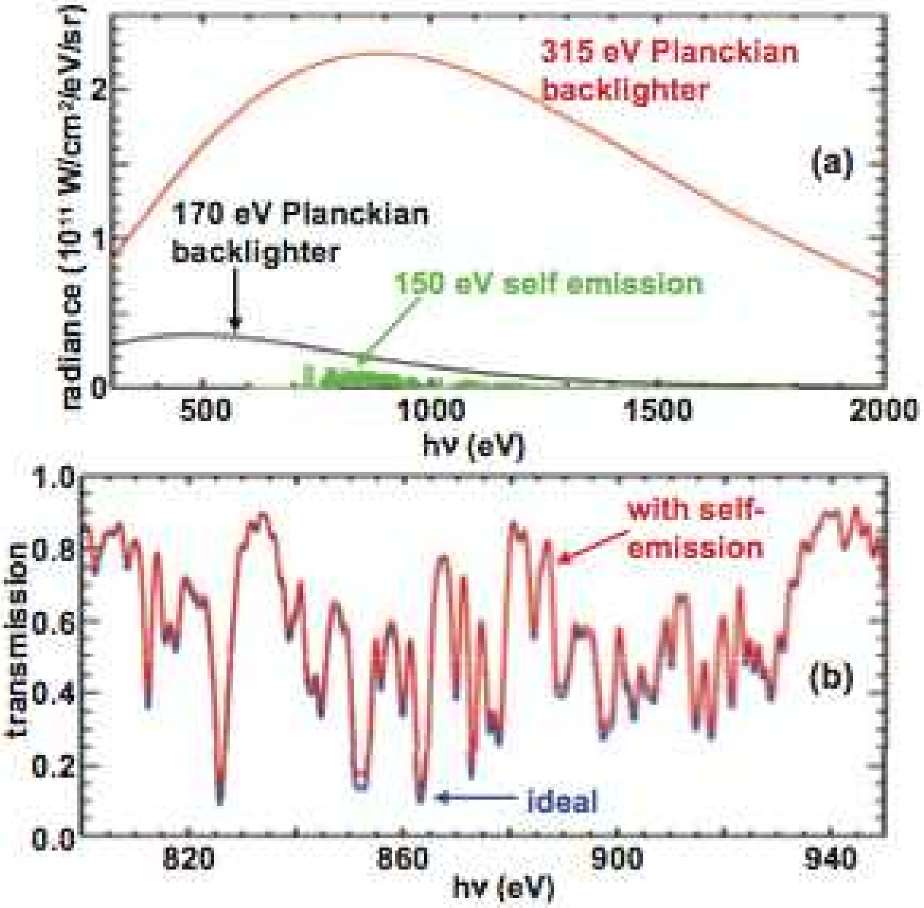

315 eV Planckian is already much brighter than Fe self-emission

ZPDH supports three requirements

1. Strong and smooth backlighter
   - 370 eV Planckian
2. Sample uniformity
   - Volumetric heating by ZPDH radiation
   - Large sample size (1-4mm)
   - Long duration (3ns)

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   - Mix Mg into Fe sample
   - Infer temperature and density from Mg K-shell absorption spectroscopy

ZPDH supports three requirements

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Focus of the talk

2. Sample uniformity
   - Volumetric heating by ZPDH radiation
   - Large sample size (1-4mm)
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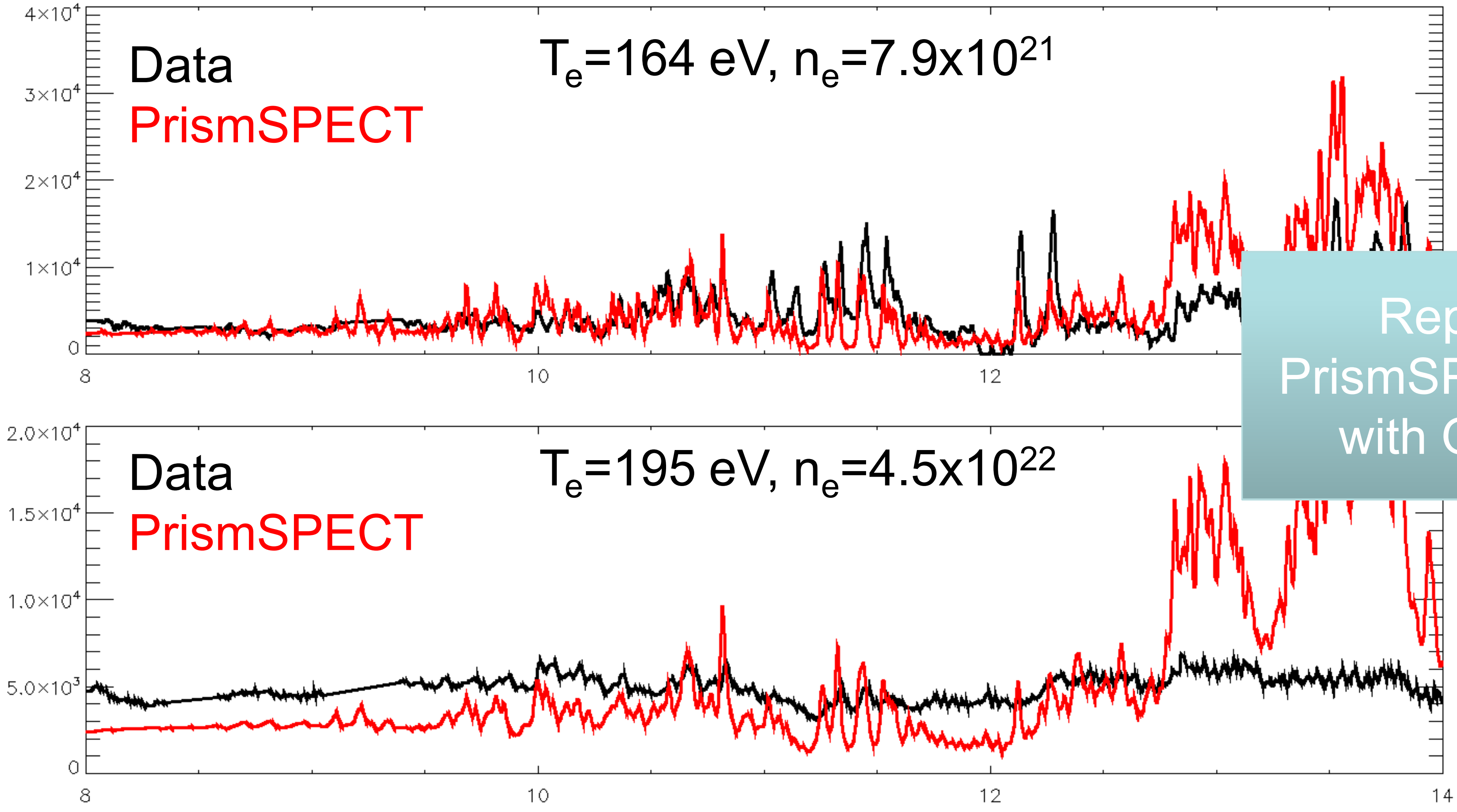
Preliminary results show the opacity that astrophysicists use are lower than data



Plot: Feb 20 12:41 2013

Impacts of the project

Goal: experimentally validate the modeled Fe opacity at CZ base condition (T_e=190 eV, n_e=9x10^{22} e/cc)

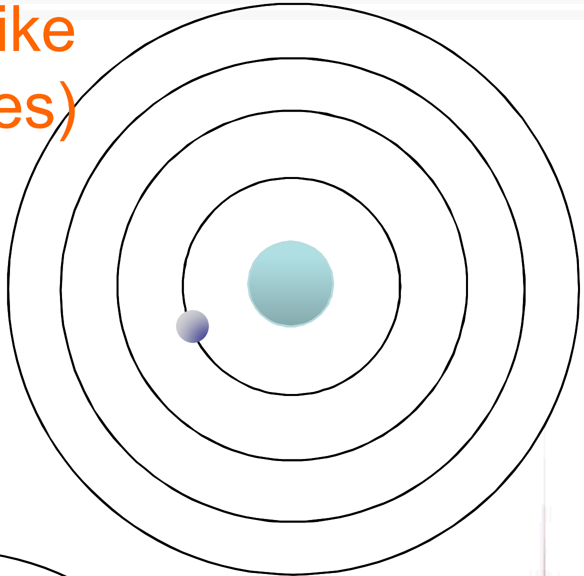
- Impact:
  - Astrophysics
  - High energy density physics (HEDP)
  - Atomic physics
  - SNL

Mg K-shell line spectroscopy

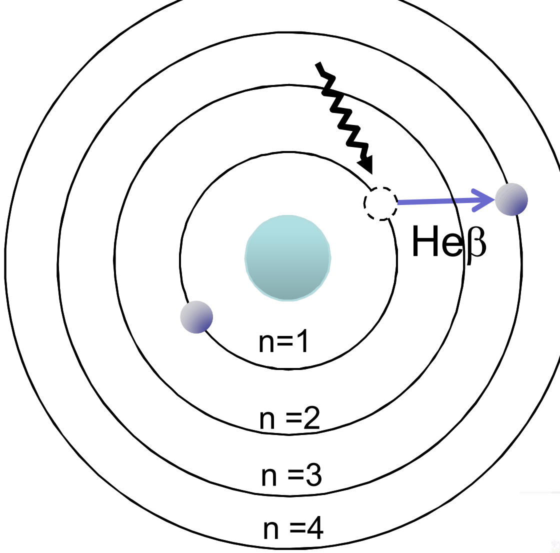
Fe plasma condition is inferred from Mg K-shell transmission spectra

- Mg is mixed into Fe
- Mg are ionized into He-like Mg
  - # of bound electrons = 2
  - Z = 12
  - K-shell spectra

H-like
(Ly series)

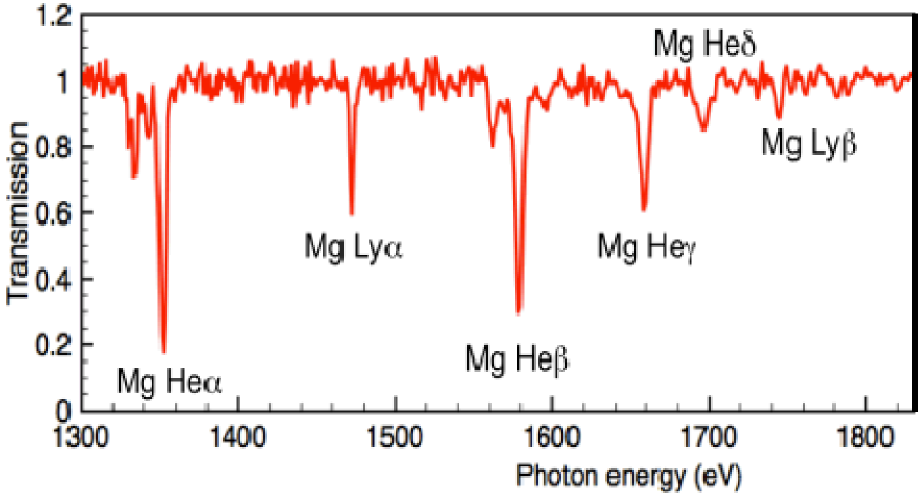


He-like



<ins>Transitions</ins>

α: n=1→2
β: n=1→3
γ: n=1→4
....



Measured transmission depends on optical depths: $T_\nu = \exp(-\tau_\nu)$

Optical depths:

$$\tau_\nu = \frac{\pi e^2}{mc} f_{lu} \cdot \left\{ N_{Mg} \Delta x \right\} \cdot \Phi_\nu \cdot p_l$$

f_{lu} = oscillator strengths

$\left\{ N_{Mg} \Delta x \right\}$ = areal density of Mg

Φ_ν = line shape

p_l = fractional population of the lower state

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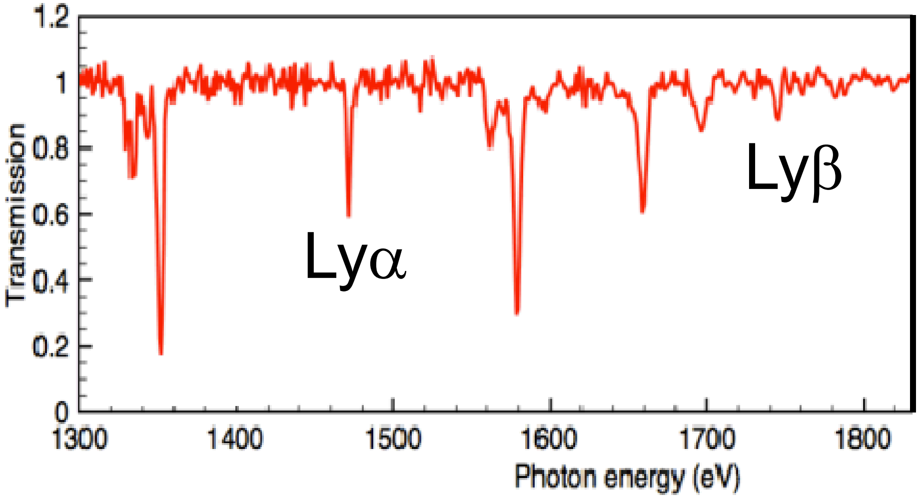
Lyα, β ... Proportional to $p_{H-like,g}$



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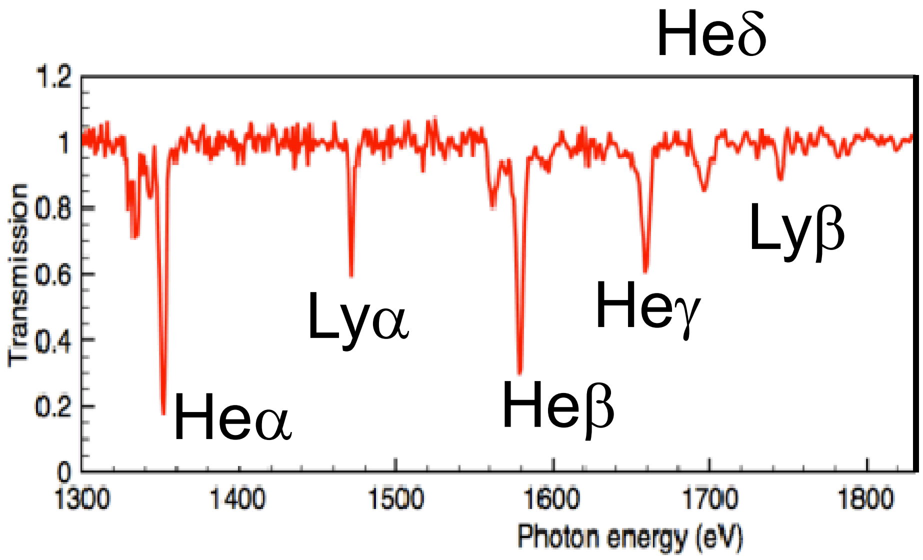

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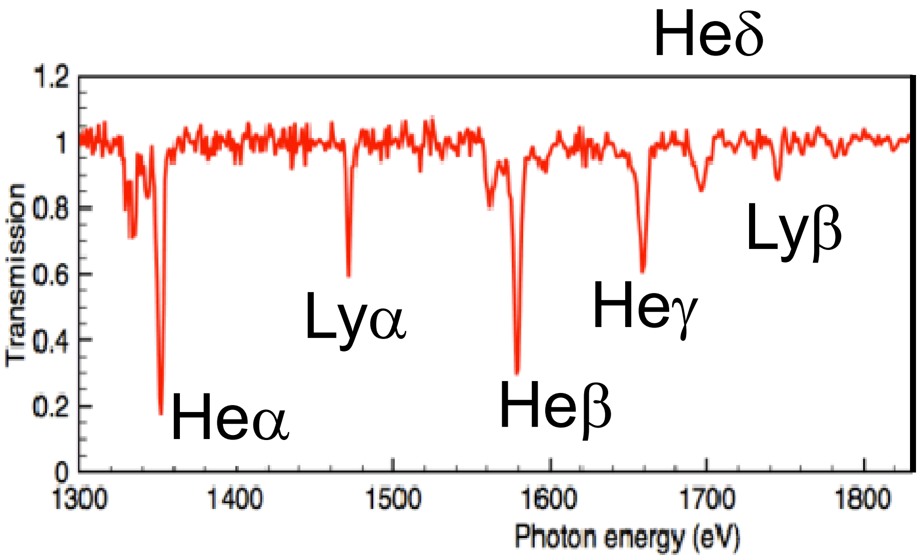

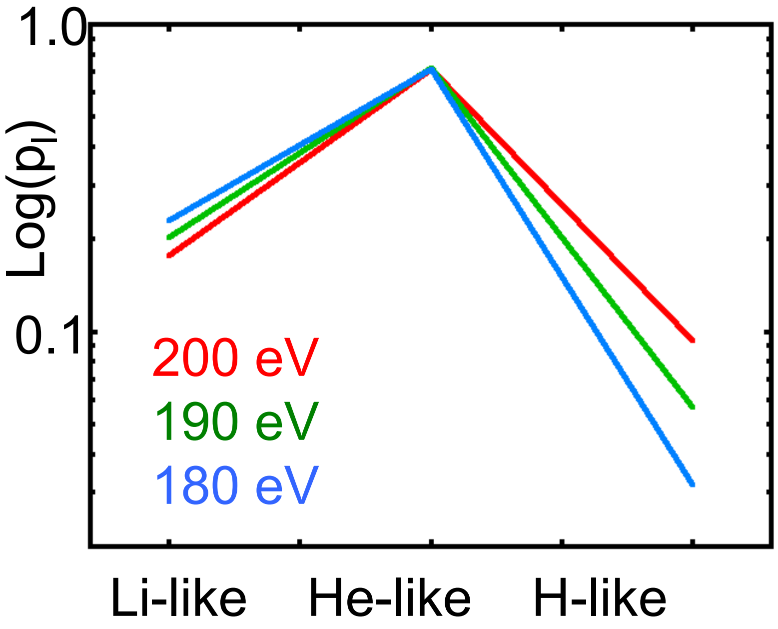

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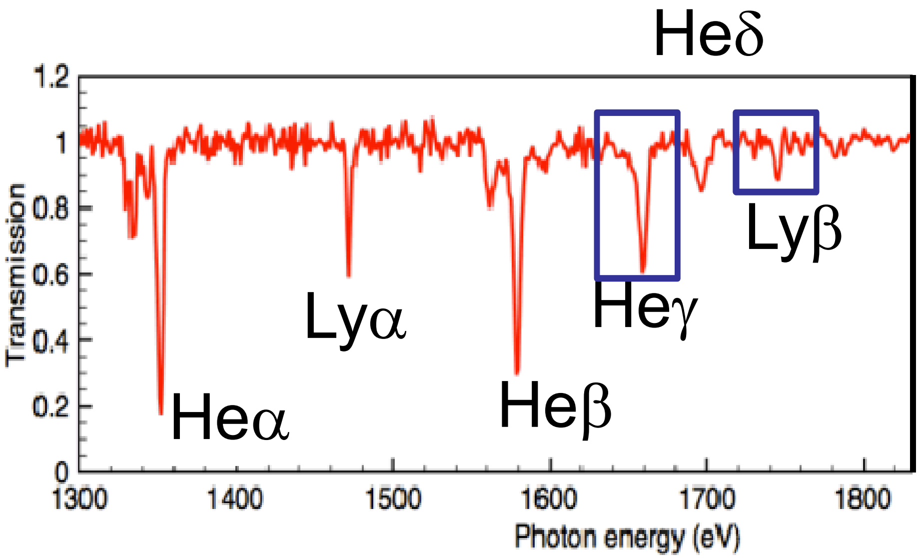

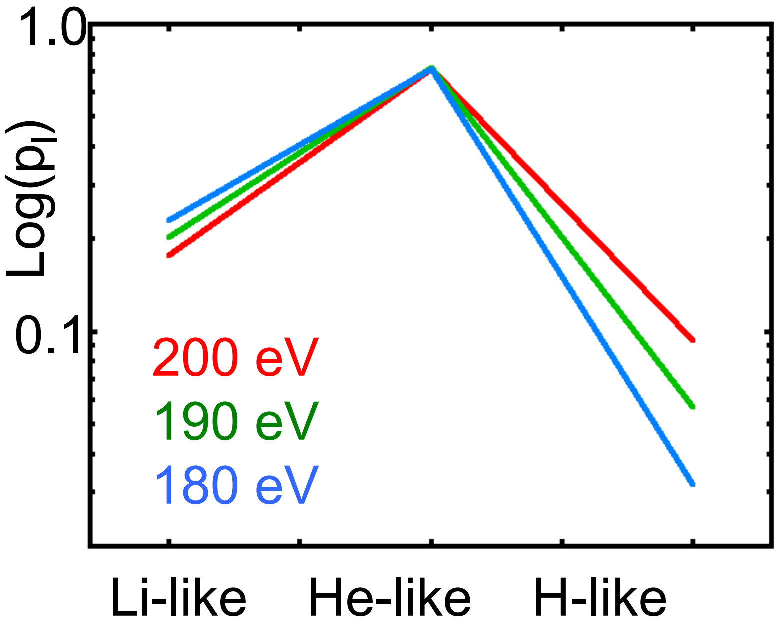

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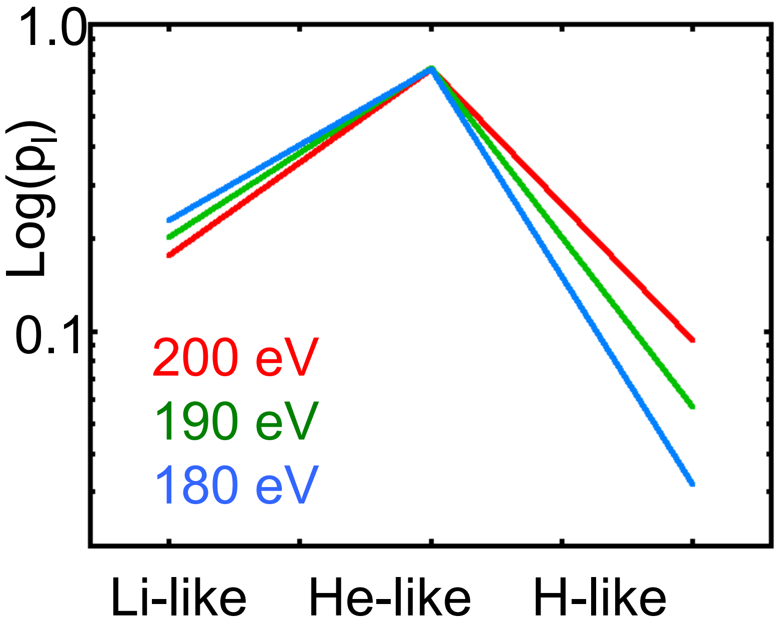

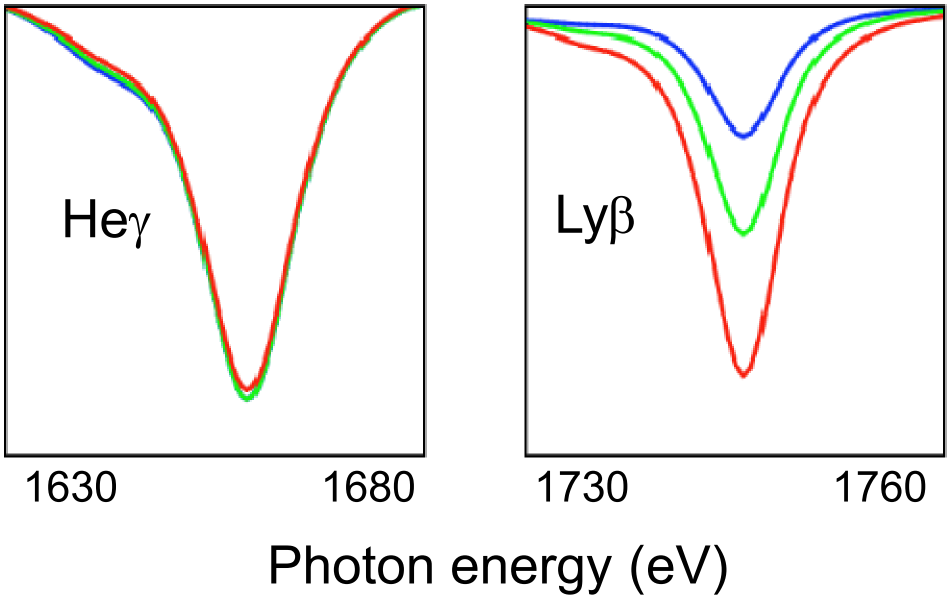

Line shape Φ_ν is sensitive to electron density, n_e

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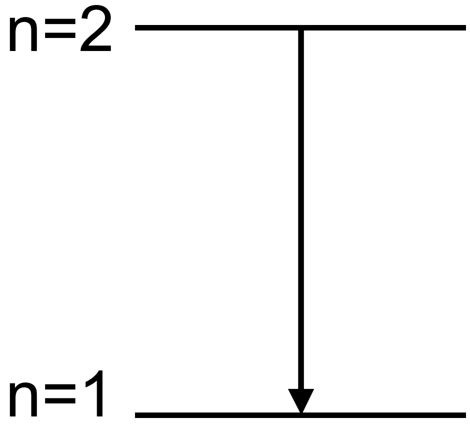
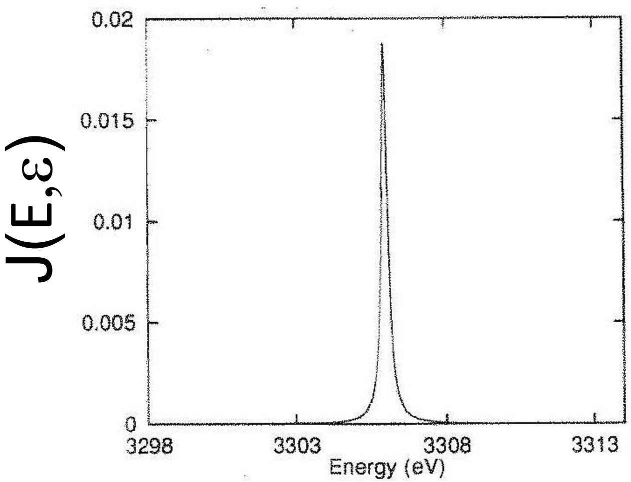
- Line shape is dominated by the Stark broadening





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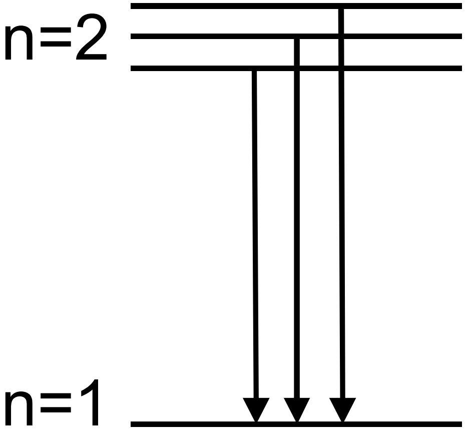
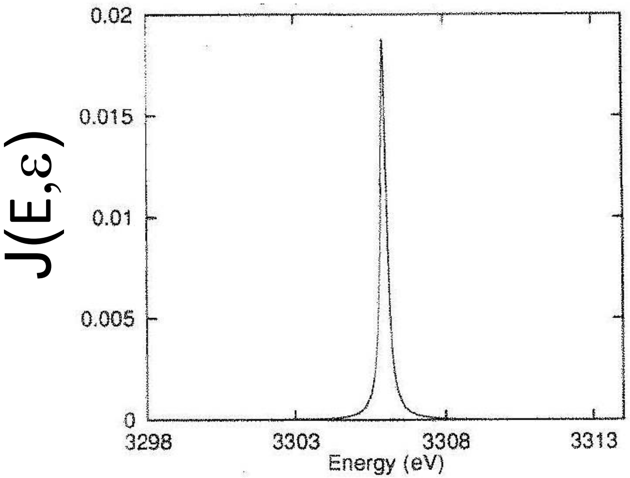
- Line shape is dominated by the Stark broadening
  - External field, ε, splits the energy levels





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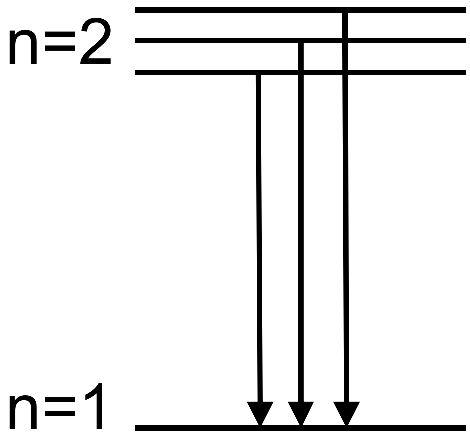
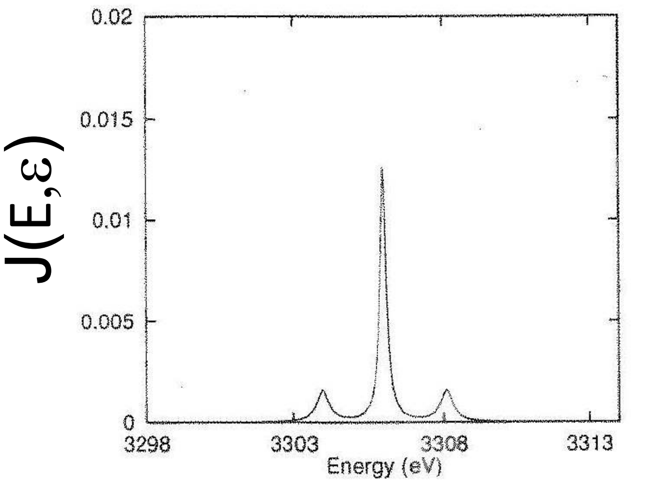


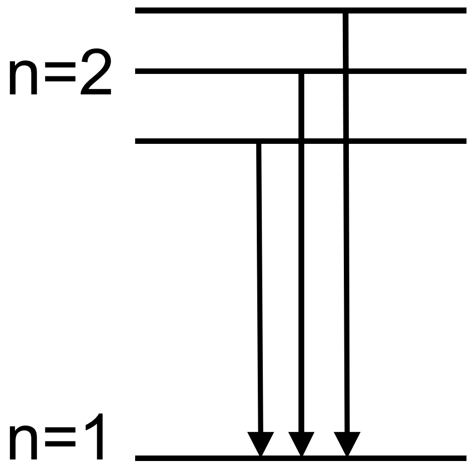

ε=1

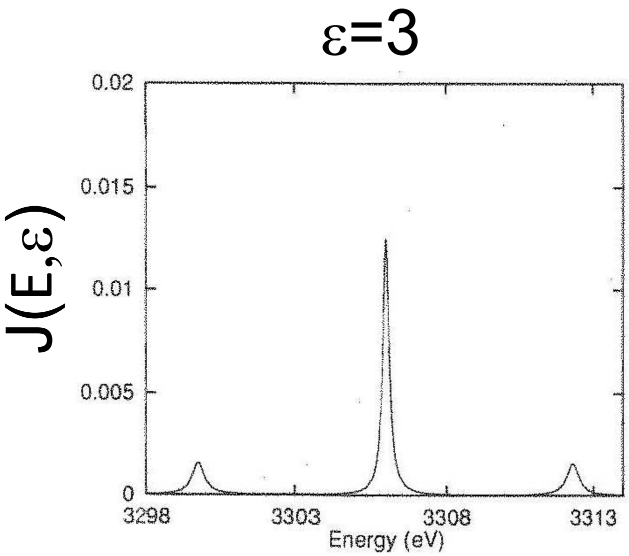
Line shape Φ_ν is sensitive to electron density, n_e

Optical depths:

$$\tau_\nu = \frac{\pi e^2}{mc} f_{lu} \cdot \left\{ N_{Mg} \Delta x \right\} \cdot \Phi_\nu \cdot p_l$$

- Line shape is dominated by the Stark broadening
  - External field, ε, splits the energy levels



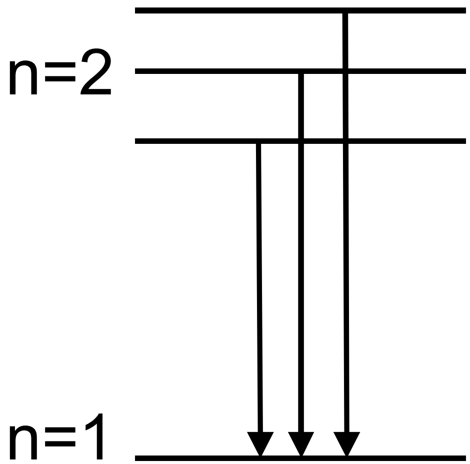


Line shape Φ_ν is sensitive to electron density, n_e

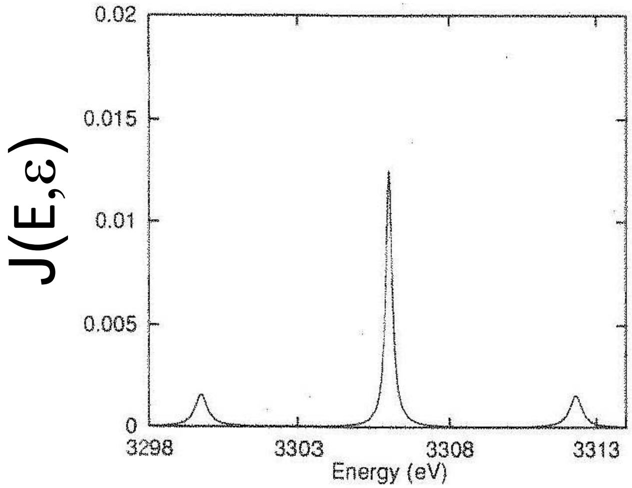
Optical depths:

$$\tau_\nu = \frac{\pi e^2}{mc} f_{lu} \cdot \{ N_{Mg} \Delta x \} \cdot \Phi_\nu \cdot p_l$$

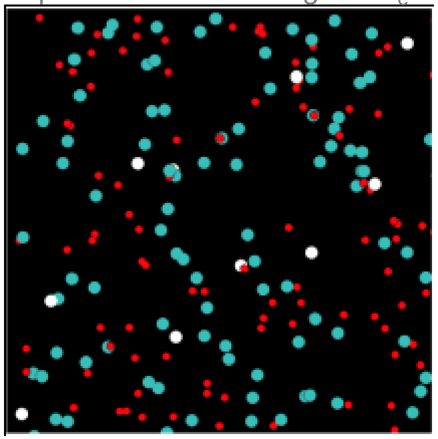
- Line shape is dominated by the Stark broadening
  - External field, ε, splits the energy levels
  - Each radiator sees different ε



ε=3



Snapshot of microscopic particle motion for a given n_e



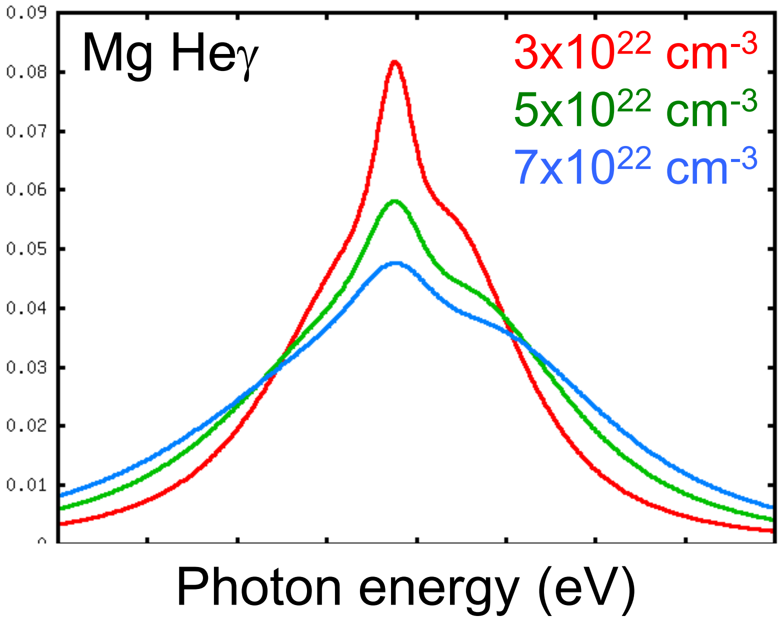
S. Ferri RPHDM2012

Line shape Φ_ν is sensitive to electron density, n_e

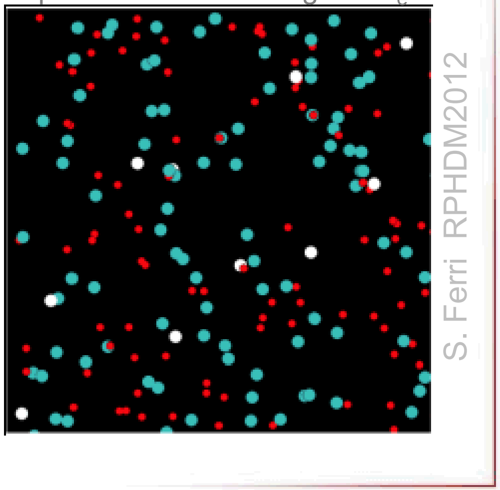
Optical depths:

$$\tau_\nu = \frac{\pi e^2}{mc} f_{lu} \cdot \{ N_{Mg} \Delta x \} \cdot \Phi_\nu \cdot p_l$$

- Line shape is dominated by the Stark broadening
  - External field, ε, splits the energy levels
  - Each radiator sees different ε
  - Net effect is broadening

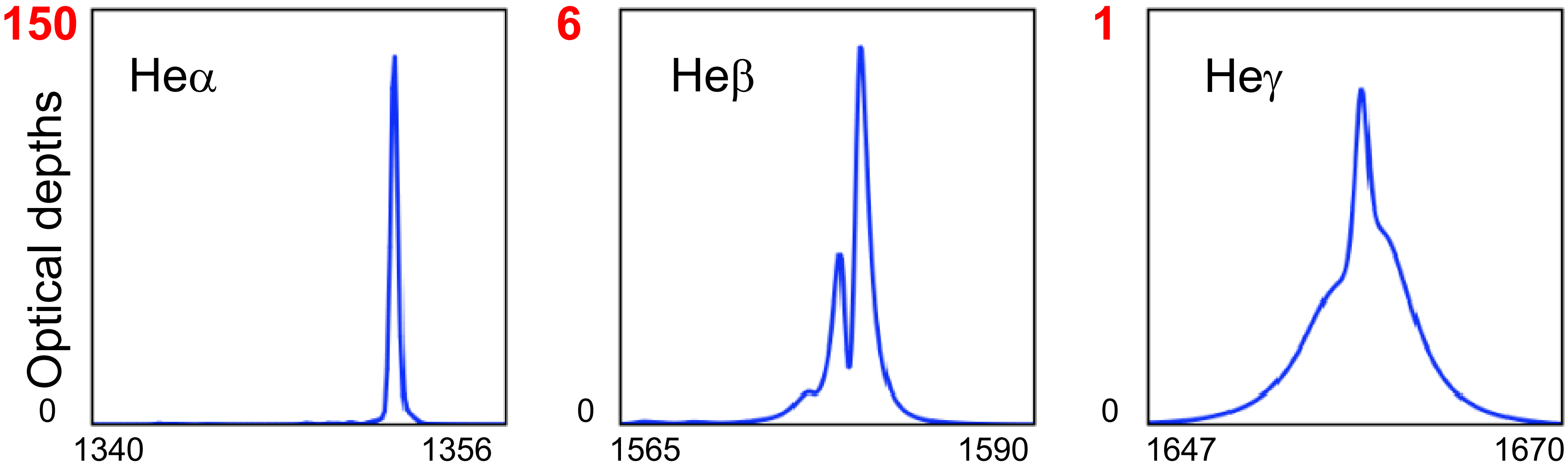


Snapshot of microscopic particle motion for a given n_e



S. Ferri RPHDM2012

Which lines should we fit?



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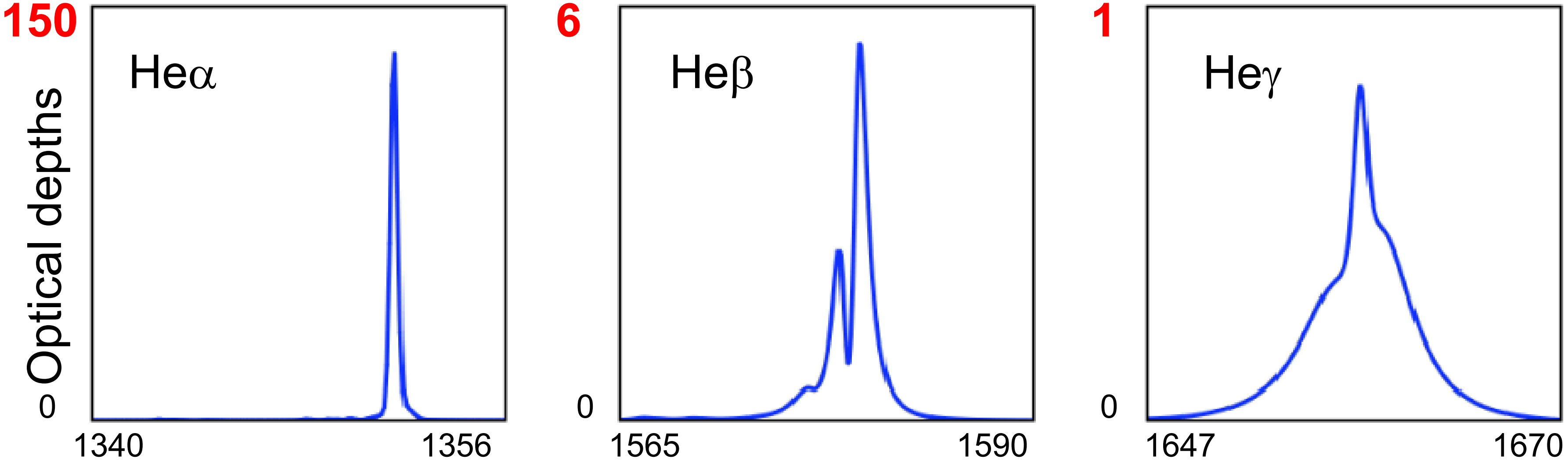
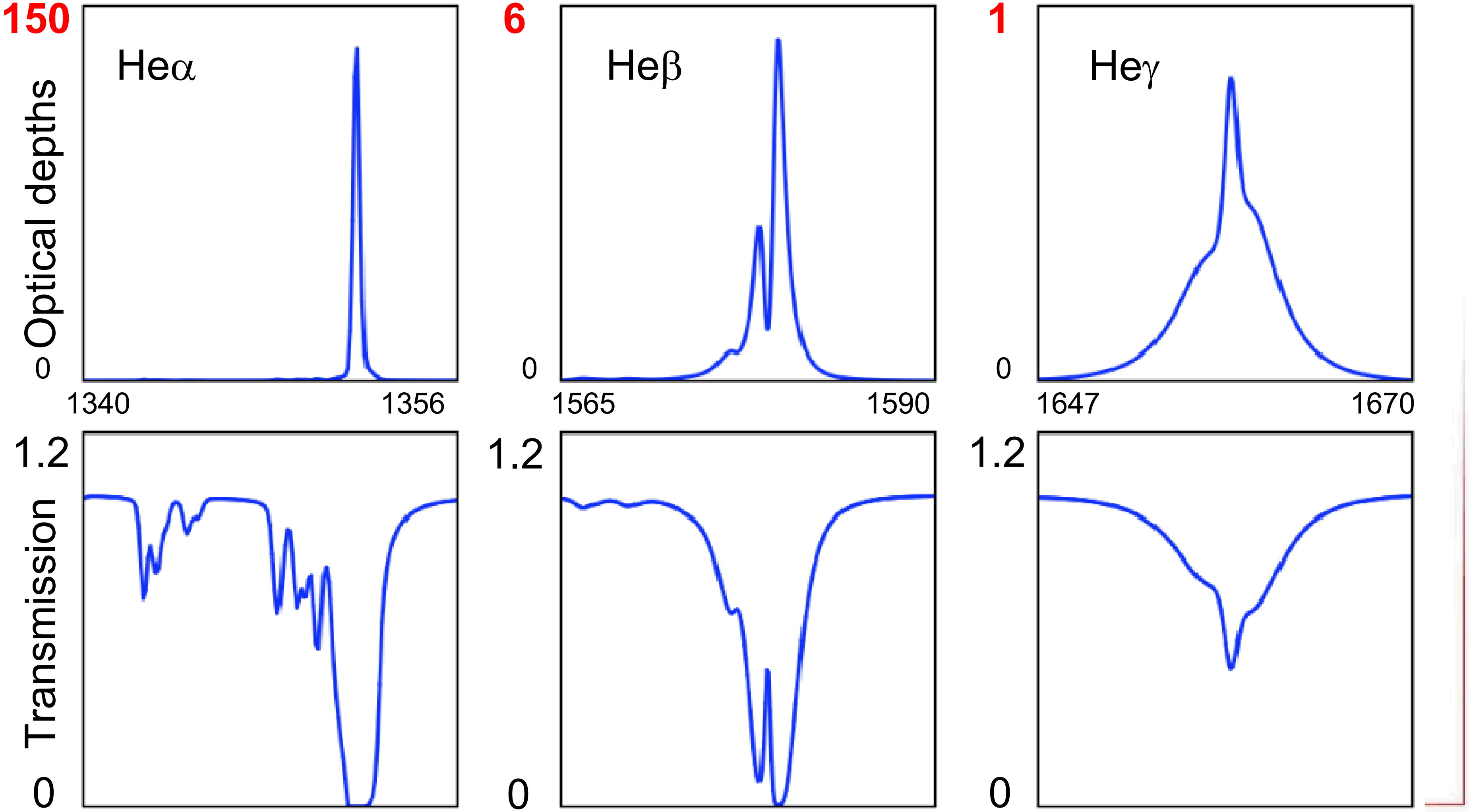


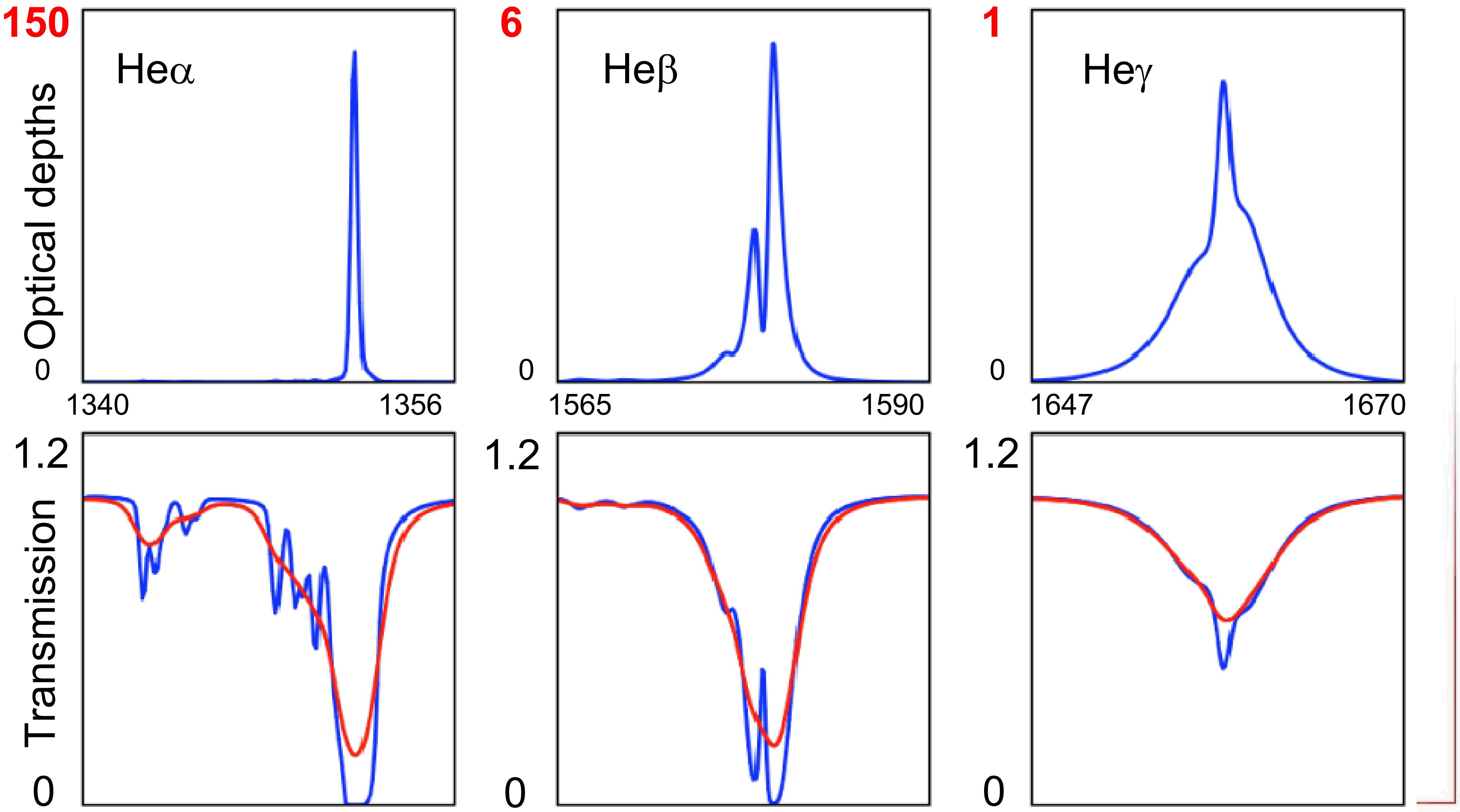
Which lines should we fit?

$$\tau_\nu = \frac{\pi e^2}{mc} f_{lu} \cdot \{ N_{Mg} \Delta x \} \cdot \Phi_\nu \cdot p_l$$



$$T_\nu = \exp(-\tau_\nu)$$

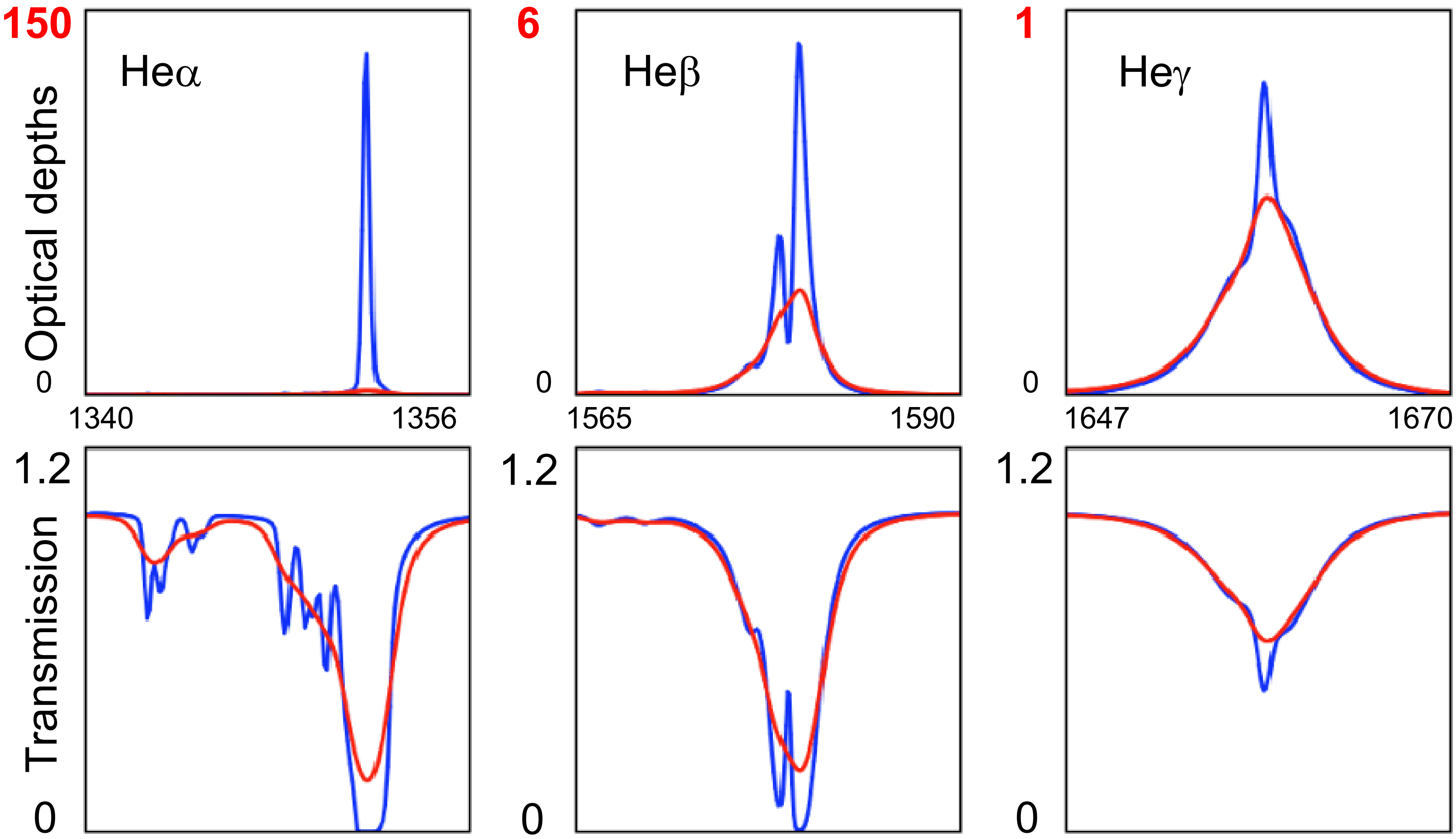
Which lines should we fit?



With the instrumental broadening

Which lines should we fit?

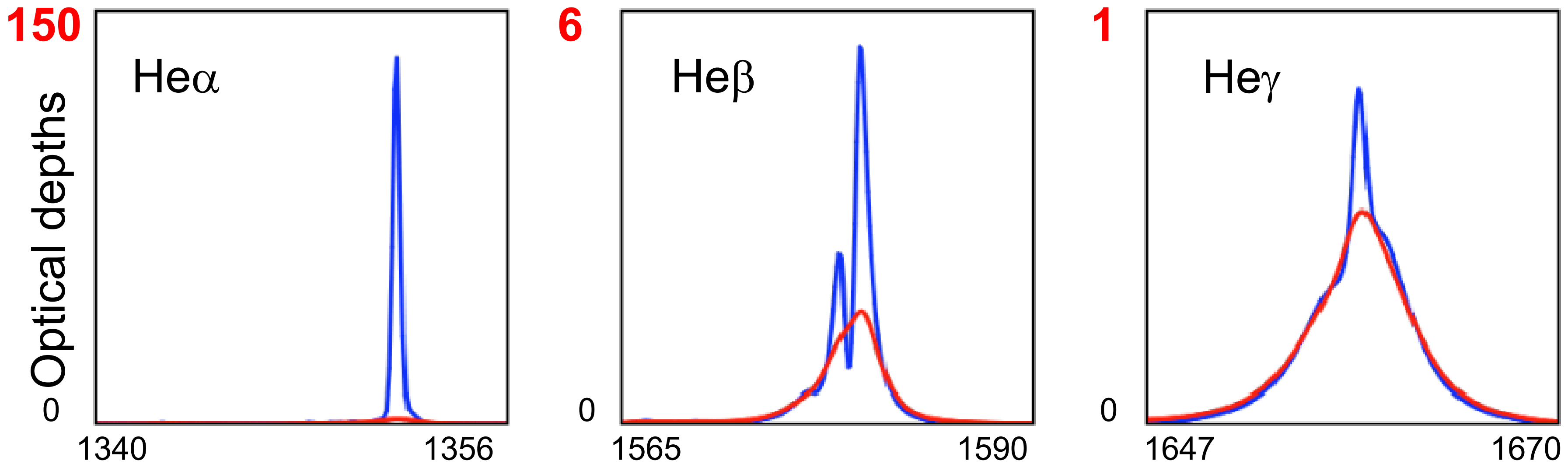
With the instrumental broadening



With the instrumental broadening

Which lines should we fit?

With the instrumental broadening



- Measuring optical depths
  - Less than 1 … reliable
  - Less than 3 … challenging
    - Precise measurement
    - Precise knowledge of instrumental broadening
  - Larger than 3 … impossible
- We should fit weaker lines

Table based flexible spectral model
And optimization

Extract emissivity and opacity database

- Use a collisional radiative model to compute fractional emissivity and opacity for a range of Te and ne
  - PrismSPECT[1] is used
  - LTE
  - ATBASE 6.1 for atomic data
  - Continuum lowering by occupation probability
  - Detailed Stark line shape calculation by MERL[2]+APEX[3]

$$\varepsilon_\nu^{frac} = \frac{1}{4\pi} p_u A_{ul} E_\nu \Phi_\nu \longrightarrow I_\nu^{opt.thin} = \varepsilon_\nu^{frac} \left(N_a \Delta x \right)$$

$$\kappa_\nu^{frac} = \frac{1}{4\pi} p_l B_{lu} E_\nu \Phi_\nu \longrightarrow T_\nu^{pure} = \exp\left\{ -\kappa_\nu^{frac} \left(N_a \Delta x \right) \right\}$$

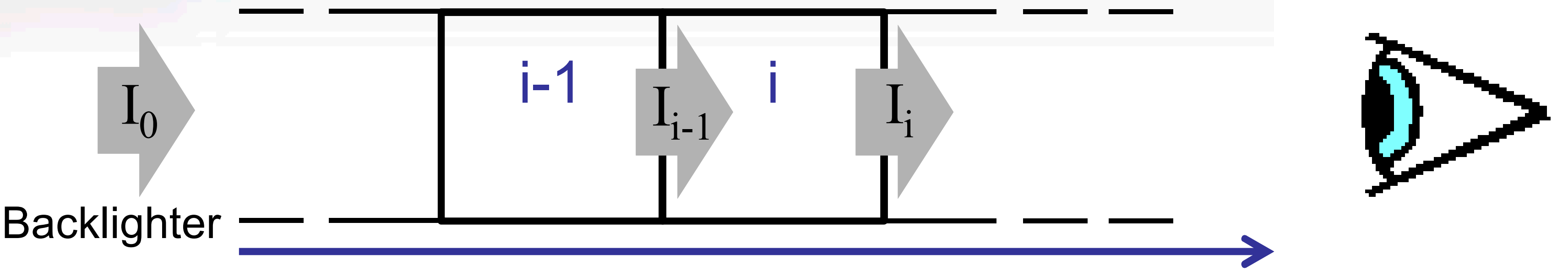
- Compute $\varepsilon_\nu^{\mathrm{frac}}$ and $\kappa_\nu^{\mathrm{frac}}$ databases for Al, Mg, and Fe

[1] J.J. MacFarlane, I.E. Golovkin, et al, High Energ Dens Phys **3**, 181 (2007).

[2] R.C. Mancini, D.P. Kilcrease, et al, Computer Physics Communications **63**, 314 (1991).

[3] C. Iglesias, H. DeWitt, et. al., Phys. Rev. A **31**, 1698 (1985).

Database + Radiation transport



Direction of radiation transport

$$I_{\nu,i} = \underbrace{I_{\nu,i-1}T_{\nu,i}}_{\text{Attenuation of } I_{\nu,i-1}} + \overbrace{\frac{\varepsilon^{frac}_{\nu,i}}{\kappa^{frac}_{\nu,i}}\left(1-T_{\nu,i}\right)}^{\text{Self-emission in cell i}}$$

where

$$\varepsilon^{frac}_{\nu,i} = \varepsilon^{frac}_{\nu}\left(T_{e,i}, n_{e,i}\right)$$

$$\kappa^{frac}_{\nu,i} = \kappa^{frac}_{\nu}\left(T_{e,i}, n_{e,i}\right)$$

$$I^{observed}_{\nu} = \sum_{i=1}^{N}\left\{I_{\nu,i-1}T_{\nu,i} + \frac{\varepsilon^{frac}_{\nu,i}}{\kappa^{frac}_{\nu,i}}\left(1-T_{\nu,i}\right)\right\}$$

- Mixture
- Gradient
- Instrumental broadening
- Detailed line shapes
- Direct dependence on Ne
- Optimization

Optimization algorithms

1. Genetic algorithms
   - Inspired by evolutionary biology
   - Search is unbiased
   - Search by population
   - Uniqueness check by changing random seed
   - Quickly find good solution
2. Levenberg-Marquardt
   - Non-linear least squares minimization
   - Quick convergence from good solution

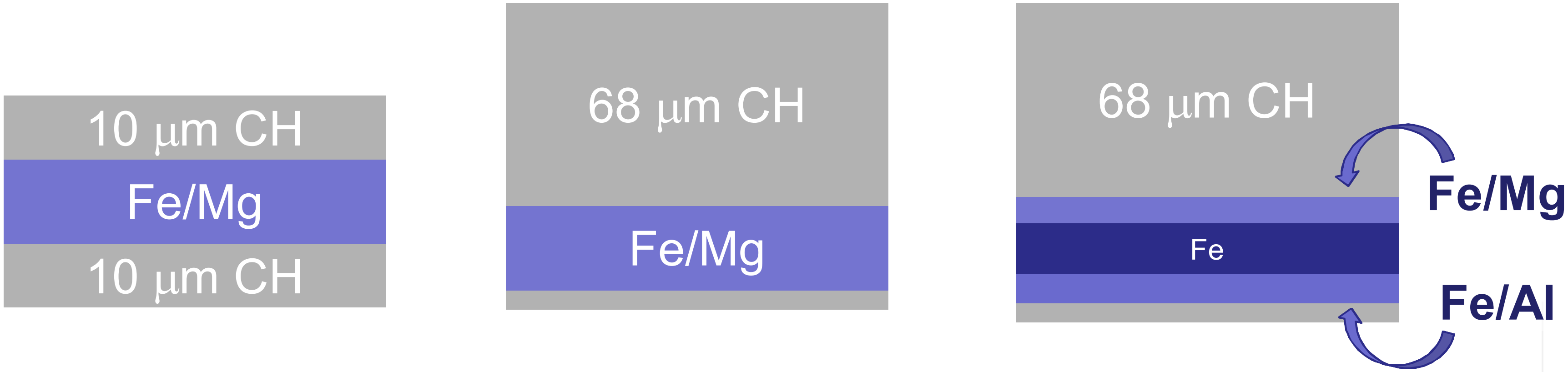
Condition analysis

Density controlled by CH tamper thickness
Uniformity measured by Mg and Al dopants

Low density

High density

Uniformity



10 μm CH

Fe/Mg

10 μm CH

68 μm CH

Fe/Mg

68 μm CH

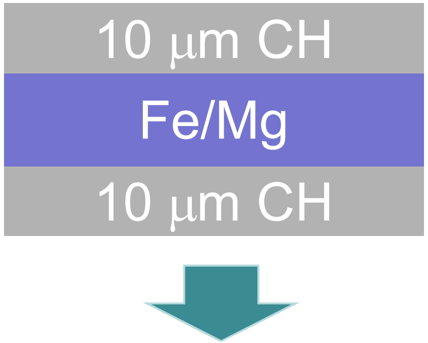
Fe

Fe/Mg

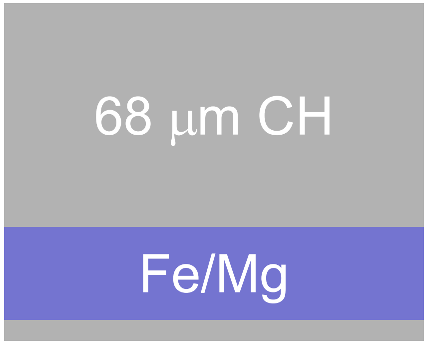
Fe/Al

Density controlled by CH tamper thickness
Uniformity measured by Mg and Al dopants

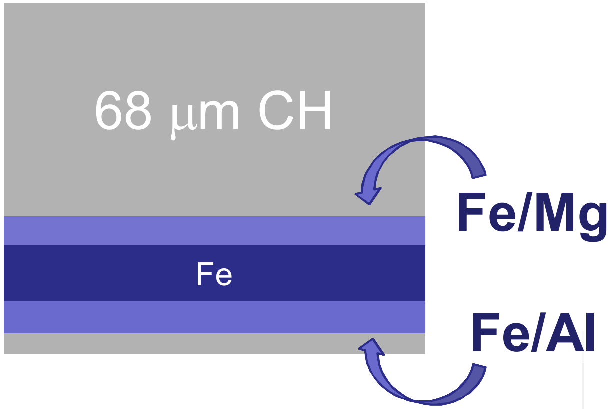
Low density

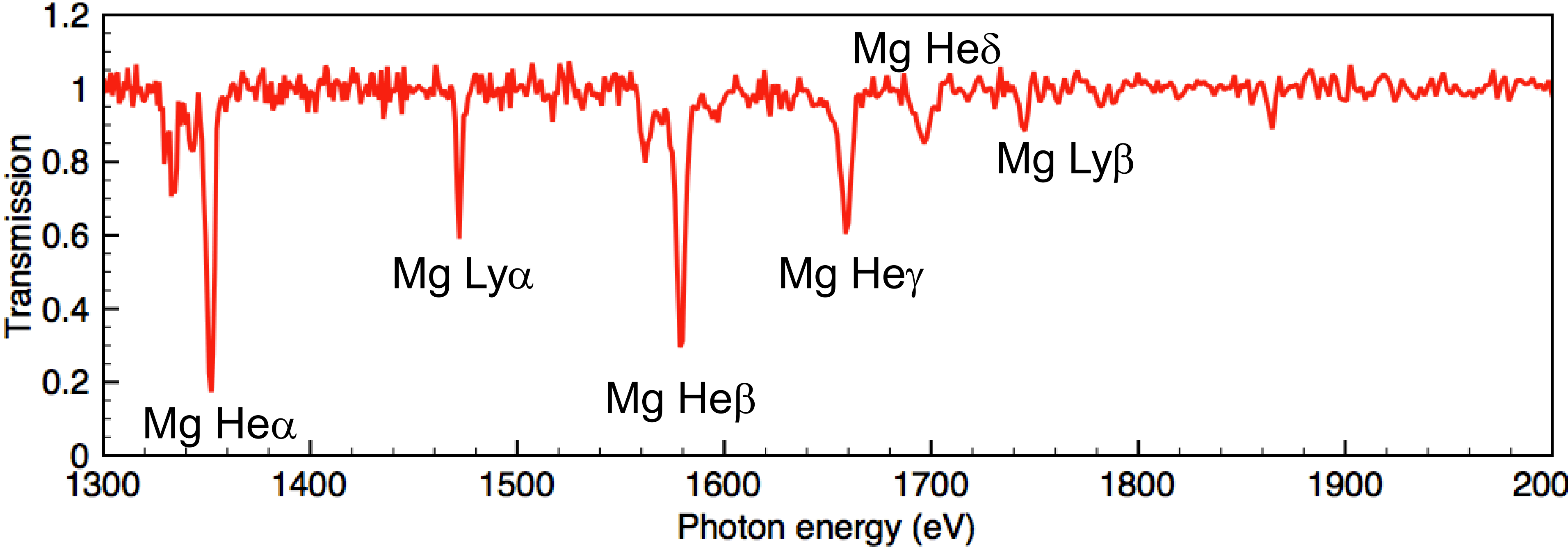


High density

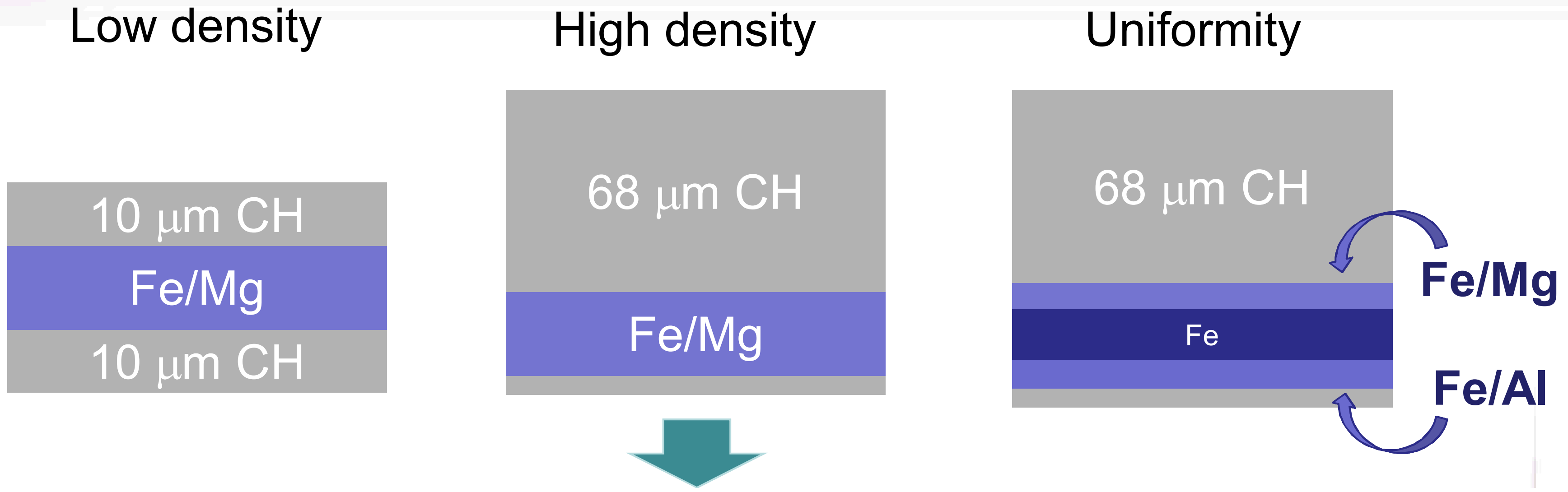


Uniformity





Density controlled by CH tamper thickness
Uniformity measured by Mg and Al dopants



Low density

10 μm CH

Fe/Mg

10 μm CH

High density

68 μm CH

Fe/Mg

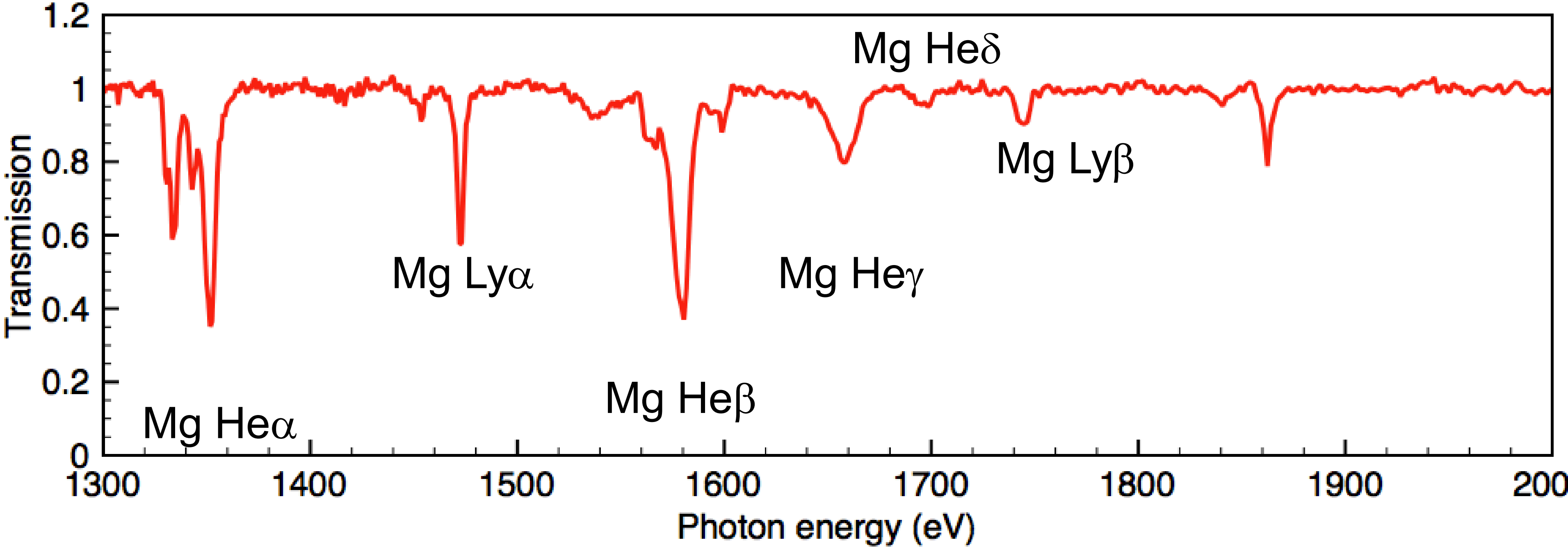
Uniformity

68 μm CH

Fe

Fe/Mg

Fe/Al

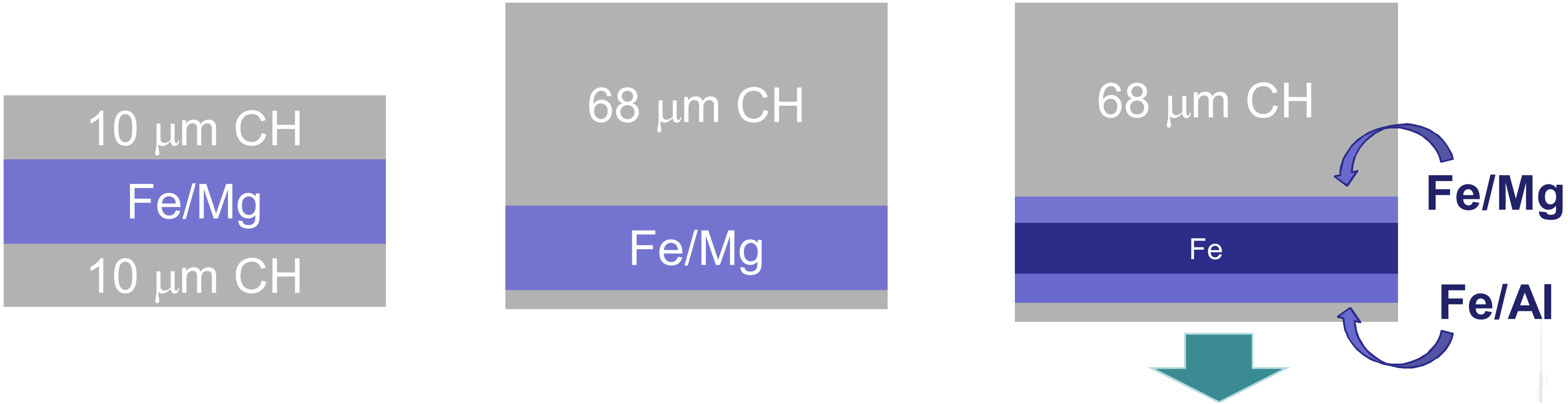


Density controlled by CH tamper thickness
Uniformity measured by Mg and Al dopants

Low density

High density

Uniformity



10 μm CH

Fe/Mg

10 μm CH

68 μm CH

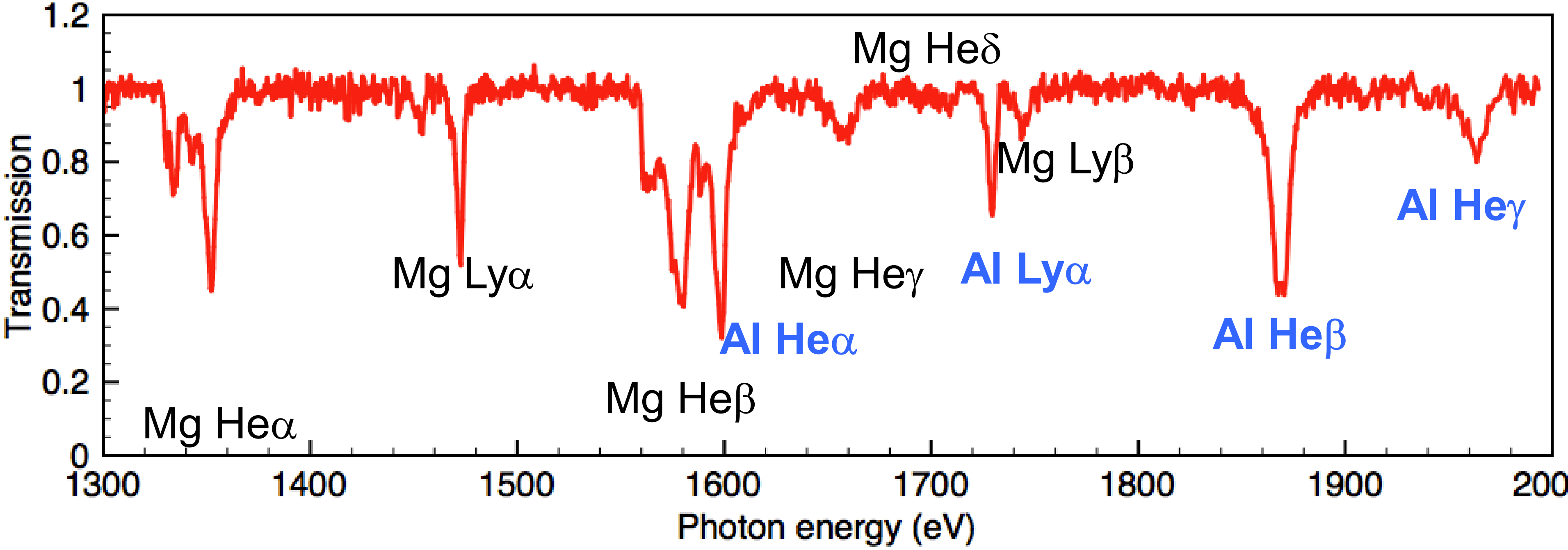
Fe/Mg

68 μm CH

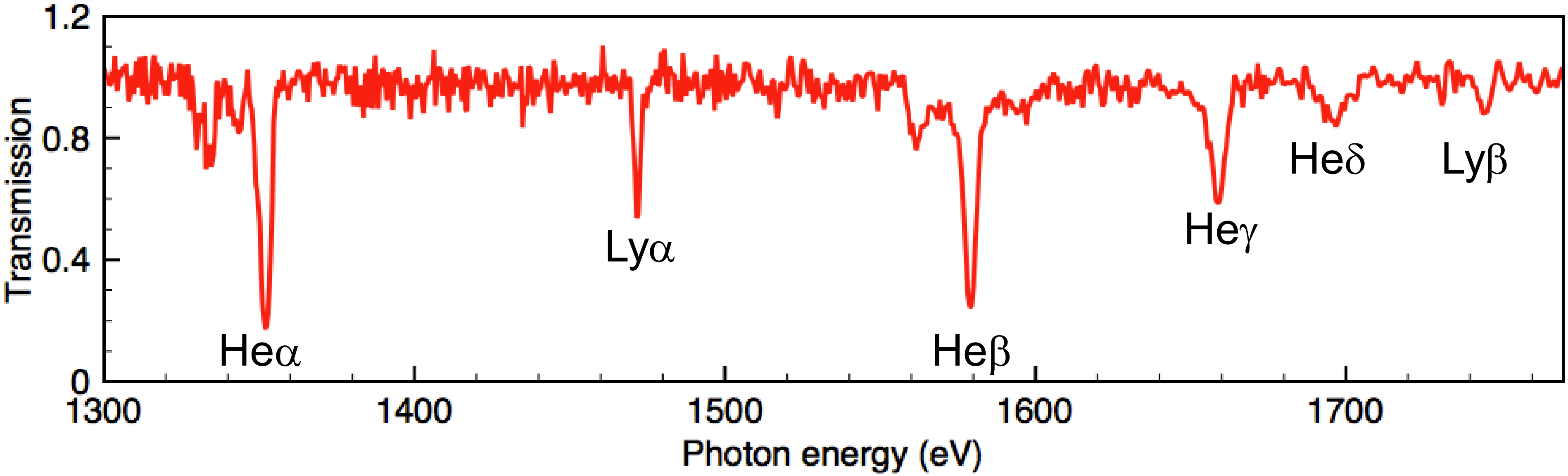
Fe

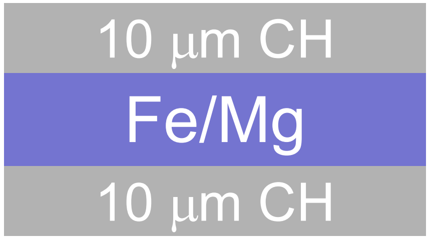
Fe/Mg

Fe/Al



Analysis of low density data gives T_e=164 eV and n_e= 7.91x$10^{21}$$cm^{-3}$





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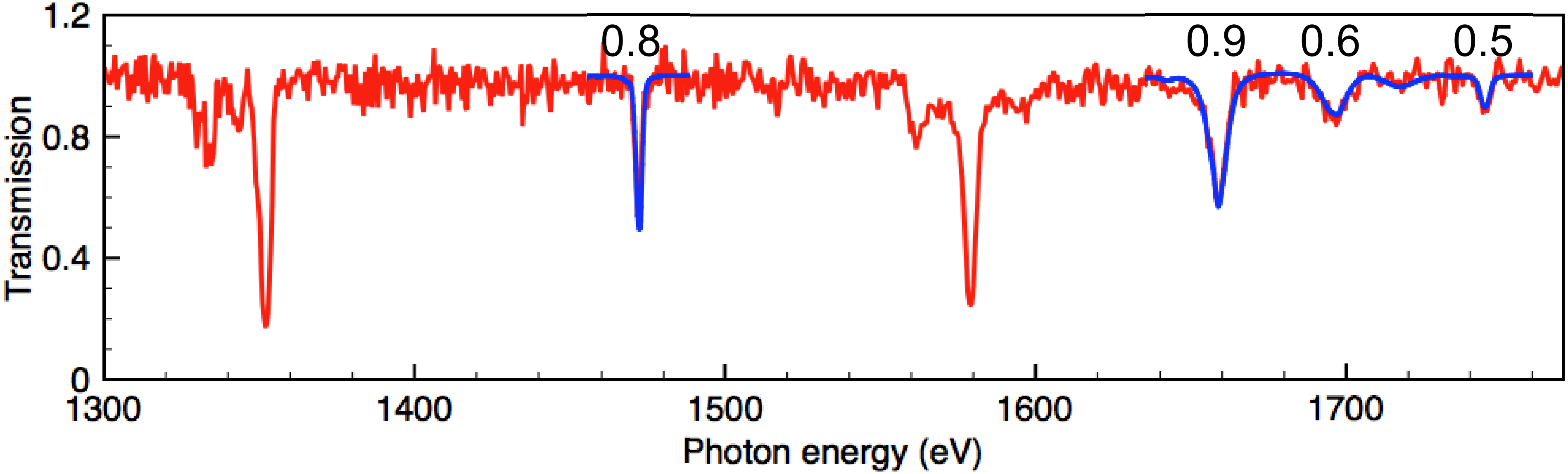

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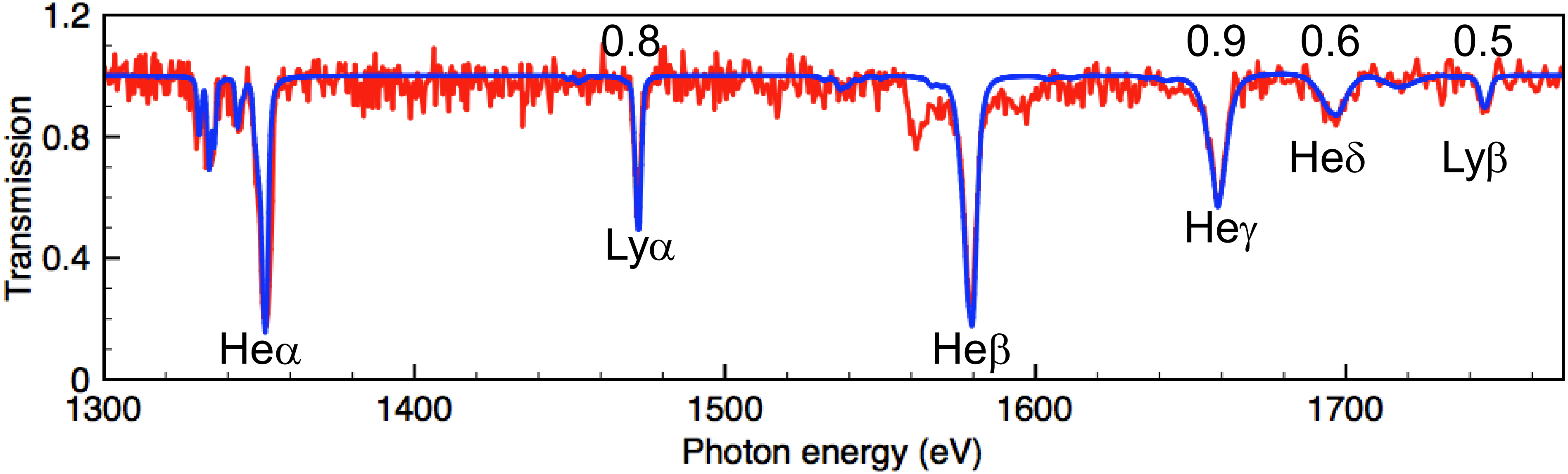
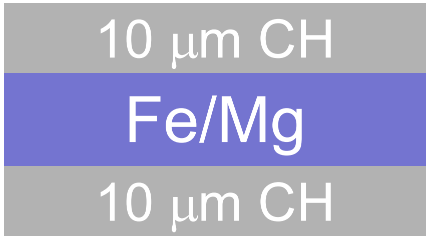


- Fitted lines: Mg Heγ and Lyβ
  - ✧ T_e=164±5 eV
  - ✧ n_e=$(7.91 \pm 1.92) \times 10^{21}$ cm^{-3}
  - ✧ ρL=$(3.30 \pm 0.35) \times 10^{-5}$ g/cm^2



10 μm CH

Fe/Mg

10 μm CH

- Model shows good agreement to all the lines
  - → Atomic data used is consistent with the data
- Inferred areal density agrees to Rutherford Back Scattering (RBS) measurements
  - Measured areal density: 3.01×10^{-5}g/cm^2

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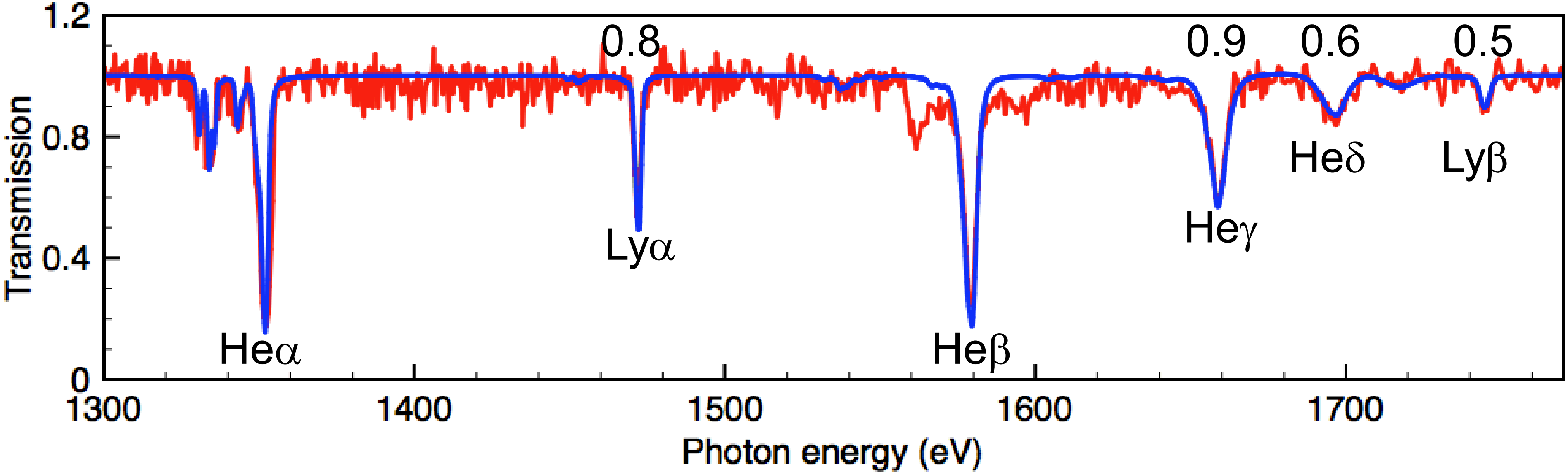

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Fe/Mg

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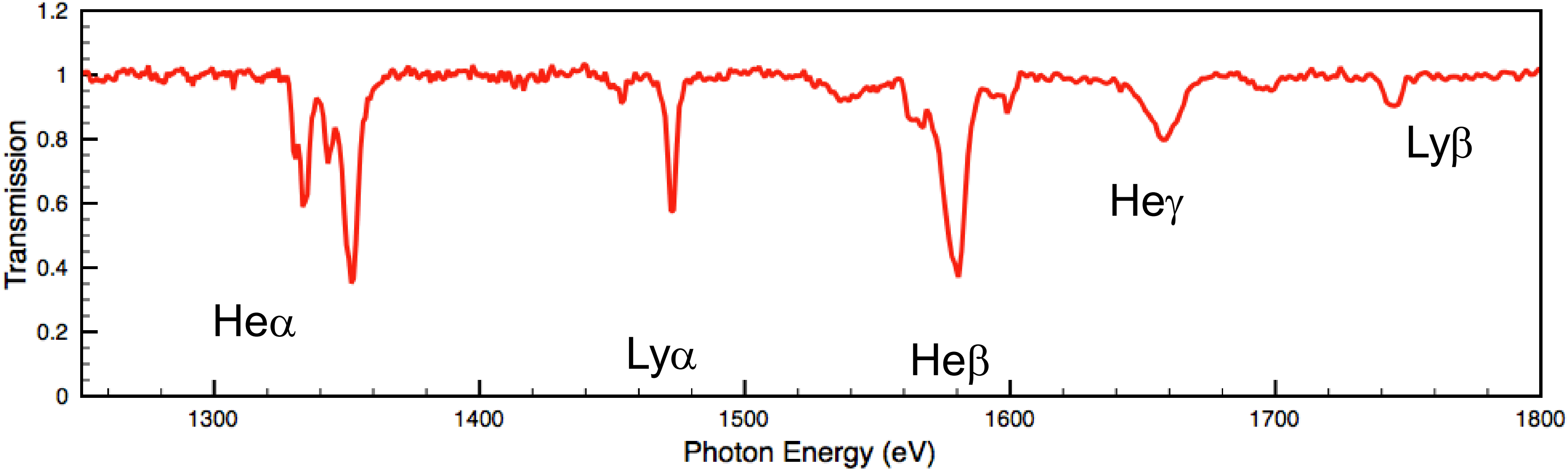
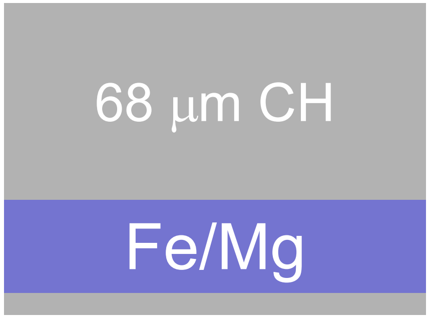
Analysis of high density data gives T_e=195 eV and n_e= 4.06x10^{22}cm^{-3}



- Fitted lines: Mg Heγ and Lyβ
  - ✧ T_e=195±3 eV
  - ✧ n_e=(4.06±0.62)x10^{22} cm^{-3}
  - ✧ ρL=(4.88±0.58)x10^{-5} g/cm^2

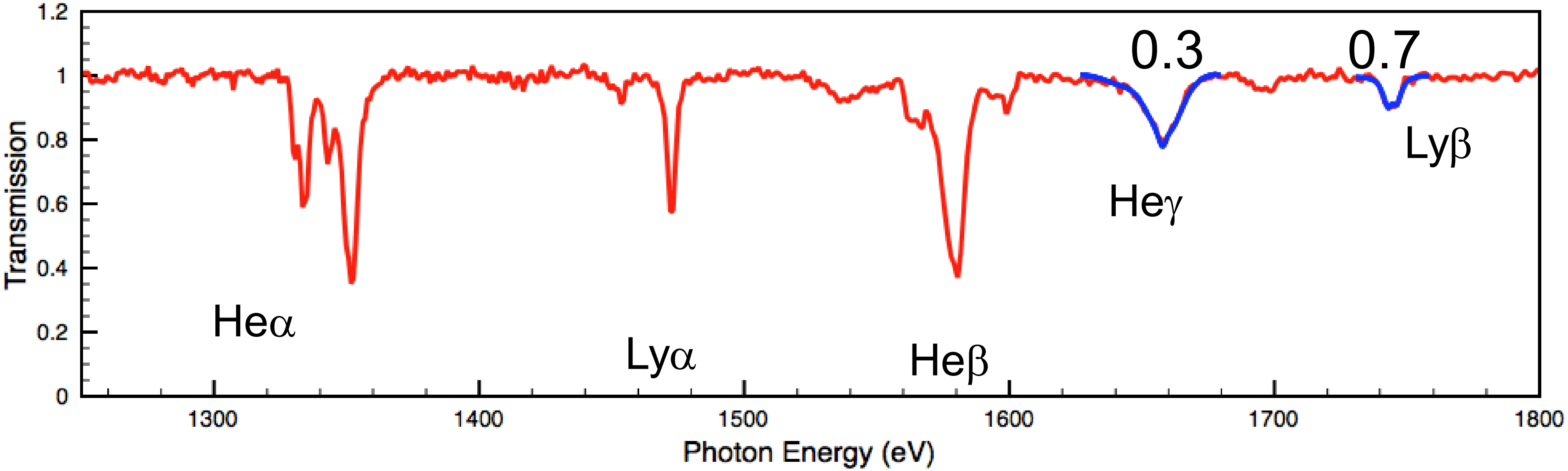
- Inferred areal density agrees to RBS measurements
  - Measured areal density: 5.00x10^{-5}g/cm^2



68 μm CH

Fe/Mg

Analysis of high density data gives T_e=195 eV and n_e= 4.06×10^{22} cm^{-3}



- Fitted lines: Mg Heγ and Lyβ
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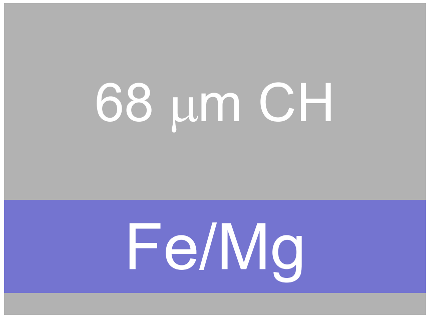
  - ρL=$(4.88 \pm 0.58) \times 10^{-5}$ g/cm^2
- Inferred areal density agrees to RBS measurements
  - Measured areal density: $5.00 \times 10^{-5} g/cm^2$



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Fe/Mg

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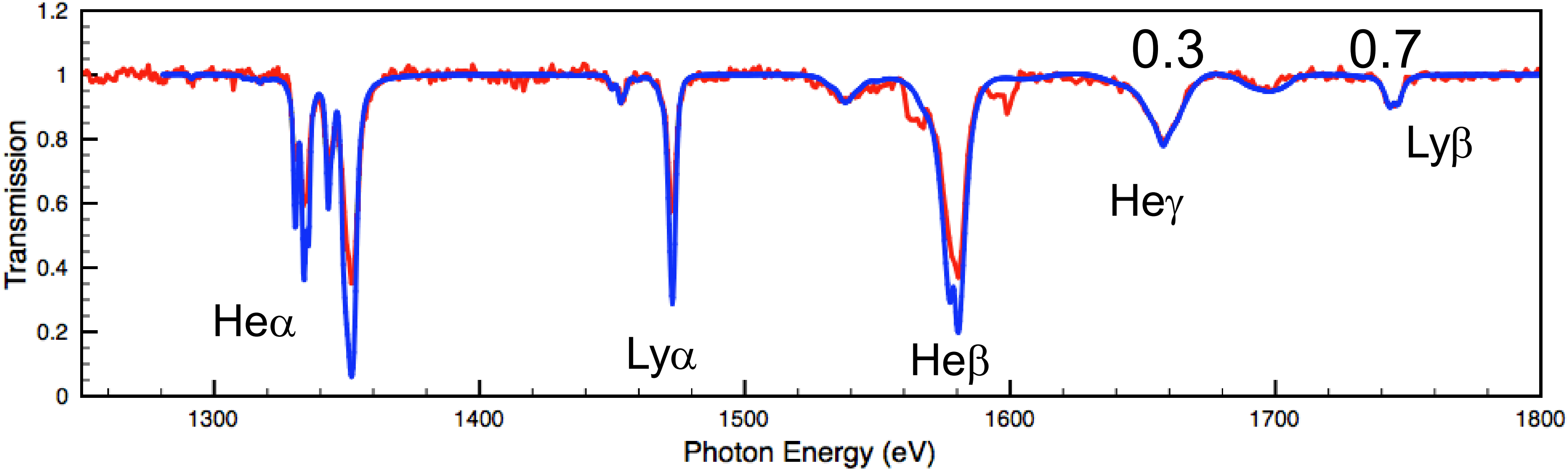

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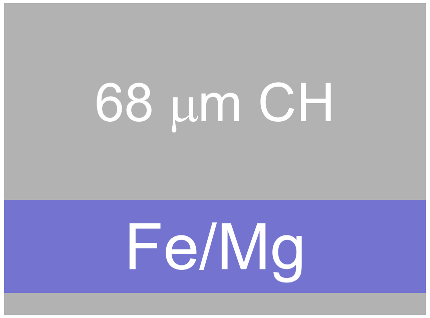
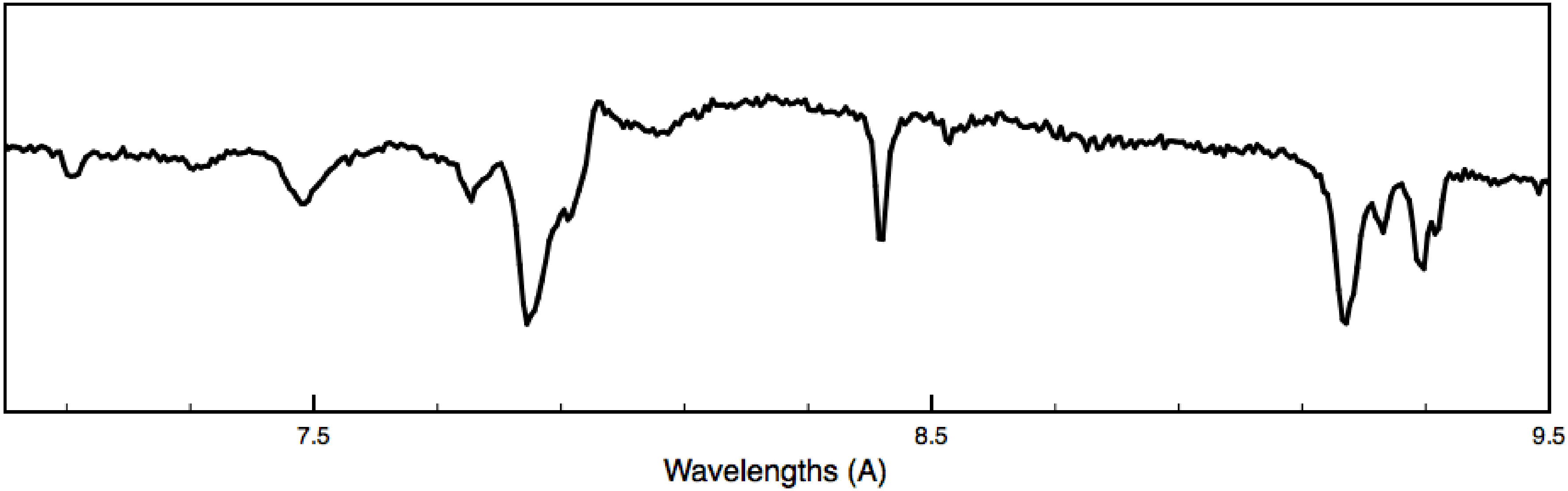


How does the additional background change the analysis results?



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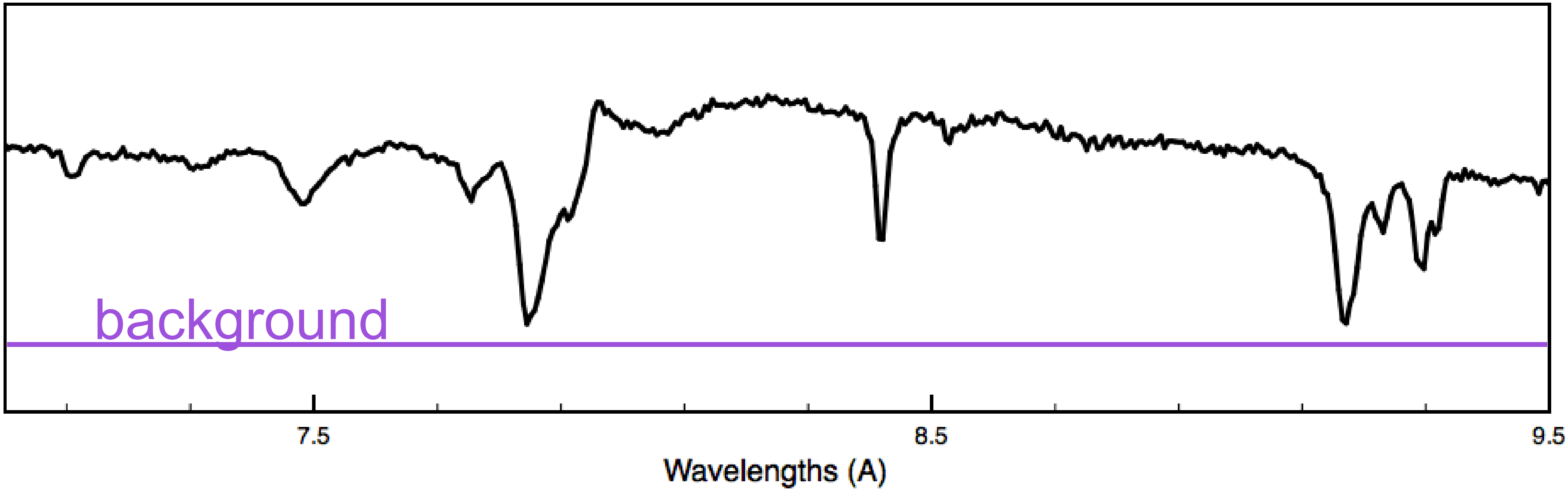

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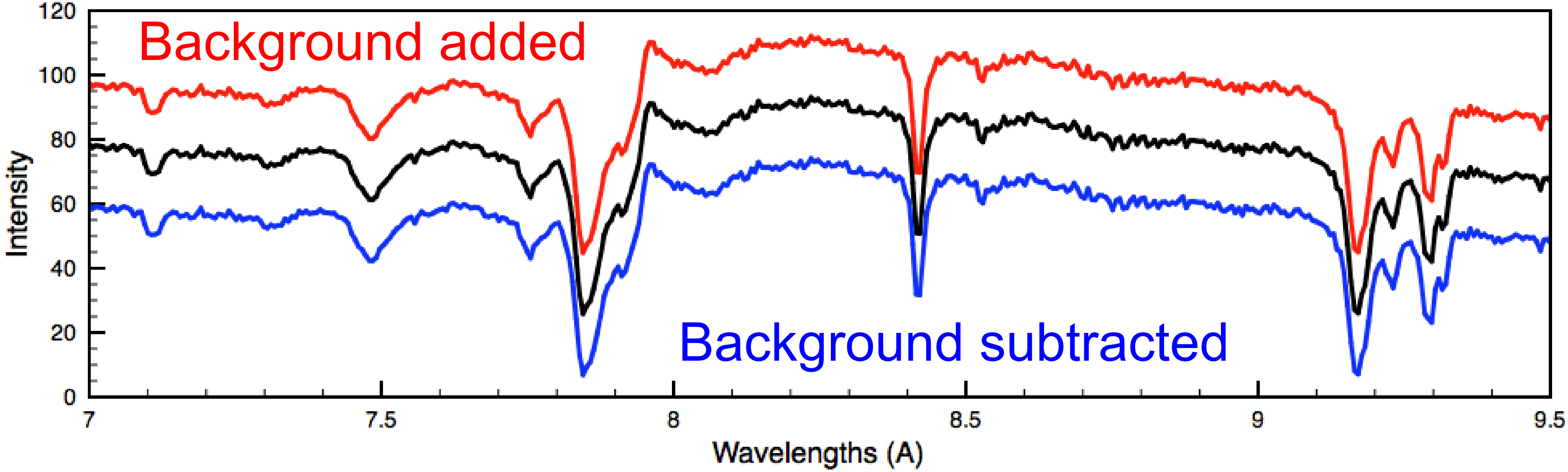

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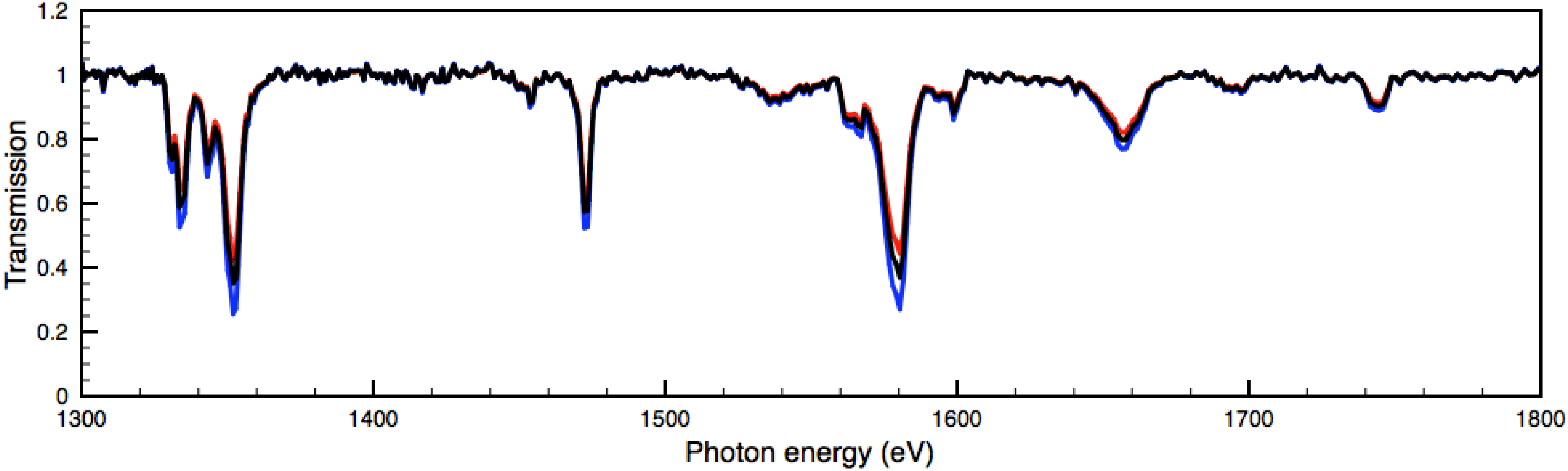

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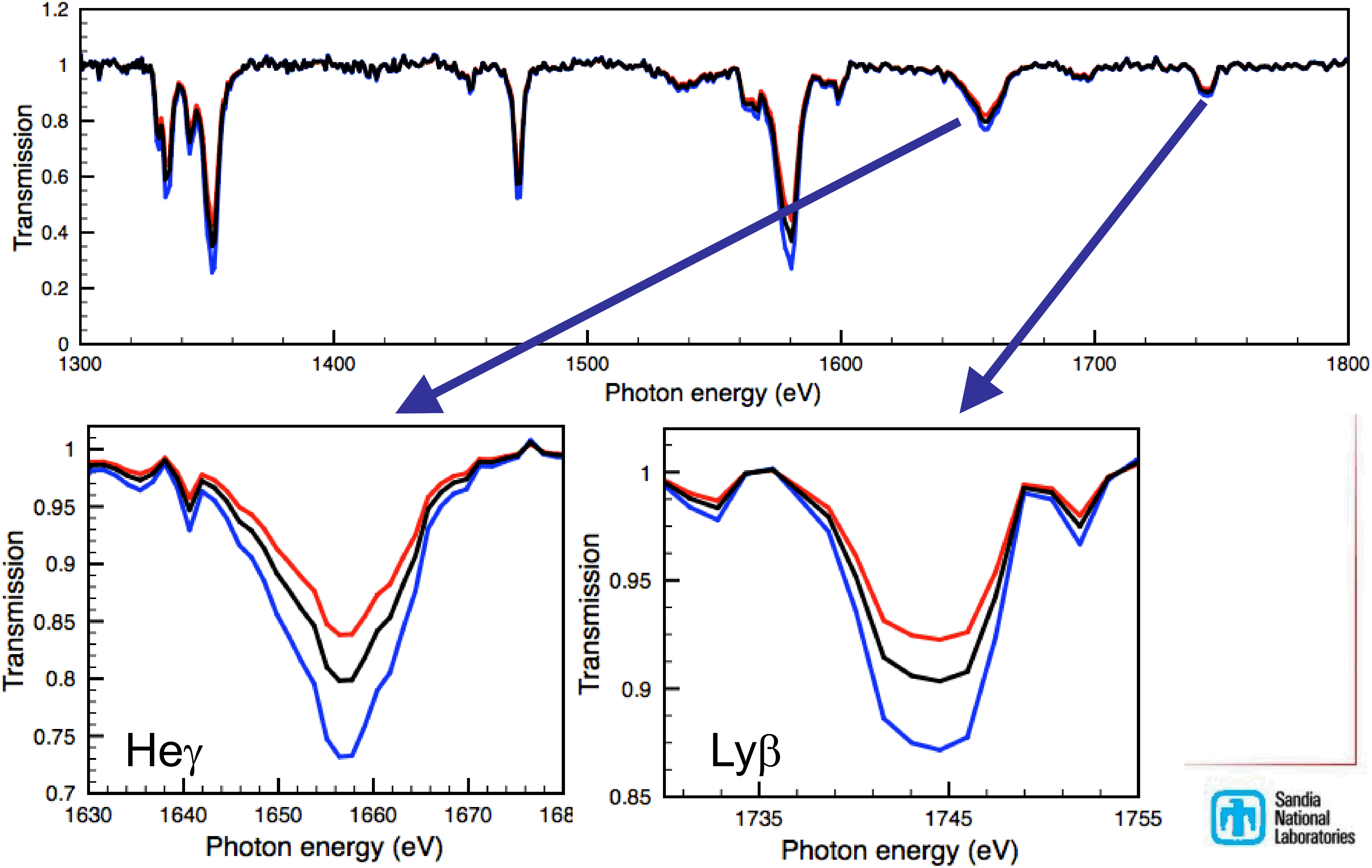

How does the additional background change the analysis results?

	T_e [eV]	n_e [10^{22} e/cc]	ρL [10^{-5} g/cm^2]
BG added	195	4.2	3.9
ORIGINAL	**195±3**	**4.1±0.6**	**4.9±0.6**
BG subtracted	194	4.0	6.6

- Analysis of Te and ne using Lyβ and Heγ lines are quite robust against background
- Inferred areal density changes due to background

- Areal density values measured prior to the experiment are closest to the one inferred from the original data (i.e. 5.00×10^{-5} g/cm^2)

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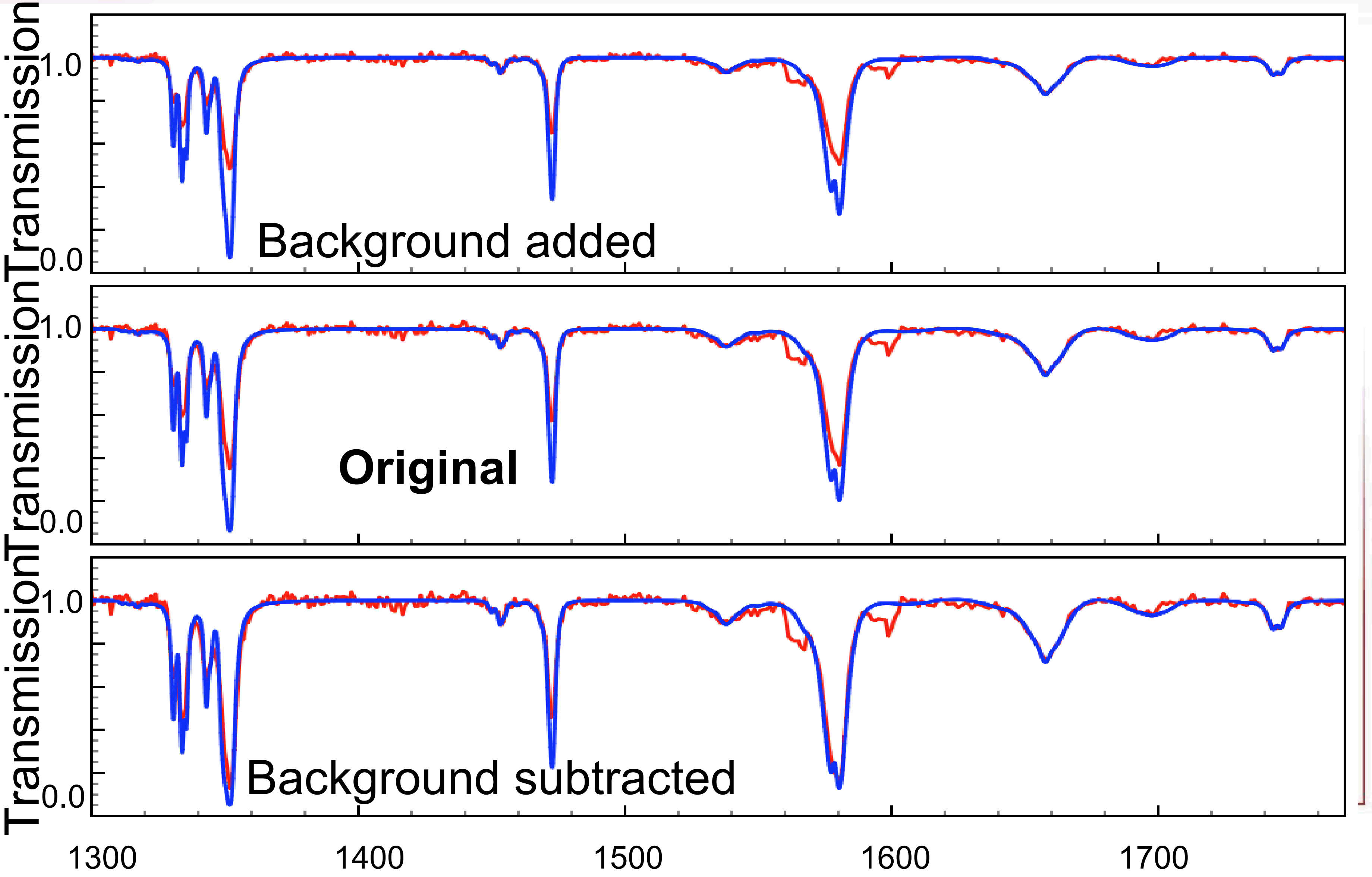
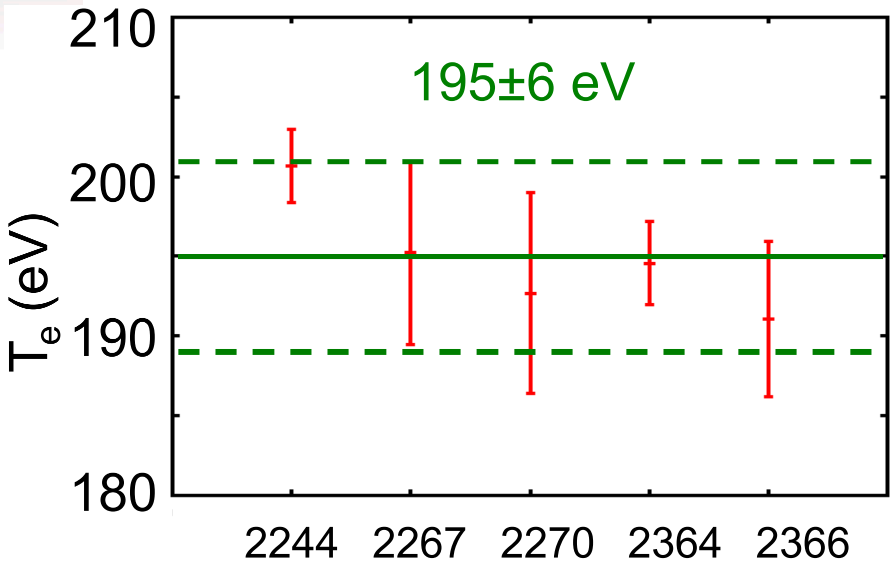
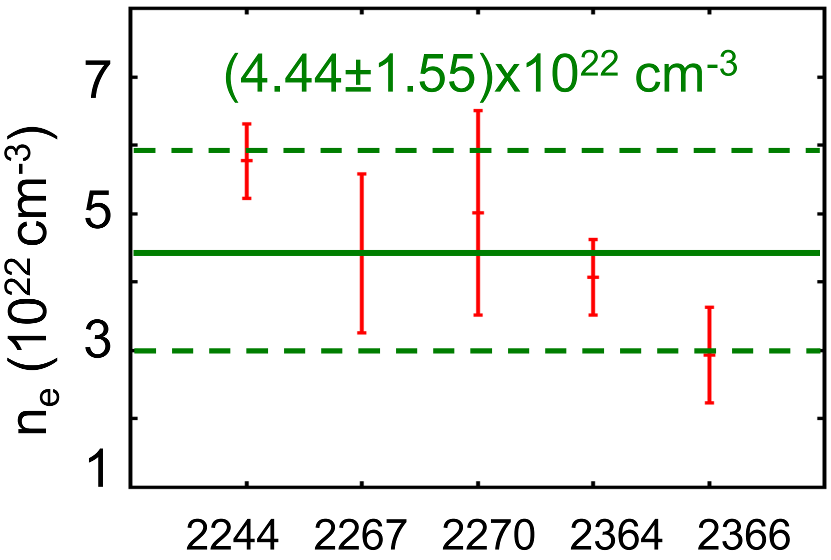
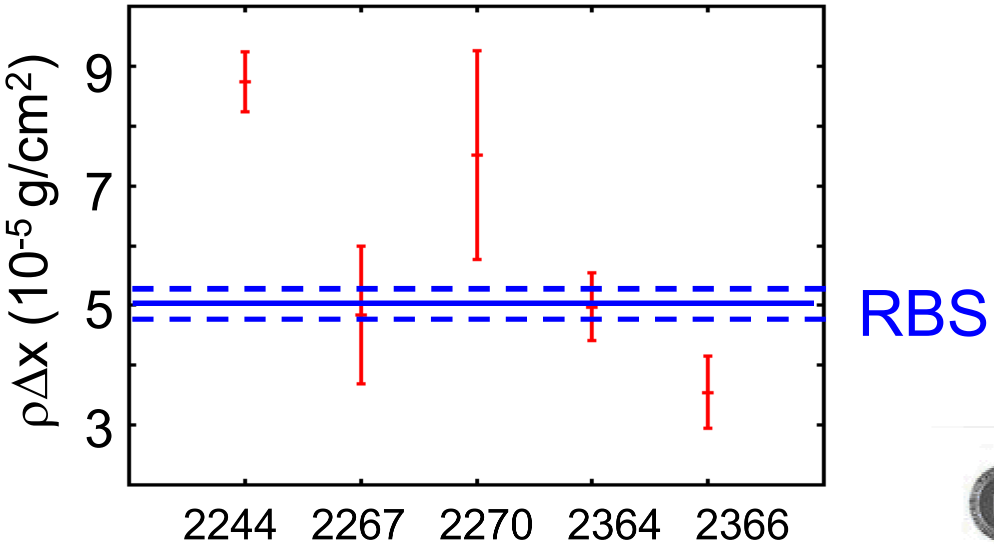


Condition reproducibility on high density data is T_e=±3% and n_e=±33%





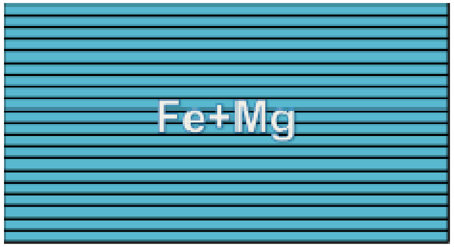


Uniformity analysis

We can model gradient. …but, does it work?

- Too many constraints will end up in non-unique solution
- Questions

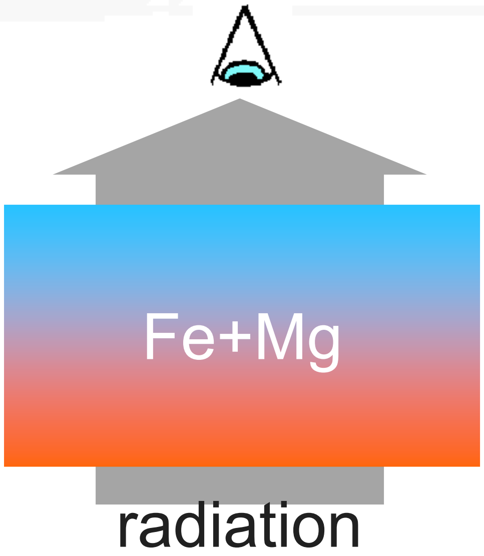
1. How does χ^2 deteriorates due to non-uniformity?
2. How does the gradient model work on Fe+Mg sample?



3. How does the gradient model work on Fe+Mg+Al sample?

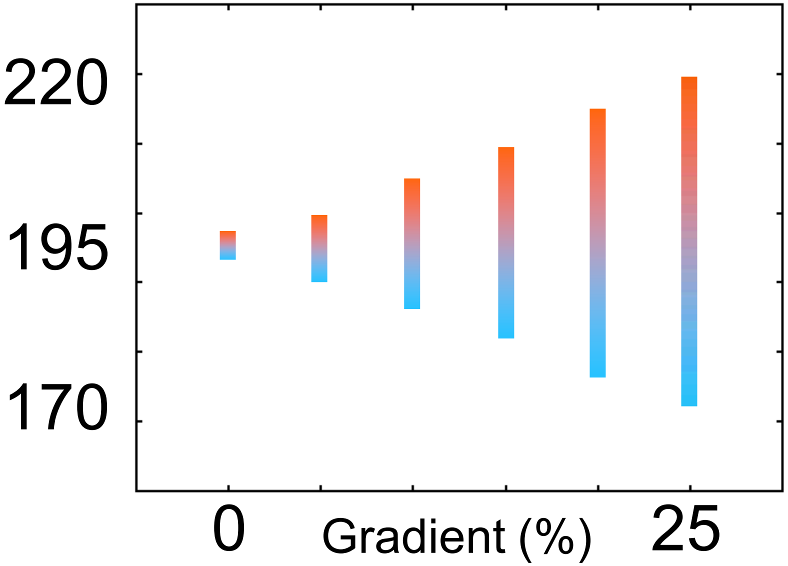
Can be studied synthetically!

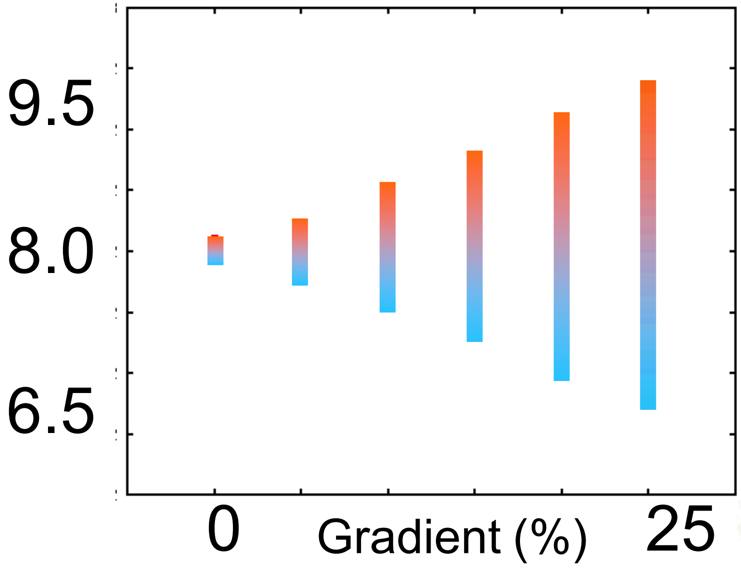
How does χ^2 deteriorates due to non-uniformity?



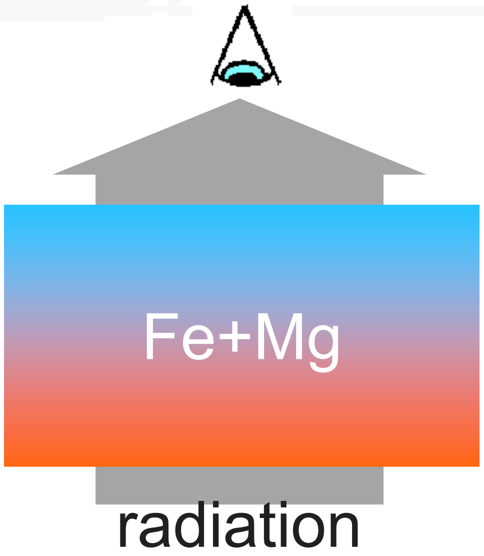
For 0% - 25 % gradient

1. Compute synthetic spectrum
2. Add some noise
3. Analyze the spectrum with uniform model



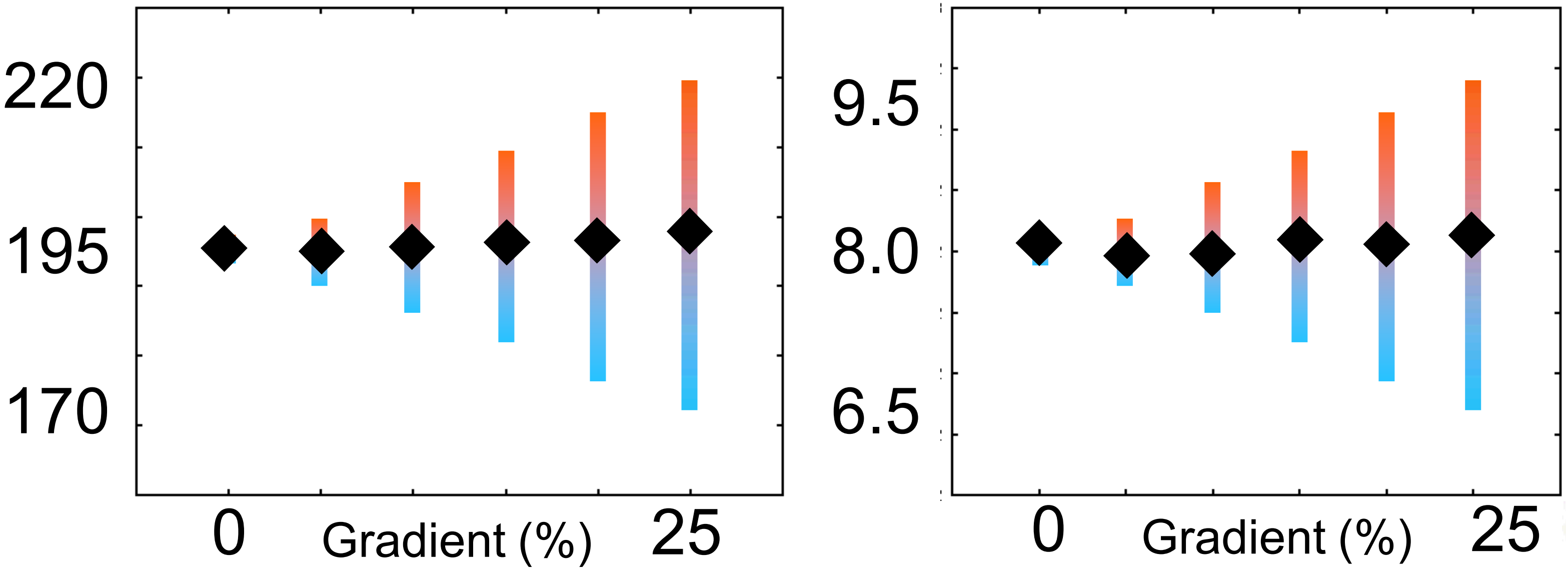


How does χ^2 deteriorates due to non-uniformity?



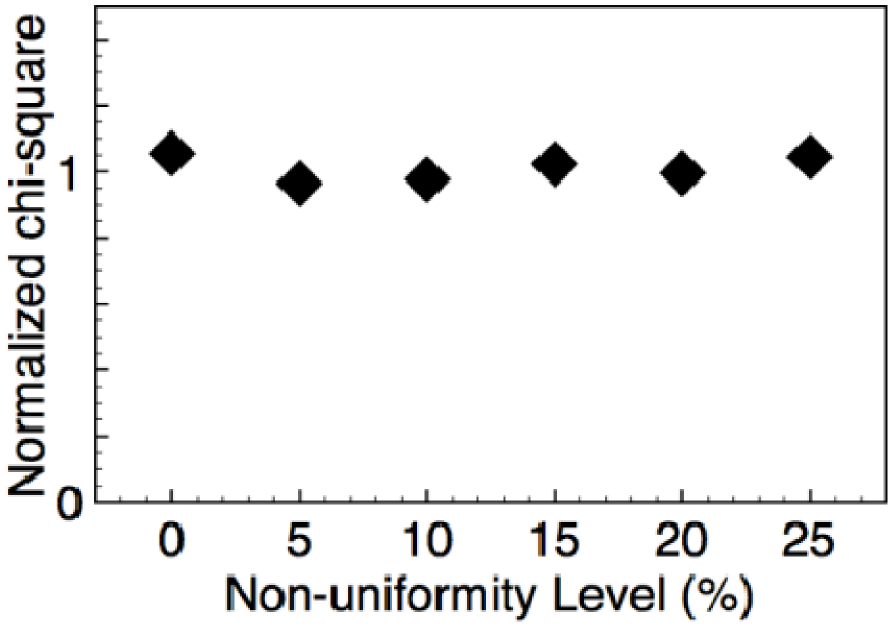
For 0% - 25 % gradient

1. Compute synthetic spectrum
2. Add some noise
3. Analyze the spectrum with uniform model

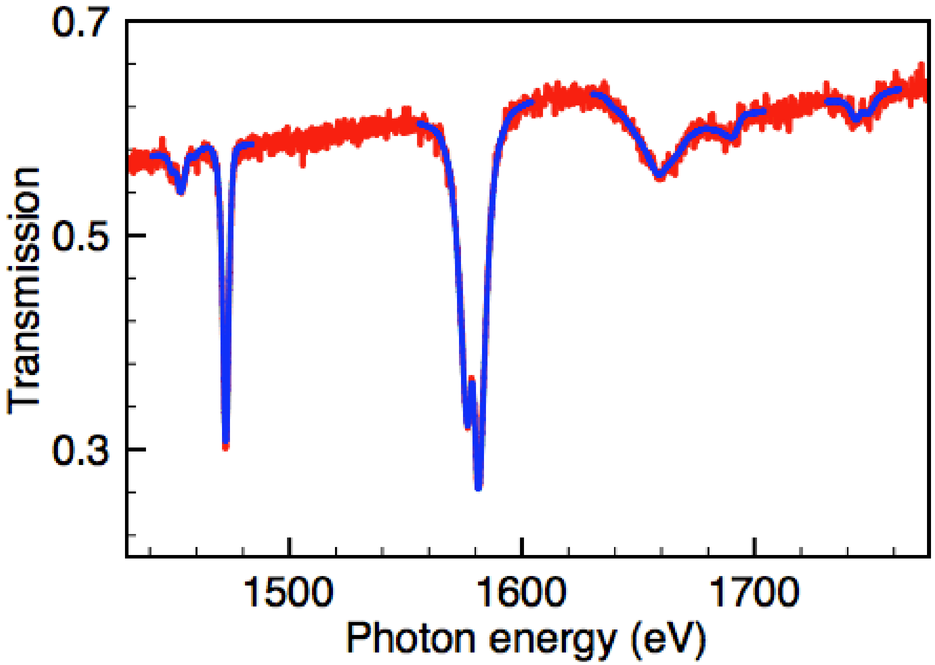


How does χ^2 deteriorates due to non-uniformity?

χ^2

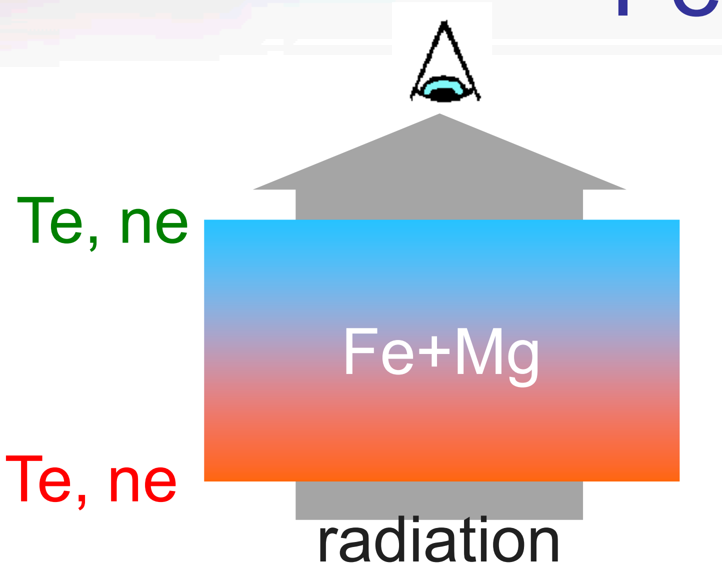


Fits for 25% non-uniformity



- Uniform model with the sample average can provide good fits even if there is a non-uniformity

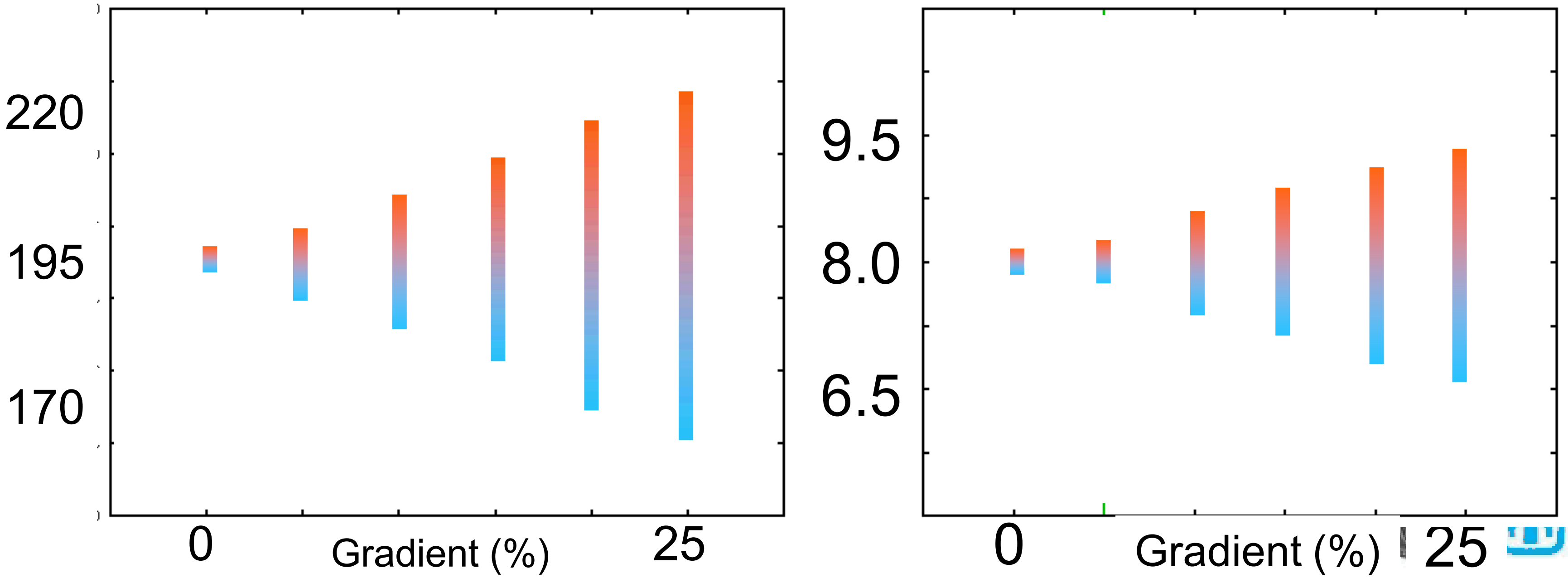
How does the gradient model work for Fe+Mg sample?



Gradient model calculation

1. For given condition on both sides, compute linear gradient
2. Numerically integrate radiation transport for mixture of Fe and Mg

PGALM+Gradient model finds (Te, ne) and (Te, ne) that optimize the fits



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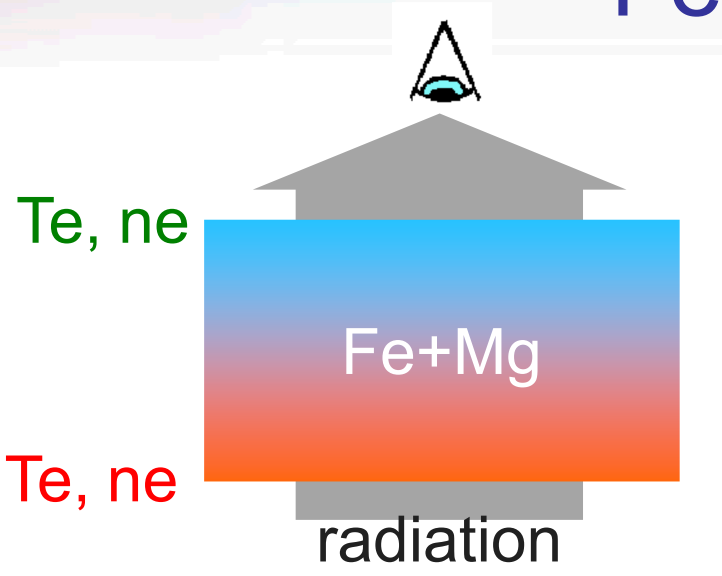

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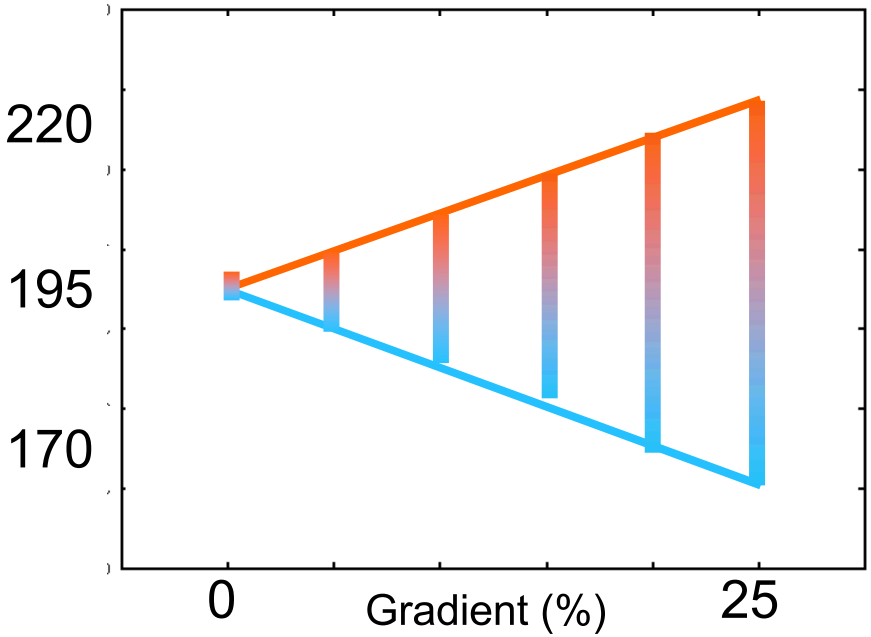
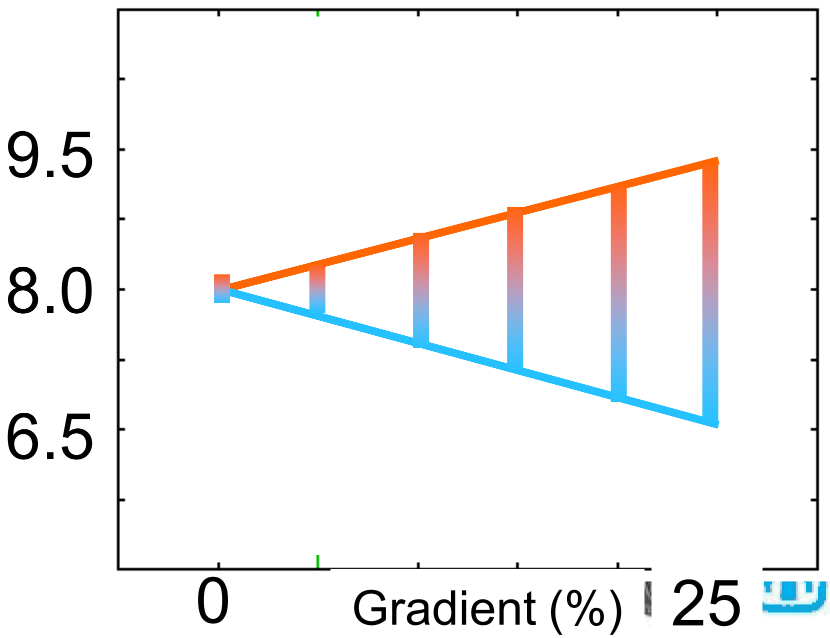
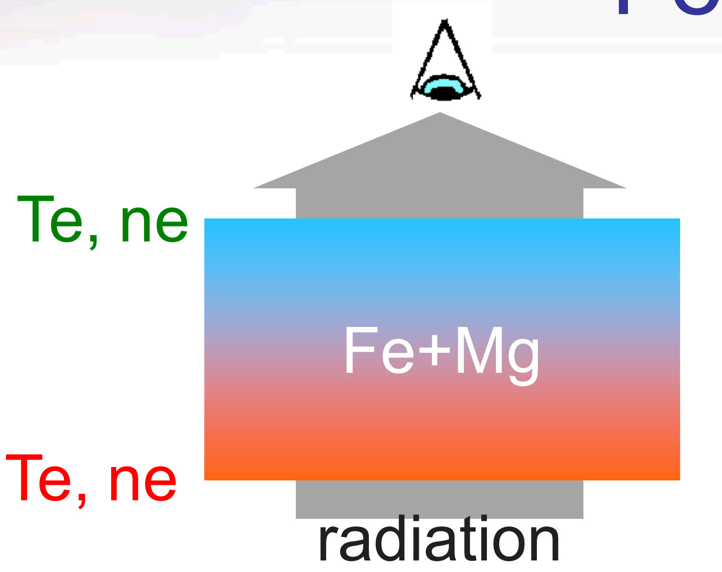




How does the gradient model work for Fe+Mg sample?



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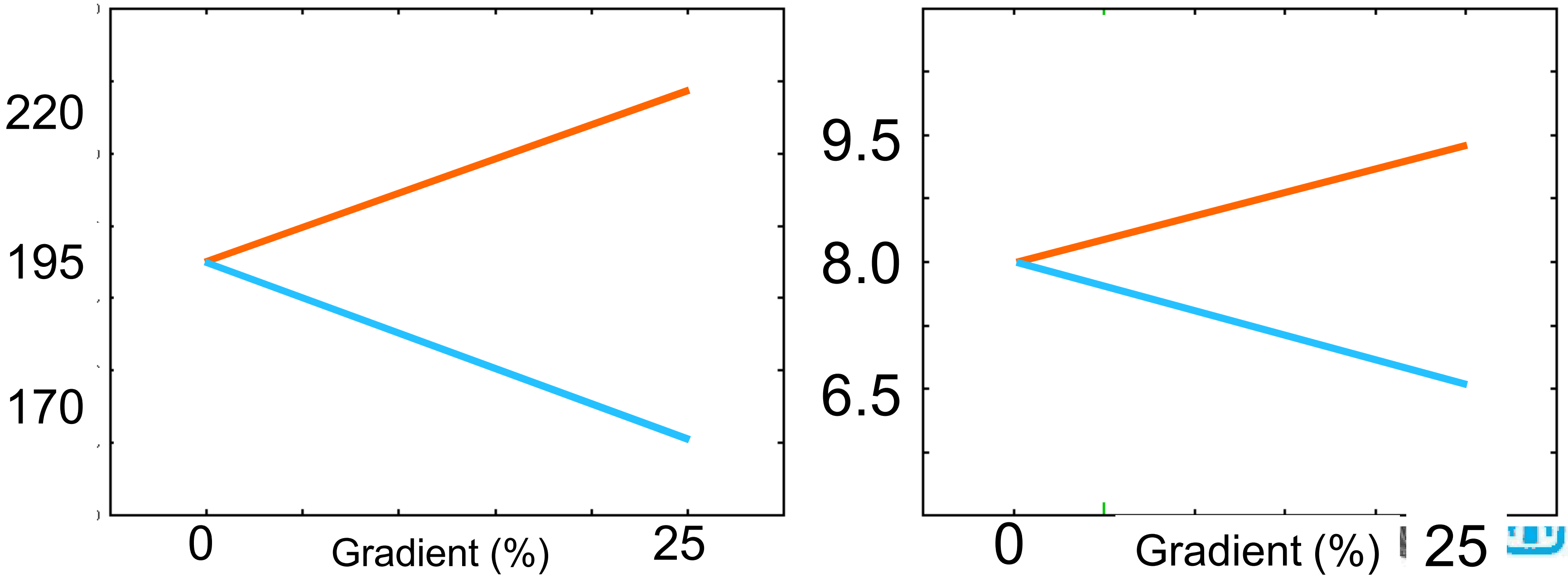
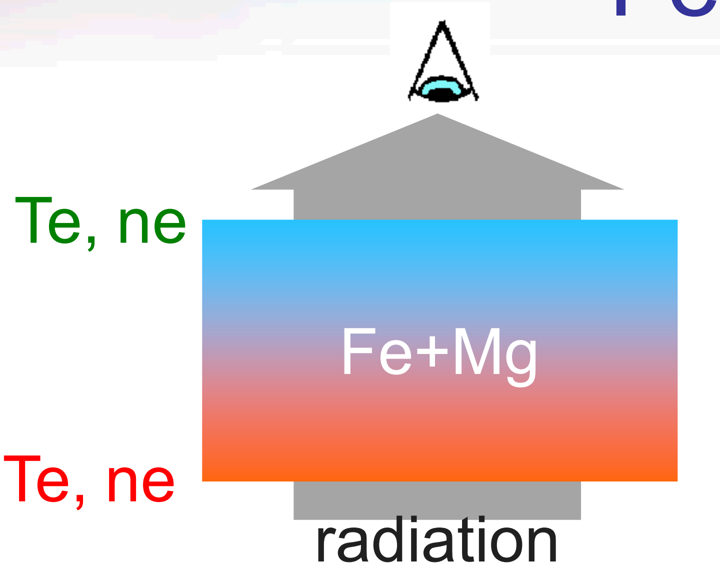


How does the gradient model work for Fe+Mg sample?



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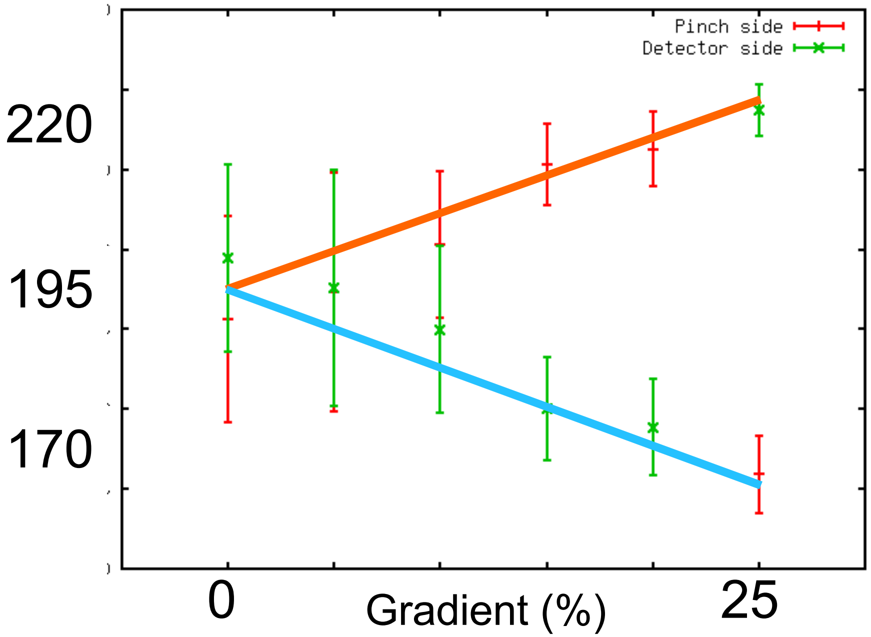
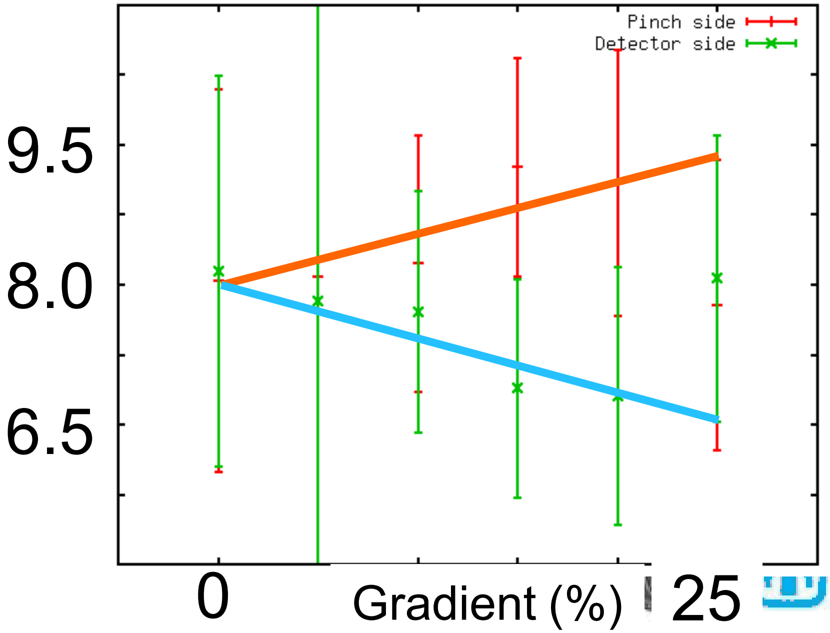
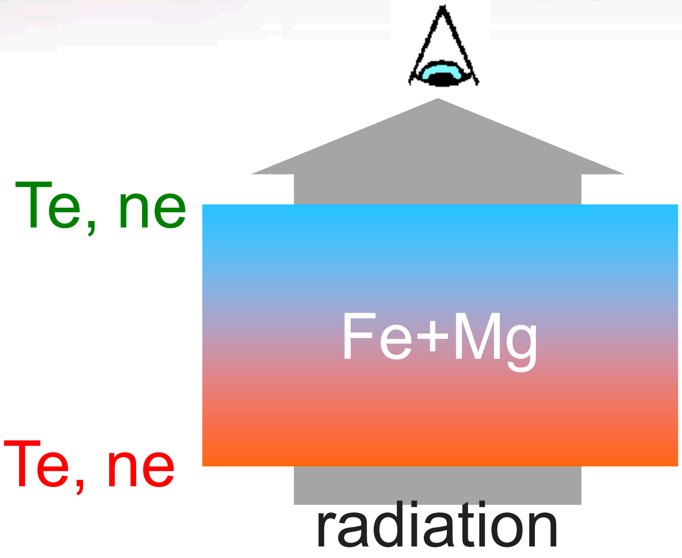




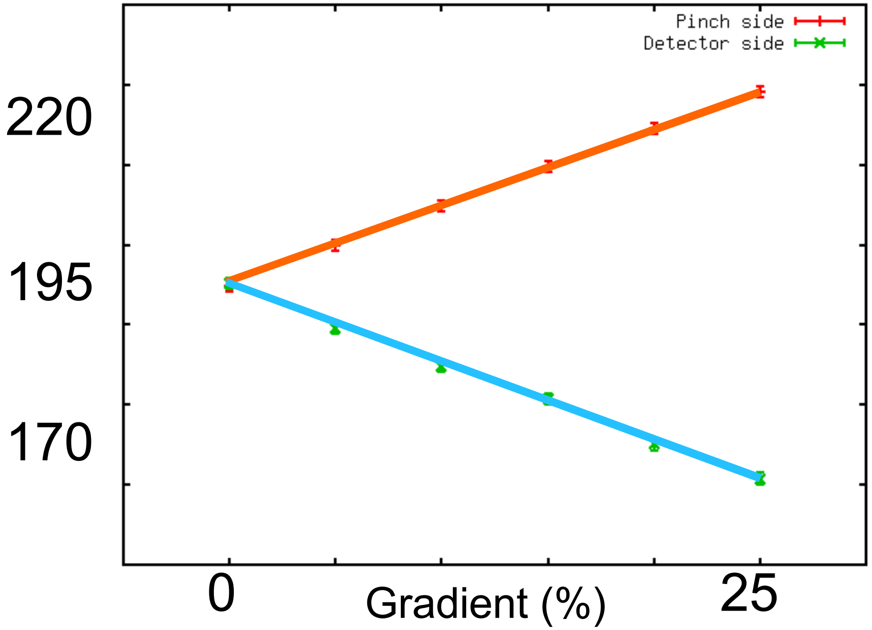
How does the gradient model work for Al+Fe+Mg sample?

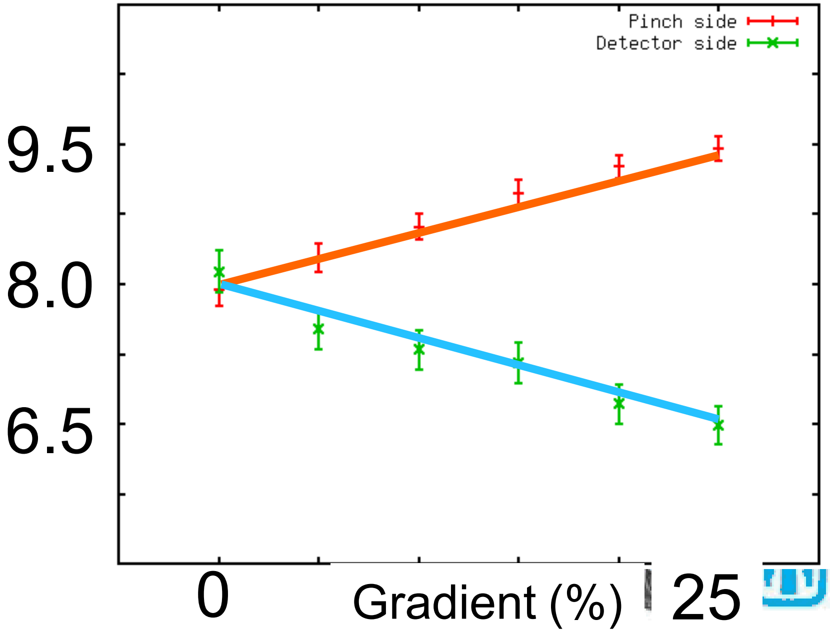


Gradient model calculation

1. For given condition on both sides, compute linear gradient
2. Numerically integrate radiation transport for mixture of Al+Fe+Mg

PGALM+Gradient model finds (Te, ne) and (Te, ne) that optimize the fits

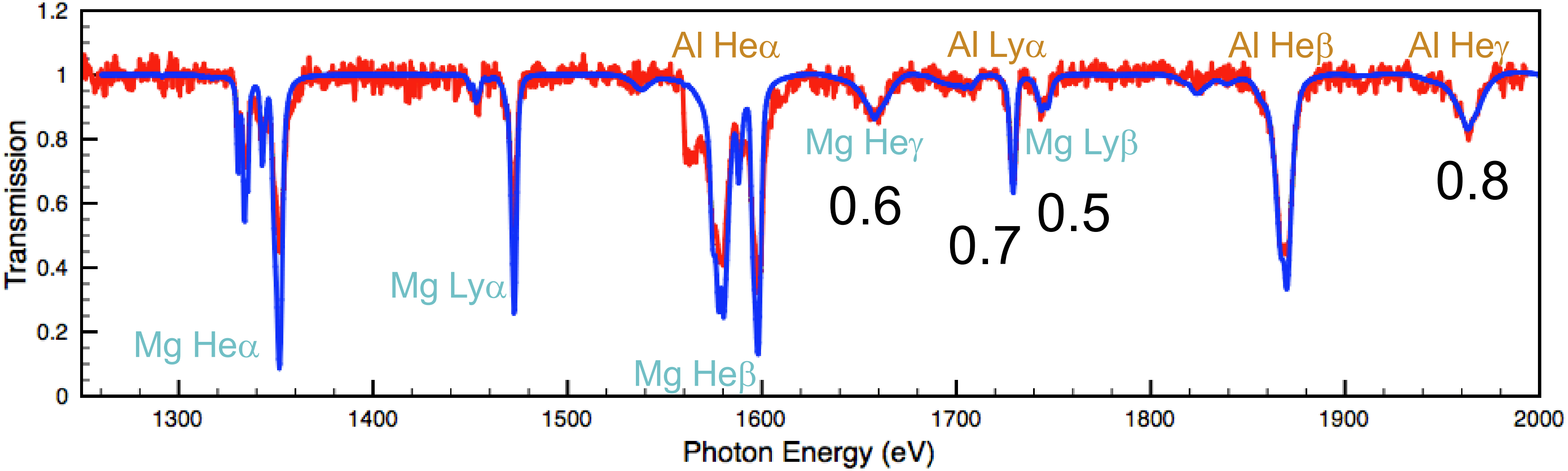




Summary of synthetic study on non-uniformity analysis

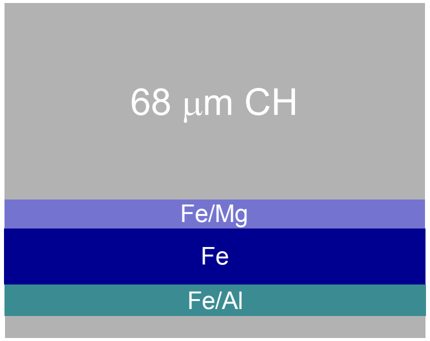
- Uniform model can fit data through non-uniform condition with average conditions
- Gradient model on Fe+Mg sample
  - Average density is reliable
  - Te gradient could be extracted when gradient is larger than 10%, but fails to find gradient direction
- Gradient model on Al+Fe+Mg sample
  - Find gradient very precisely

Direct uniformity measurement confirmed there is no gradient within the experimental uncertainties



- Al Lyα and Heγ and Mg Lyβ and Heγ are simultaneously fit.

- Weaker lines are fit very well
- All stronger lines are heavily saturated



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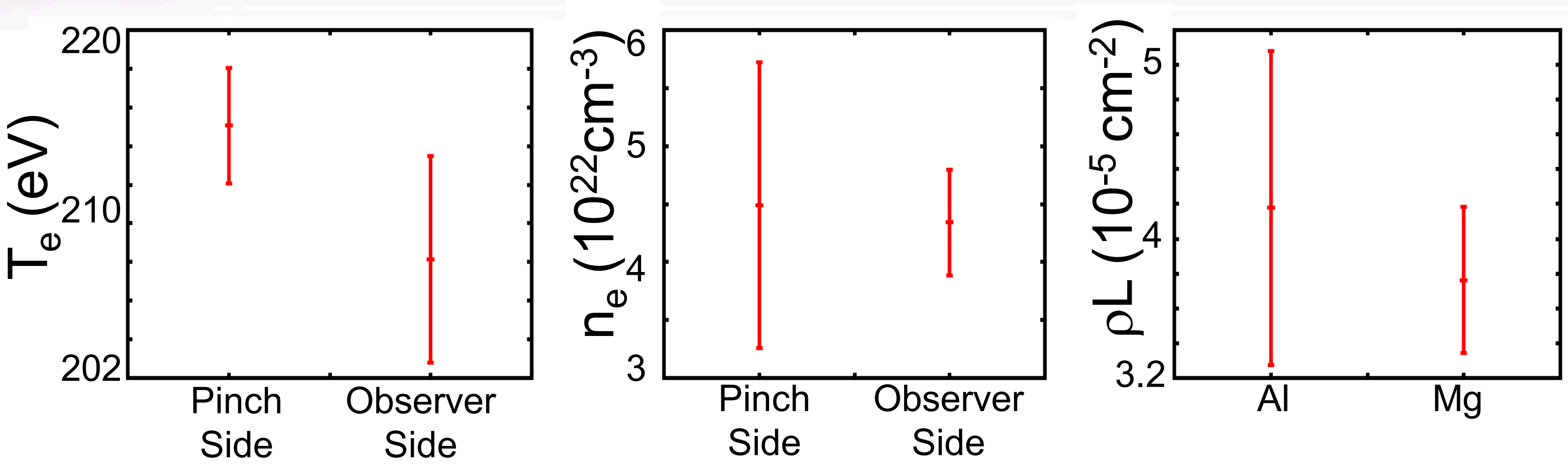
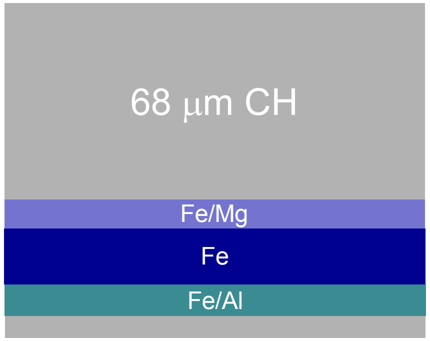


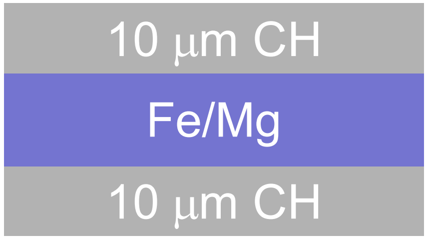
	Te	Ne (10^{22} cm^{-3})	rL (10^{-5} g/cm^{-2})
Pinch side	215±3	4.49±1.23	3.78±0.90
Obs. side	208±5	4.34±0.46	3.36±0.42



- Temperature turned out to be somewhat higher than other thick target cases
- Inferred areal densities are about 80% of RBS measurement (81% for Mg, 79% for Al)

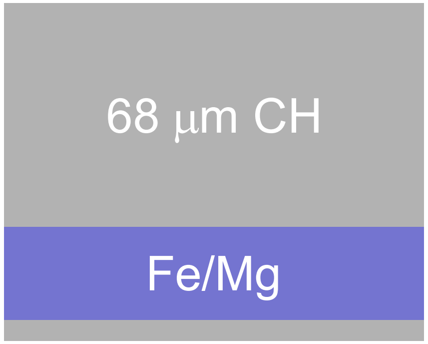
Summary and future work

Sample1: Low density



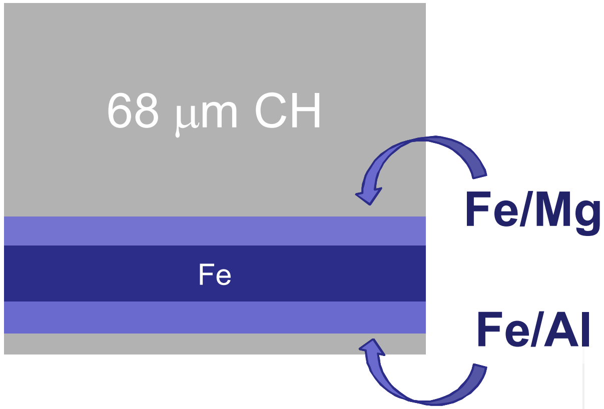
- T_e=164±5 eV
- n_e=(7.91±1.92)x10^{21}

Sample2: High density



- T_e=195±6 eV
- n_e=(4.44±1.55)x10^{22}

Sample3: Uniformity



=======Mg========

- T_e=208±5 eV
- n_e=(4.34±0.46)x10^{22}

======= Al ========

- T_e=215±3 eV
- n_e=(4.49±1.23)x10^{22}

- We inferred Te and ne by fitting weaker lines
- This method is insensitive to possible additional background

- Future work:
  - Iron opacity modeling with the inferred conditions
  - Investigate possible background

Conclusions

Sandia
National
Laboratories