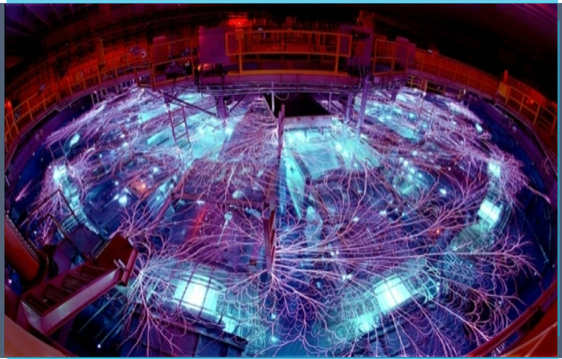
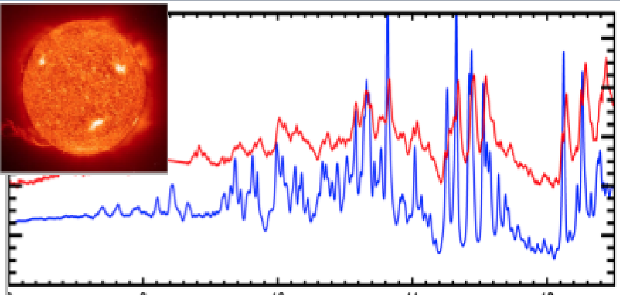
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

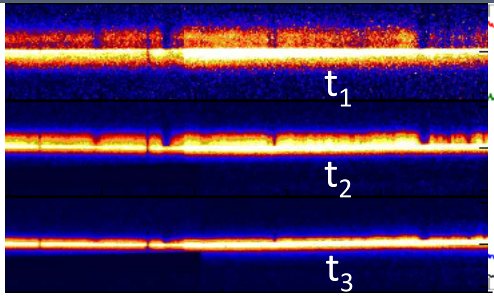
SAND2022-15835C

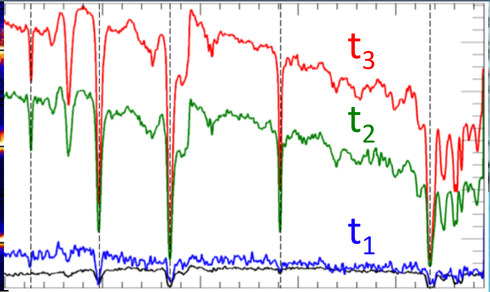
Sandia National Laboratories

Transforming the opacity science on Z using novel time-resolved spectroscopy









PRESENTED BY

Guillaume Loisel for the Z opacity team

RPHDM 2022
Nov. 14-18 2022
Santa Fe, NM, USA

U.S. DEPARTMENT OF ENERGY NNSA

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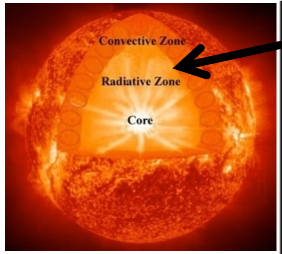
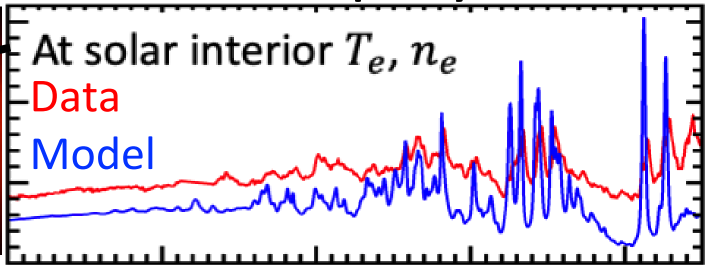
Executive summary: Time-resolution transforms opacity research on Z to advance HED physics and astrophysics

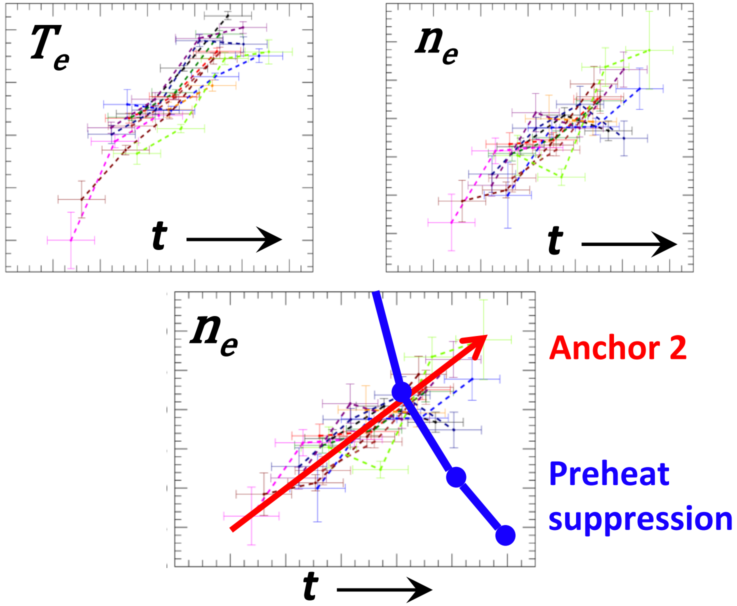
- **The solar problem still exists**
  - → Helioseismology ≠ solar models predictions
- **Fe L-shell opacity was measured at solar interior conditions and revealed severe model-data discrepancy**
- **While theoretical refinements are studied, experimental scrutiny is underway**
  - → test of time-dependent effects
- **Opacity sample evolution was measured using novel UXI technology**
  - → Challenge our picture of how the experiment works
- **Time-resolved measurements also increase knowledge and parameter space of the Z opacity platform**
  - →Preheat suppression test shows path for novel high density regime
- **Temporal gradient effect are synthetically investigated**
- **Absolute time-resolved opacity measurements are underway**

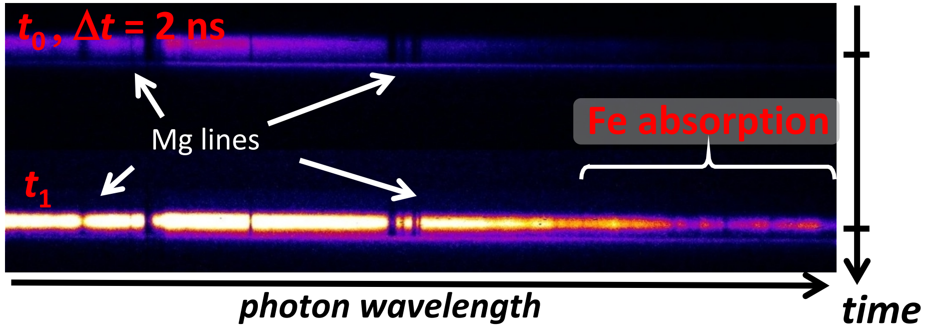
Anchor 2 Fe opacity





Anchor 2 Fe evolution





The stellar opacity collaboration involves universities, a private company, U.S. national labs, the French CEA, and the Israeli NRCN laboratories

J.E. Bailey, T. Nagayama, G.P. Loisel, G.A. Rochau, S.B. Hansen, G.S. Dunham, R. More, T.A. Gomez
P. D. Gard, A. P. Colombo, A. D. Edens, R. Speas, Q. Looker, M. Kimmel, J. Stahoviak, J. L. Porter
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French Alternative Energies and Atomic Energy Commission (CEA)

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J. Colgan, C. Fontes, D. Kilcrease, and M. Sherrill
Los Alamos National Laboratory

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University of Nevada – Reno

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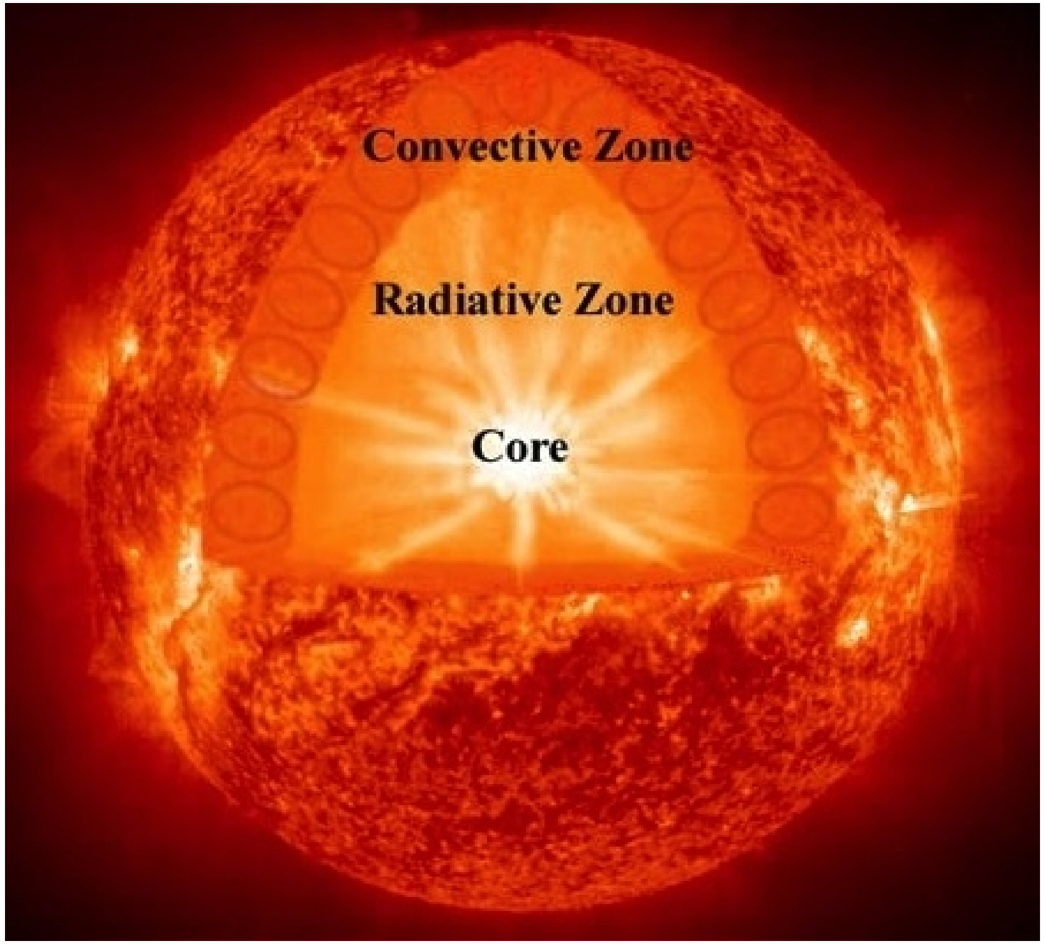
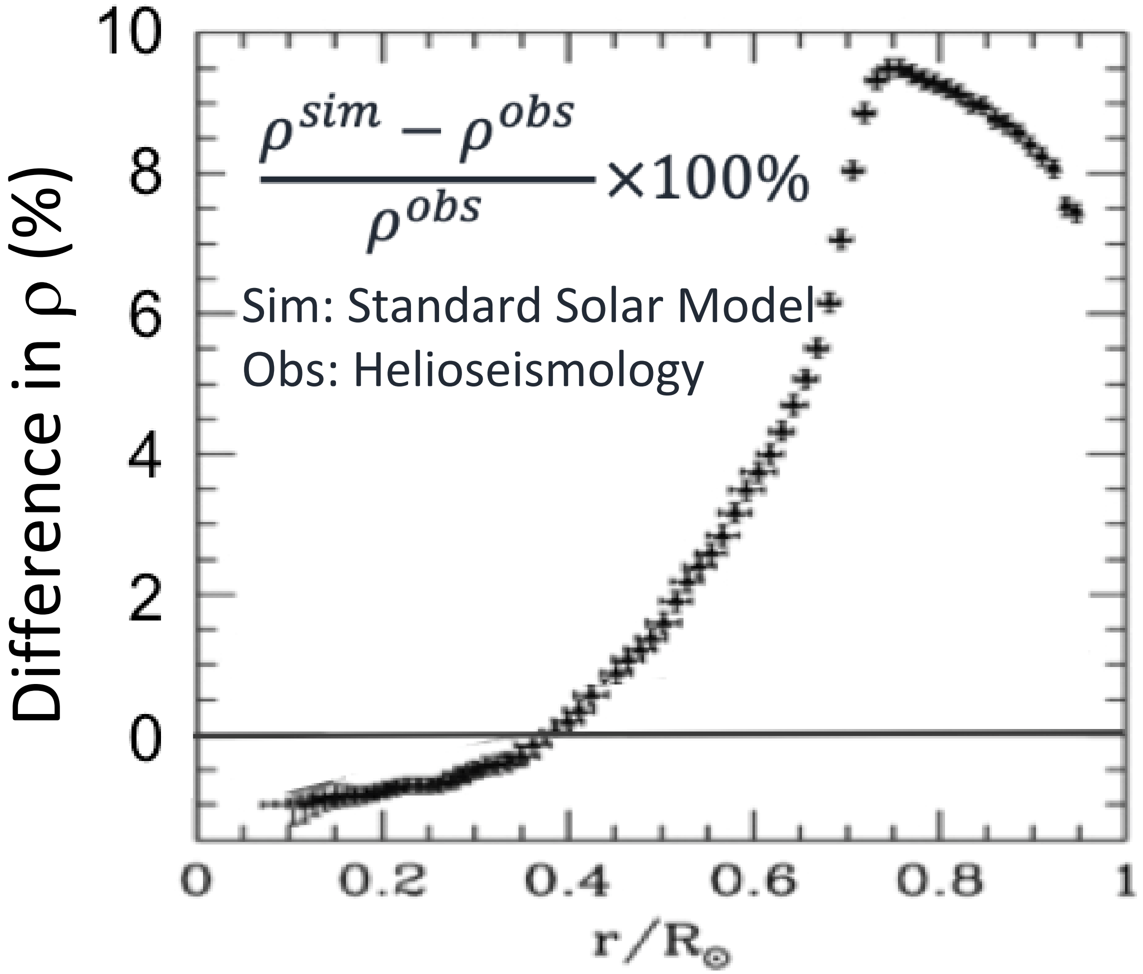
Prism Computational Sciences

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

Solar structure simulated by Standard Solar Model disagrees with helioseismic measurements [1]





[1] Basu, S. & Antia, H. M. *Physics Reports* 457, 217–283 (2008)

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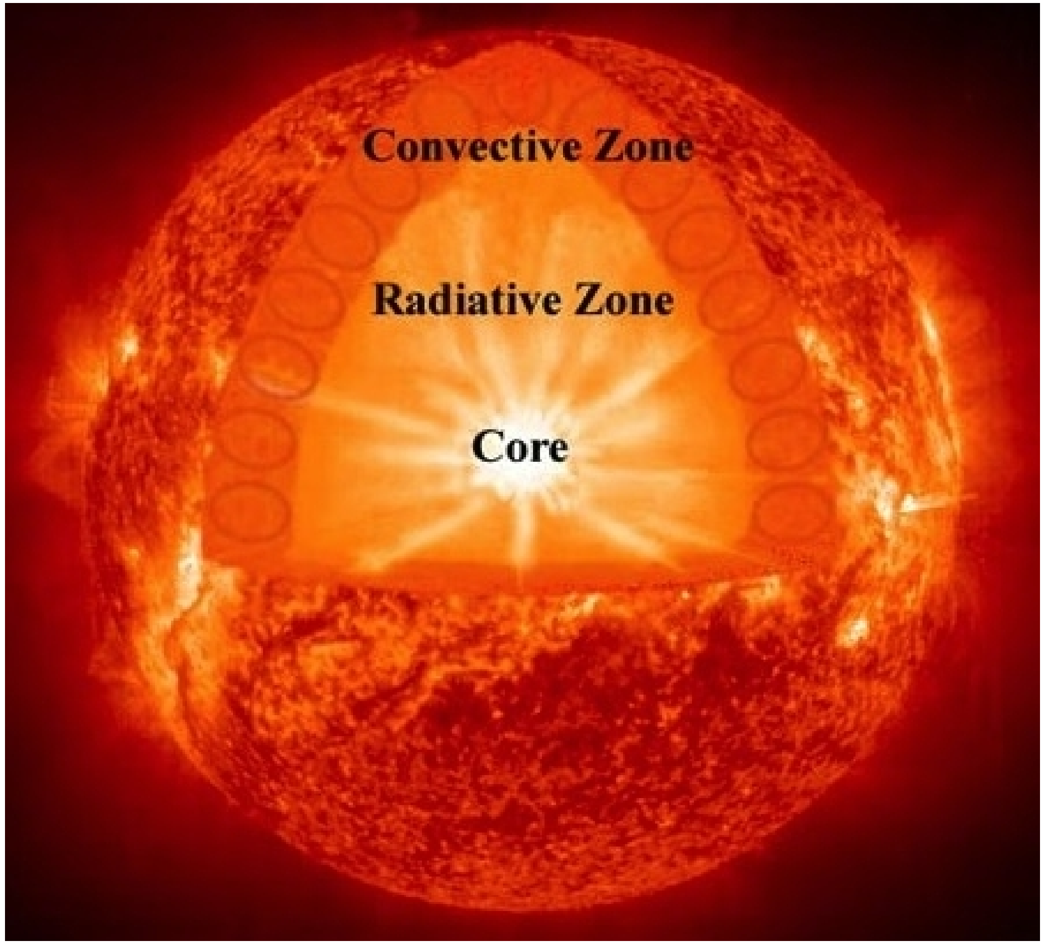

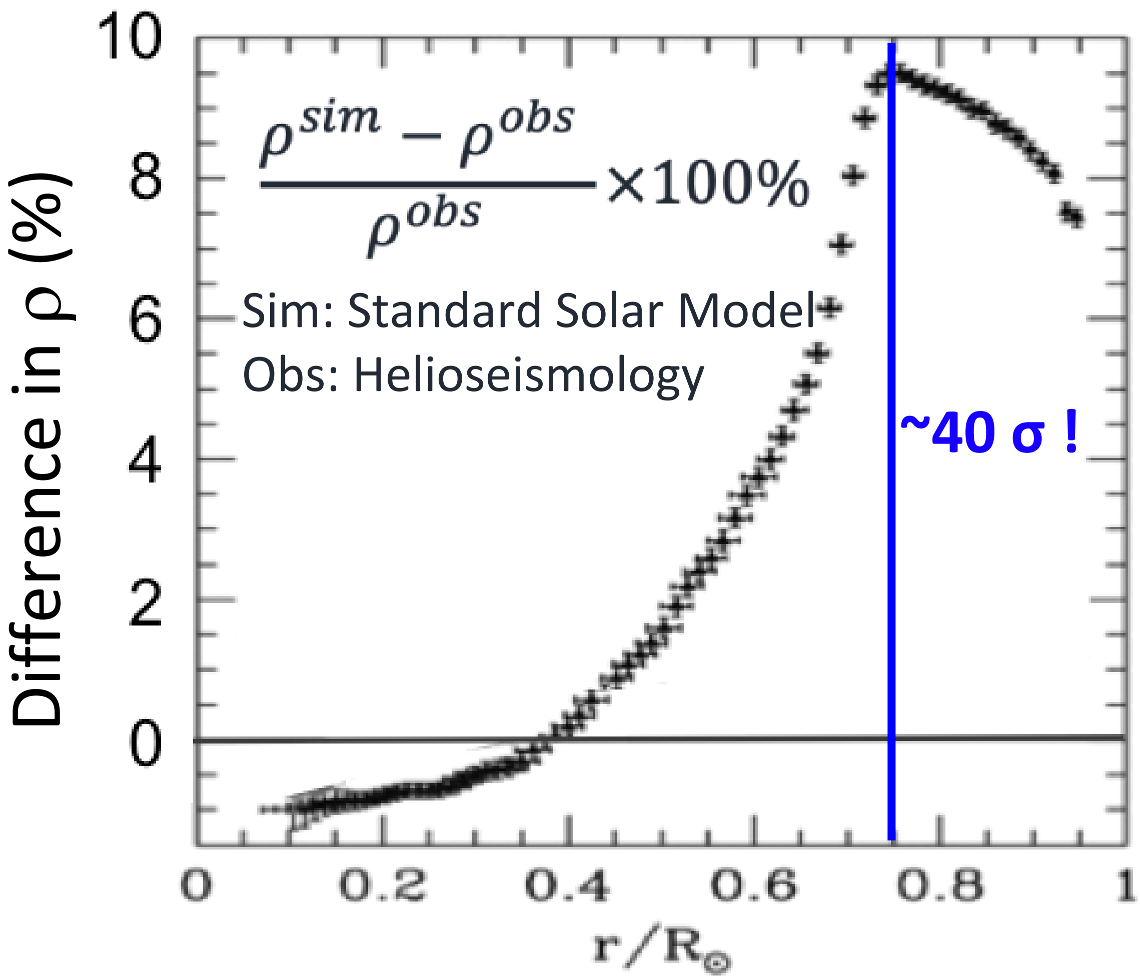

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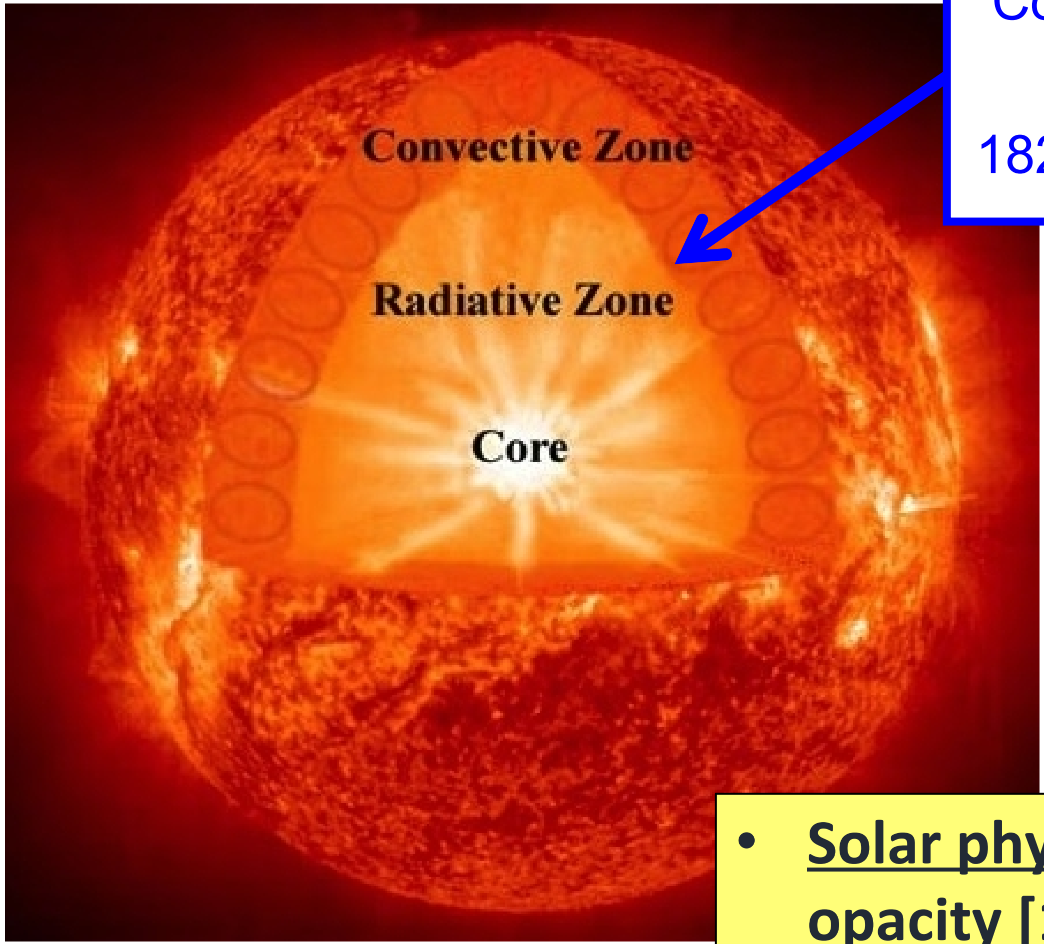
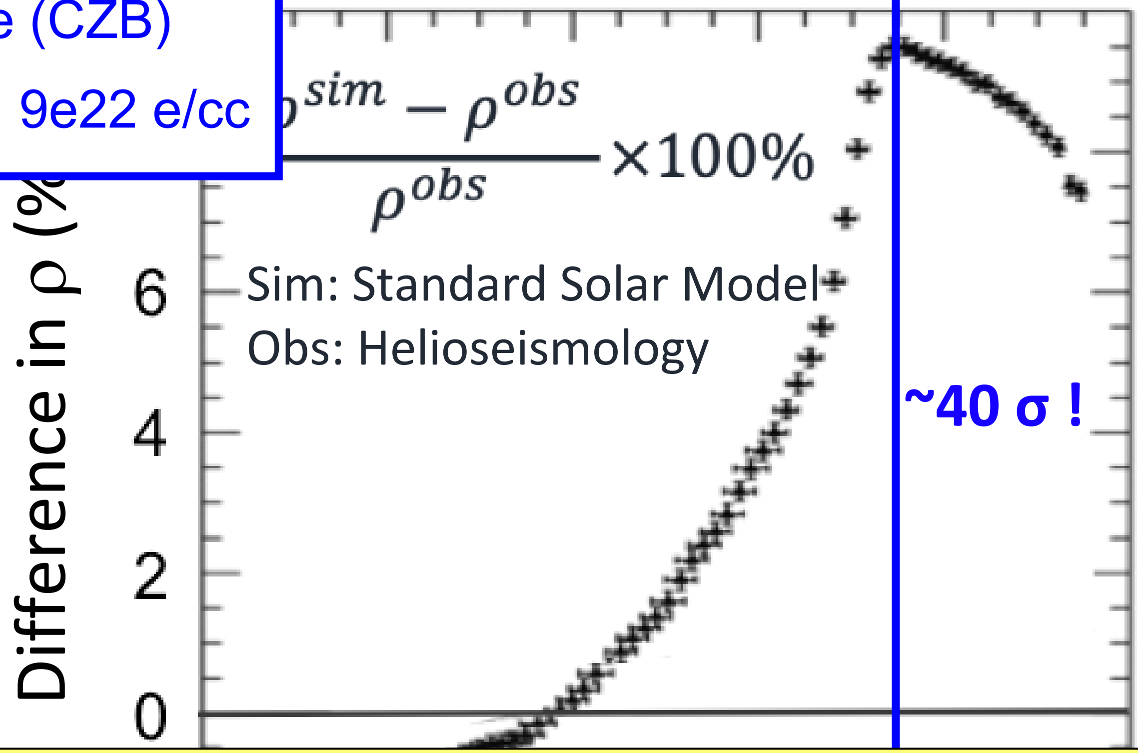
Is the decade-old solar problem caused by inaccuracy of modeled opacity?



Convection zone base (CZB)

182 eV, 9e22 e/cc



- **<u>Solar physicists:</u> solar models need 10-30% higher mean opacity [1]**
- **<u>Hypothesis:</u> Iron opacity calculated at CZB is underestimated**

[1] Basu, S. & Antia, H. M. *Physics Reports* 457, 217–283 (2008)

[2] C. Blancard et al., *ApJ.* 745, 10 (2012)

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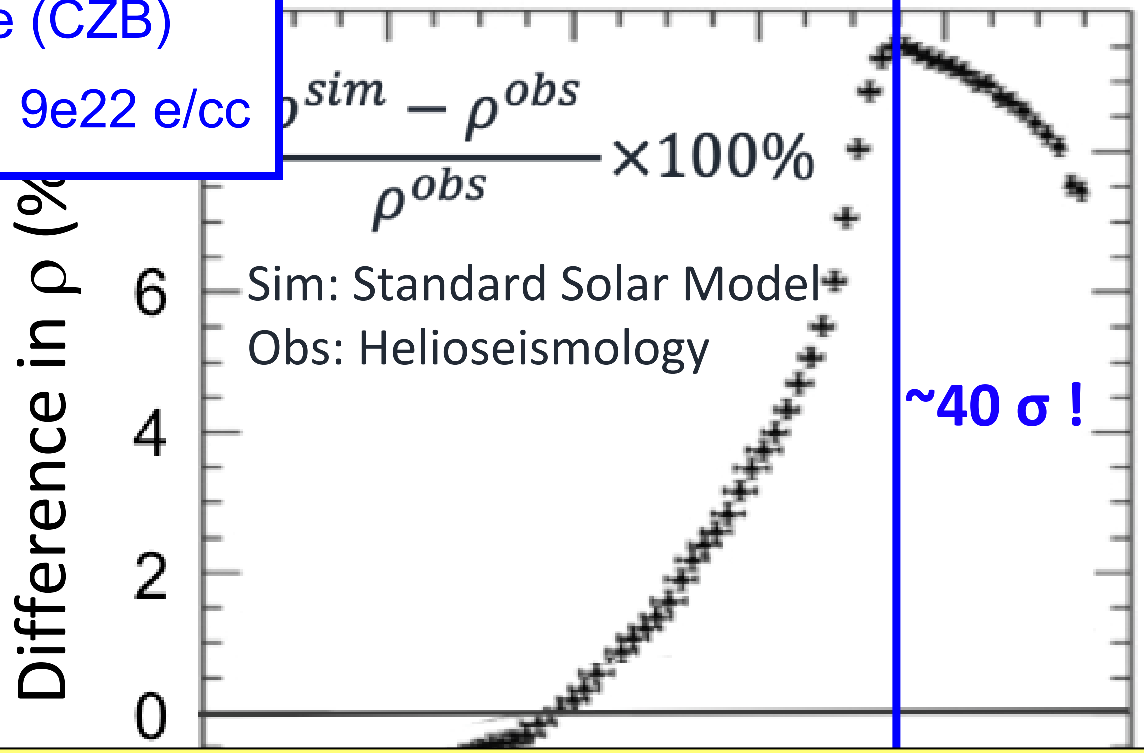

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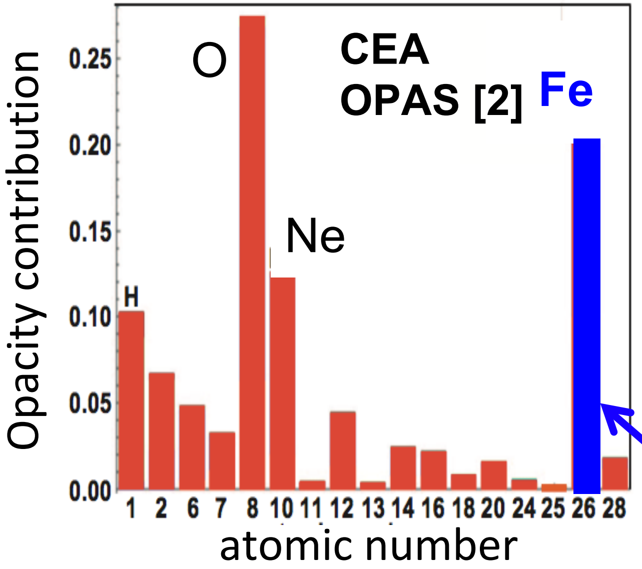

Fe is second largest opacity source at CZB

[1] Basu, S. & Antia, H. M. *Physics Reports* 457, 217–283 (2008)

[2] C. Blancard et al., *ApJ.* 745, 10 (2012)

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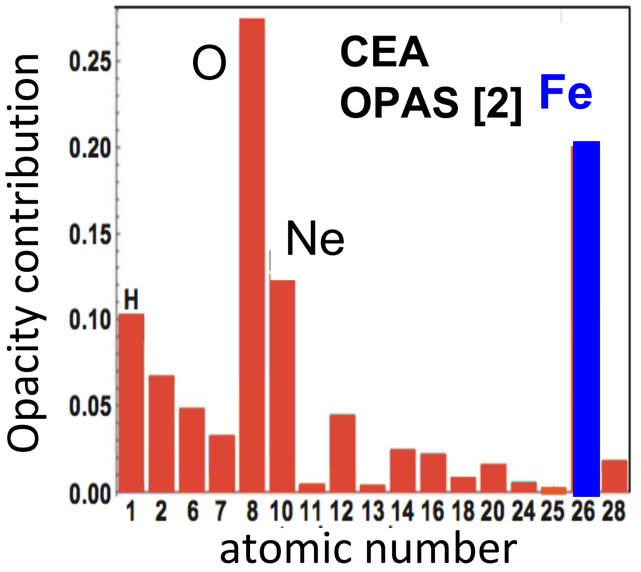
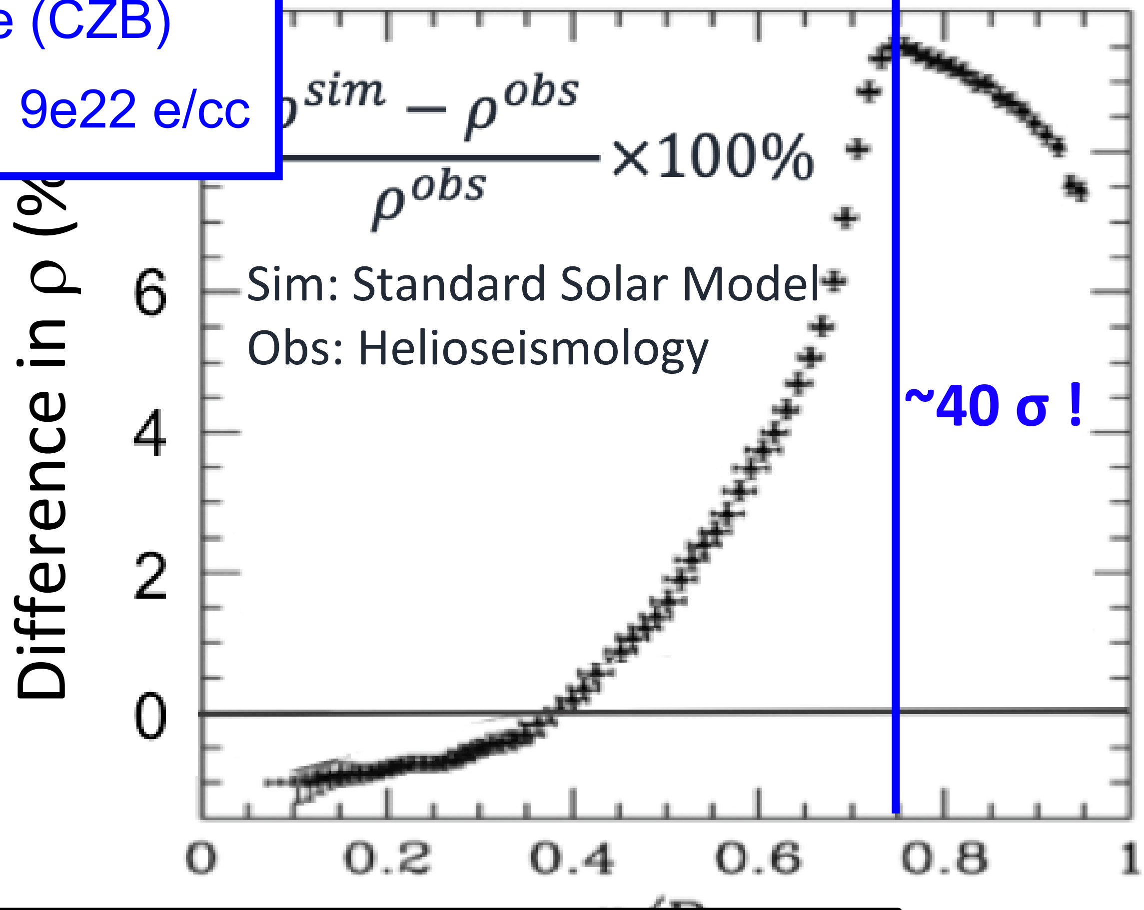


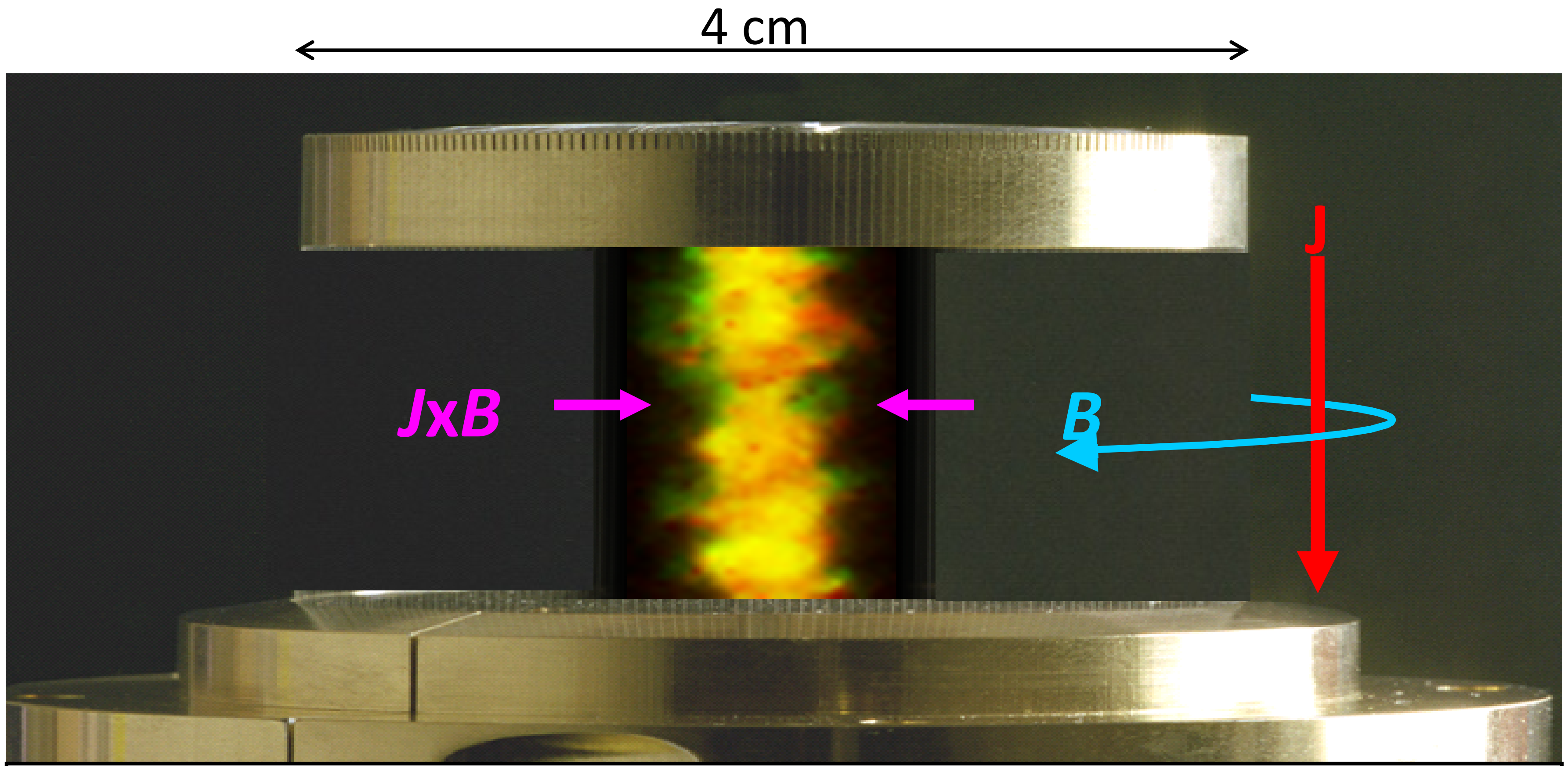


We used the most powerful x-ray generator Z to measure Fe opacity near CZB conditions

[1] Basu, S. & Antia, H. M. *Physics Reports* 457, 217–283 (2008)

[2] C. Blancard et al., *ApJ.* 745, 10 (2012)

The Z machine uses 27 million Amperes to create x-rays



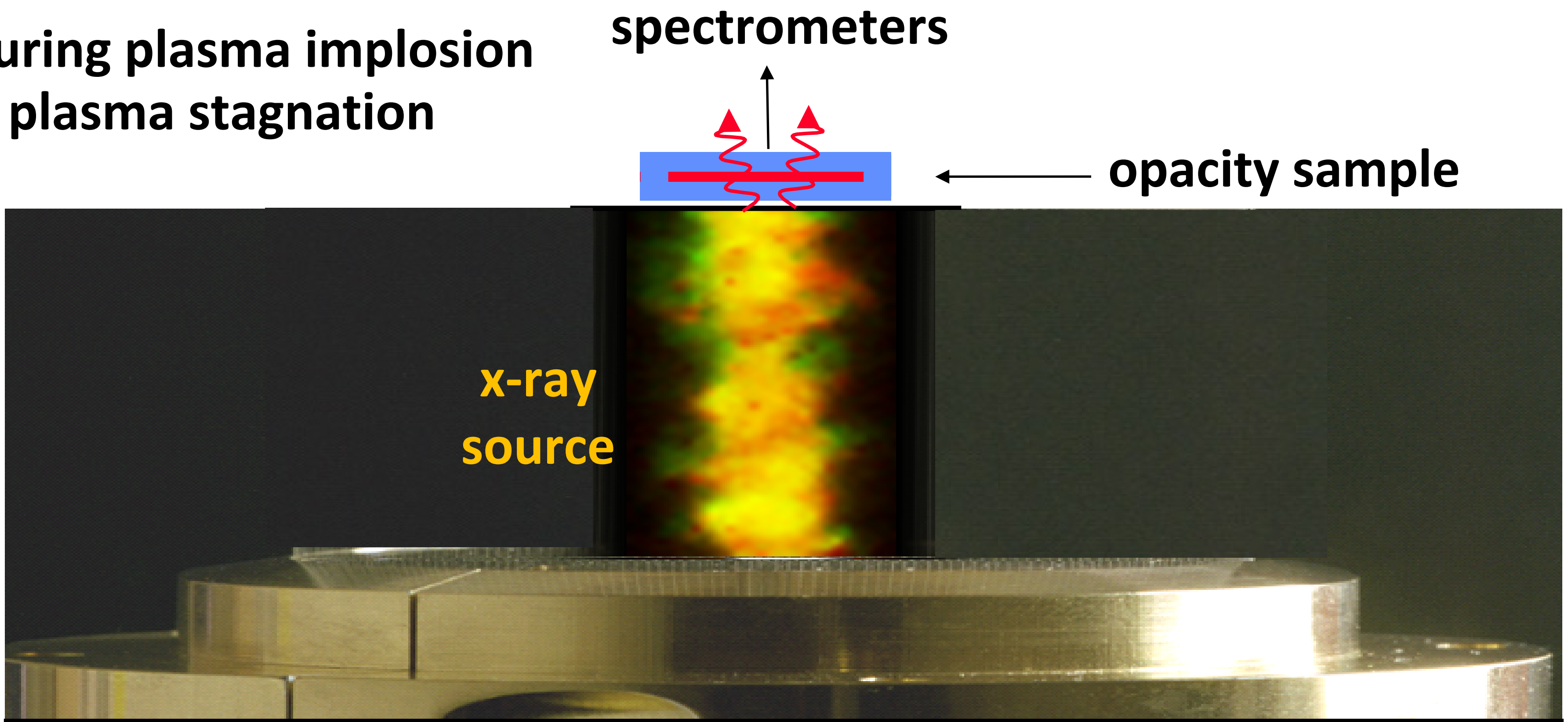
P_{rad} ~ 220TW (±10%), Y_{rad} ~ 1.6 MJ (±7%)

Sanford, PoP (2002); Bailey et al., PoP (2006); Slutz et al., PoP (2006); Rochau et al., PPCF (2007)

The Z x-ray source both heats and backlights samples to stellar interior conditions

<u>Sample is:</u>

- Heated during plasma implosion
- Backlit at plasma stagnation



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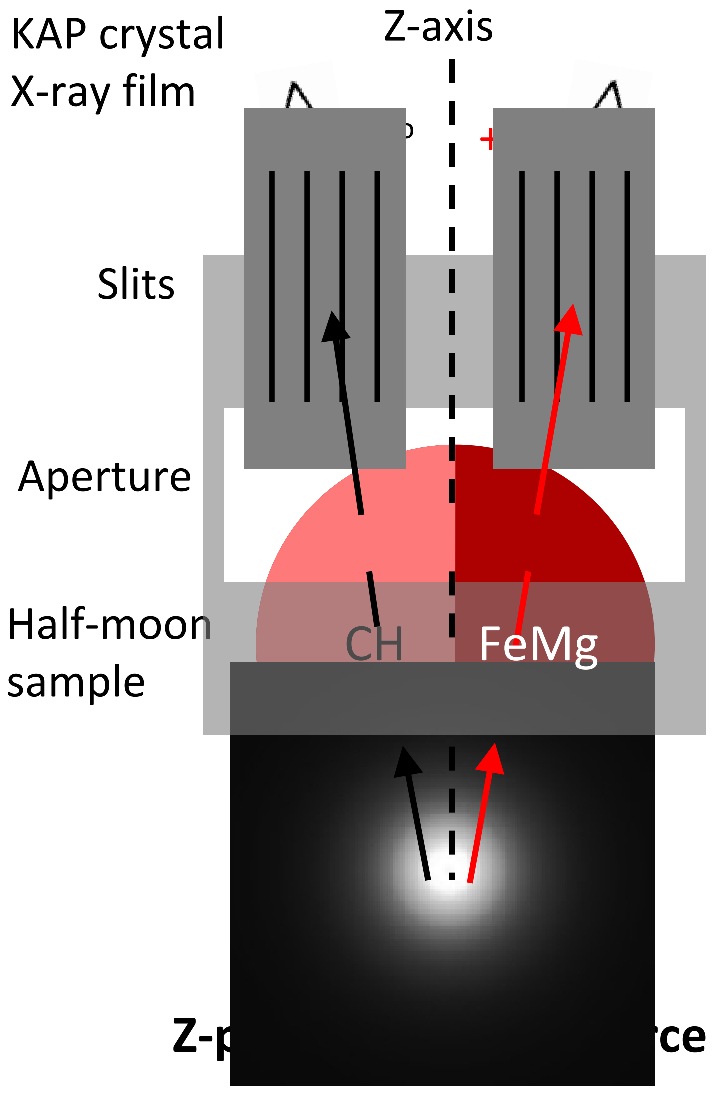
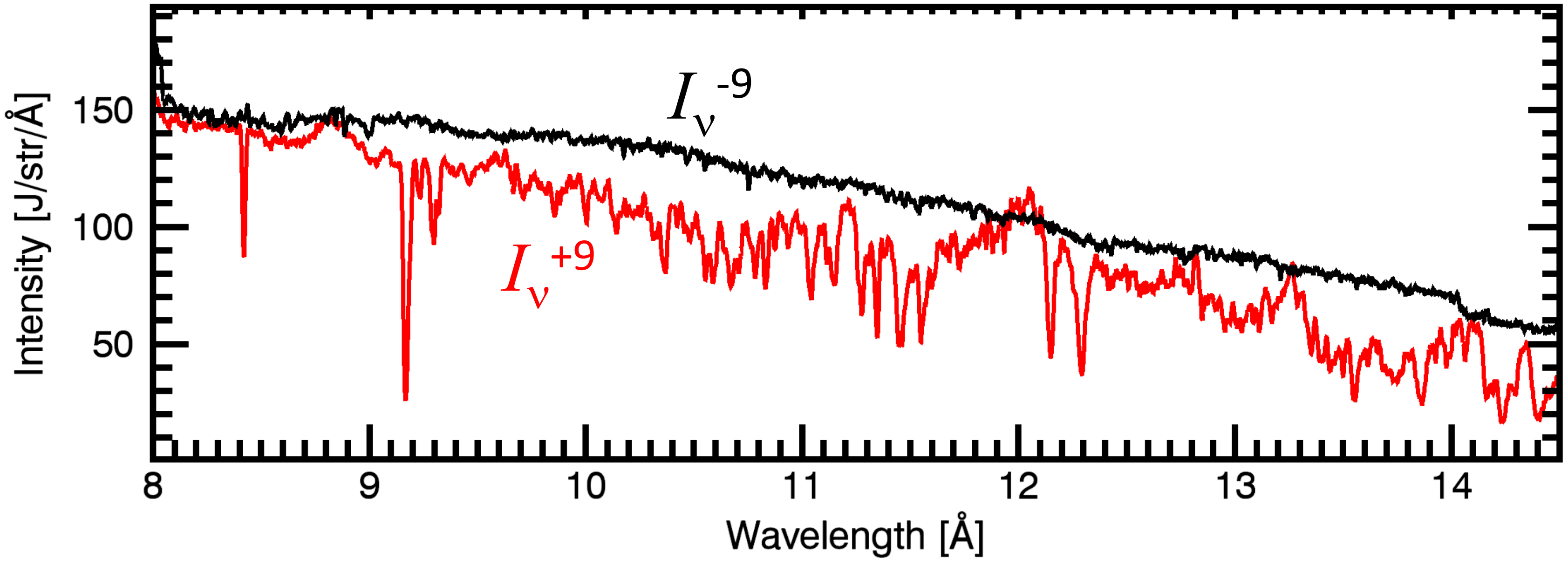
High-temperature Fe opacities are measured using the Z-Pinch opacity science platform





Requirements	SNL Z satisfies:
• Uniform heating →	Volumetric heating
• Mitigating self emission →	350 eV Planckian backlight (>> 200eV sample self-emission)
• Condition measurements	
• Checking reproducibility	

[1] Bailey et al., Phys Plasmas 16, 058101 (2009)
[2] Nagayama et al., Phys Plasmas 21, 056502 (2014)

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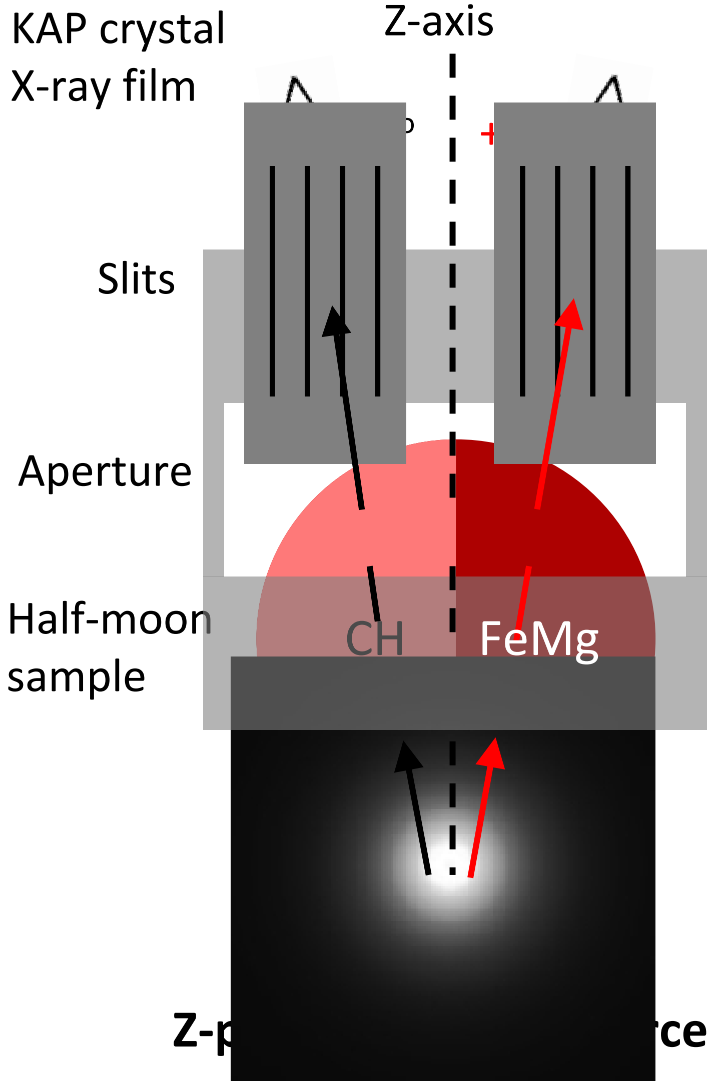

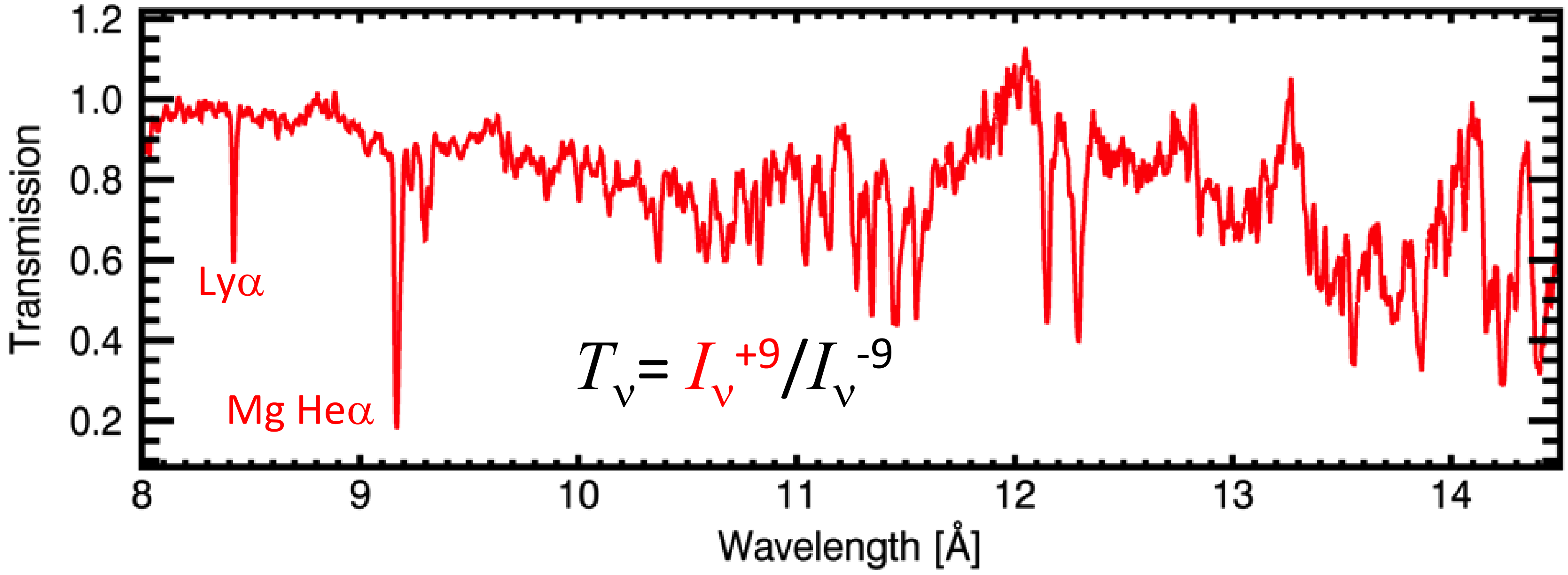

Requirements		SNL Z satisfies:
• Uniform heating	→	Volumetric heating
• Mitigating self emission	→	350 eV Planckian backlight
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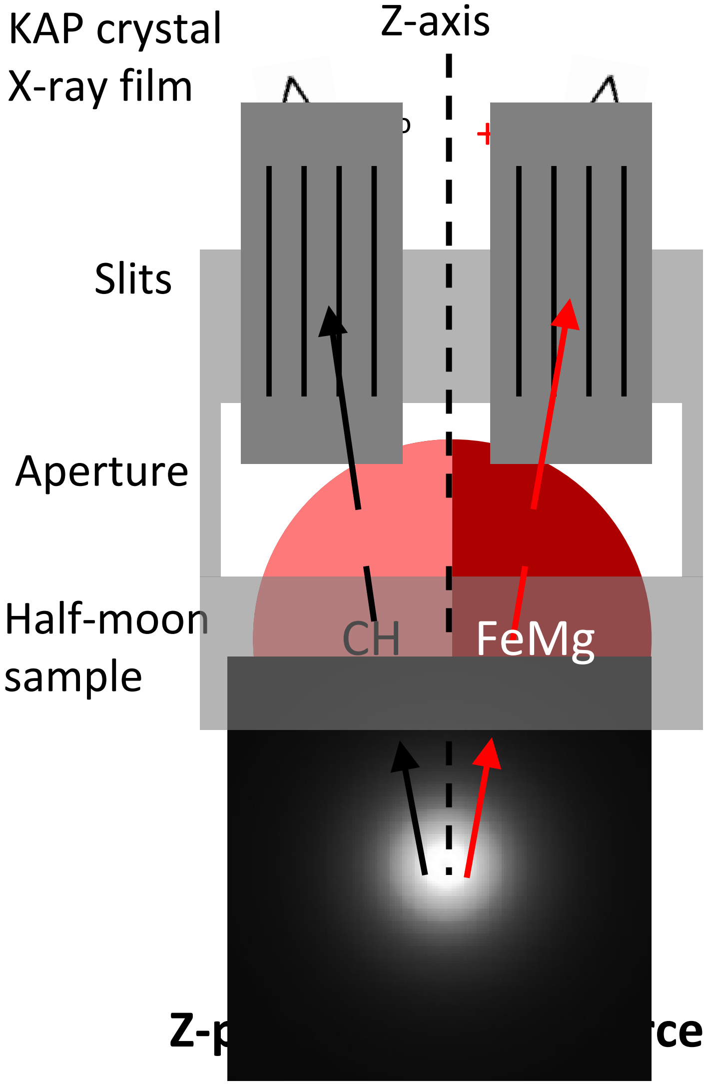

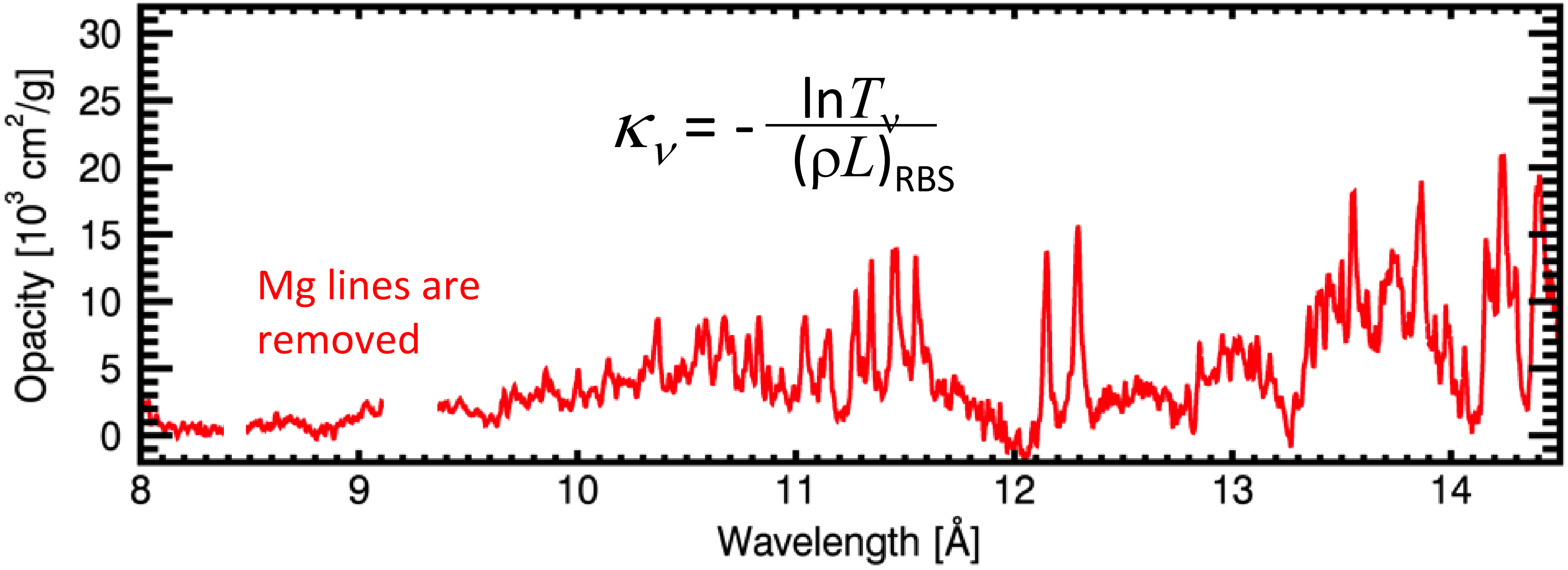

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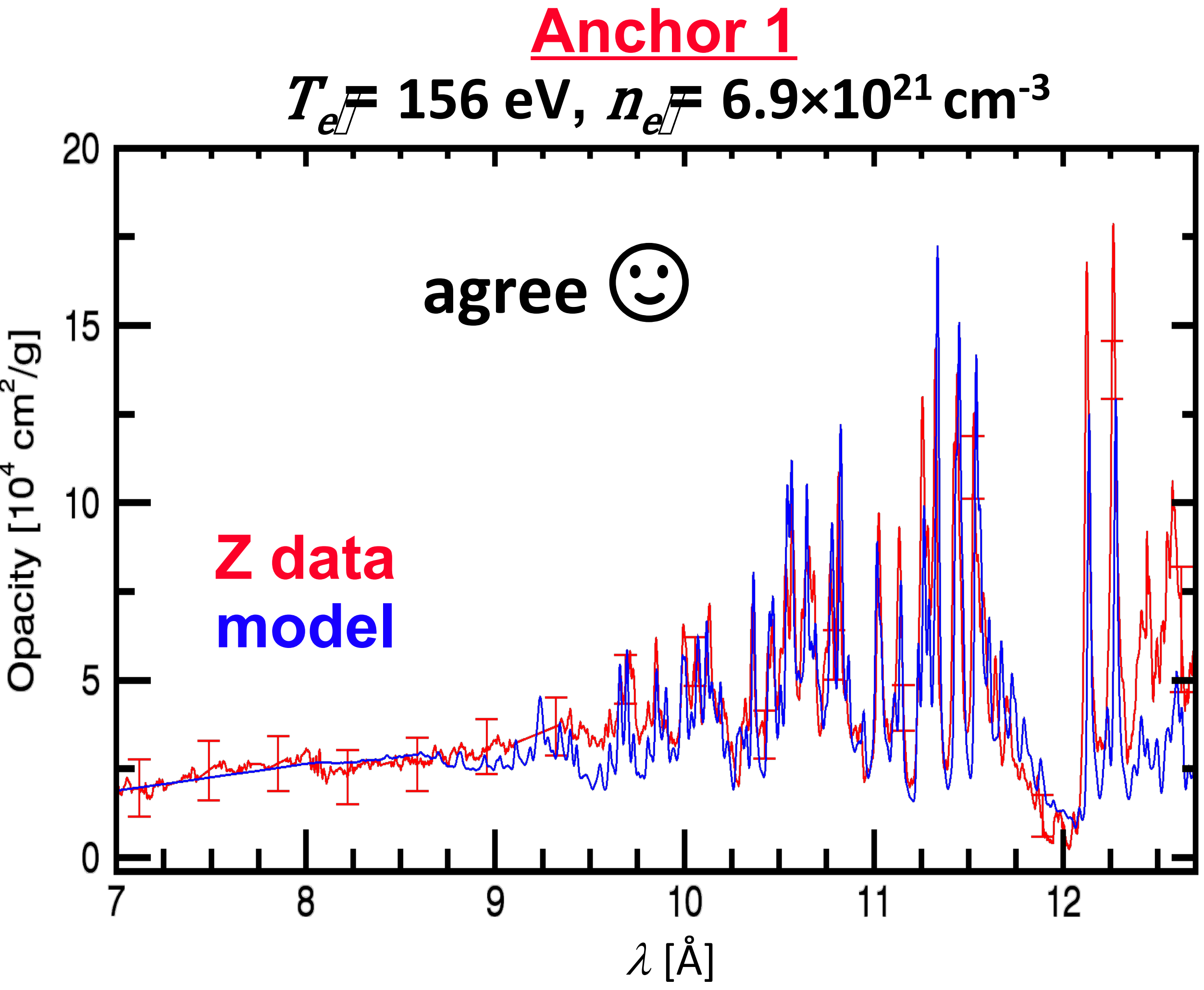
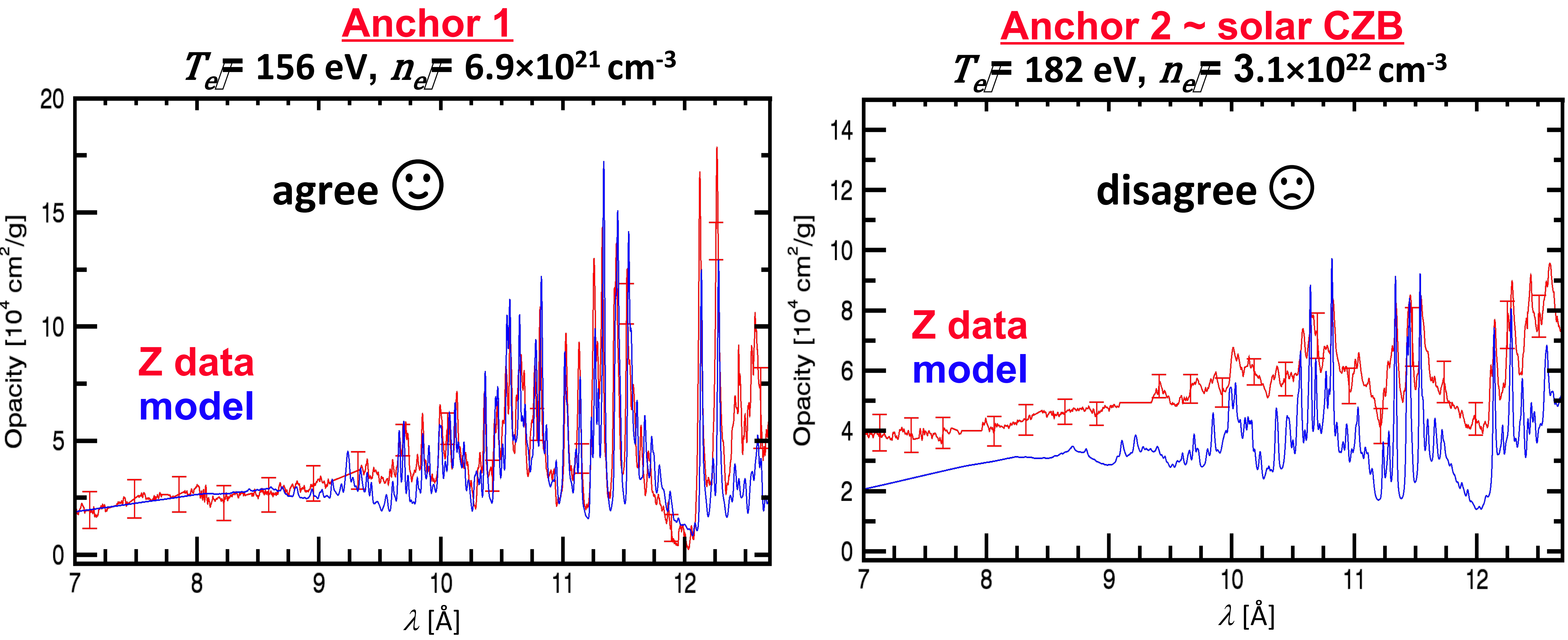
Modern best-effort models agree very well with the Z iron data at T_e ~ 156 eV, n_e=7x10^{21} cm^{-3}



Bailey *et al.*, *PRL*, **99**, (2007)

… but disagree at near CZB conditions



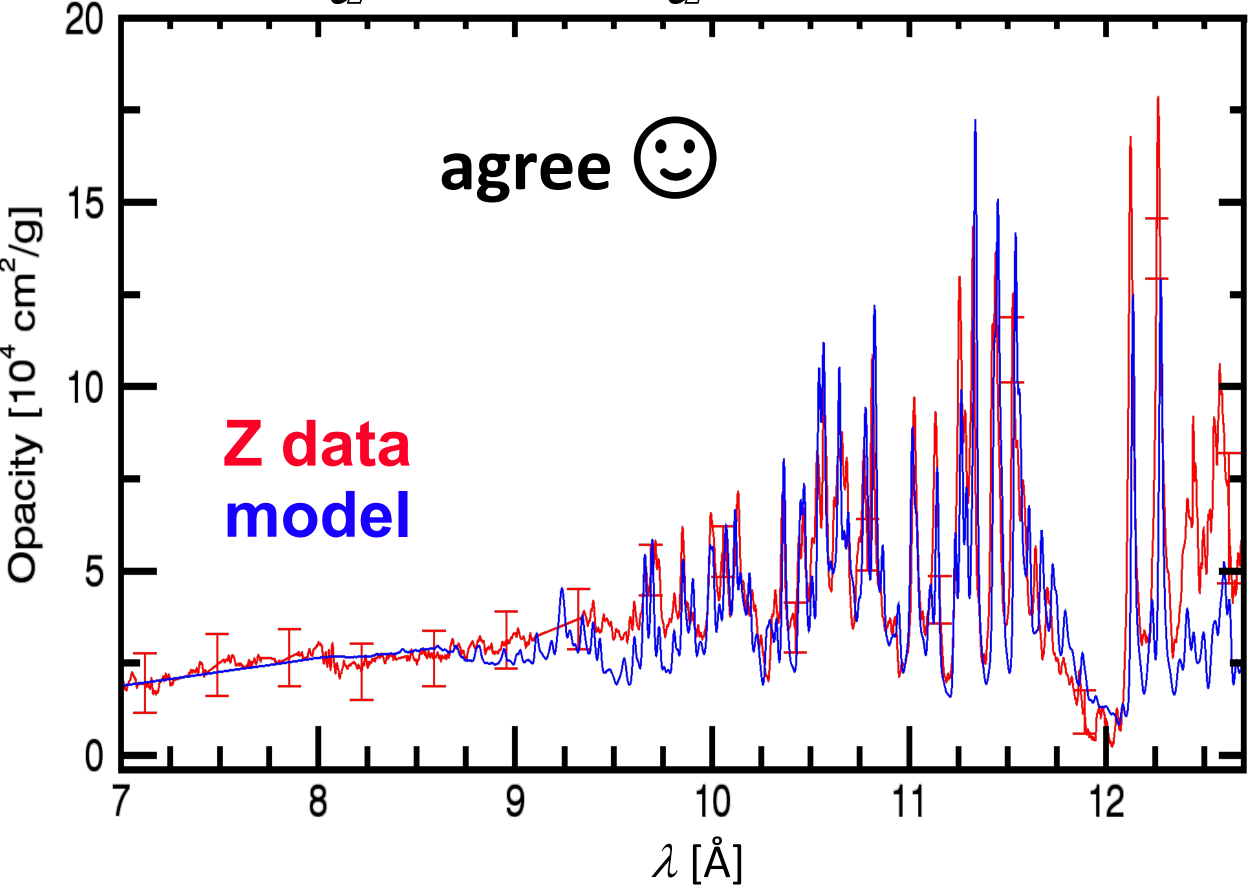
- The difference accounts for roughly half the opacity change needed to solve the solar problem
- Is opacity theory inaccurate? Is opacity experiment flawed?

Bailey *et al.*, *PRL*, **99**, (2007), Bailey *et al.*, *Nature*, **517** (2015)

… but disagree at near CZB conditions

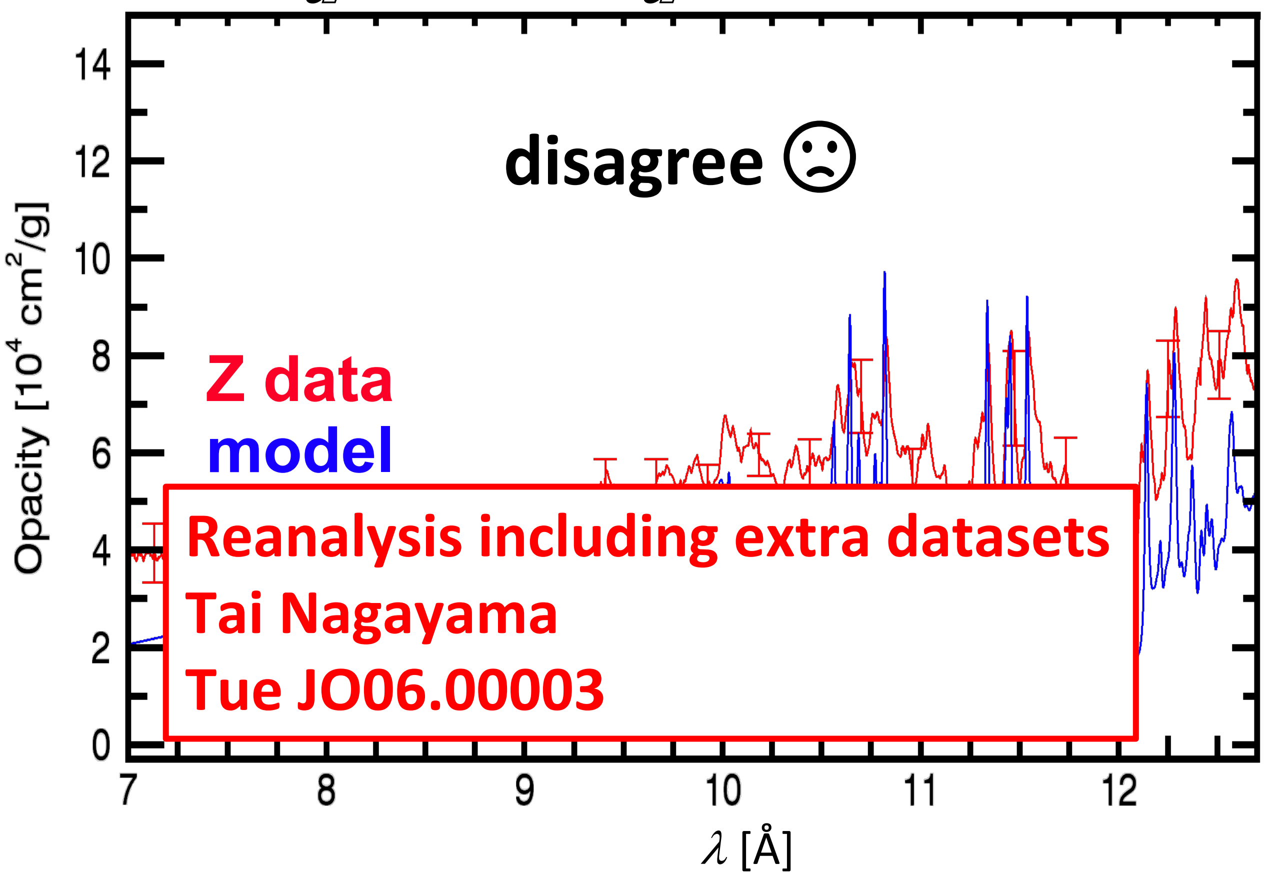
Anchor 1

T_e = 156 eV, n_e = 6.9×10^{21} cm^{-3}



Anchor 2 ~ solar CZB

T_e = 182 eV, n_e = 3.1×10^{22} cm^{-3}



Reanalysis including extra datasets
Tai Nagayama
Tue JO06.00003

- **The difference accounts for roughly half the opacity change needed to solve the solar problem**
- **Is opacity theory inaccurate? Is opacity experiment flawed?**

Bailey *et al.*, *PRL*, **99**, (2007), Bailey *et al.*, *Nature*, **517** (2015)

Time-resolved measurements can improve our opacity investigations in multiple ways

- ***Understand and refine opacity experiments by measuring Te(t) and ne(t)***
  - → Refine the experiments to reach higher density
  - → Experimentally test the importance of time-integration effects

- ***Test accuracy of radiation-hydrodynamics simulations***

- ***Evaluate proposed model refinements that address the model-data discrepancies***
  - → Line broadening
  - → 2-photon absorption
  - → Excited states distribution

- ***Increase efficiency of absolute opacity measurements***
  - → Multiple opacity measurements over different T_e, n_e within a single experiment

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Time-integration effects are a potential source of systematic error on opacity measurements

Potential systematic errors[1]:

- Error in T_e and n_e determination
- Sample areal density error
- Sample spatial gradients
- Sample self-emission
- Background determination

⋮

Time-dependent effects:

Effect 1: Transient kinetics. Excluded from high density and agreement at anchor 1

Effect 2: Temporal gradients

→ First approach: field ultra-fast detector to assess the Z opacity sample evolution

[1]Nagayama *et al.*, *PRE*, **95**, (2017), Nagayama *et al.*, *RSI*, **83**, (2012), H. Morris et al., *PoP*, **24**, (2017)

We used the Ultrafast X-ray Imager - UXI[1] to record time -gated spectral images

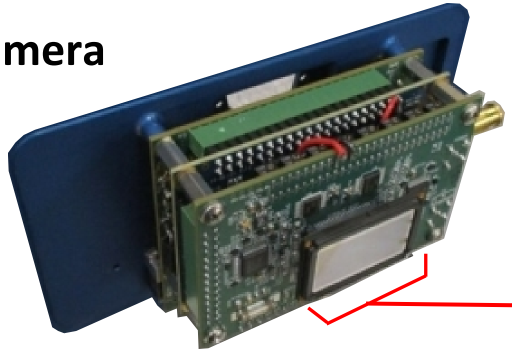
Requirements for condition measurements

- Accurate Mg ***line*** transmission measured →
  - high S/N spectra →
  - linear photon intensity →
  - enough spectral resolution →
  - avoid line saturation
  - reproducibility
- Multiple time-steps to observe actual evolution →
- Line transmission model

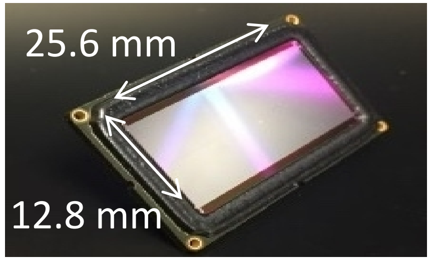
UXI characteristics:

- High single photon, soft x-ray response. Absolutely calibrated for the slit pattern[2]
- Very good linearity[2] **<3%**
- Pixel size → **λ/δλ = 1100-1200** (~7mÅ)
- Highly uniform response[2] ~**2%**
- Time-resolution = **1.9 ns** adequate to collect 5 or 6 frames /camera /exp

UXI camera



sensor



1024x512 25-µm pixels

➢ **Meets requirements to obtain the sample evolution**

[1]**UXI**=**U**ltra-fast **X**-ray **I**mager: Claus *et al.*, *Proc. SPIE*, **9591**, (2015), *Proc. SPIE*, **10390**, (2017), [2]Looker *et al.*, *RSI*, **91**, 043502 (2020)

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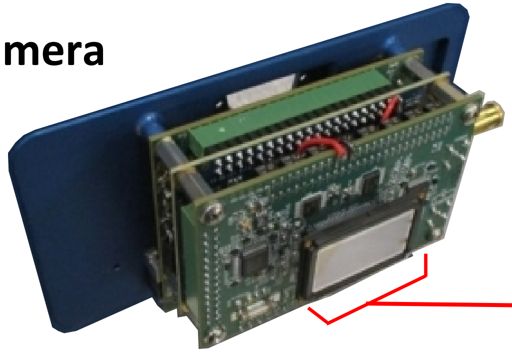
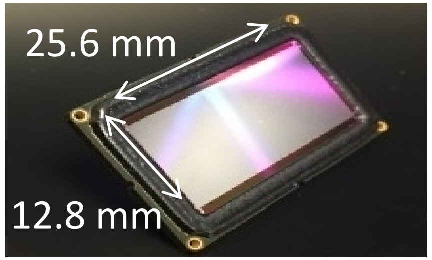


sensor



1024x512 25-µm pixels

John Porter
Wed QI02.00004

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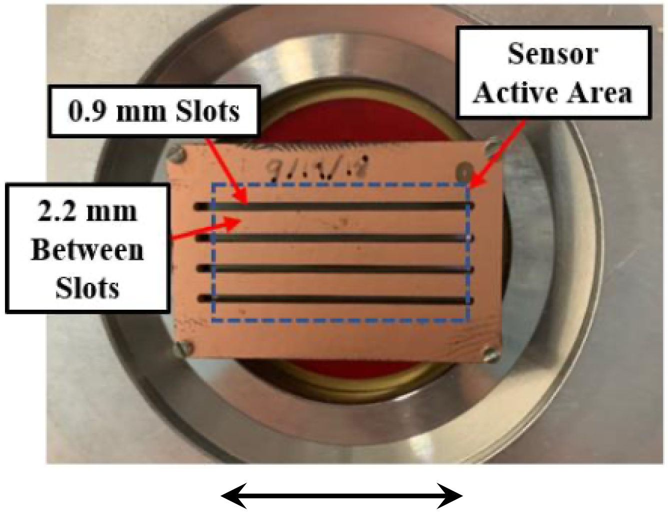
[1]**UXI**=**U**ltra-fast **X**-ray **I**mager: Claus *et al.*, *Proc. SPIE*, **9591**, (2015), *Proc. SPIE*, **10390**, (2017), [2]Looker *et al.*, *RSI*, **91**, 043502 (2020)

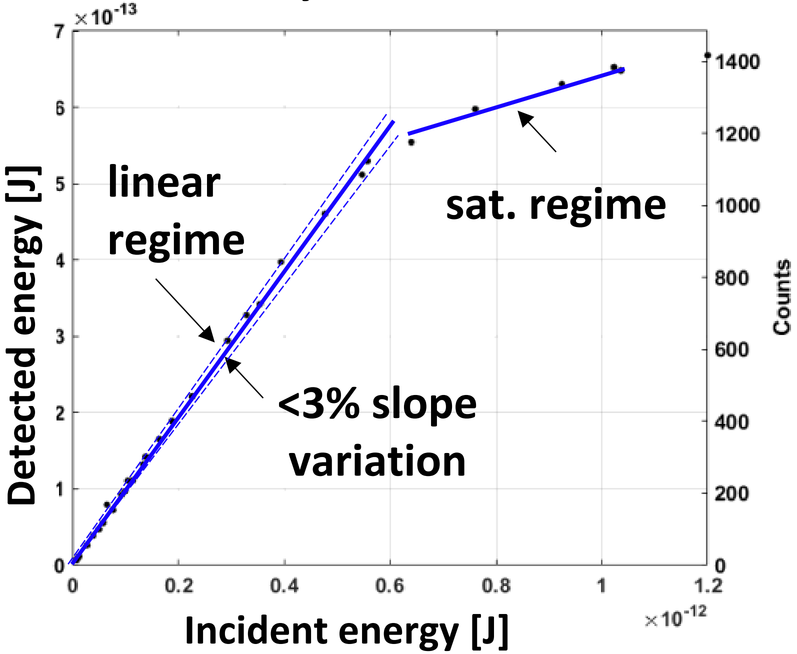
The UXI detector was characterized in a usage regime relevant to the Z opacity experiment[1]

Same slit pattern as opacity



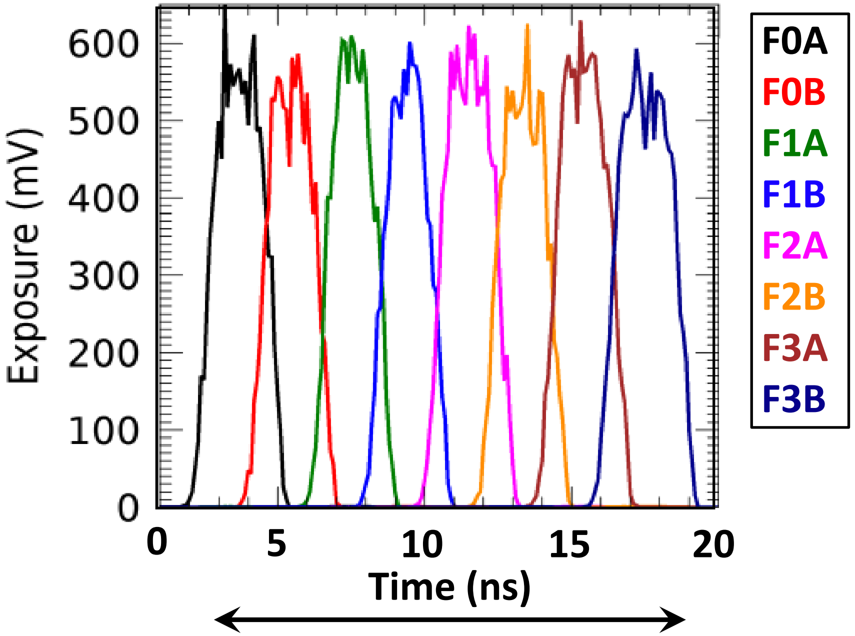
sensor size = 1in in spectral dimension ~ ¼ of full spectrum

Linearity & saturation



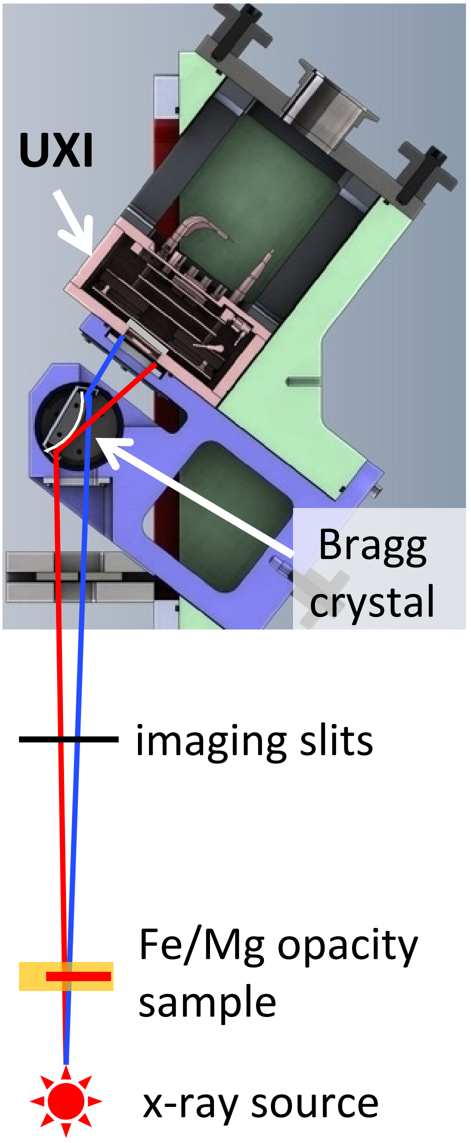
The 8 time-gates are measured

2/2ns trigger mode, FWHM = 1.86 ns



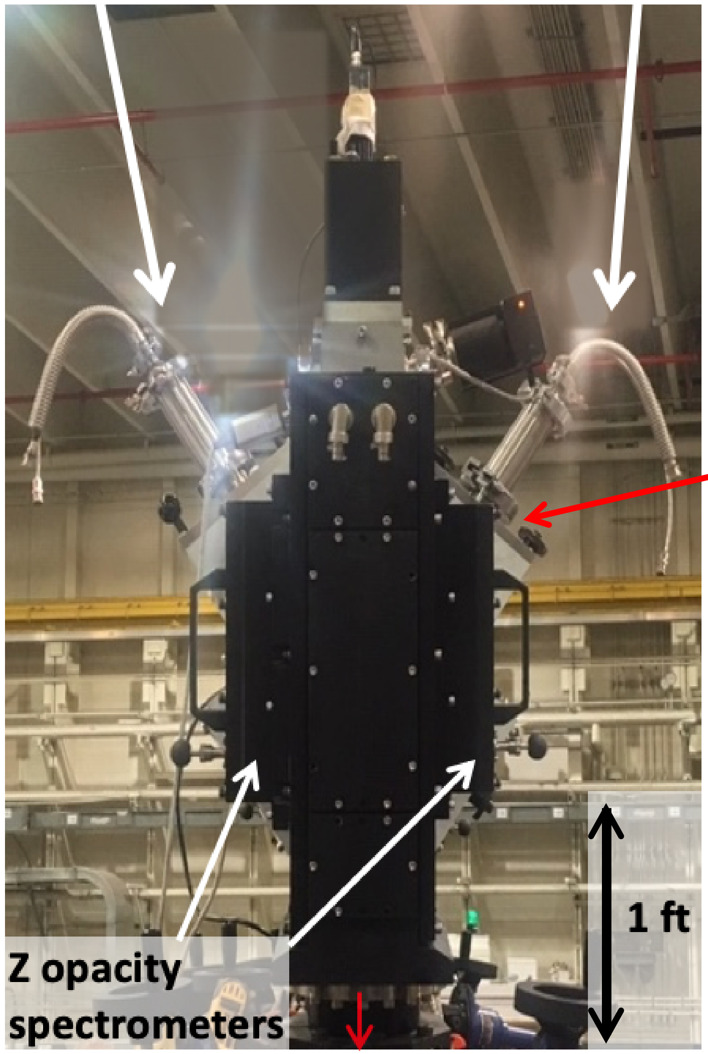
[1]Looker *et al.*, *RSI*, **91**, 043502 (2020)

UXI detector successfully fielded in Z opacity spectrometers

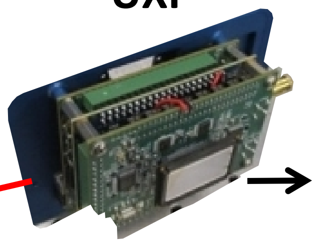


UXI 1

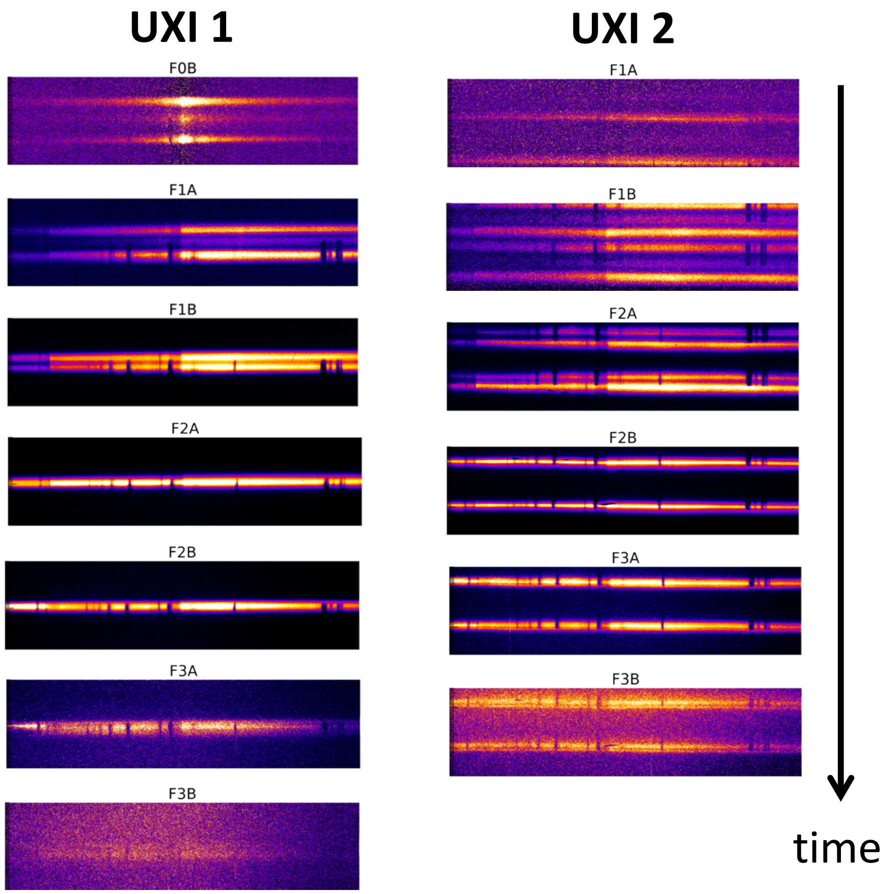
UXI 2



UXI



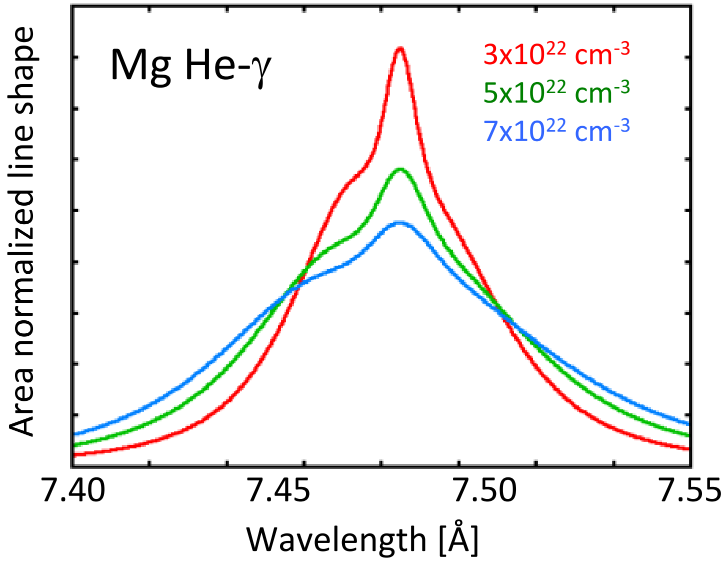
z3460 - Anchor 1 Fe



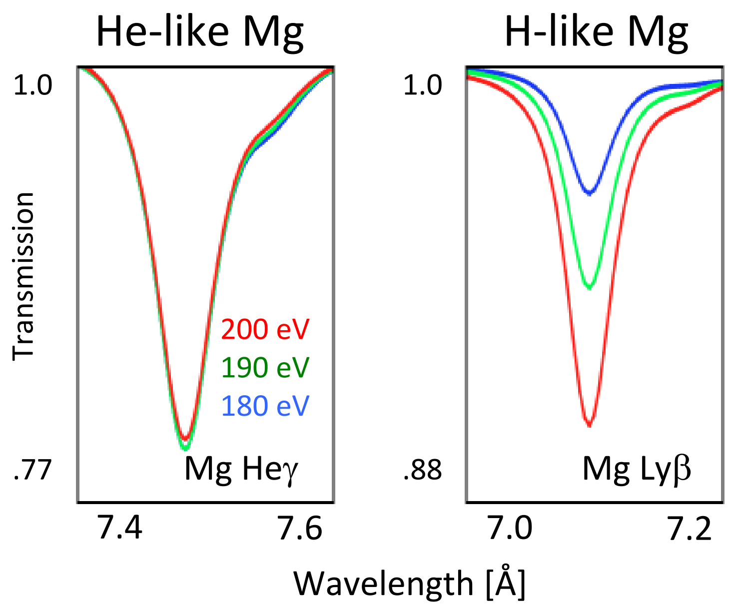
- Average of 8 frames per shot, with max of 13 frames on a single shot with 2 UXI cameras.
- March 2022: 39 images on 3 shots

n_e and T_e are inferred from measured Mg K-shell line absorption spectrum[1]

- Line shape: sensitive to electron density, n_e



- Line ratio: sensitive to electron temperature, T_e



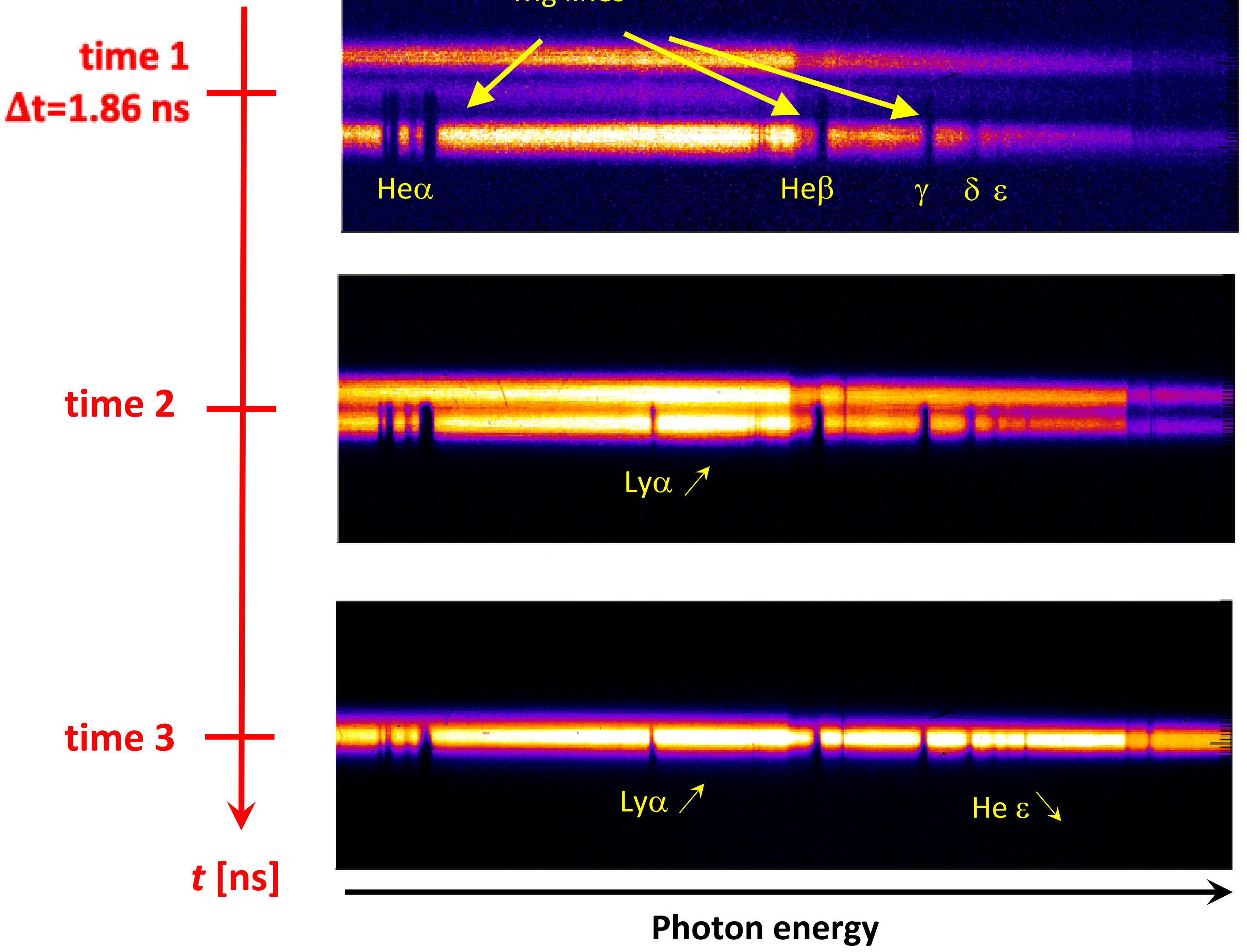
Plasma T_e and n_e can be extracted by reproducing measured spectra with spectral models

[1]Bailey, *et al. RSI* **79**,3104 (2008), Nagayama *et al.*, *PoP* 21, 056502 (2014), Nagayama *et al. HEDP* **20,** 17 (2016), R.C. Mancini, D.P. Kilcrease, *et al.*, *Comp. Phys. Com.* **63**, 314 (1991), C. Iglesias, H. DeWitt, *et. al.*, *PRA* **31**, 1698 (1985).

Temporally resolved UXI images are *spectrally* resolved in the Mg K-shell absorption range

size of detector is limited to ~ 3 Å

Fe/Mg example images

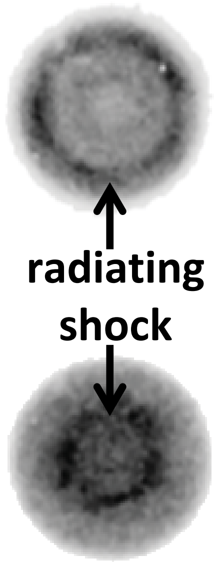


He-like = Mg +10
→ Heα, Heβ, Heg …

H-like = Mg +11
→ Lyα, Lyβ

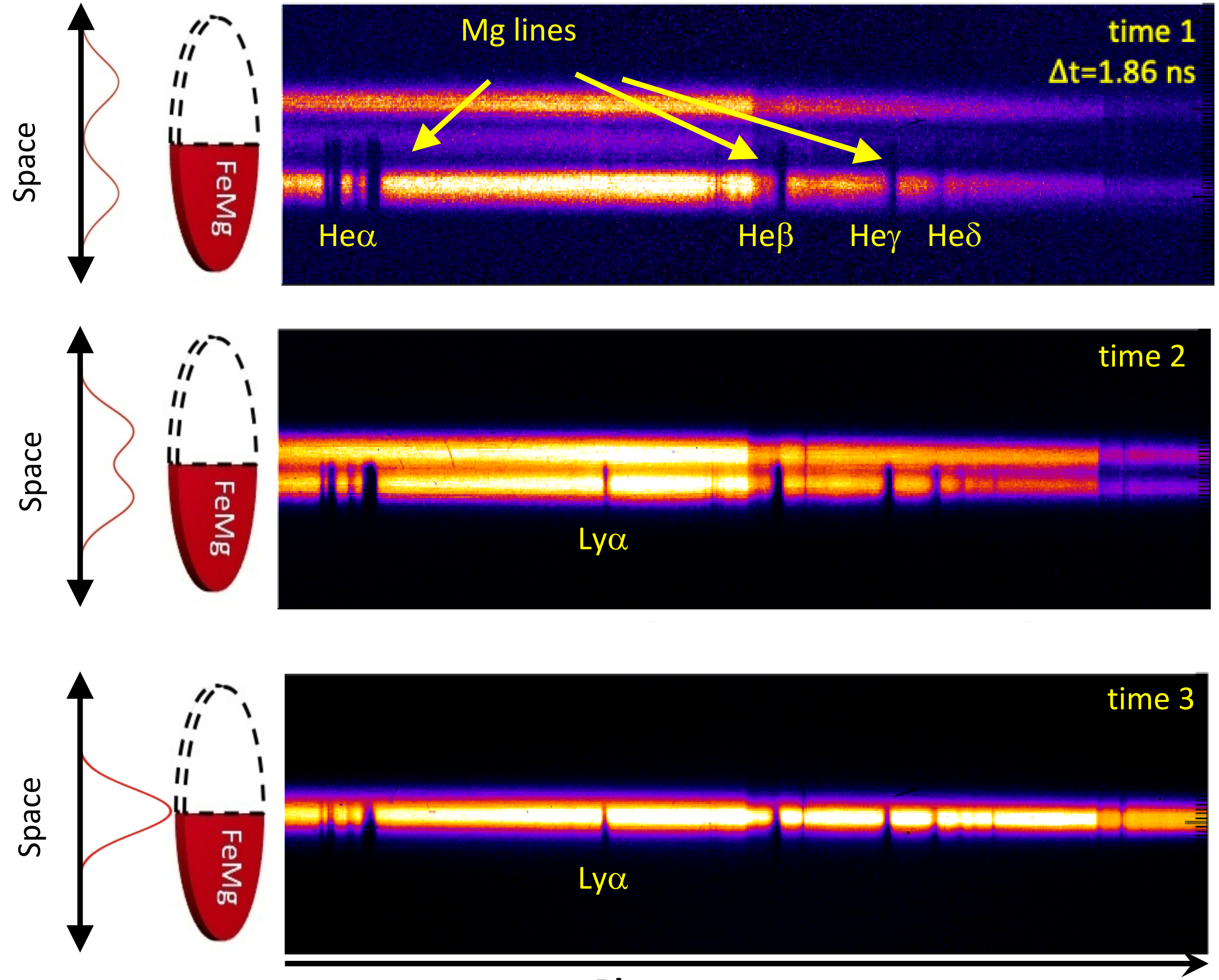
temperature increases since Lyα line deepens

UXI images are also *spatially* resolved → backlighter spatial profile

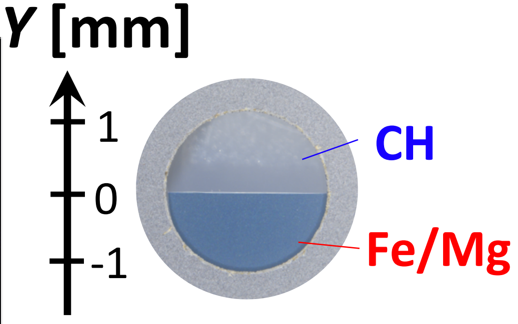


2D pinhole images[1]

~stagnation

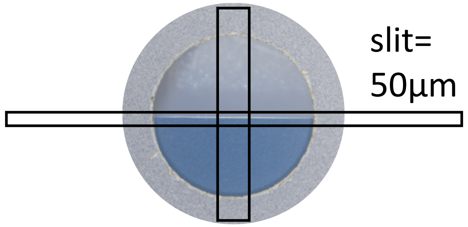


Photon energy



half-moon sample

Space resolution = slits
Space integration limits = aperture

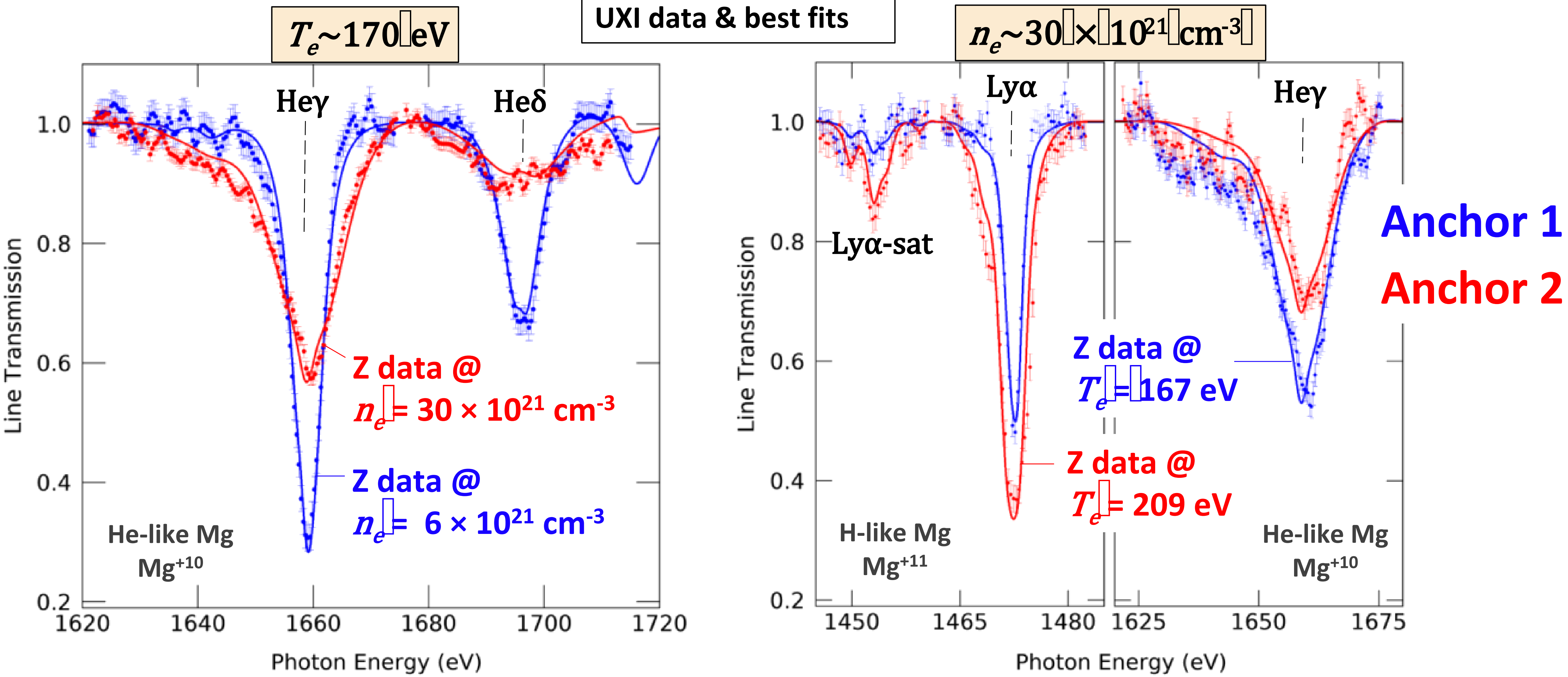


L.A. ~ 1mm

➢ **The reproducible (320 km/s ± 8%) radiating shock is used to cross-time datasets[1]**

[1]G. Rochau *et al.*, *PRL*, **100** (2008)

Conditions were obtained for both anchor 1 & 2 Fe

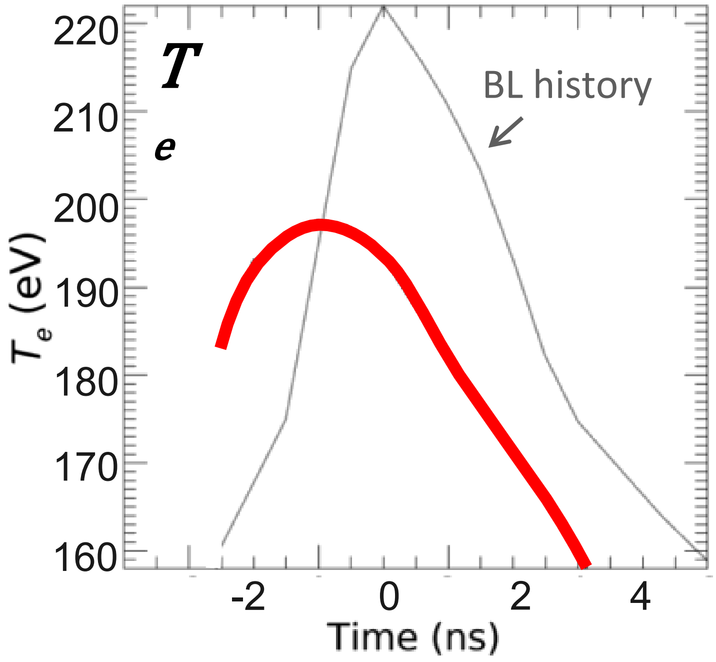


- ➢ **One condition can be varied while the other stay the same (here on two experiments)**

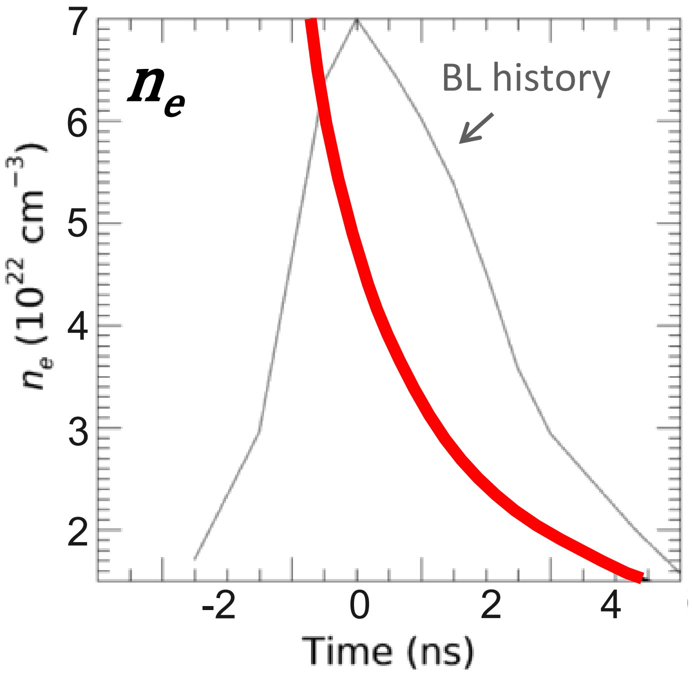
Nagayama et al., *PoP*, **95**, (2014), Bailey et al., *RSI*, **79**, (2008), MacFarlane *et al.*, *HEDP*, **3** (2007)

Simulations* predict T_e , n_e evolution for anchor 2 Fe

Anchor 2 T_e



Anchor 2 n_e

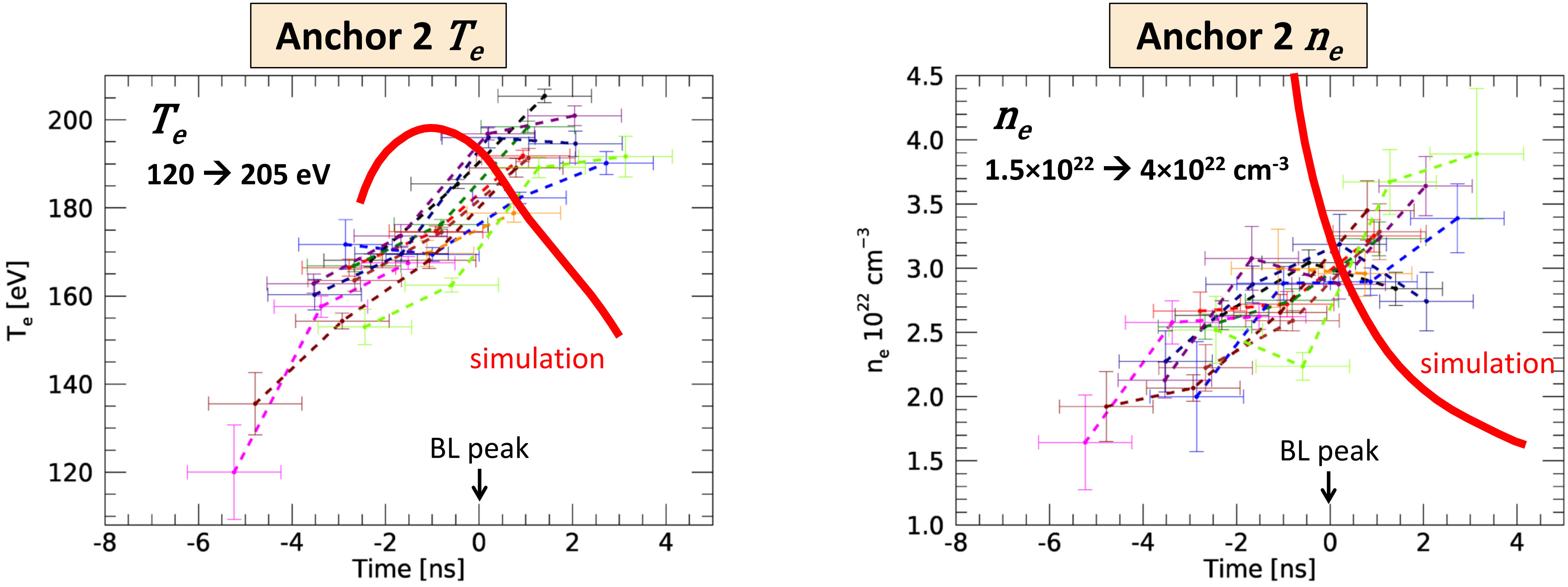


T_e decrease after peak temperature 1 ns before BL peak

n_e constant drastic decrease

*Nagayama *et al.*, *PRE*, **93** (2016)

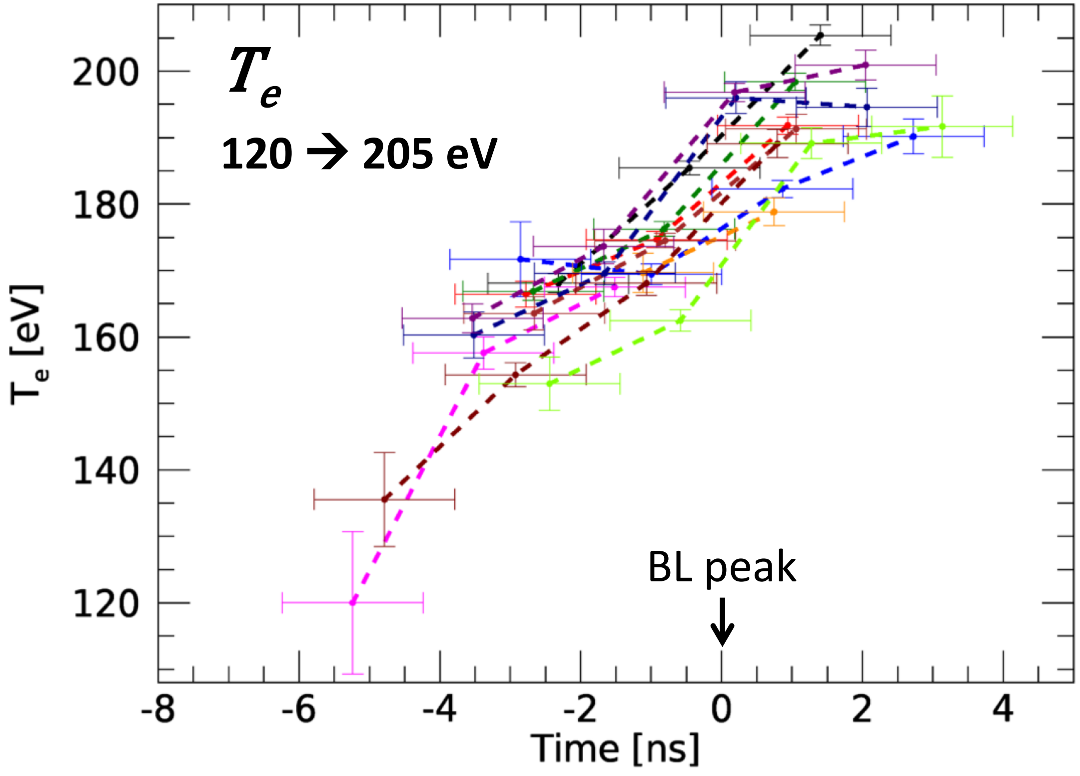
Anchor 2 Fe conditions evolution trends disagree with simulation predictions



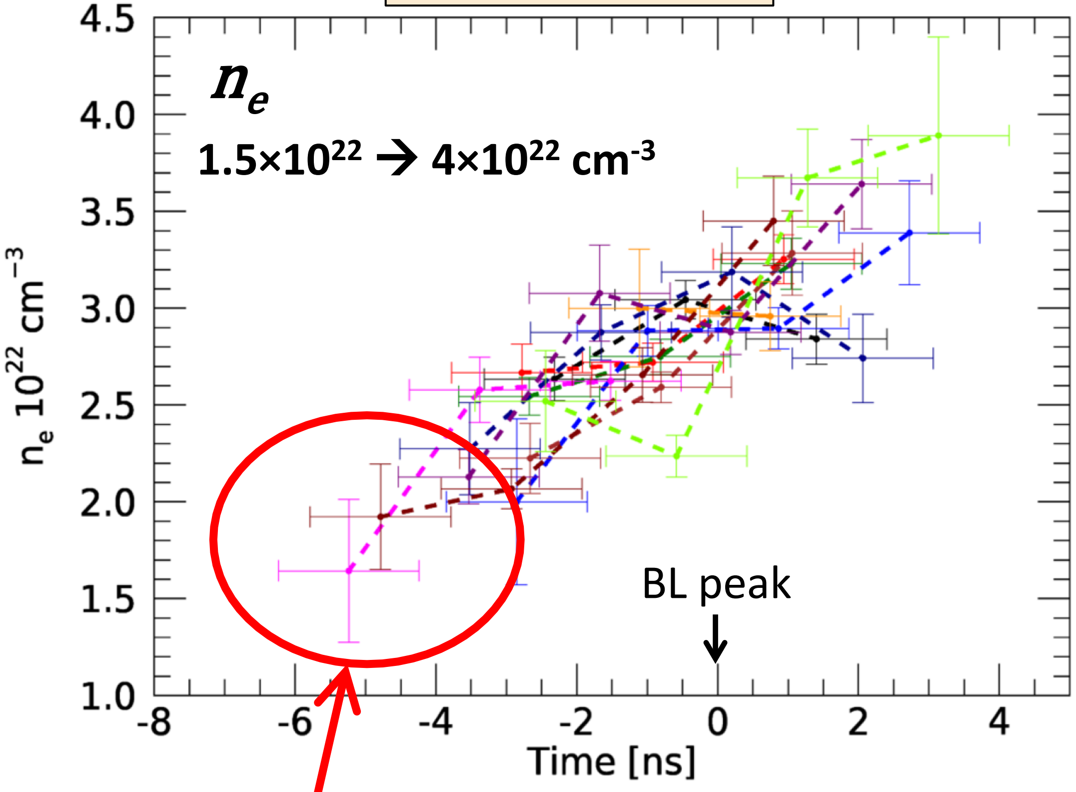
➢ **Multiple datasets (7 experiments) → reliability of novel measurements, clearer trends**

Anchor 2 Fe conditions evolution trends disagree with simulation predictions

Anchor 2 T_e

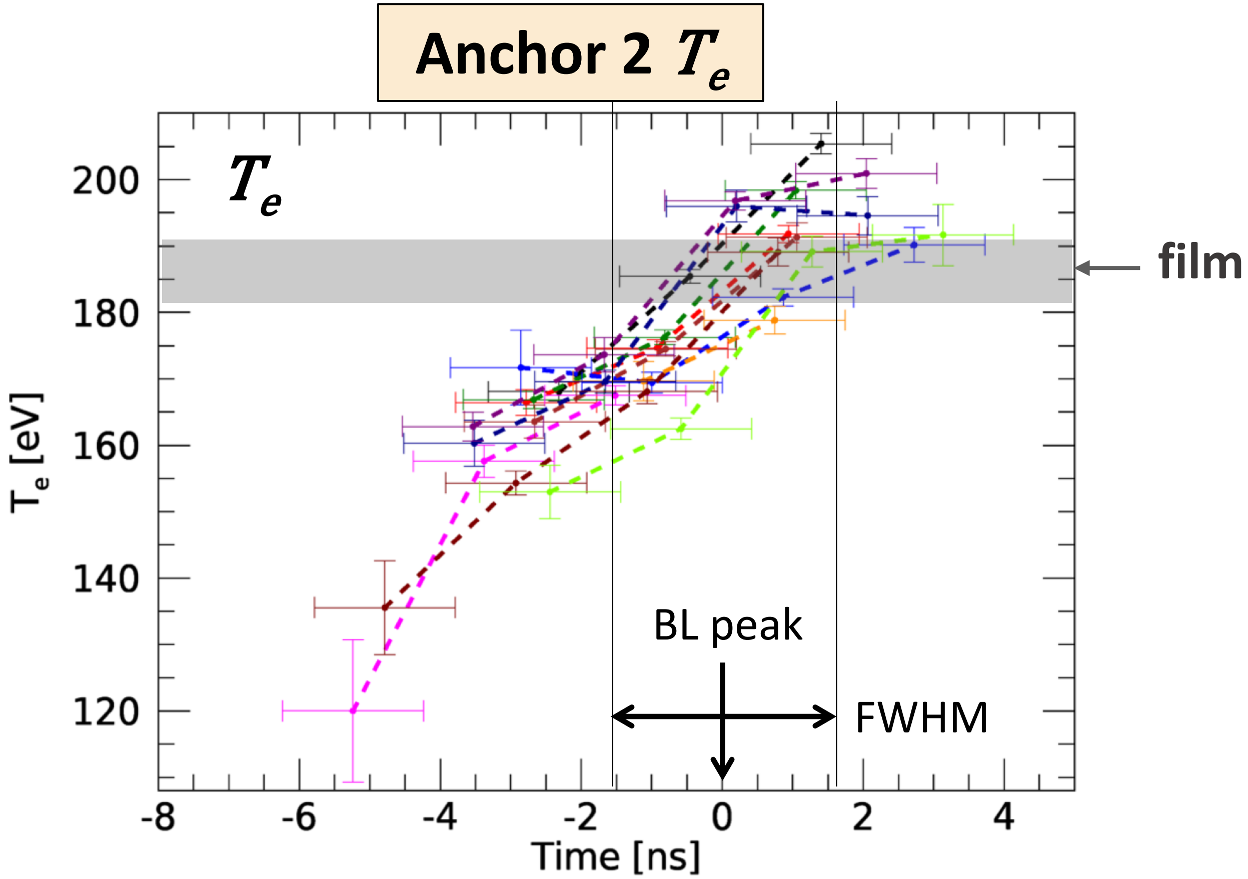


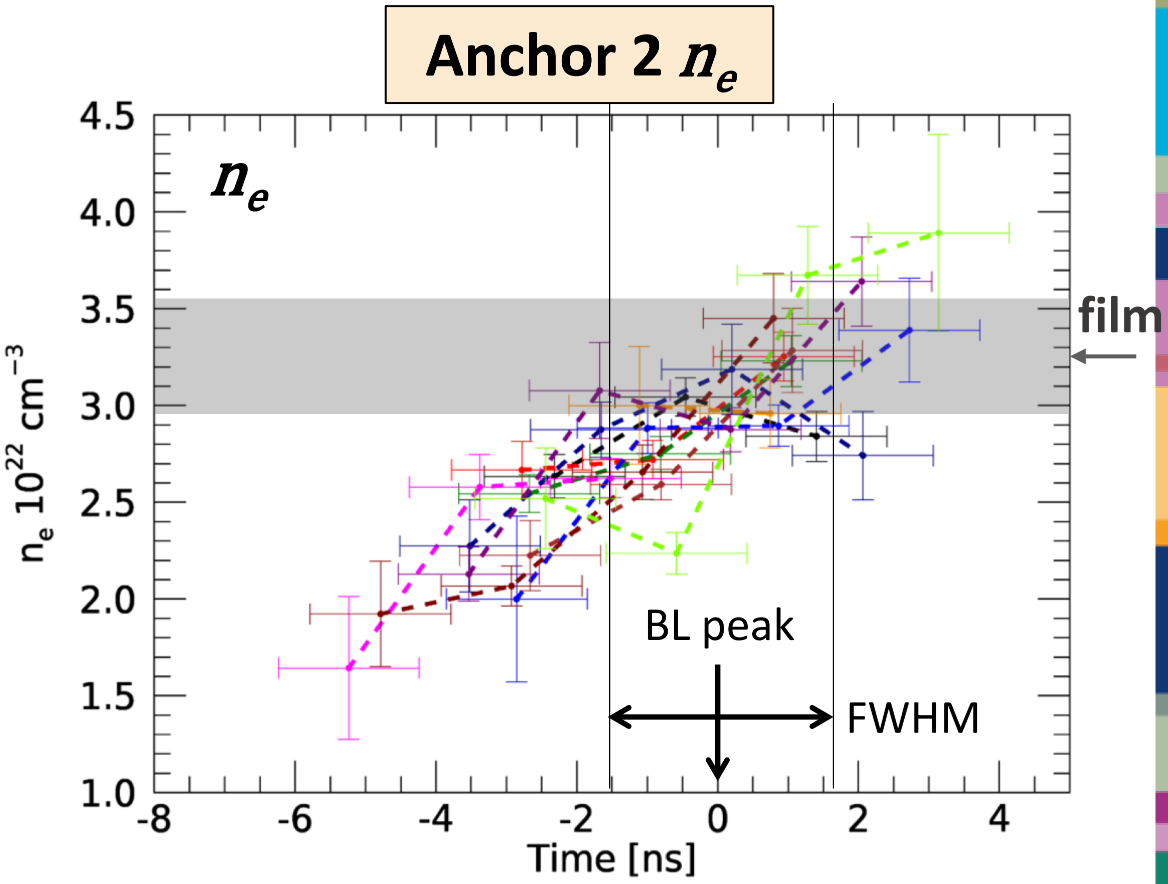
Anchor 2 n_e



Sample already expanded 10x even before BL peak!

Anchor 2 Fe conditions evolution trends disagree with simulation predictions





➢ **Sample evolution is consistent with past conditions inferred on film-based measurements**

Time-resolved measurements can improve our opacity investigations in multiple ways

- ***Understand and refine opacity experiments by measuring Te(t) and ne(t)***
  → Refine the experiments to reach higher density
  → Experimentally test the importance of time-integration effects

- ***Test accuracy of radiation-hydrodynamics simulations***

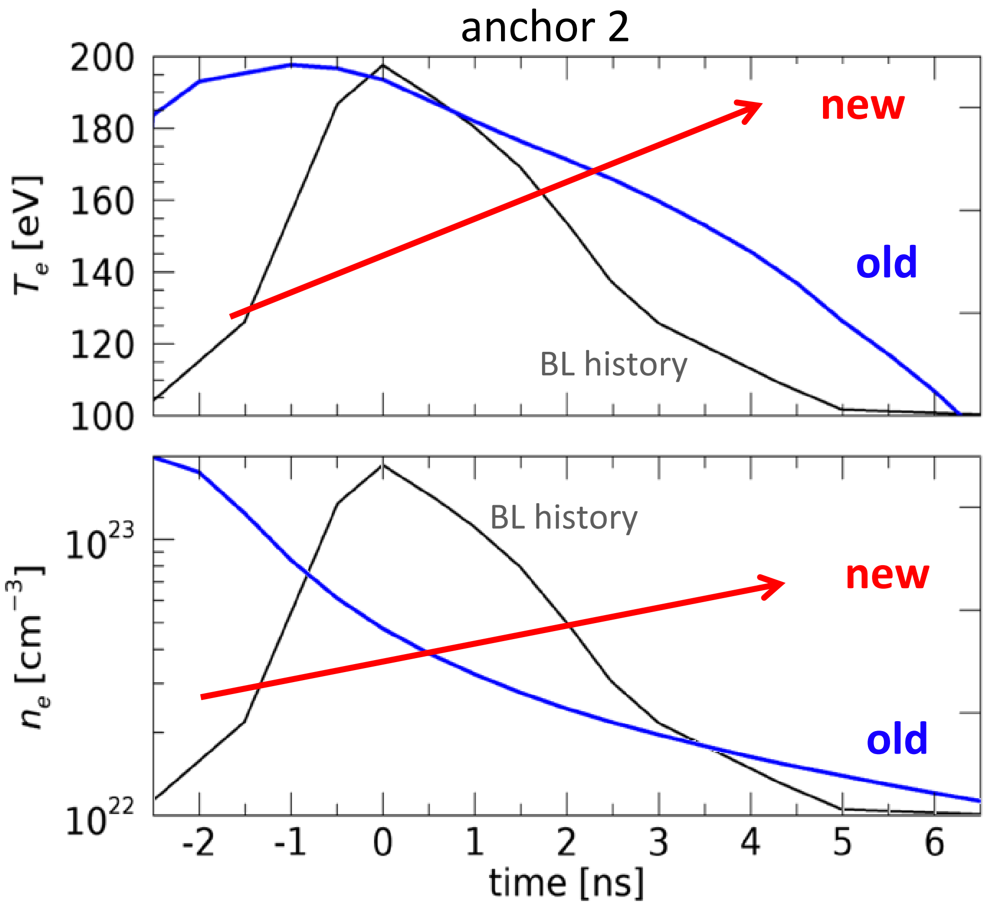
- ***Evaluate proposed model refinements that address the model-data discrepancies***
  → Line broadening
  → 2-photon absorption
  → Excited states distribution

- ***Increase efficiency of absolute opacity measurements***
  → Multiple opacity measurements over different T_e, n_e within a single experiment

Measured anchor 2 condition evolution challenges our picture of how the experiment works

Temperature T_e

Density n_e



1) **Temperature keeps increasing:**
- Is sample and source moving closer together?
- Are heating/cooling rates off?

2) **Density low at early times:**
- Is there significant preheat that allows for early expansion?

3) **Anchor 2 density increasing over time:**
- Is source plasma pushing on sample?

Allows to form and test novel hypotheses which will increase platform knowledge

Measured anchor 2 condition evolution challenges our picture of how the experiment works

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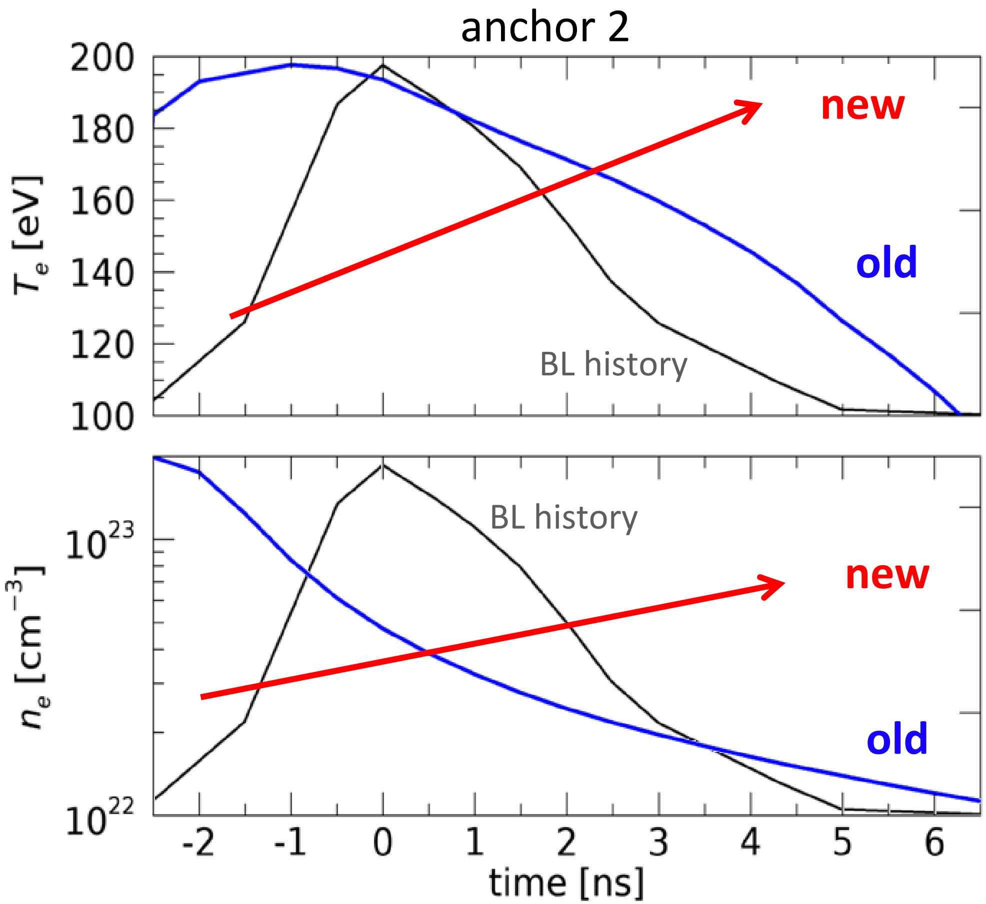
Density n_e



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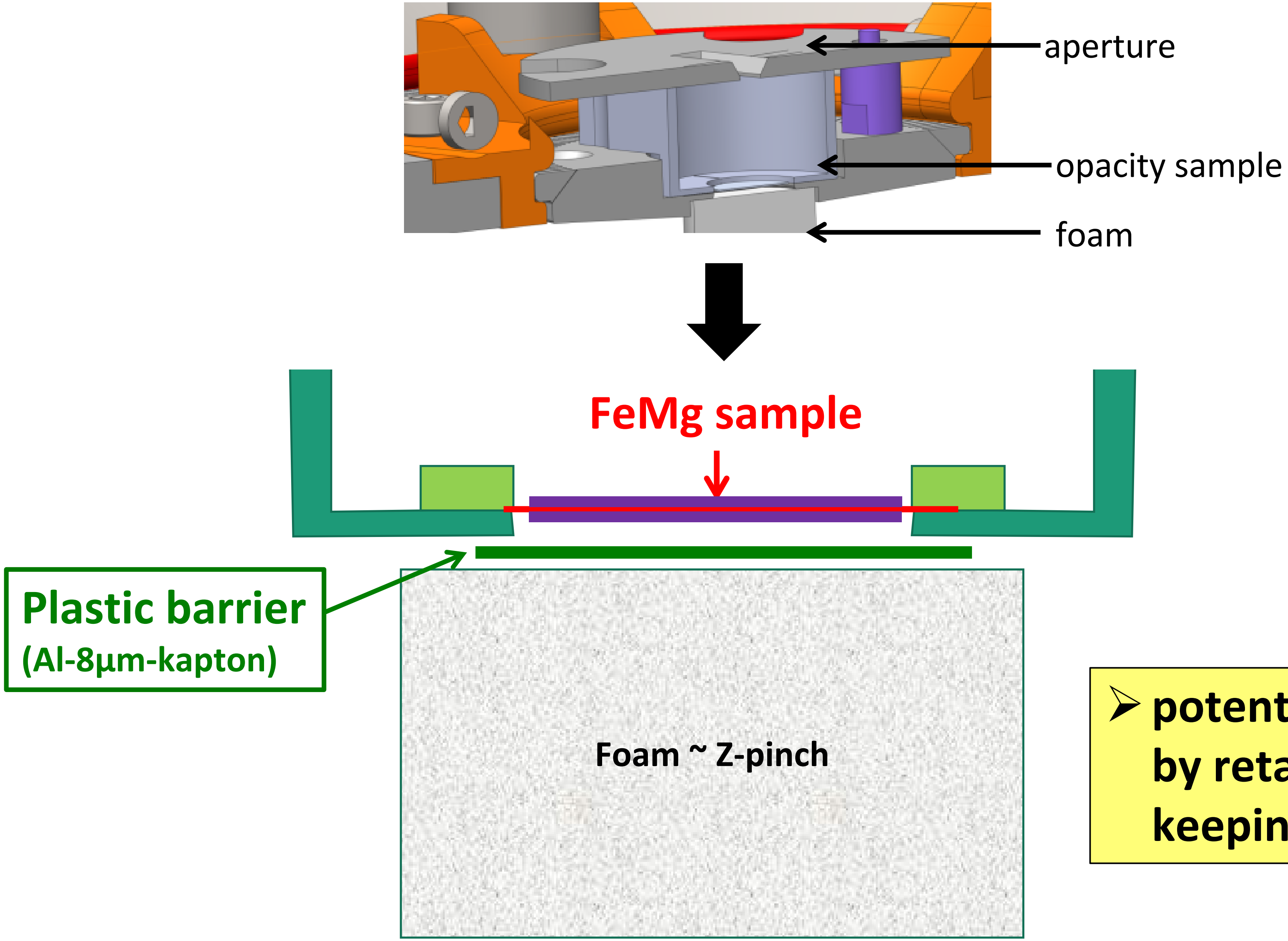
- Is source plasma pushing on sample?

Allows to form and test novel hypotheses which will increase platform knowledge

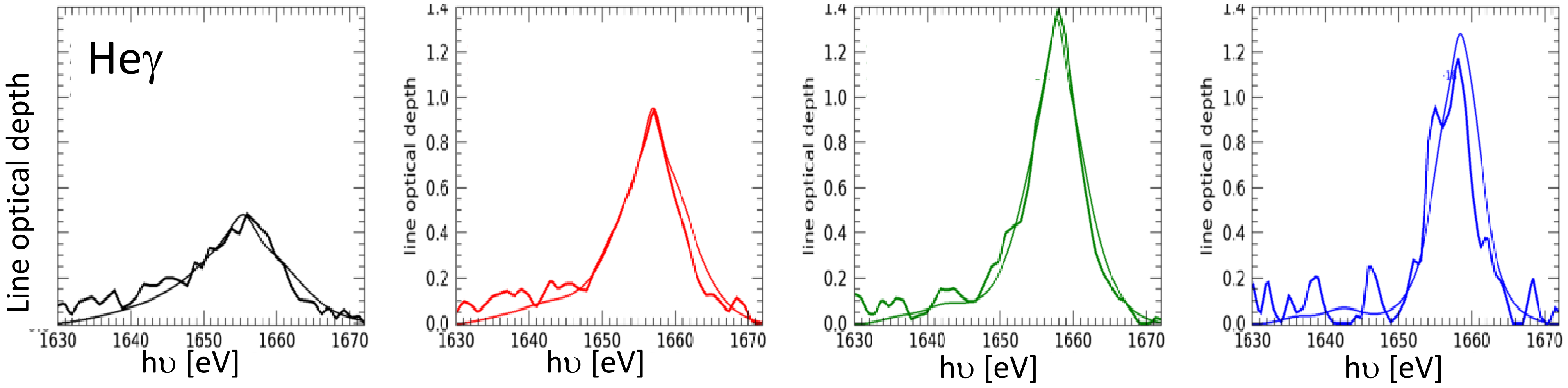
We tested a preheat suppression barrier



- ➢ potentially reach higher densities by retarding expansion while keeping high temperature

Preheat suppression test experiment showed line widths decreasing with time

t = -2 ns | 0 ns | 2 ns | 4 ns



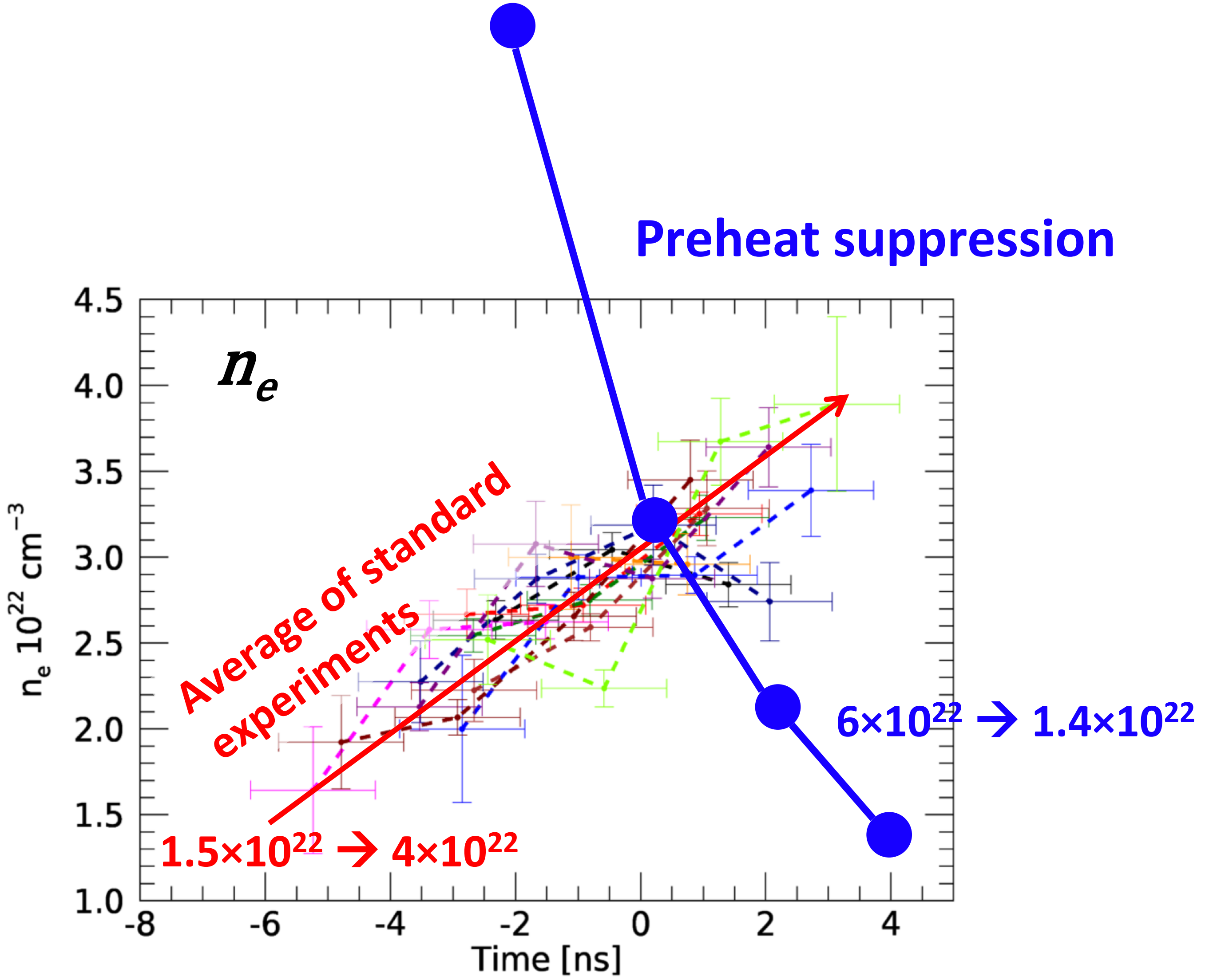
n_e [e⁻/cc] 6×10²² → 3.2×10²² → 2.1×10²² → 1.4×10²²

(T_e ~155 eV)

→ **Time-resolved line widths suggest electron density successfully decreases with time**

→ **x2 highest density**

… shows inverse trend as anchor 2 and potentially reach novel regime



Needs to be repeated with higher S/N for accurate opacity measurements

Time-resolved measurements can improve our opacity investigations in multiple ways

- ***Understand and refine opacity experiments by measuring Te(t) and ne(t)***
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  - → Line broadening
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- ***Increase efficiency of absolute opacity measurements***
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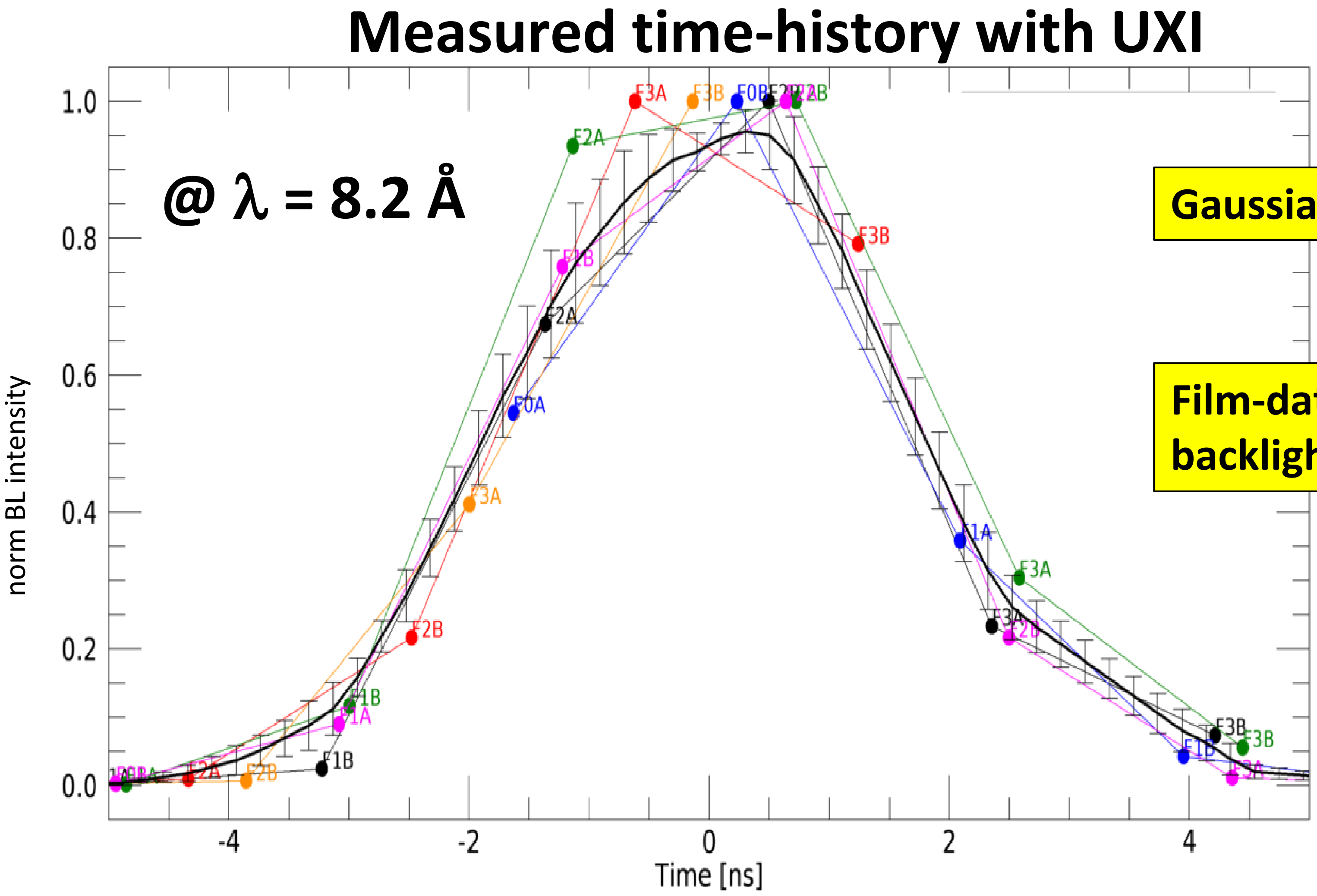
Temporal gradients could be a source of systematic error on film-integrated measurements

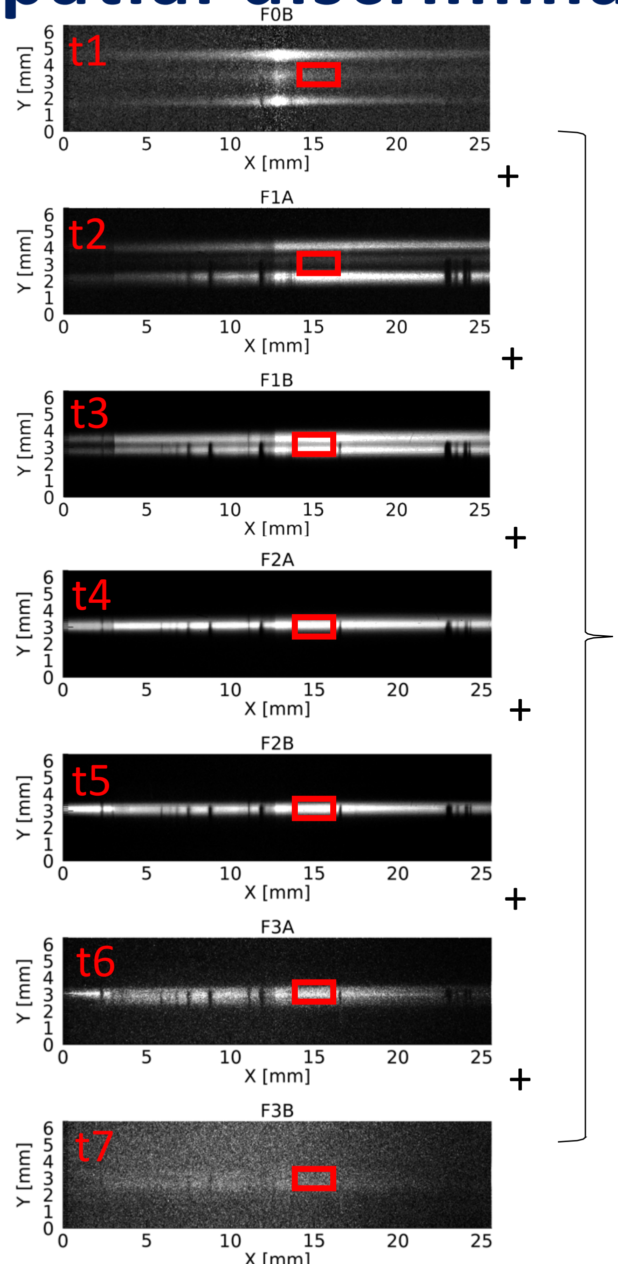


Gaussian shape with 3.29 ± 0.13 ns FWHM

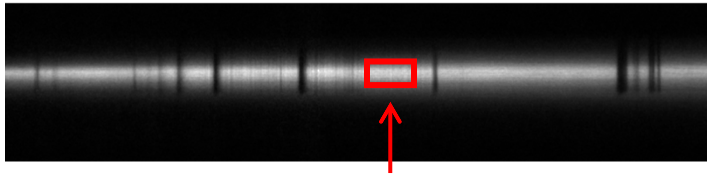
Film-data is therefore limited to when the backlighter is bright enough in time.

The temporal gradient effect on film is also smaller than due to spatial discrimination

z3460 - UXI



z3460 – film data ≃ addition of UXI images



area in film-data analysis

Film signal is thus significant only when:

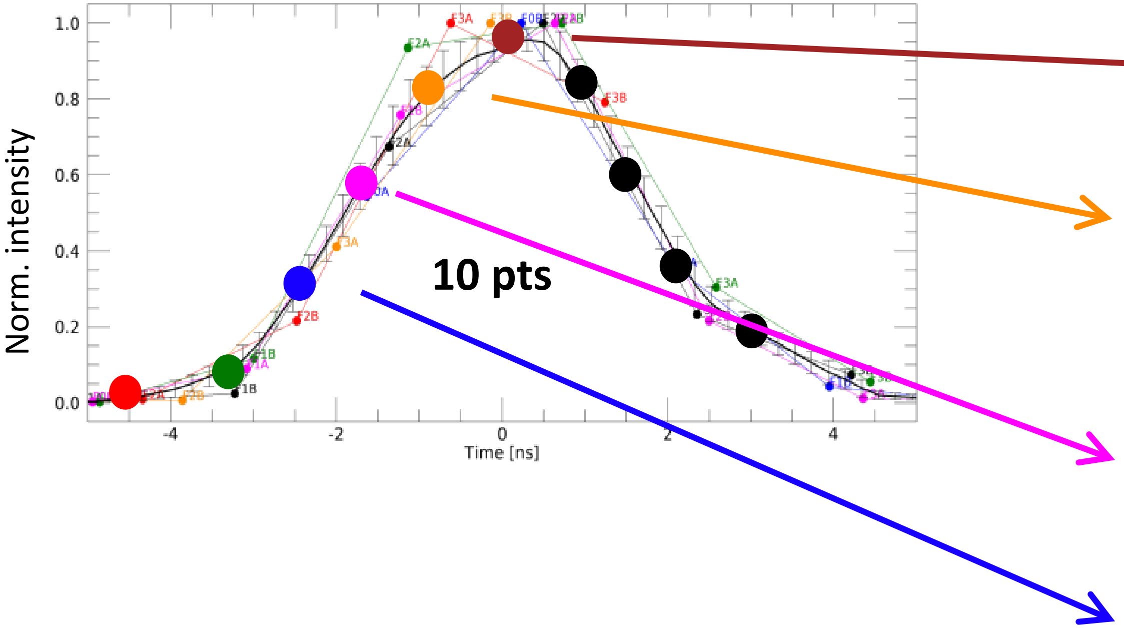
- **BL is peaking in time**
- **BL is centered in position**

Still, are temporal gradients significant?

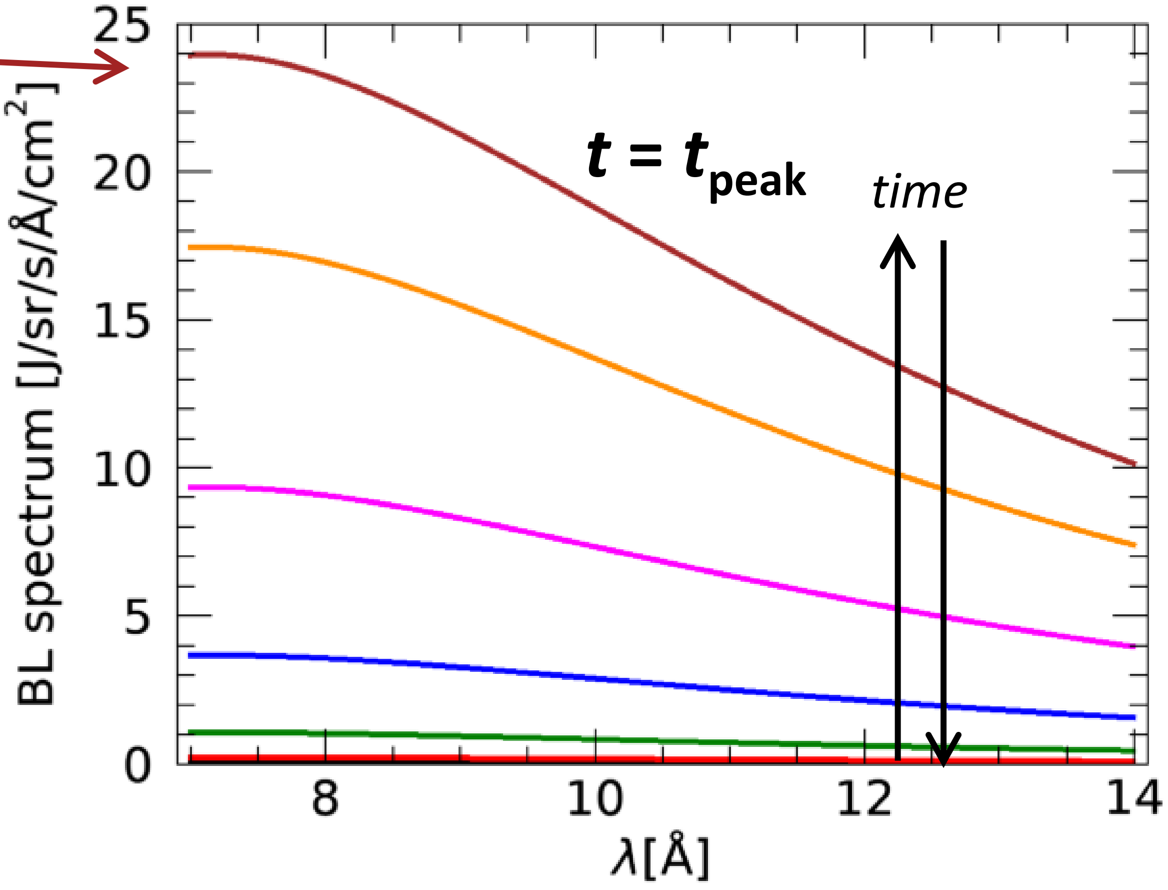
Could the observed gradient explain the anchor 2 model-data discrepancy? Let's investigate!

We need:

1) Relative BL temporal shape



Unattenuated BL*



*Planckian shape assumed (T_c=350 eV)

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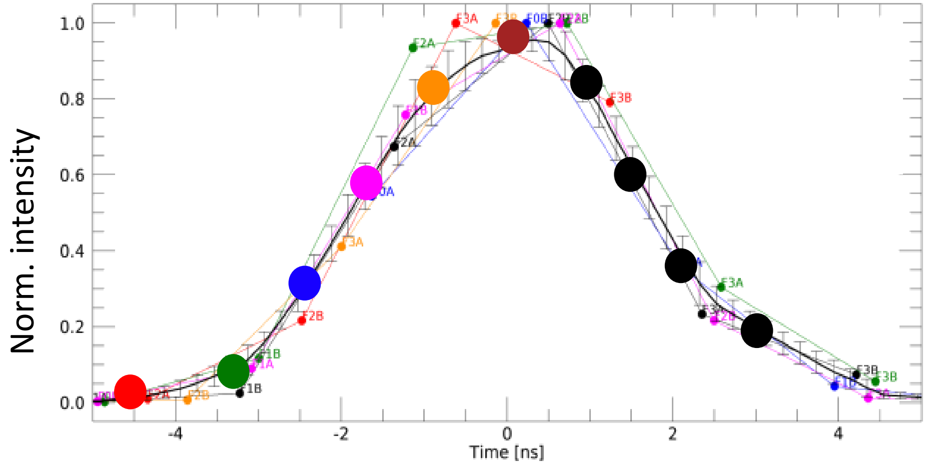
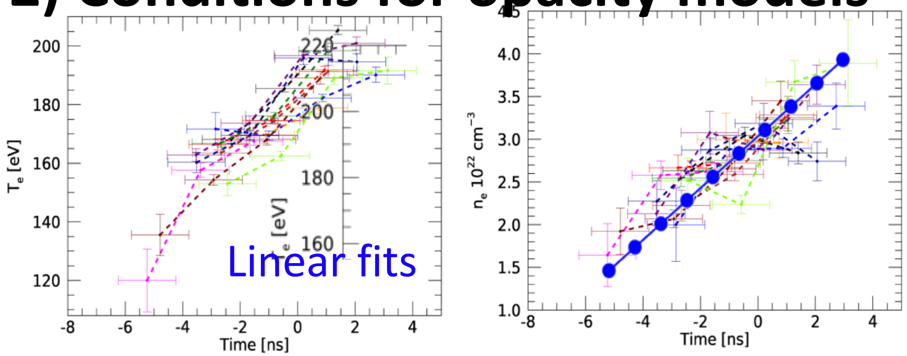
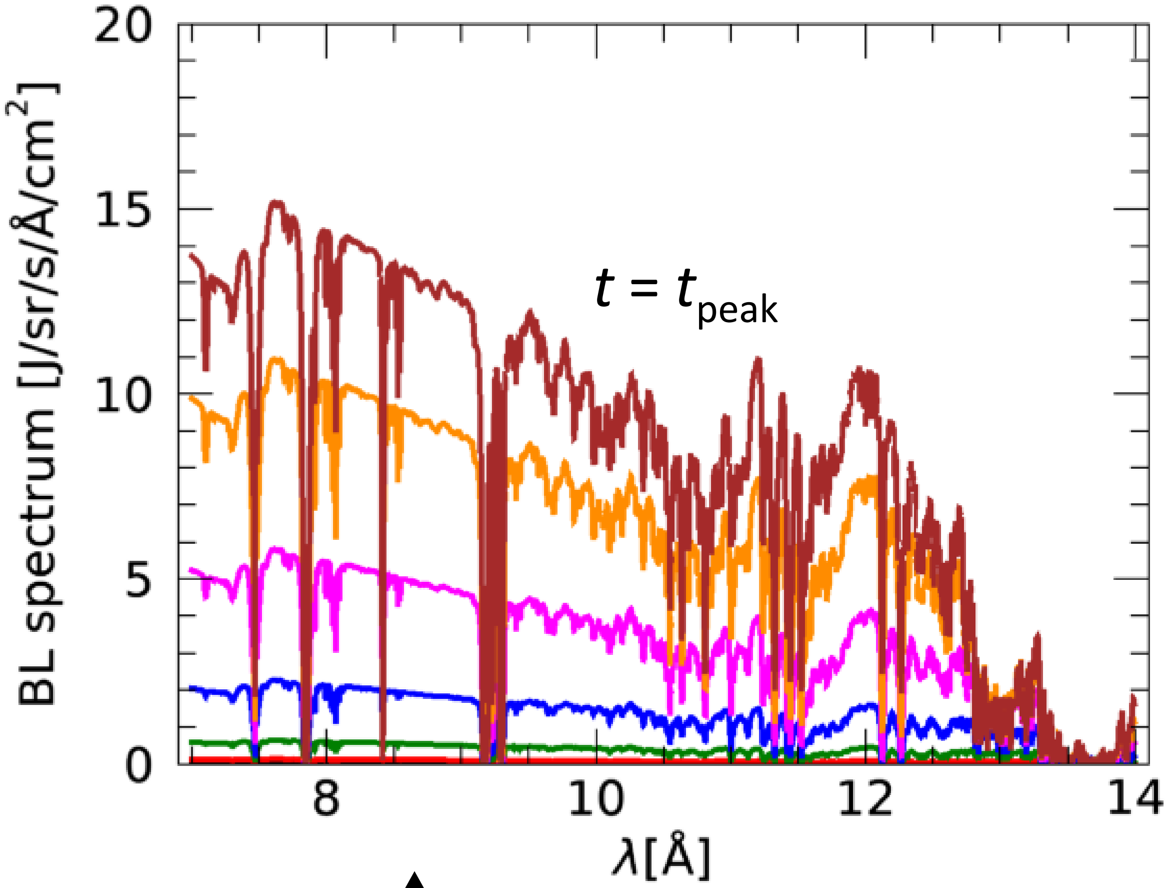


2) Conditions for opacity models



Attenuated = BL x transmission**



transmission

*Planckian shape assumed (T_c=350 eV)

****ATOMIC**: Fontes et al., *J. Phys. B* **48** (2015)

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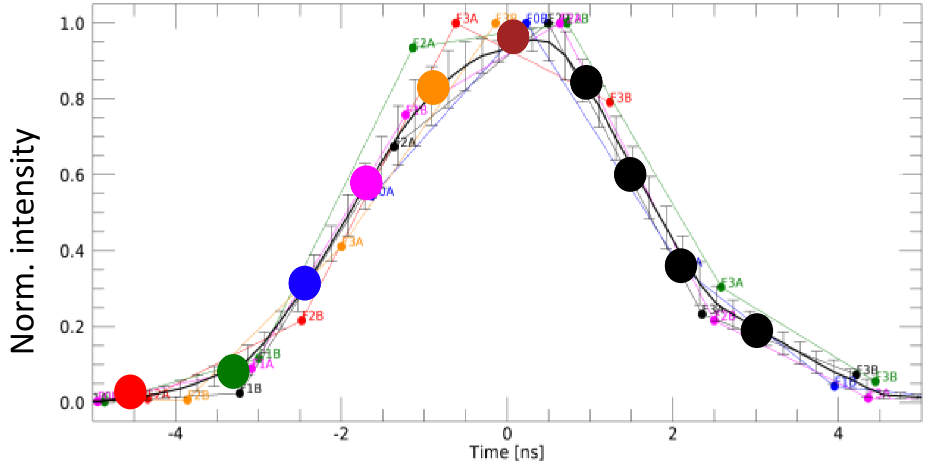

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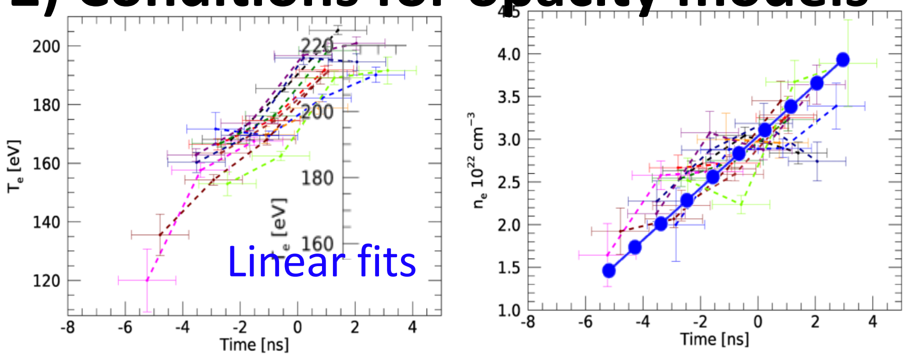
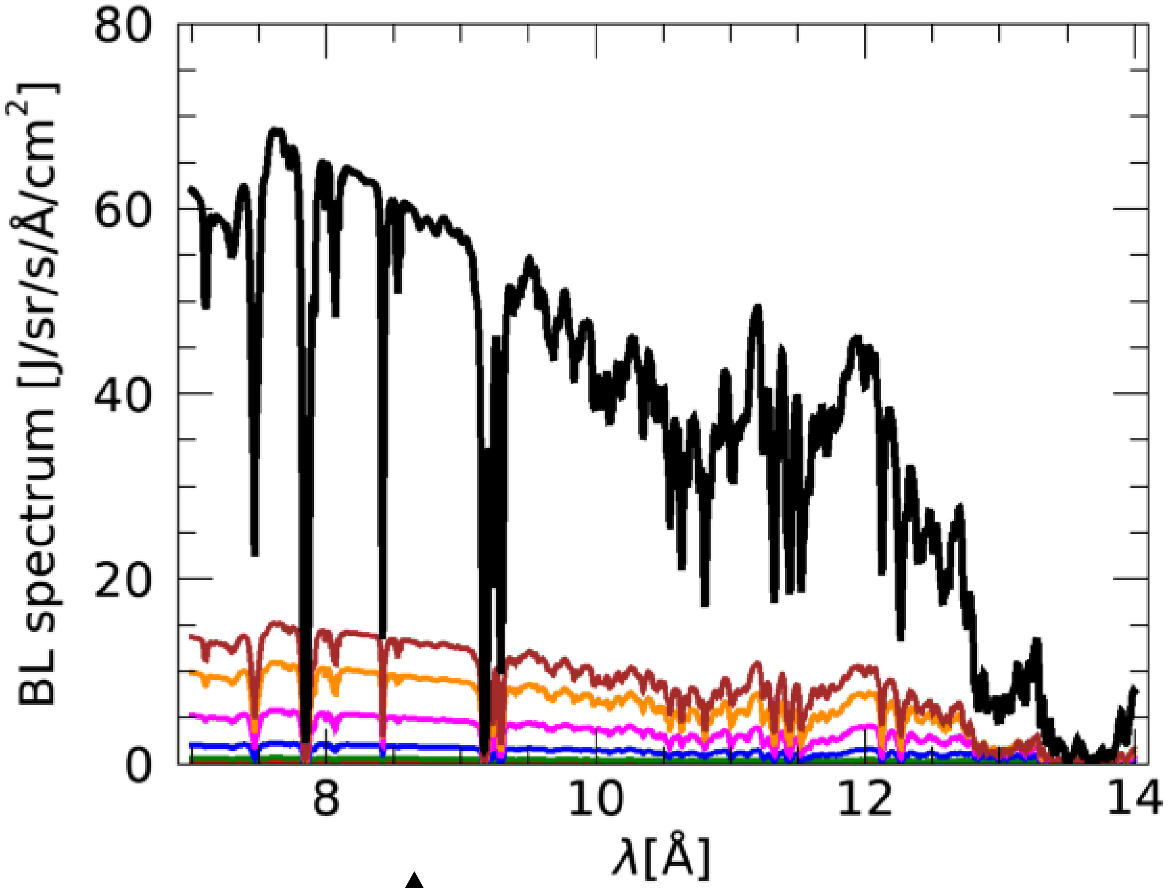


Sum = film-detected

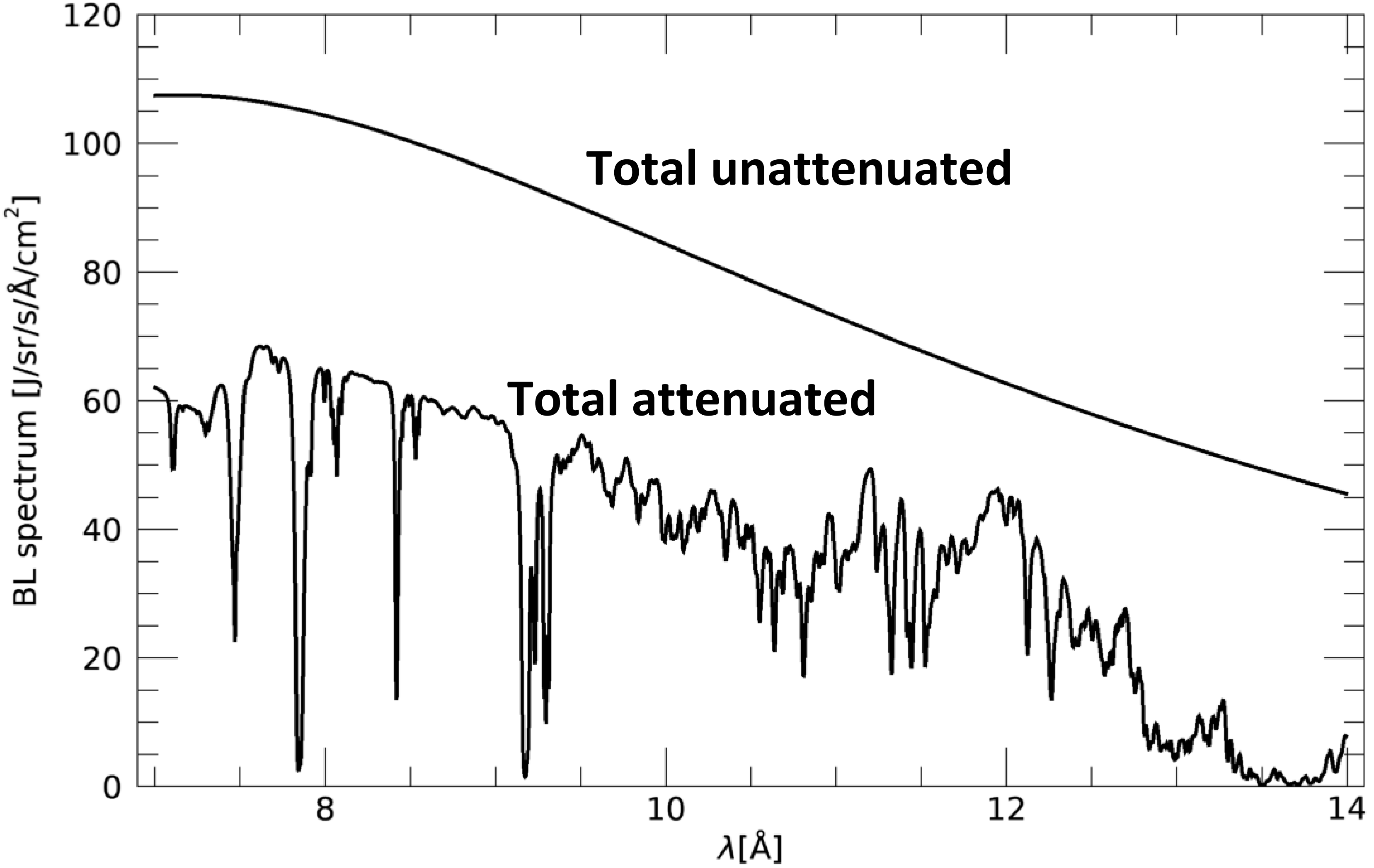


transmission

***Planckian shape assumed (T_c=350 eV)**

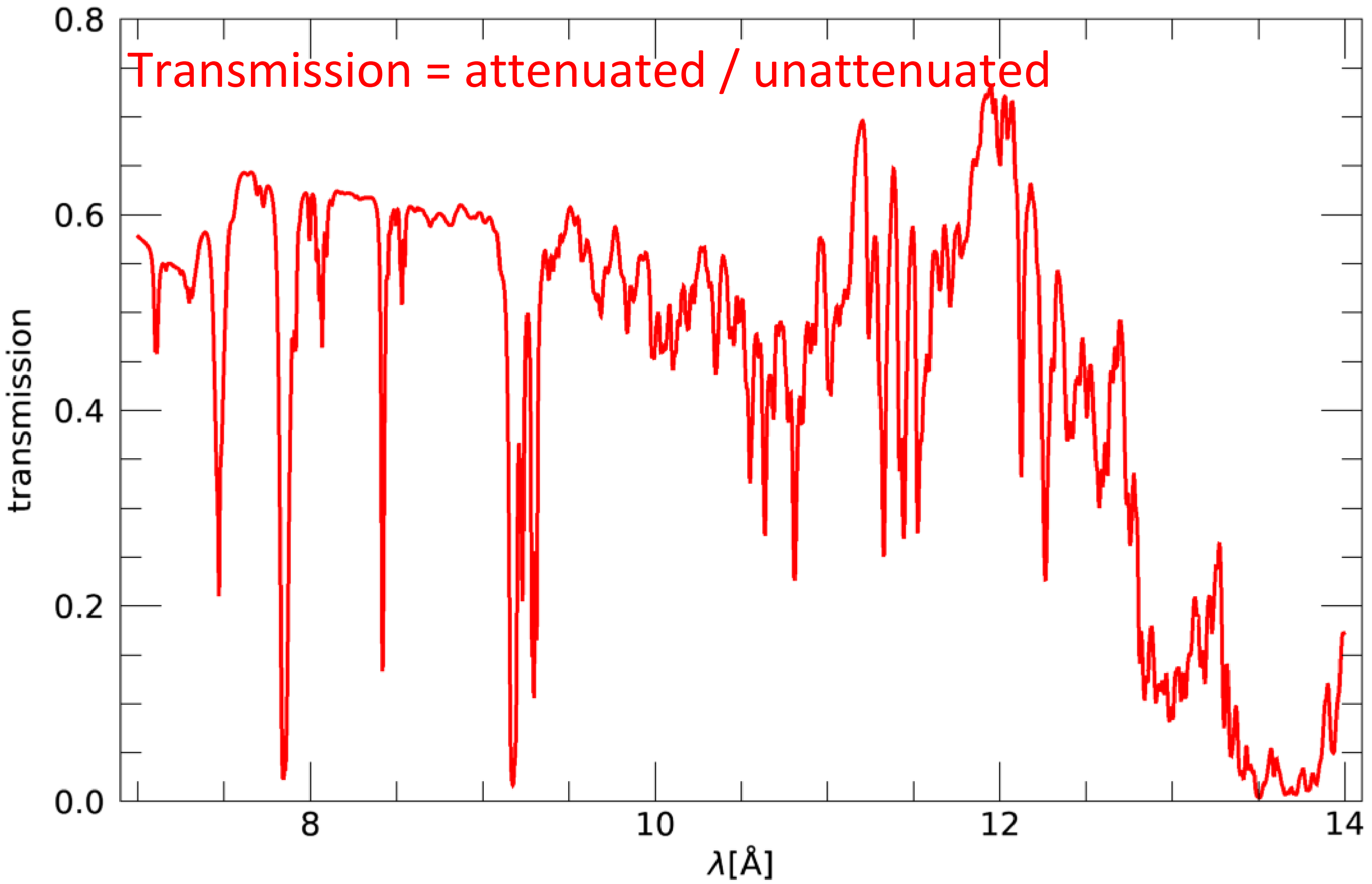
****ATOMIC**: Fontes et al., *J. Phys. B* **48** (2015)

With the film-integrated unattenuated spectrum…



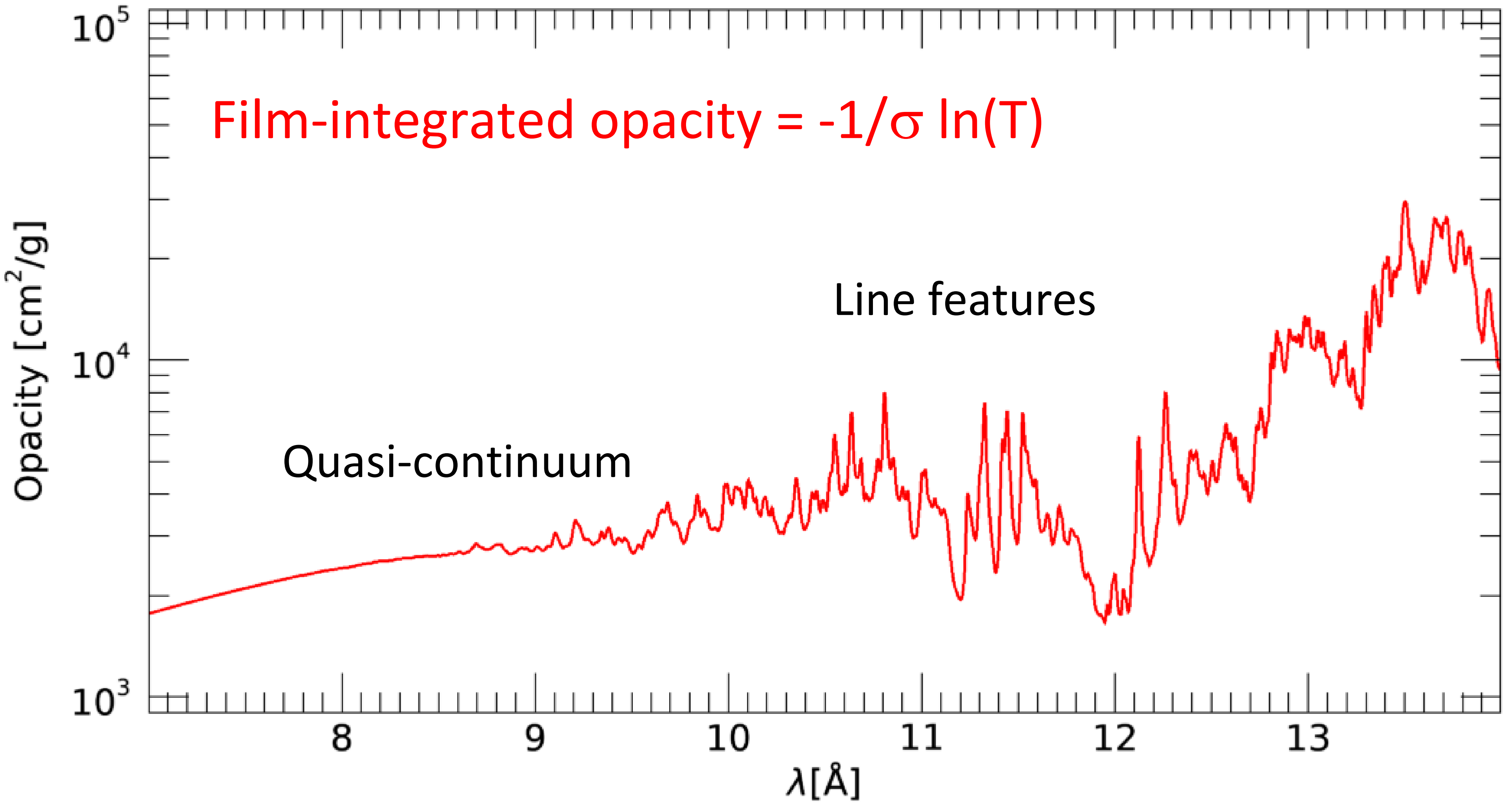
ATOMIC: Fontes et al., *J. Phys. B* **48** (2015)

… we can form the film-integrated transmission



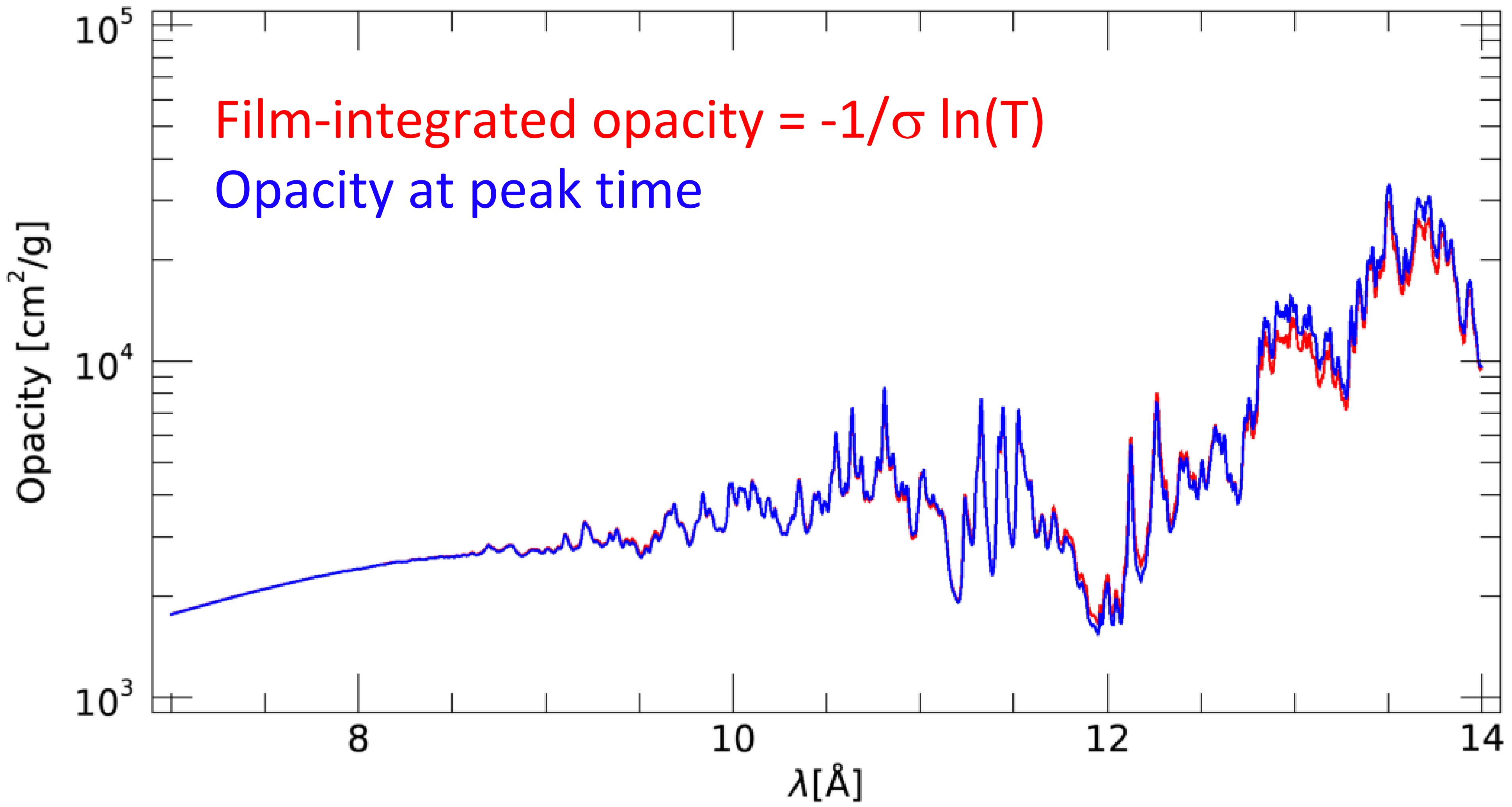
ATOMIC: Fontes et al., *J. Phys. B* **48** (2015)

Then converted into opacity



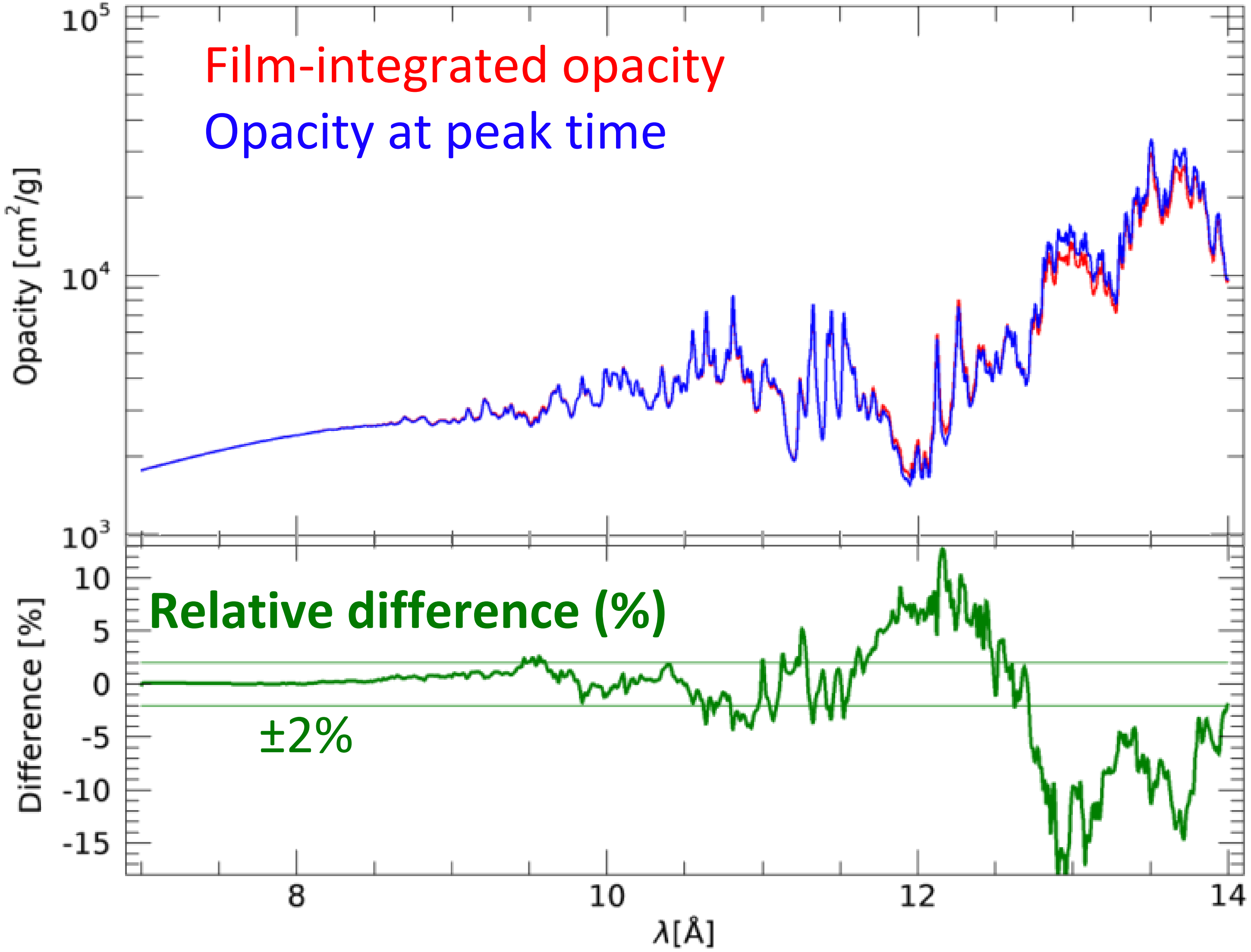
ATOMIC: Fontes et al., *J. Phys. B* **48** (2015)

And compared to single-time opacity to evaluate temporal integration effects



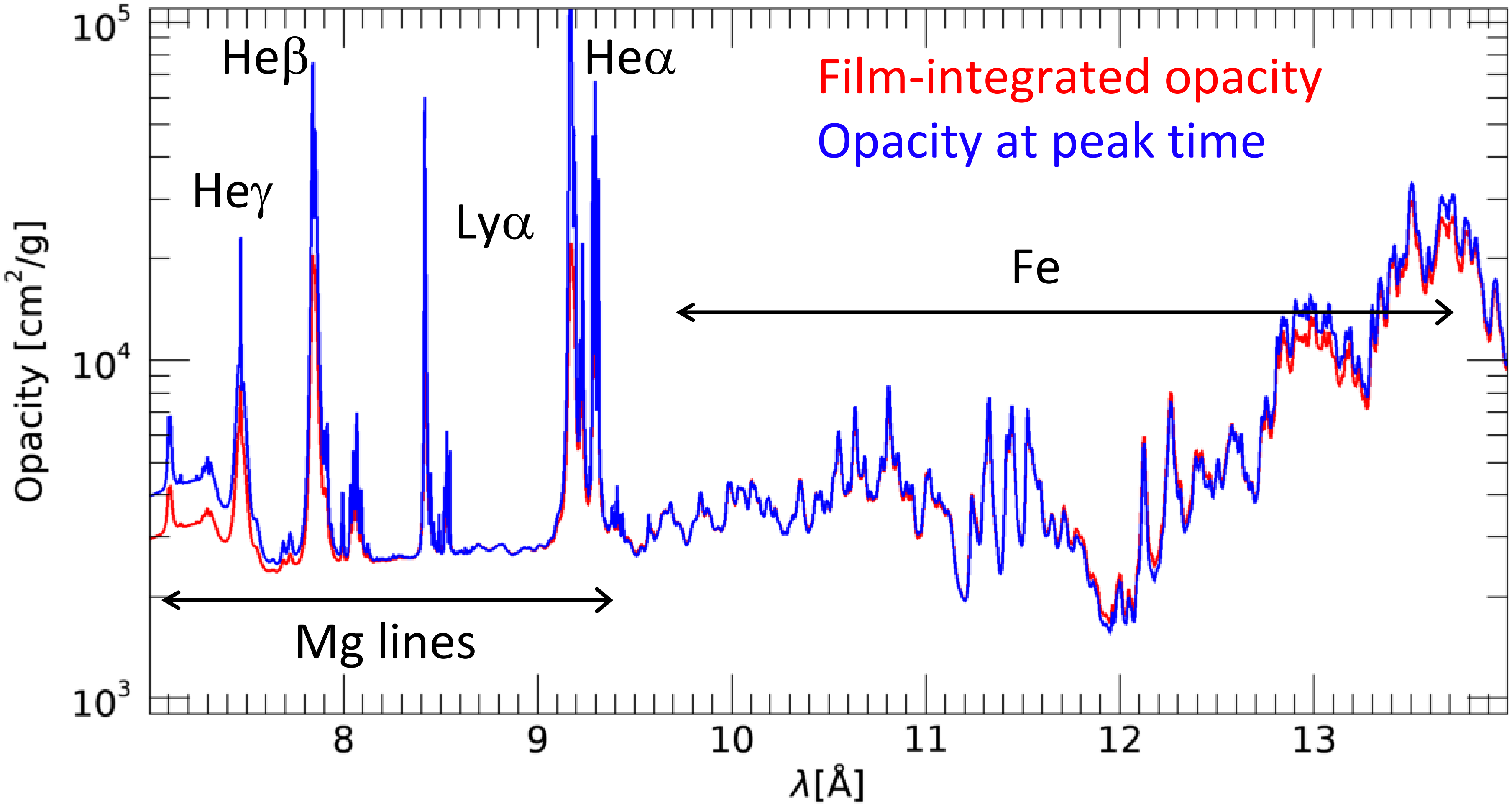
ATOMIC: Fontes et al., *J. Phys. B* **48** (2015)

Because of gaussian backlighter history, film-integrated opacity is close to opacity at peak time



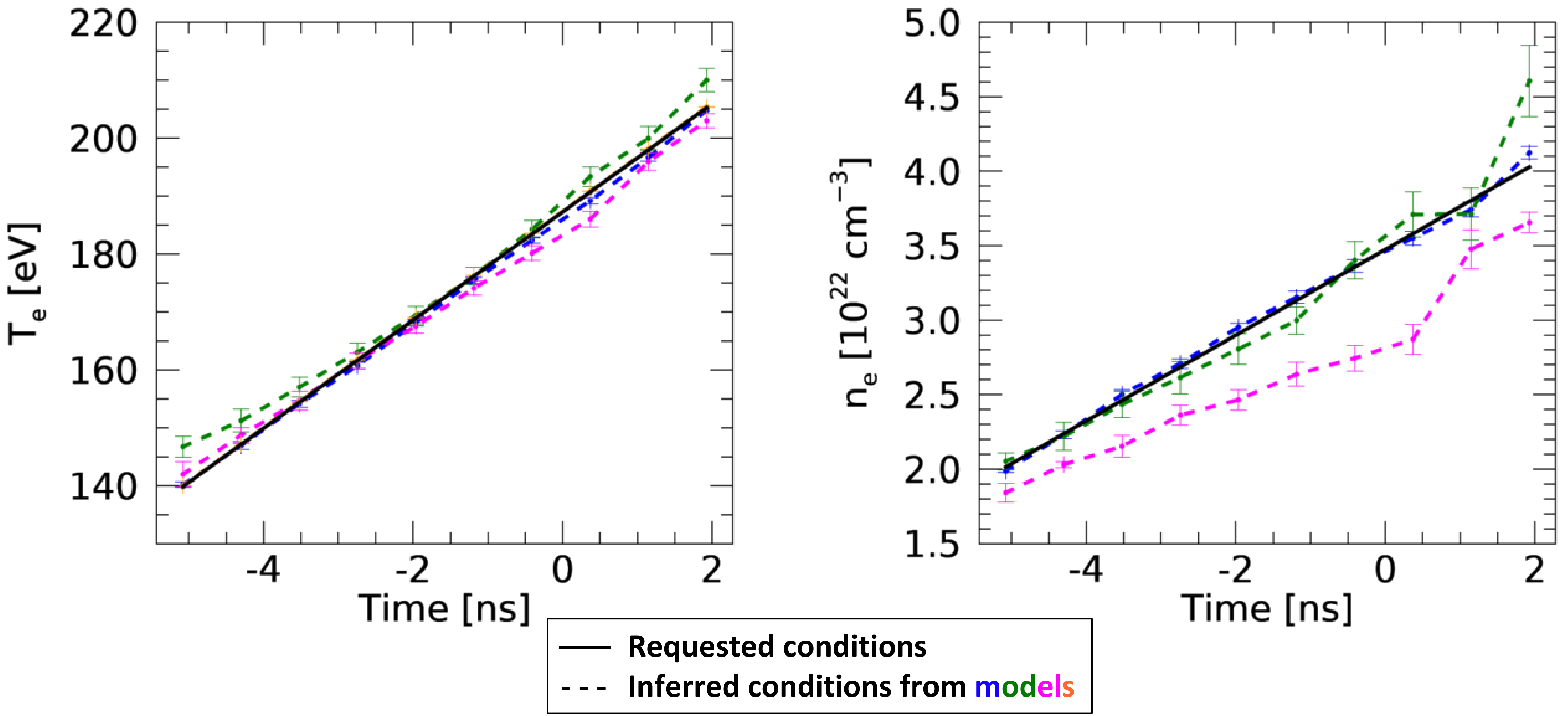
- Less than 2% difference in quasi-continuum and 10% above 11 Å.
- Need to improve this study using the measured time-dependent spectral shape (from tamper-only shots)
- We need to assess the effect with actual measurements.

Same synthetic study can be done adding Mg absorption



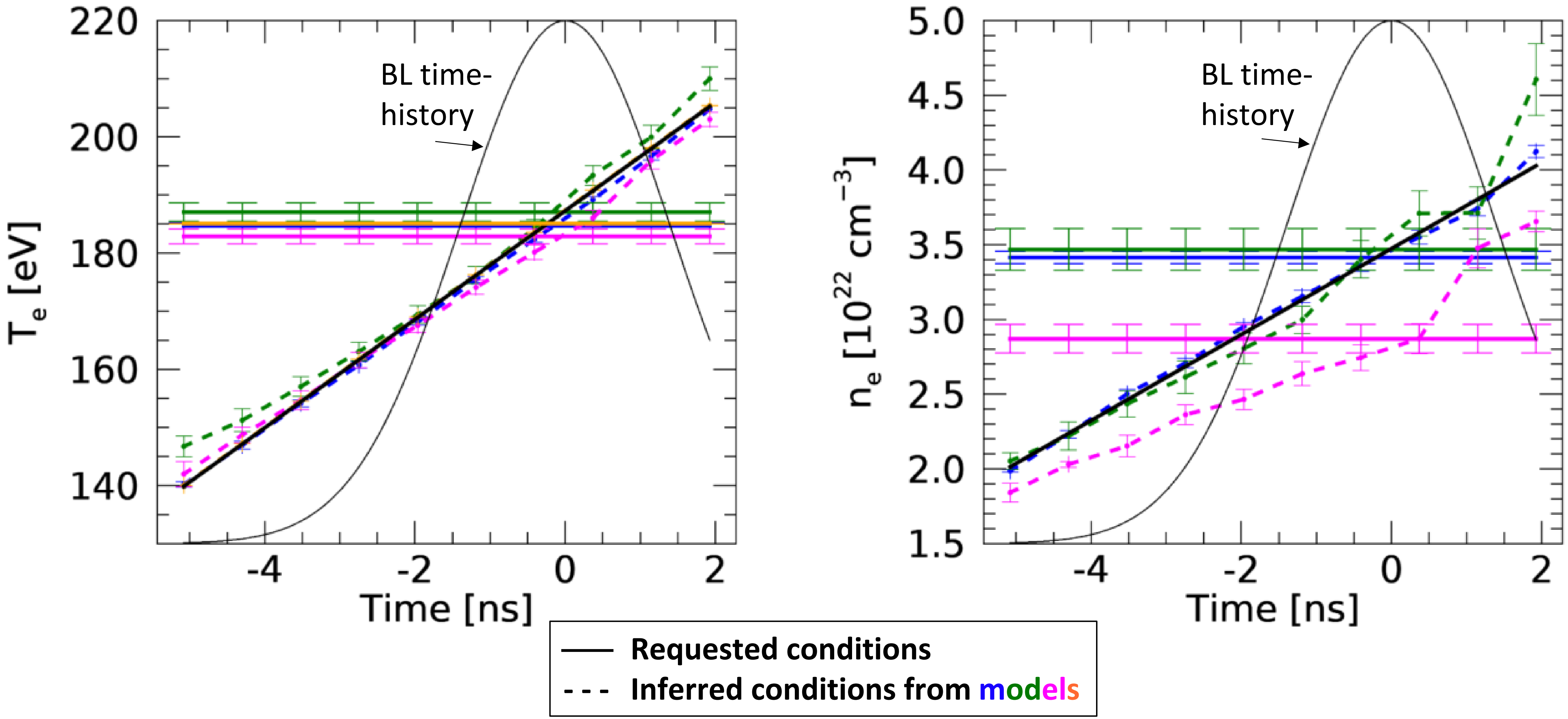
What is the effect on film inferred conditions?

Synthetic spectra were converted into line transmission and conditions were inferred



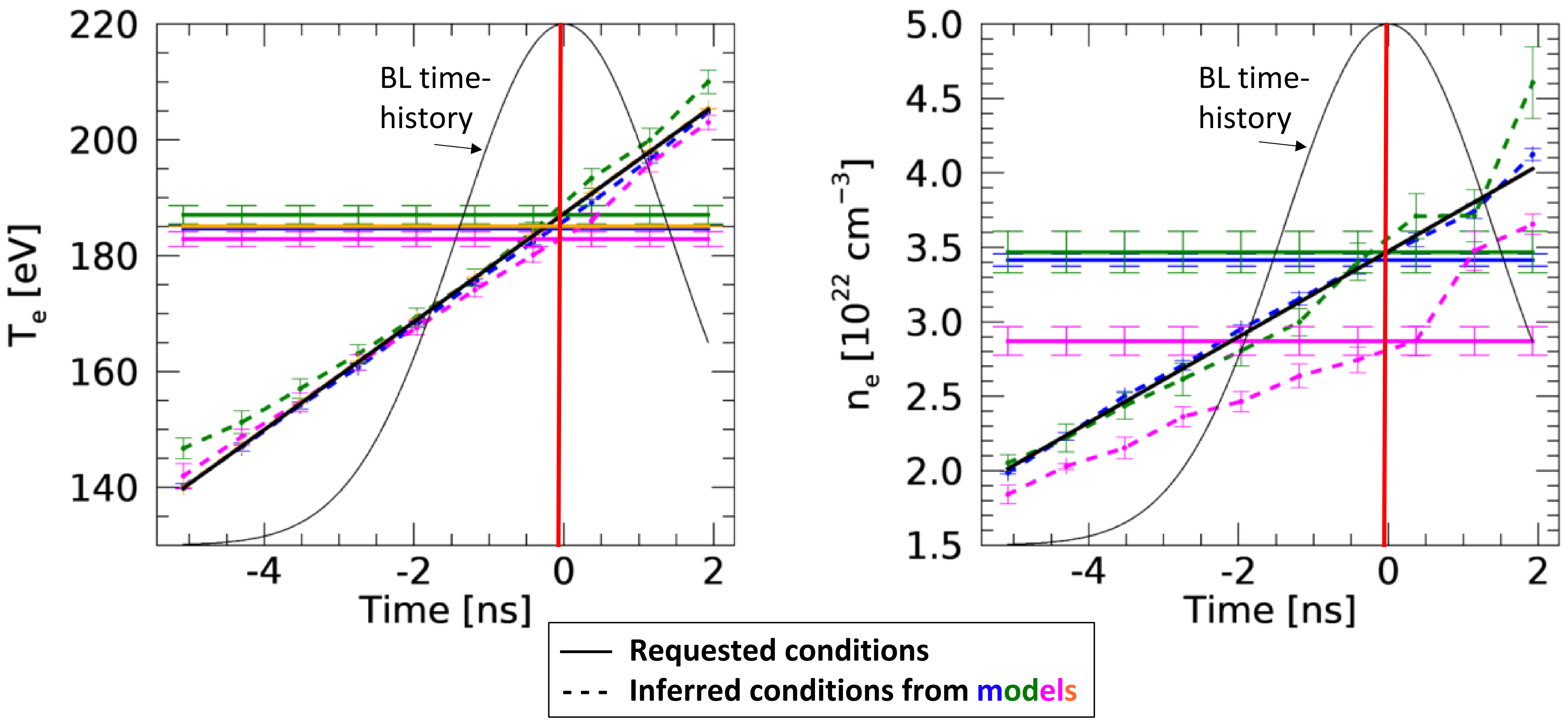
When fitting the time-resolved spectra, the codes return similar values close to the original values

And similarly on the film-integrated spectrum



Models = ATOMIC, SCO-RCG, OPUS-TOPAZ, PRISMSPECT

And similarly on the film-integrated spectrum



Time-integrated values roughly match the time-resolved at time of peak

Models = ATOMIC, SCO-RCG, OPUS-TOPAZ, PRISMSPECT

Time-resolved measurements can improve our opacity investigations in multiple ways

- *Understand and refine opacity experiments by measuring Te(t) and ne(t)*
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  → Line broadening
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  → Multiple opacity measurements over different T_e, n_e within a single experiment

Absolute opacity measurements

The requirements are more stringent for measuring time-resolved opacity $\kappa_\upsilon(t)$ than sample conditions $n_e(t)$, $T_e(t)$

opacity $\kappa_\upsilon(t)$ requirements

- Typical requirements for opacity measurement:

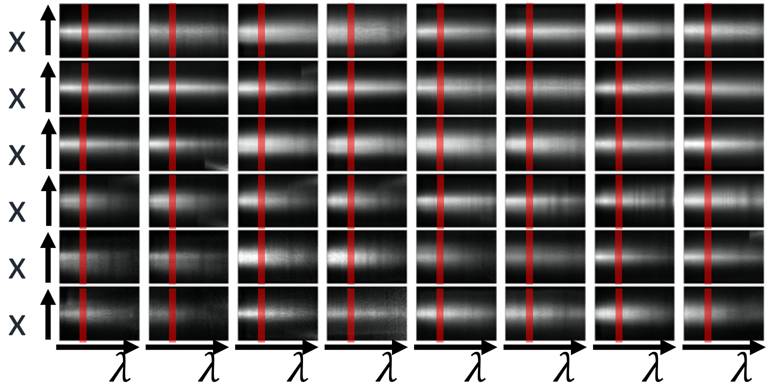
Bailey *et al.*, *PoP*, **16** (2009)

- uniformity
- freedom from self-emission, background
- multiple areal densities
- measured plasma conditions
- reproducibility demonstrated
- …

- Accurate ***absolute*** transmission measurements

→ *requires tamper-only statistics for accurate analysis*

48 spectral images from 12 calibration shots → unatt. statistics



→ Evaluate how many to repeat due to spatial-distribution temporal variation

$n_e(t)$, $T_e(t)$ requirements

- Accurate Mg ***line*** transmission measured
  - high S/N absorption spectrum
  - linear photon intensity
  - avoiding line saturation
  - reproducibility demonstrated
- Multiple time-steps to observe actual evolution
- Inference using fitting techniques to line transmission

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opacity $\kappa_\upsilon(t)$ requirements

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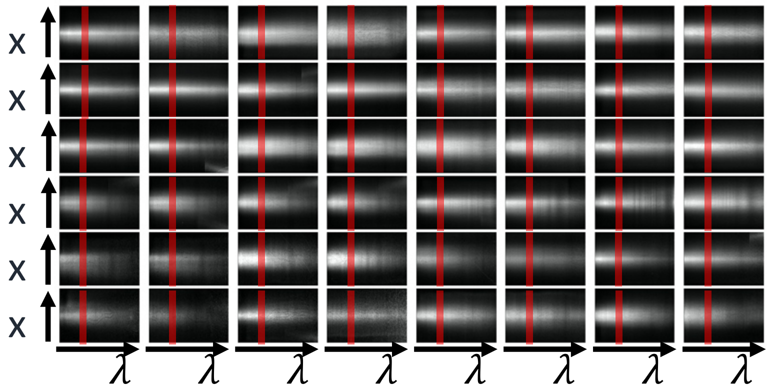
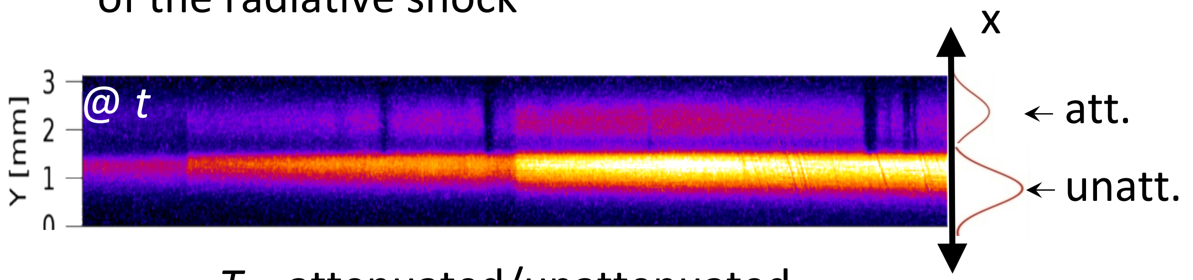


→ Evaluate how many to repeat due to spatial-distribution temporal variation

Preliminary analysis strategy:

1) Use quantified symmetry of the unatt. vs att. sides of the radiative shock



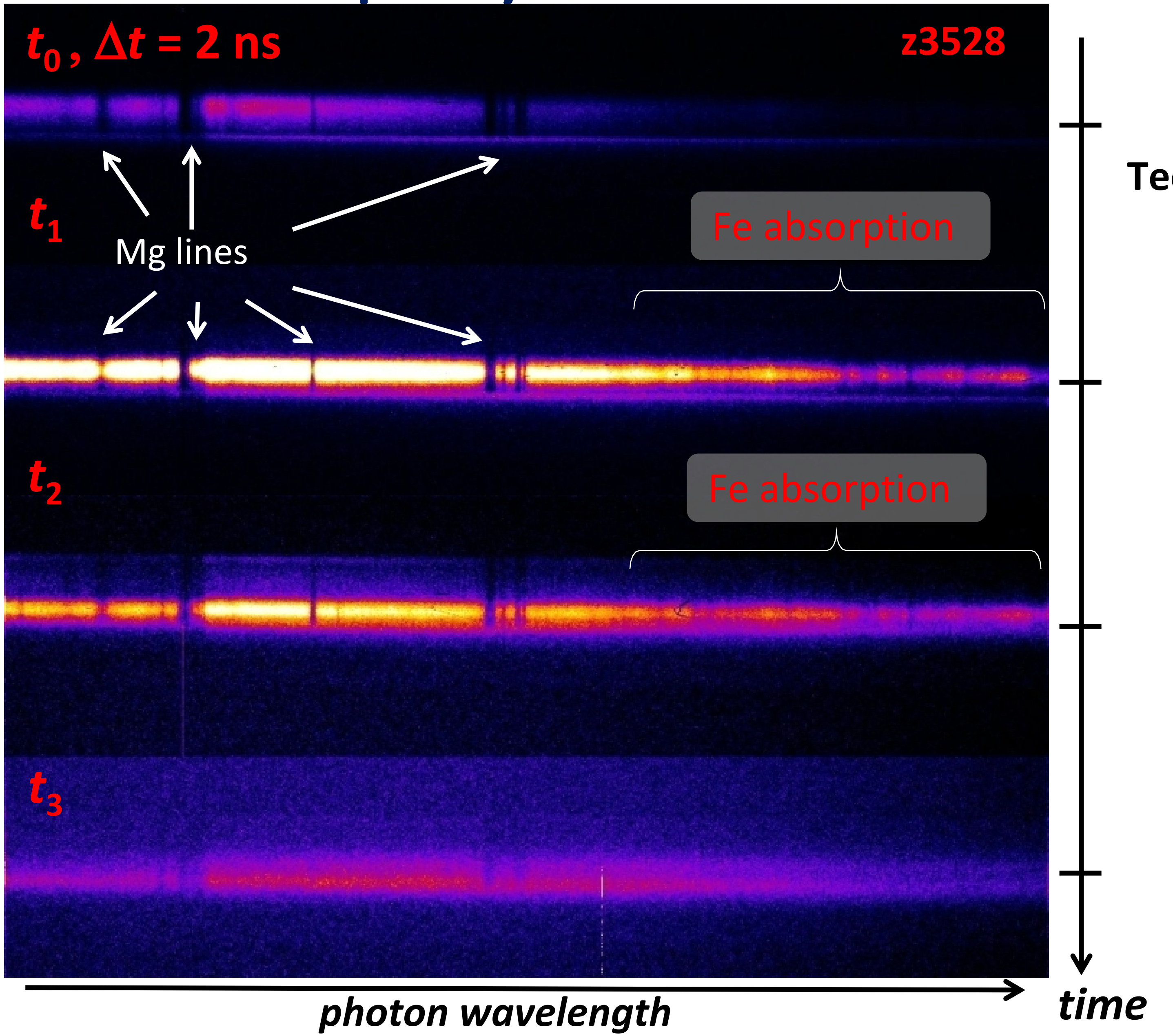
T = attenuated/unattenuated

But how asymmetric is the backlighter spatial distribution between the attenuated and unattenuated sides?

2) Collect calibration shots to obtain symmetry statistics

→ Measuring absolute opacity requires calibration shots (BL) at enough time-steps

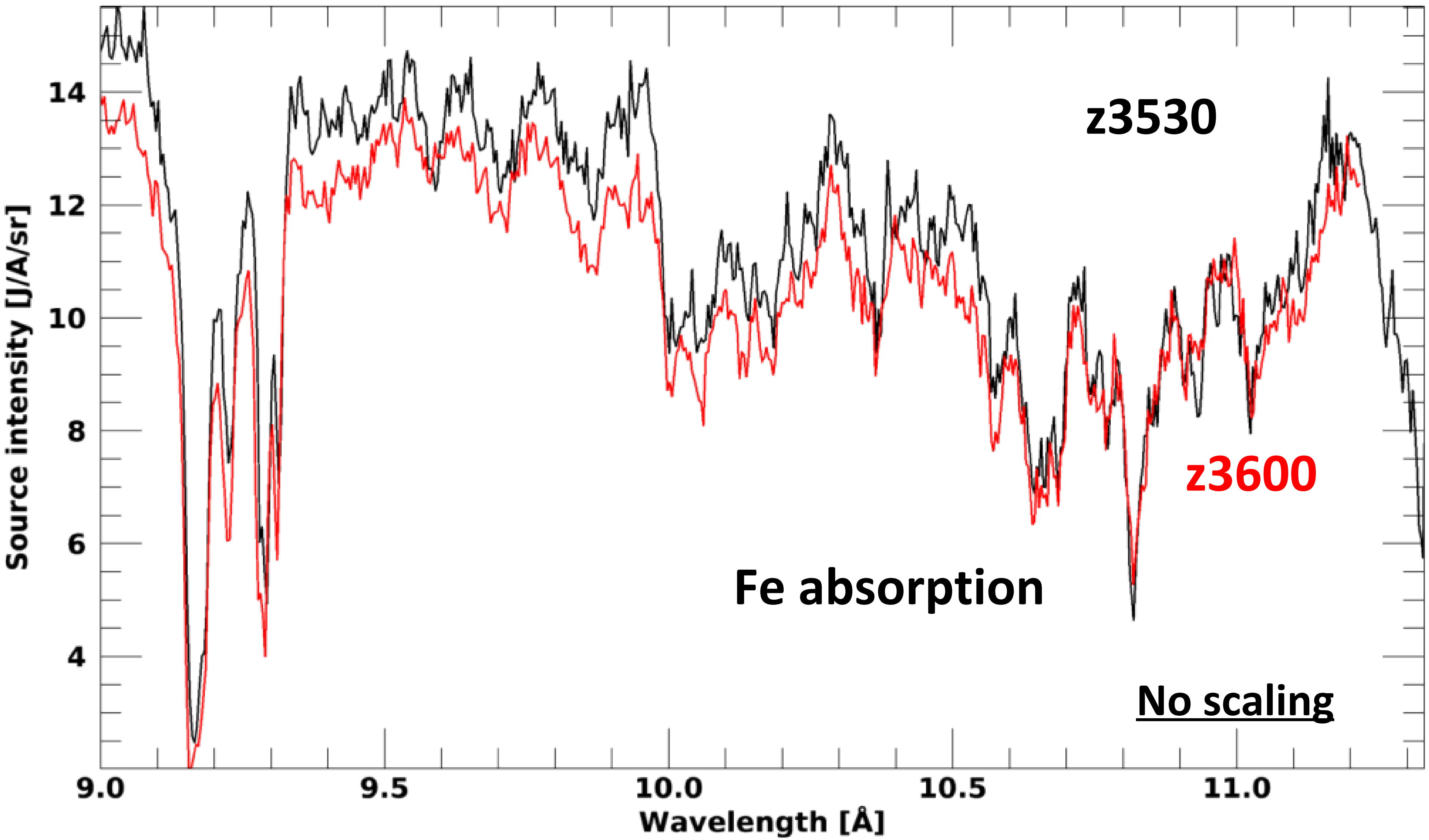
We have started to measure data for time-dependent absolute opacity measurements



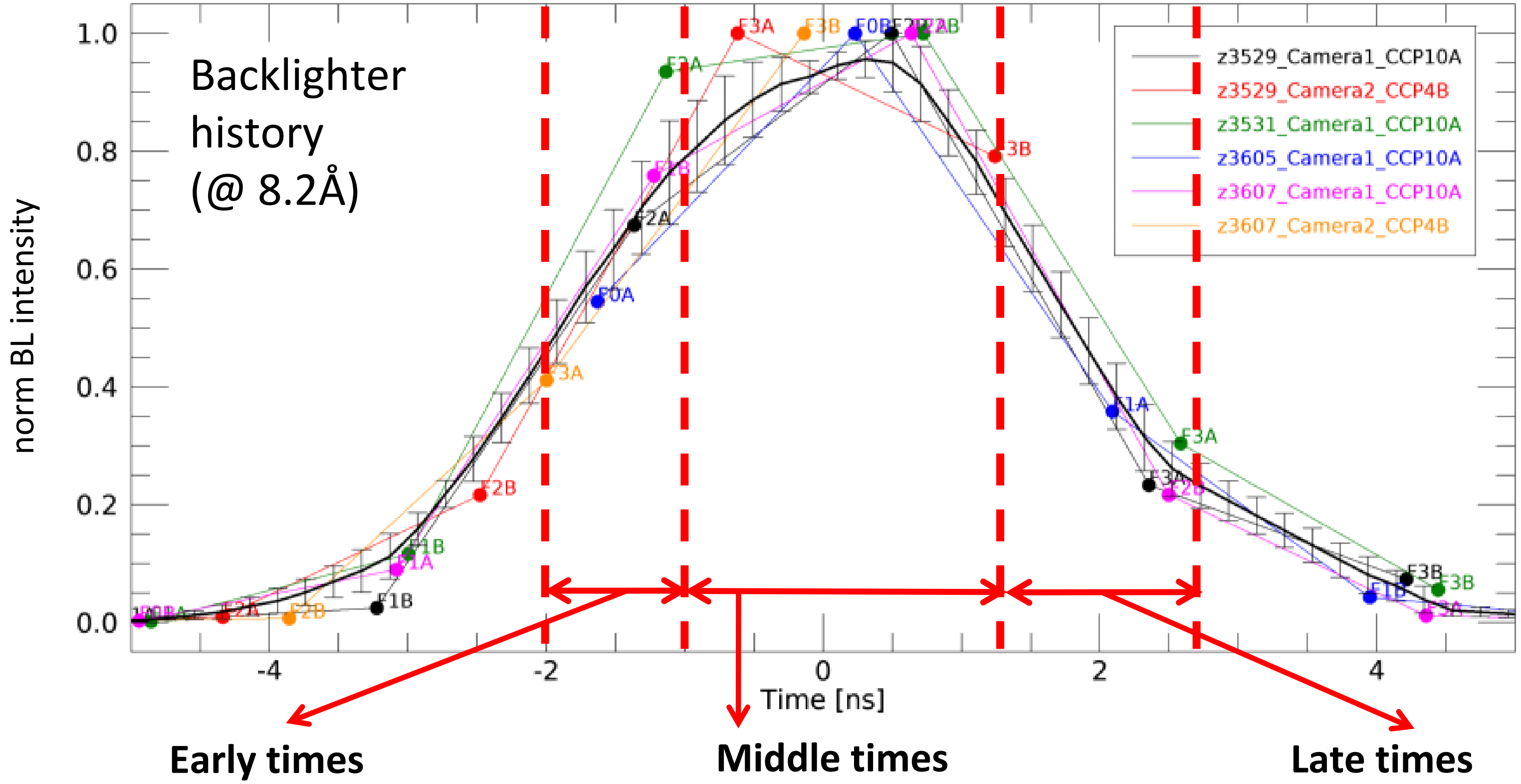
Technical obstacles:

- EMP issues, electronics failure, timing
- debris amount in -9º instruments

Initial reproducibility has been observed and is encouraging



We are assessing the evolution of the backlighter spectra



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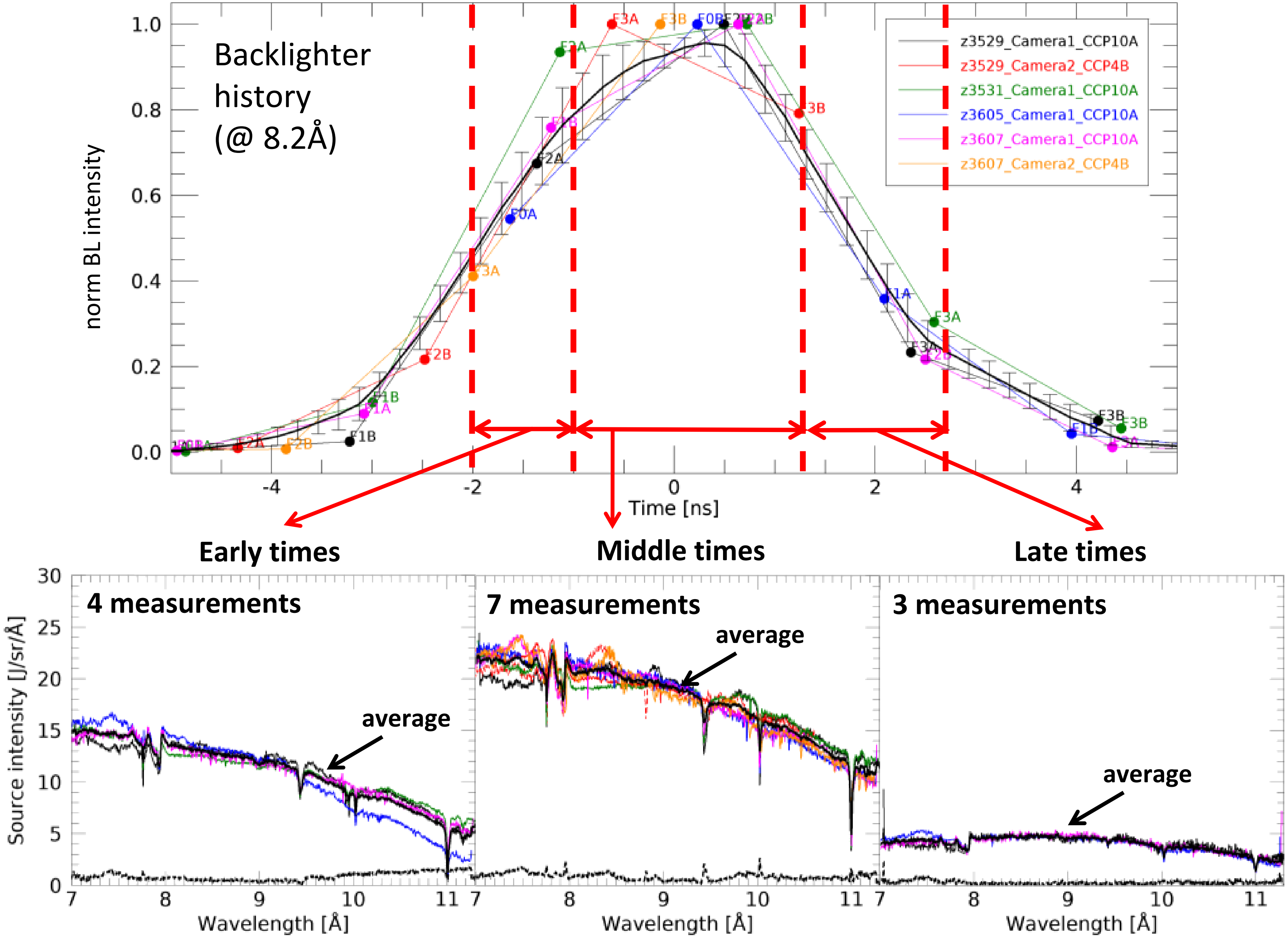

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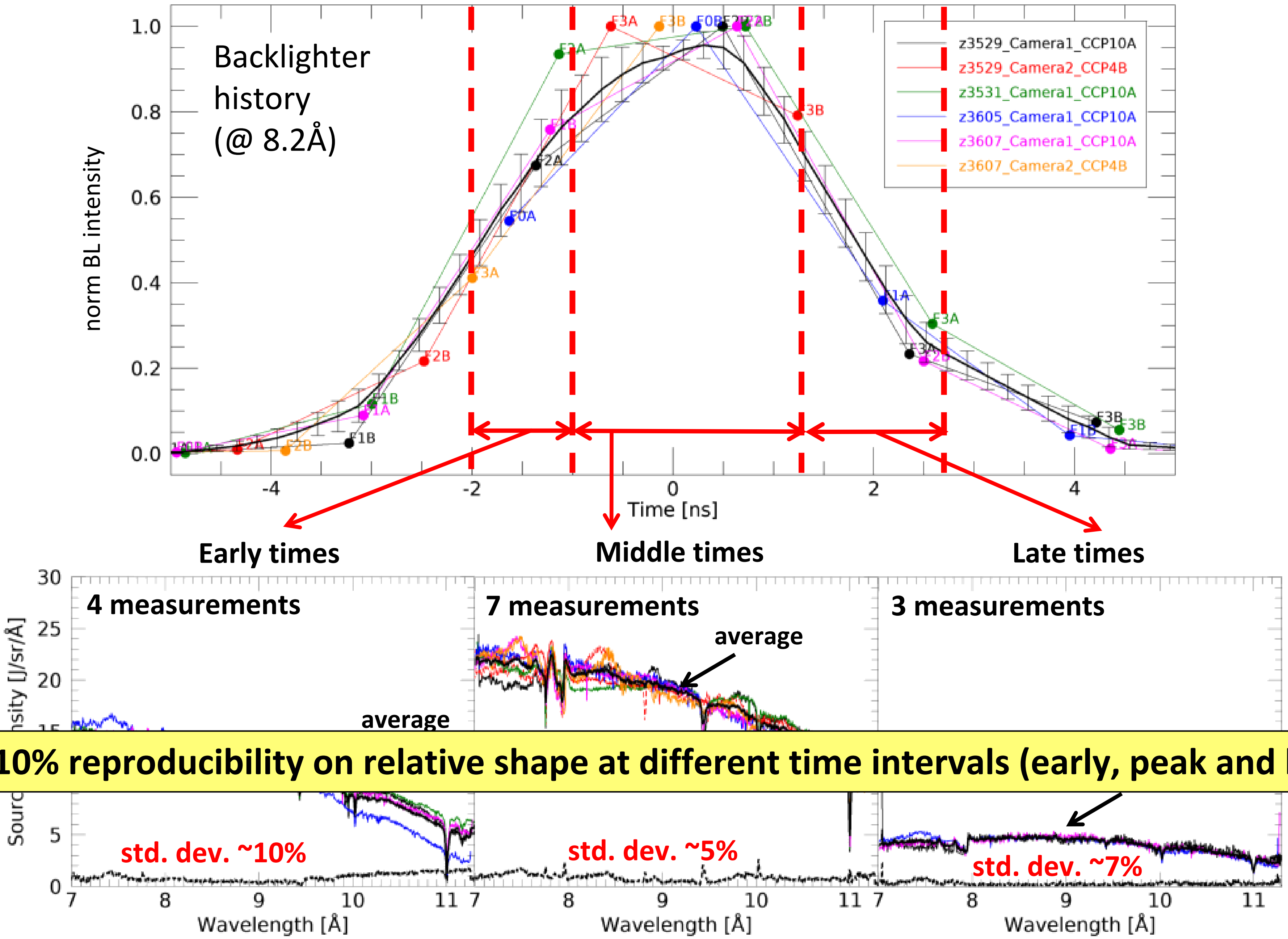
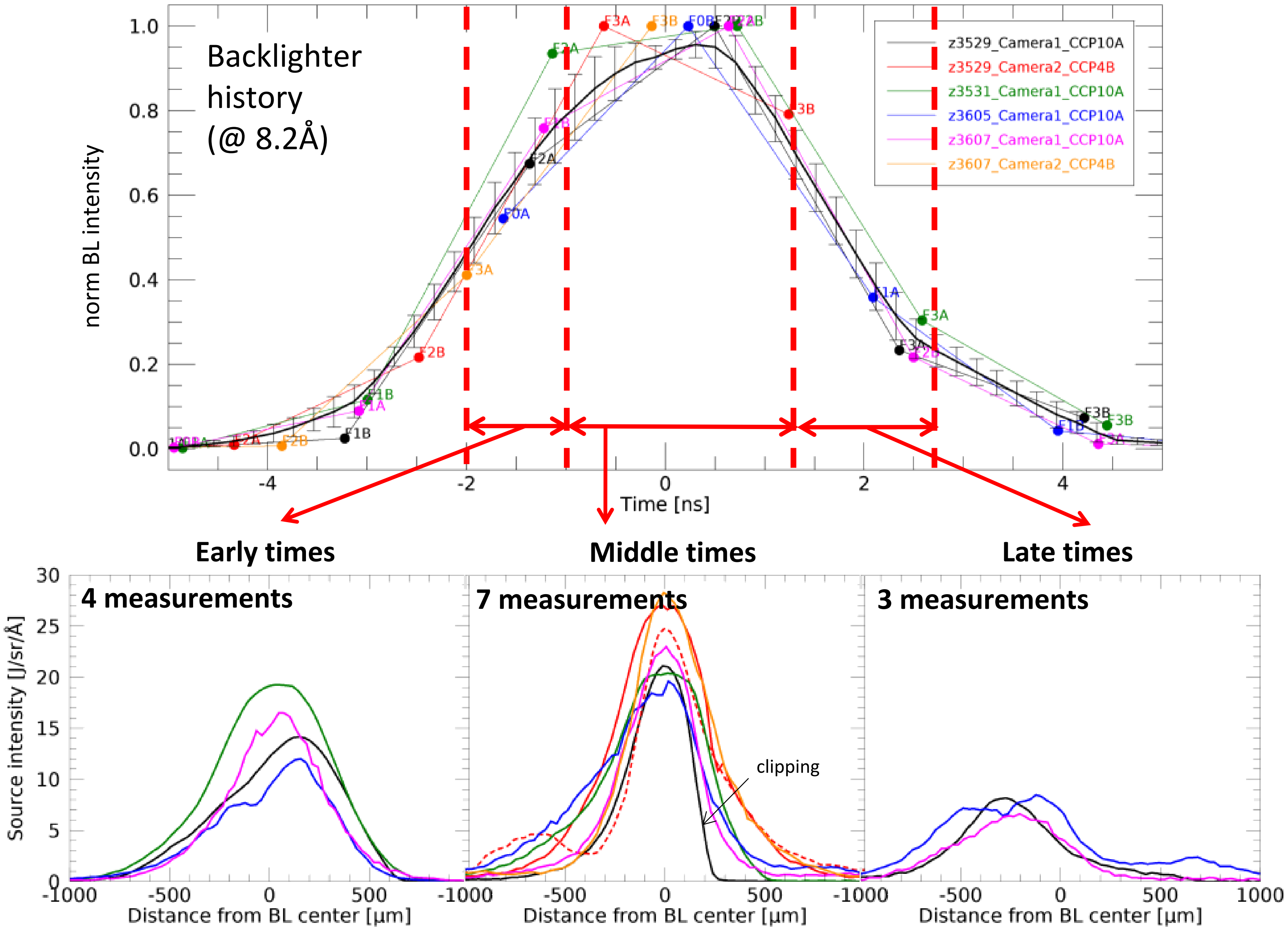
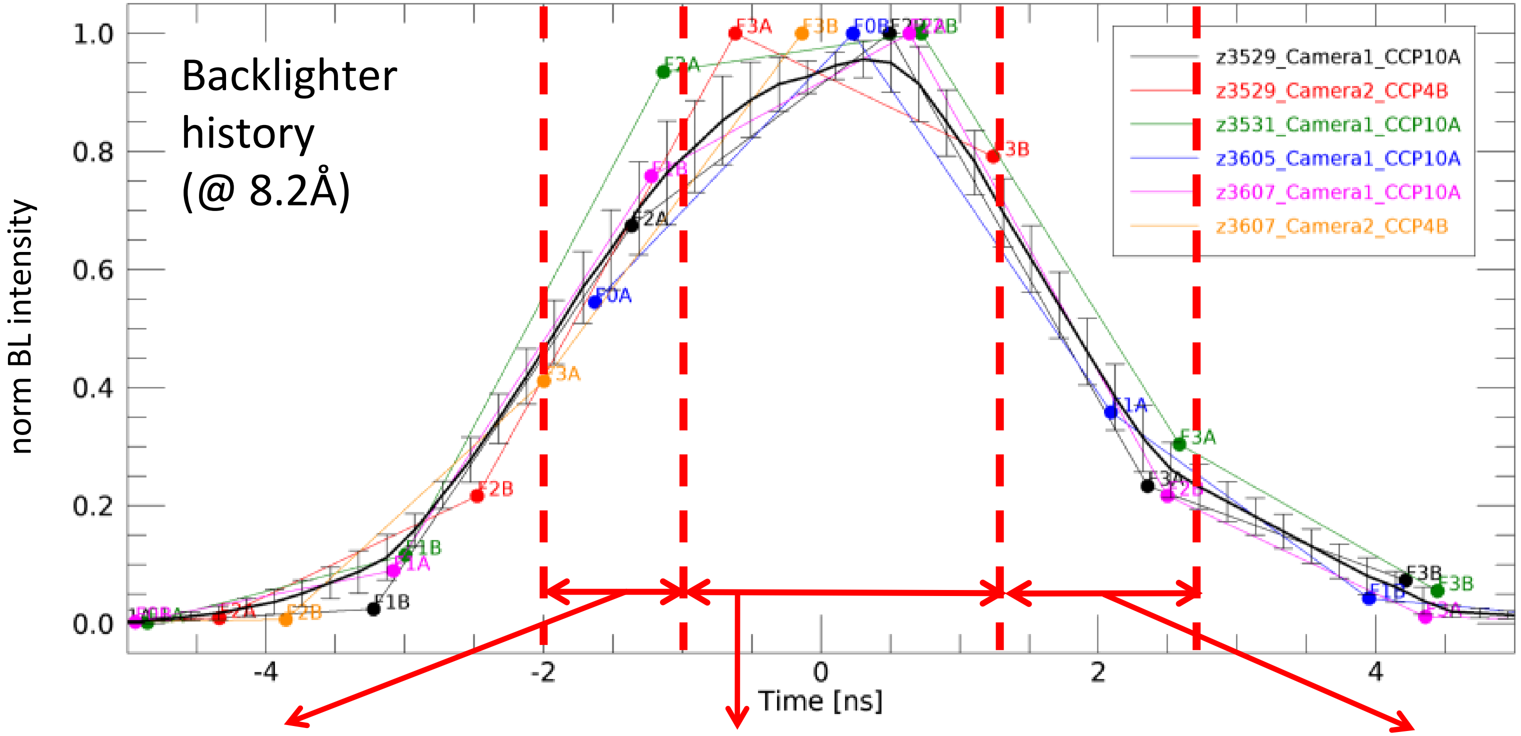


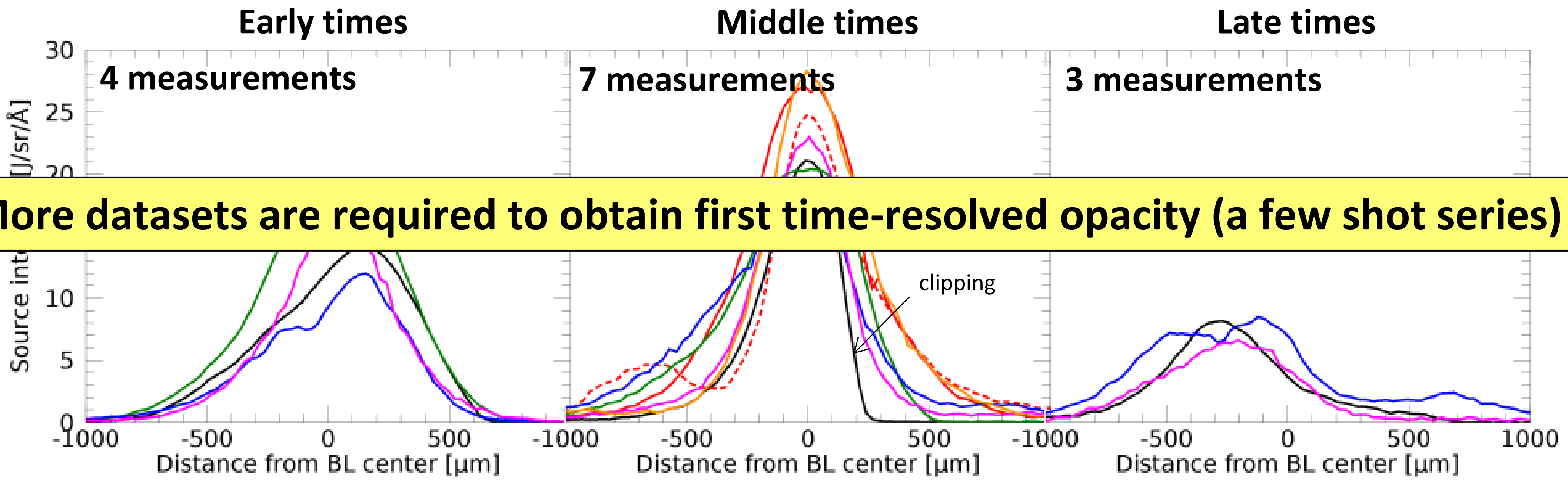
➢ **5-10% reproducibility on relative shape at different time intervals (early, peak and late)**

… and assessing backlighter spatial distribution vs time



… and assessing backlighter spatial distribution vs time





➢ **More datasets are required to obtain first time-resolved opacity (a few shot series)**

The Z opacity research presents future exciting opportunities

Fe opacity from film-based measurements

- Update statistical analysis techniques and report
- Include additional ~20 datasets

Tai Nagayama
Tue JO06.00003

Time-resolved opacity

- Finalize condition analysis using new algorithm
- Evaluate importance of time-dependent effects on previously reported data
- Finalize dataset collection for first absolute opacity measurements time-resolved
- Request support for shorter duration measurements (~1ns) - Daedalus

Oxygen opacity

- Finalize oxygen measurements for accurate O opacity
- Finalize oxygen platform condition analysis
- Time-resolved measurements

Dan Mayes
Tue JO06.00004

High-density opacity

- Optimize preheat suppression idea to reach highest density ever ~10^{23} e^-/cc (CZB) – most anticipated stress on models

Cross-comparison effort with NIF opacity

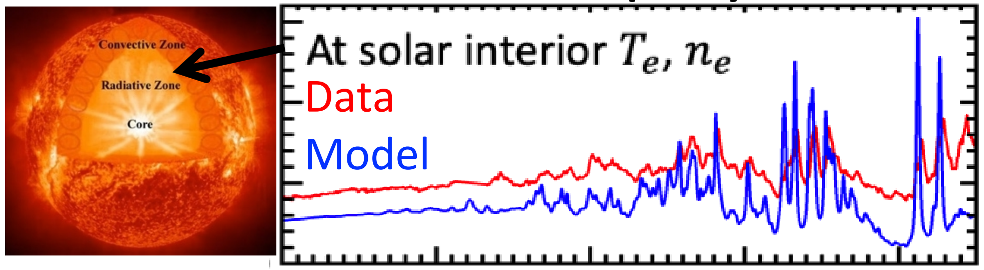
- Fe opacity, define comparison technique
- Anchor 0 (150eV , 3 10^{23} e^-/cc) opacity
- Oxygen opacity, time-resolved

Ted Perry
Mo CO06.00004
Heather Jones
Mo CO06.00003

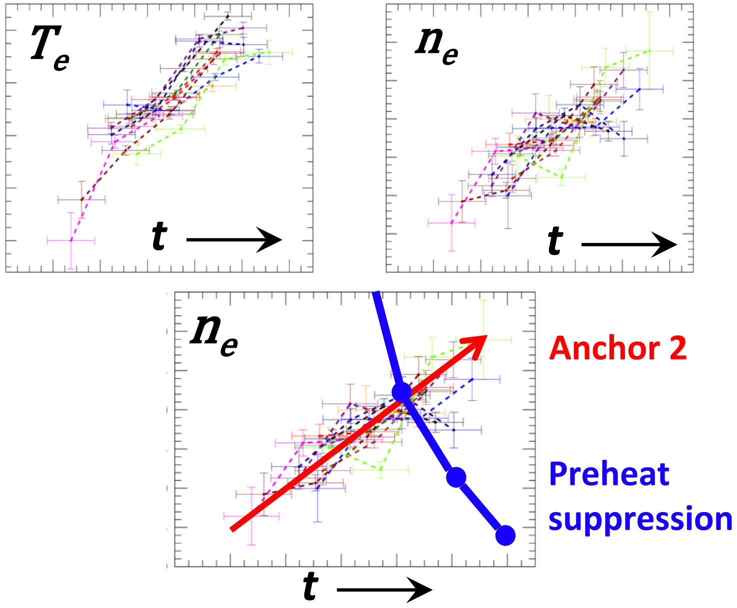
Executive summary: Time-resolution transforms opacity research on Z to advance HED physics and astrophysics

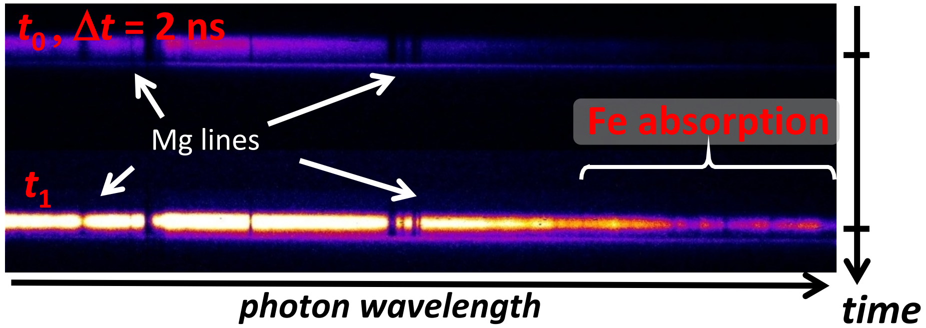
- **The solar problem still exists**
  - → Helioseismology ≠ solar models predictions
- **Fe L-shell opacity was measured at solar interior conditions and revealed severe model-data discrepancy**
- **While theoretical refinements are studied, experimental scrutiny is underway**
  - → test of time-dependent effects
- **Opacity sample evolution was measured using novel UXI technology**
  - → Challenge our picture of how the experiment works
- **Time-resolved measurements also increase knowledge and parameter space of the Z opacity platform**
  - →Preheat suppression test shows path for novel high density regime
- **Temporal gradient effect are synthetically investigated**
- **Absolute time-resolved opacity measurements are underway**

Anchor 2 Fe opacity



Anchor 2 Fe evolution





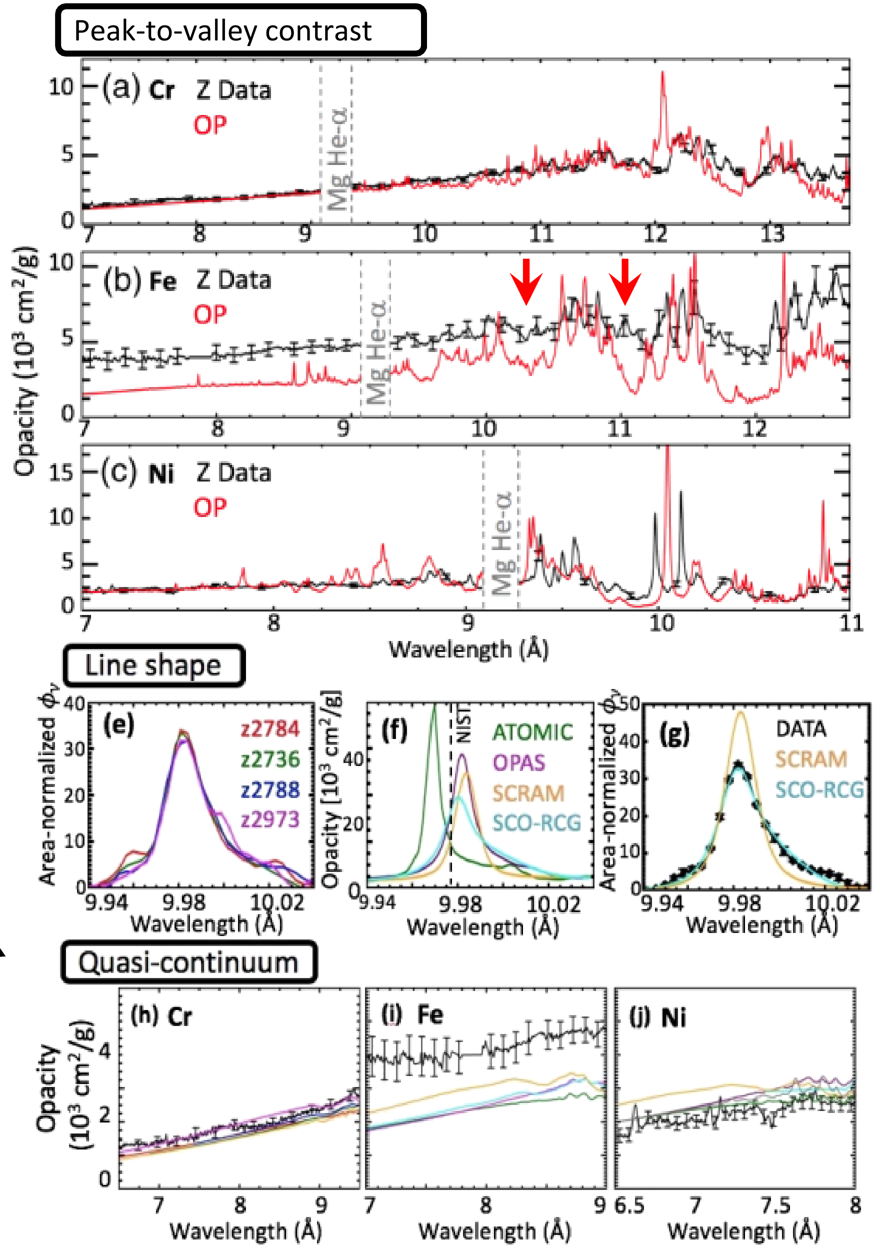
BACK-UP SLIDES

We are now poised to measure time-dependent absolute opacity

Why is it important?

We could test

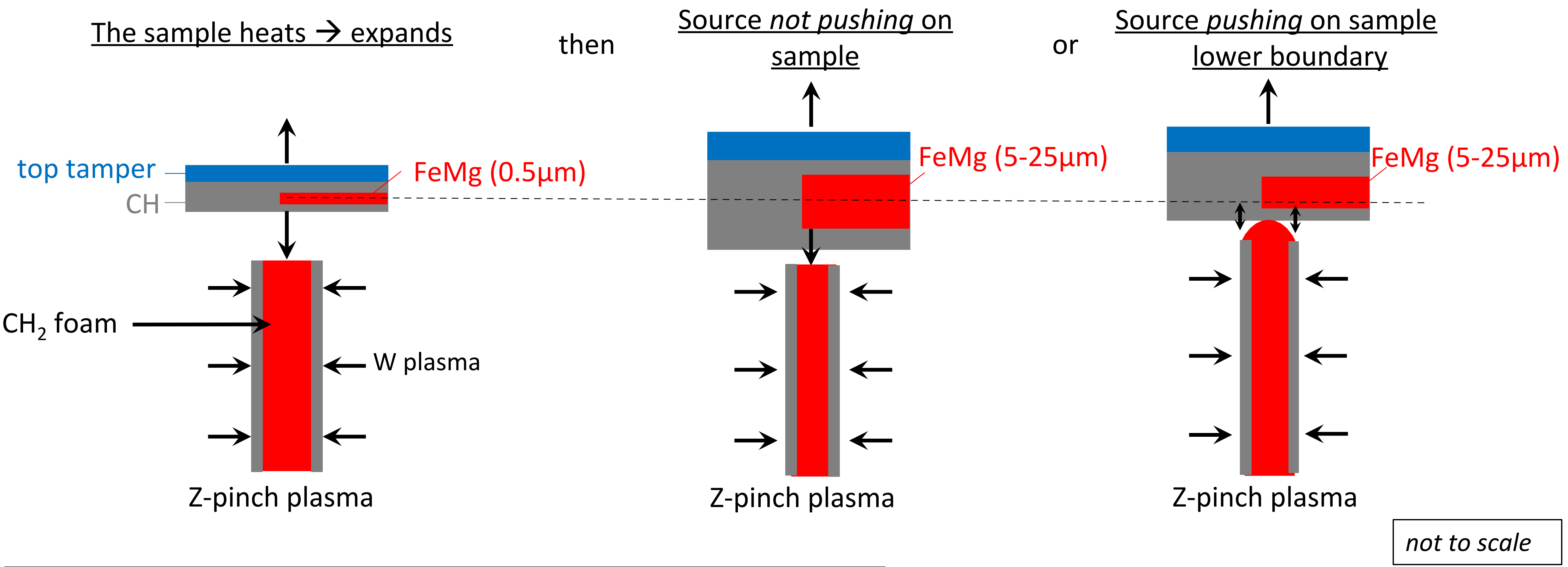
- peak-to-valley contrast in Fe opacity
- line shapes discrepancies
- quasi-continuum?



The time-dependence on how the opacity forms will be very informative even if existing puzzles are not solved through time-gated measurements.

Nagayama et al., *PRL*, **122** (2019)

The tamper mass controls sample expansion and density

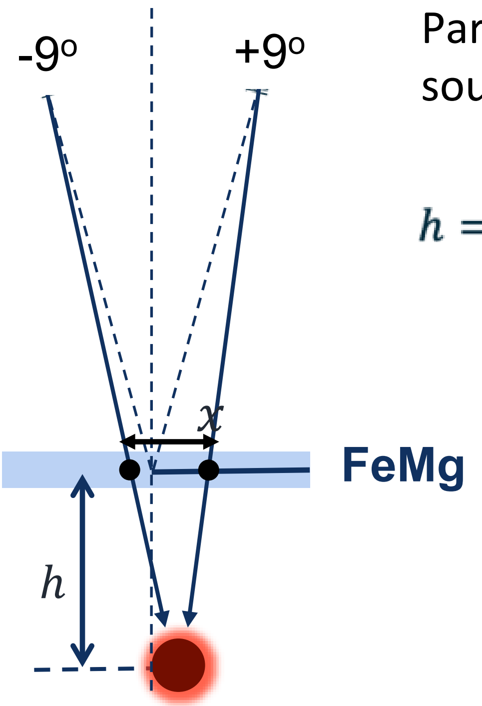


Expansion, therefore density, at backlighter peak depends on:

- **top tamper thickness**
- **bottom plasma pressure**
- **potential preheat**

Nagayama *et al.*, *PRE*, **93**, (2016)

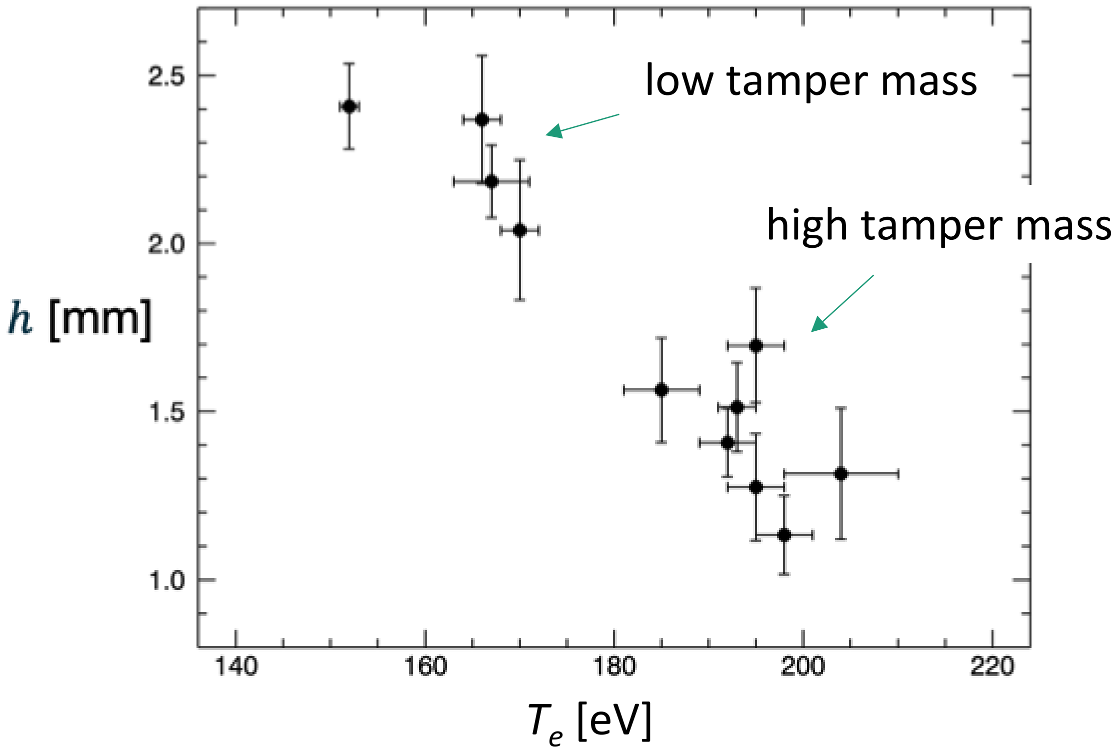
Note: Parallax measurements reveal sample temperature is closely related to source-to-sample distance



Parallax determines source-to-sample distance:

$$h = \frac{x}{2 \tan 9^\circ}$$

Sample gets hotter as it gets closer to the radiation source



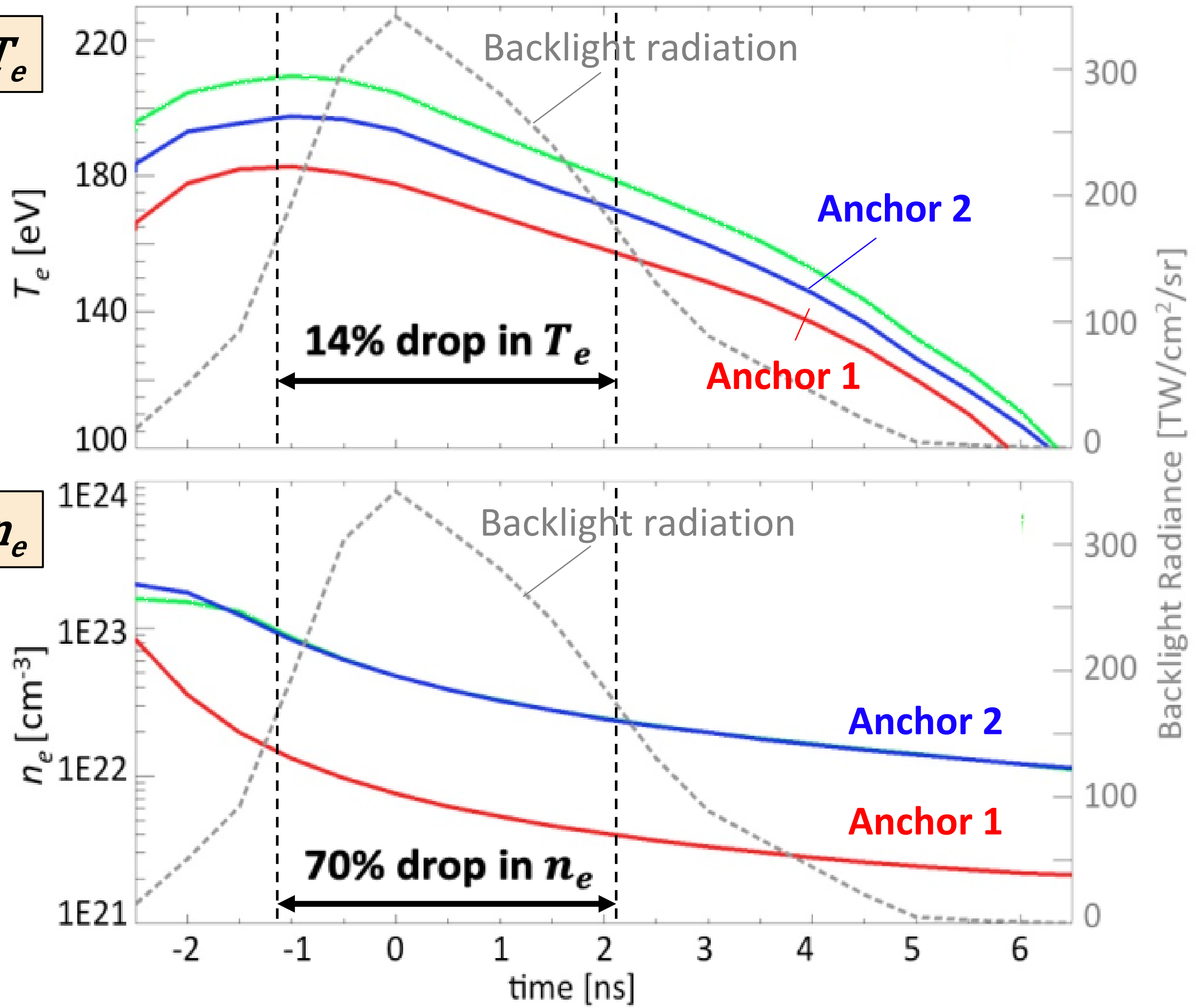
This suggests that the sample is moving upward and the amount of motion is controlled by higher tamper mass

Nagayama *et al.*, *PRE*, **93**, (2016)

Simulations results build our picture of the sample evolution

Temperature T_e

Density n_e



Our current sample evolution picture:

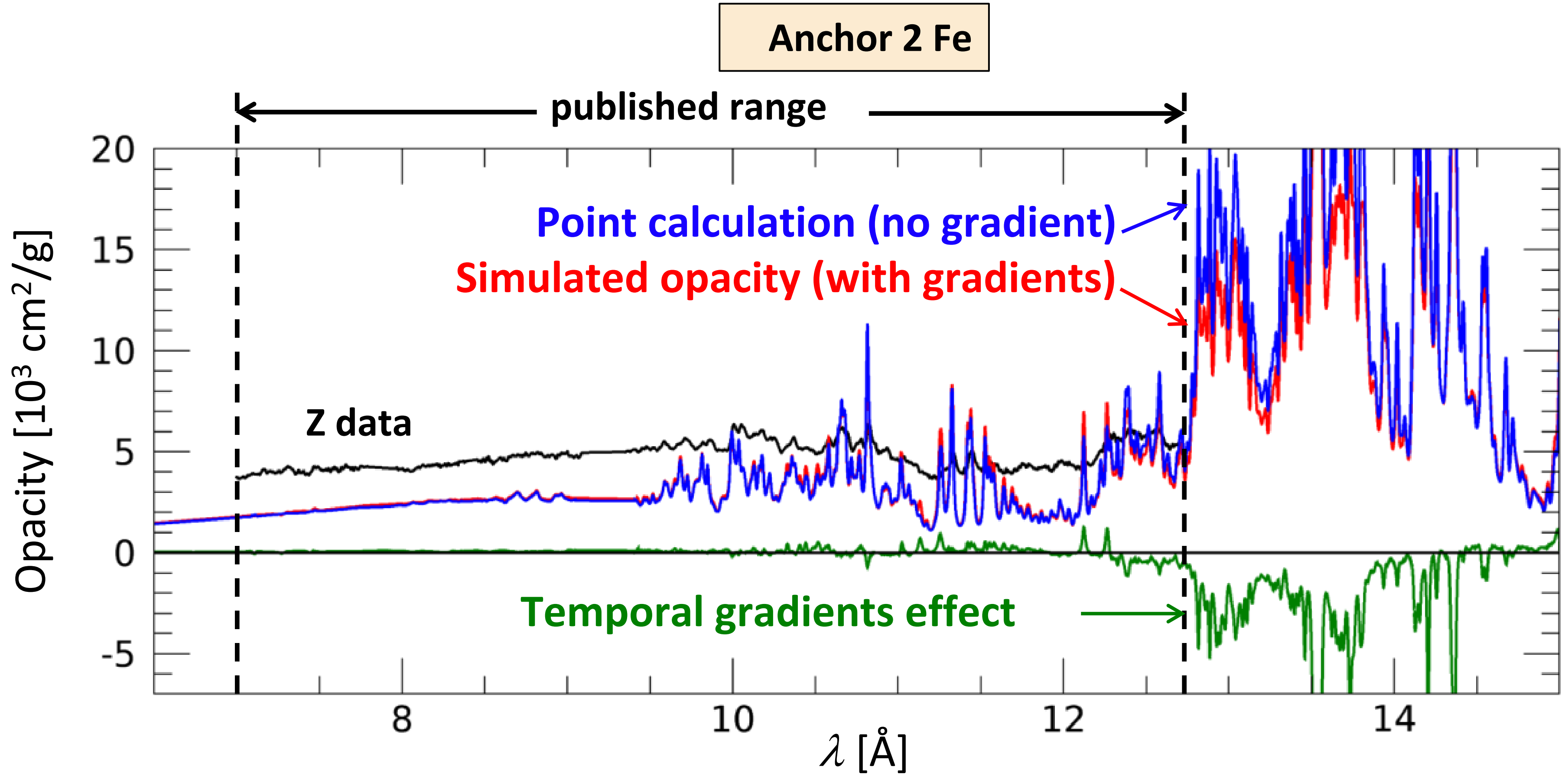
1. Temperature drops because of upward sample motion
2. Density continuously drops due to sample expansion

➢ These effects are modulated by the tamper thickness

➢ **Predicted temporal gradients in T_e , n_e over the backlight duration are concerning.**

Nagayama et al., PRE, 93 (2016), *MacFarlane et al., JQSRT, 99 (2006) & MacFarlane et al., PRE, 72 (2005)

Yet, post-processed simulations predict spectrum is unaffected[1]



- But are the simulations accurate?
  Circular argument: simulations use calculated opacity, the same quantity being experimentally tested here.
- Temporal gradients cannot be precluded without experimental evidence.

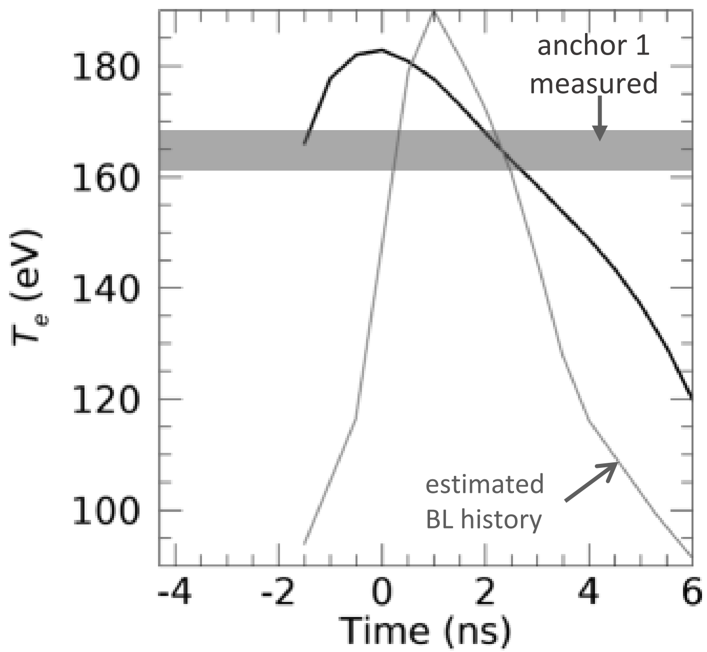
[1]Nagayama et al., PRE, 95 (2017), MacFarlane et al., HEDP, 3 (2007)

Simulations predict T_e , n_e evolution trends for anchor 1 Fe

Temperature T_e

Z data

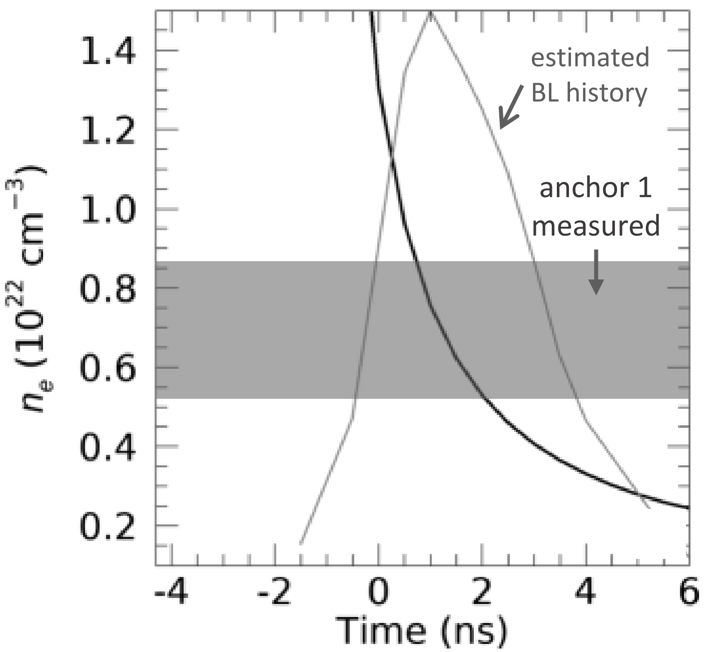
simulation*



Density n_e

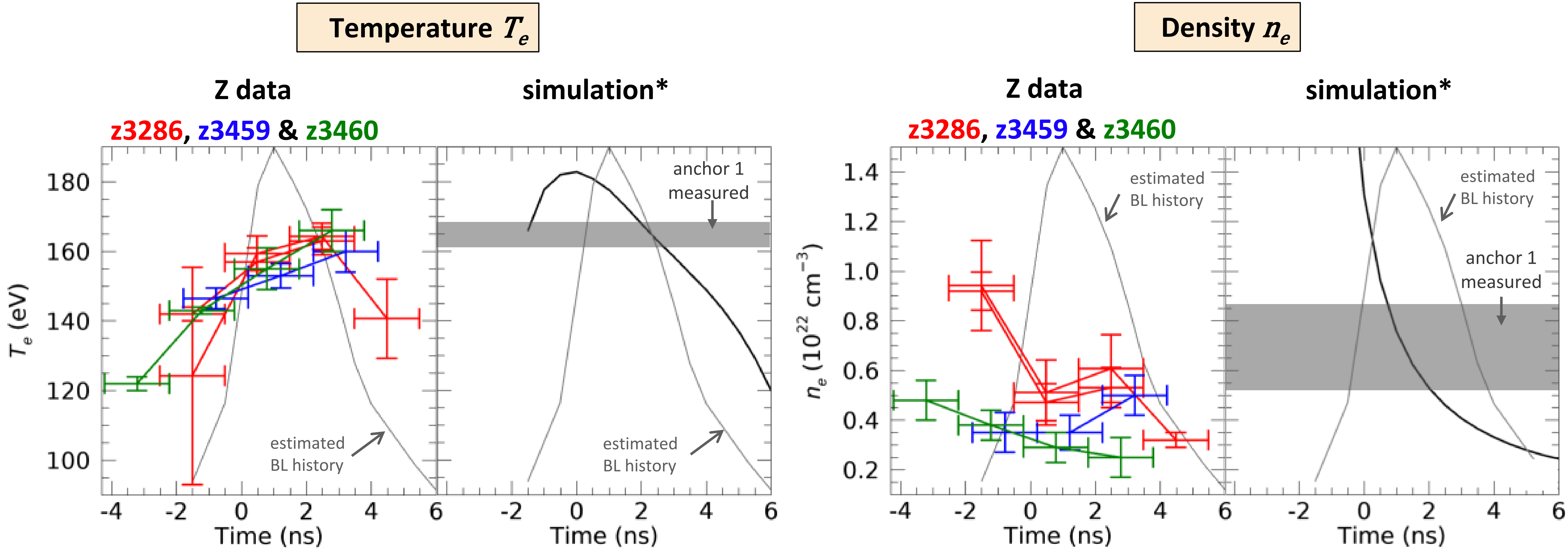
Z data

simulation*



*Nagayama et al., PRE, 93 (2016)

Anchor 1 Fe evolution shows consistent trends with predictions



➢ **Convolve simulation results with the UXI gates and backlighter history for better comparison**

*Nagayama et al., PRE, 93 (2016)