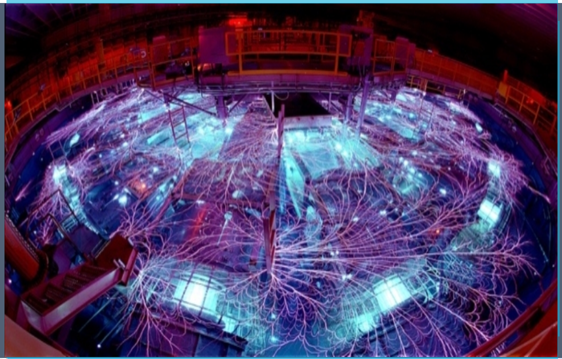
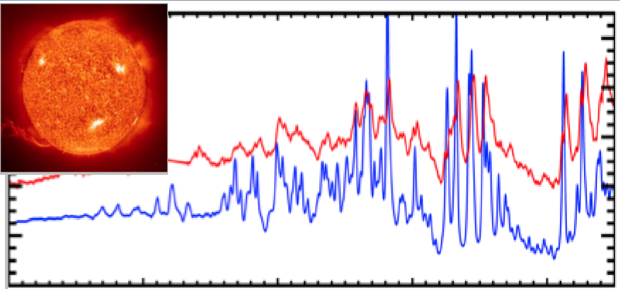
SAND2024-15653C

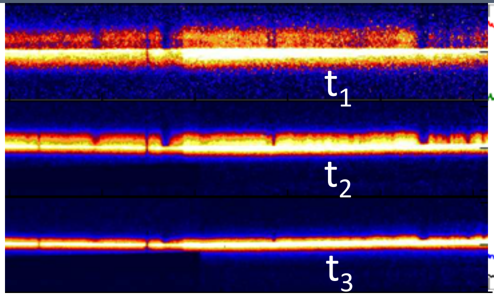
SAND2024-15653C

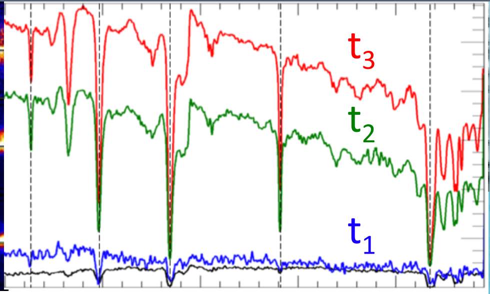
Sandia National Laboratories

Time-resolved spectroscopy for Z stellar opacity research









Guillaume Loisel on behalf of the Z opacity team

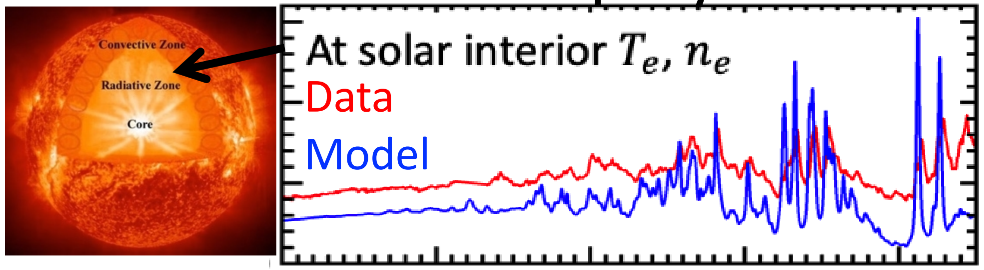
Dan Mayes
Jim Bailey
Taisuke Nagayama

20th RPDHM
Nov 18-22
Paris, France

Summary: Advancing stellar opacity testing with novel time-resolved spectroscopy on Z

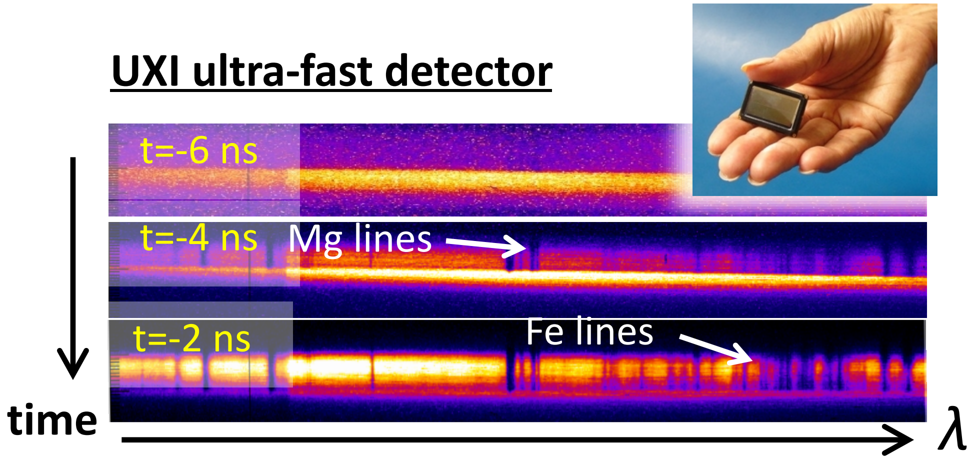
- **Puzzle:** the modeled and measured solar structure disagree
  - → *Is calculated iron opacity underestimated?*
  - → ***Initial Z experiments raised controversy***

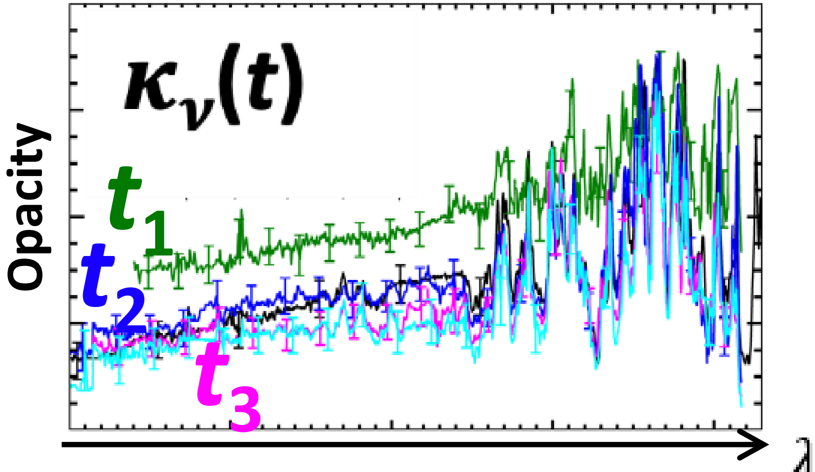
Anchor 2 Fe opacity



- **Experimental scrutiny:**
  - **Refining data analyses**
    - T_e, n_e analysis
    - Opacity analysis
  - **Time resolved measurements**
    - Tested temporal gradient effects → Found negligible

    → Transform experiments in 4 significant ways
    - Progress towards absolute time-resolved opacity measurements





Continued experimental and theoretical scrutiny are underway to answer this astrophysical puzzle

The opacity collaboration includes investigators from US National labs, US university, the French CEA and private companies

G. Loisel, J. Bailey, T. Nagayama, G. Dunham, E. Harding, S. Hansen, G. Rochau, R. More, T. Gomez, P. Lake, A. Maestas, T. Orozco, R. Harmon, L. Molina, A. Edens, C. Aragon, B. Ritter, K. Seals, M. McCall, J. Mignon, J. Swalby, K. Leonard, P. Gard, Q. Looker, A. Edens, T. Colombo, R. Speas, M. Kimmel, J. Porter
– **Sandia National Laboratories**, NM

C. Fontes, J. Colgan, D. Kilcrease and T. S. Perry
– **Los Alamos National Laboratories**, NM

R. F. Heeter, C. Iglesias, B. Wilson, D. Aberg, P. Grabowski
– **Lawrence Livermore National Laboratories**, CA

D. Mayes, T. Gomez, D.E. Winget, and M. Montgomery
– **UT Austin**, TX

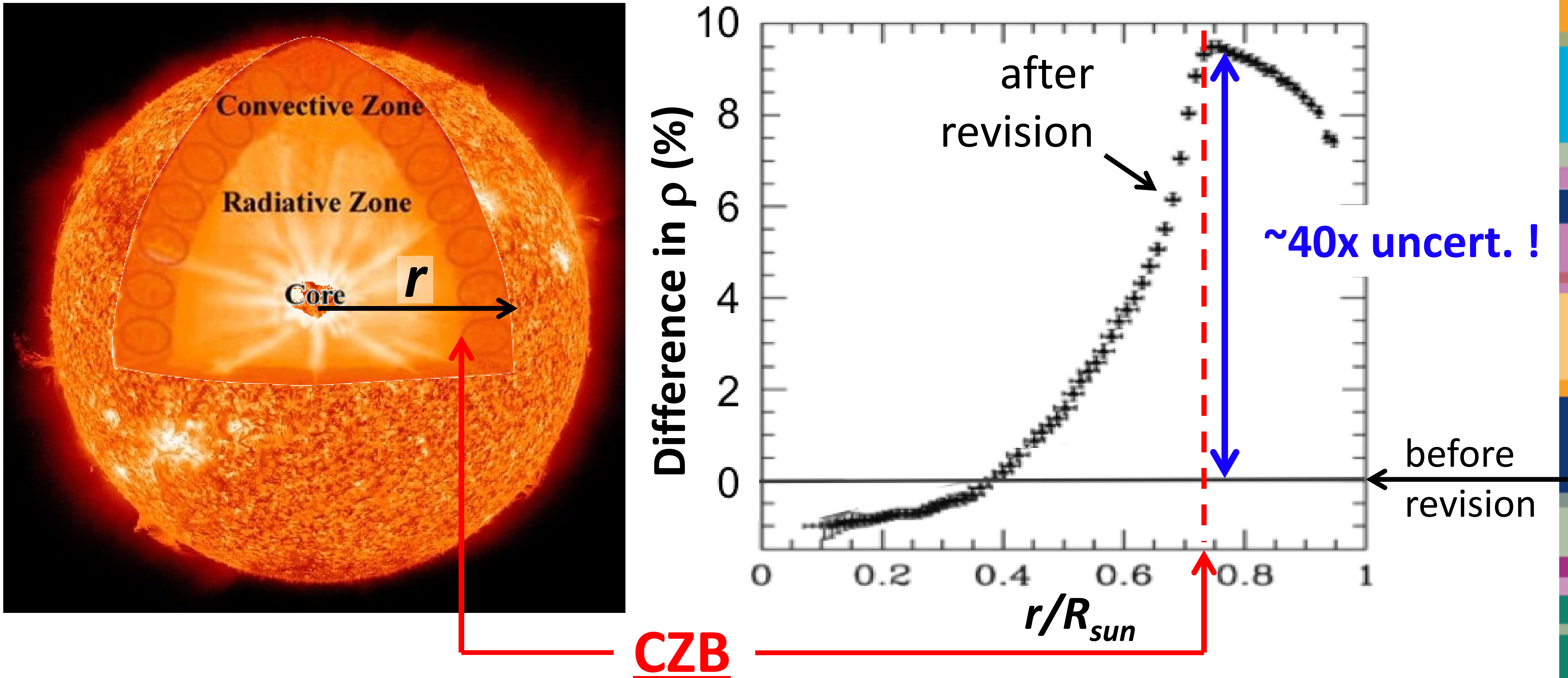
Ch. Blancard, Ph. Cossé, G. Faussurier, F. Gilleron, J.-Ch. Pain
– **French Alternative Energies and Atomic Energy Commission (CEA)**, France

H. Huang, R. Paguio, C. Monton, R. Santana, J. Taylor
– **General Atomic**, CA

I. Golovkin, M. F. Gu
– **Prism Computational Sciences**, WI

Wootton Center for Astrophysical Plasma Properties
– **DOE NNSA Center of Excellence**

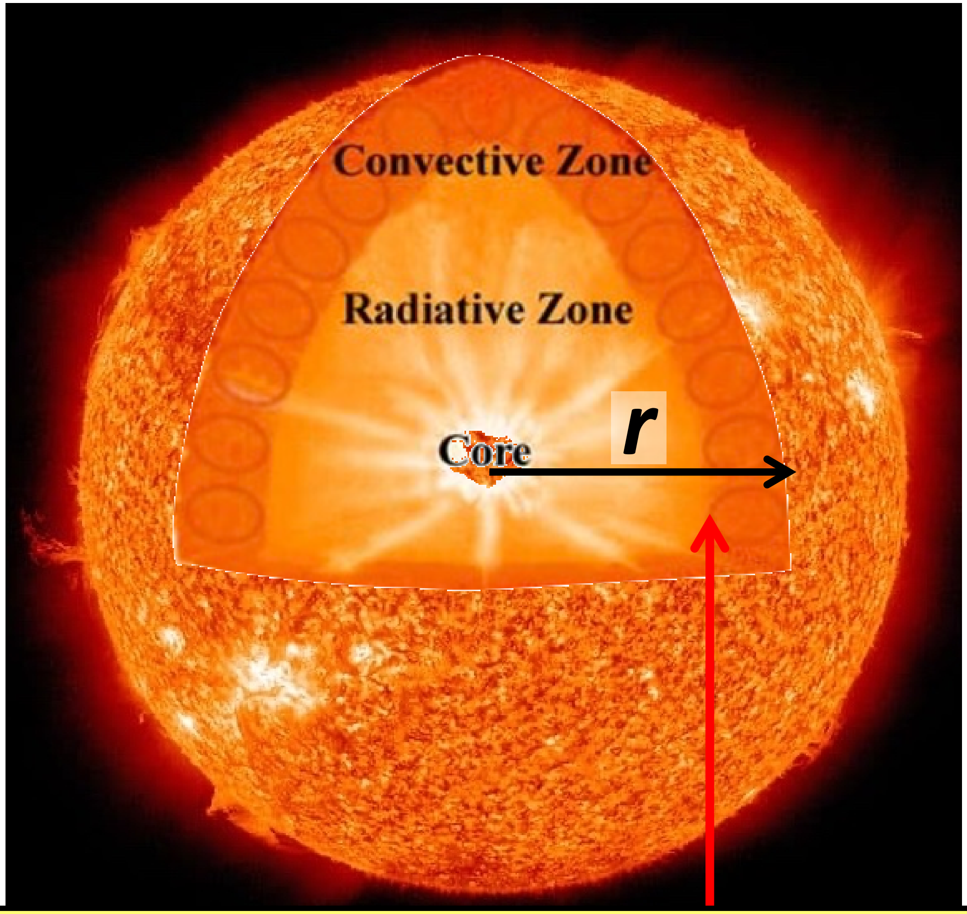
An outstanding problem: structure disagree with models of the Sun after metal abundances were reduced two decades ago*

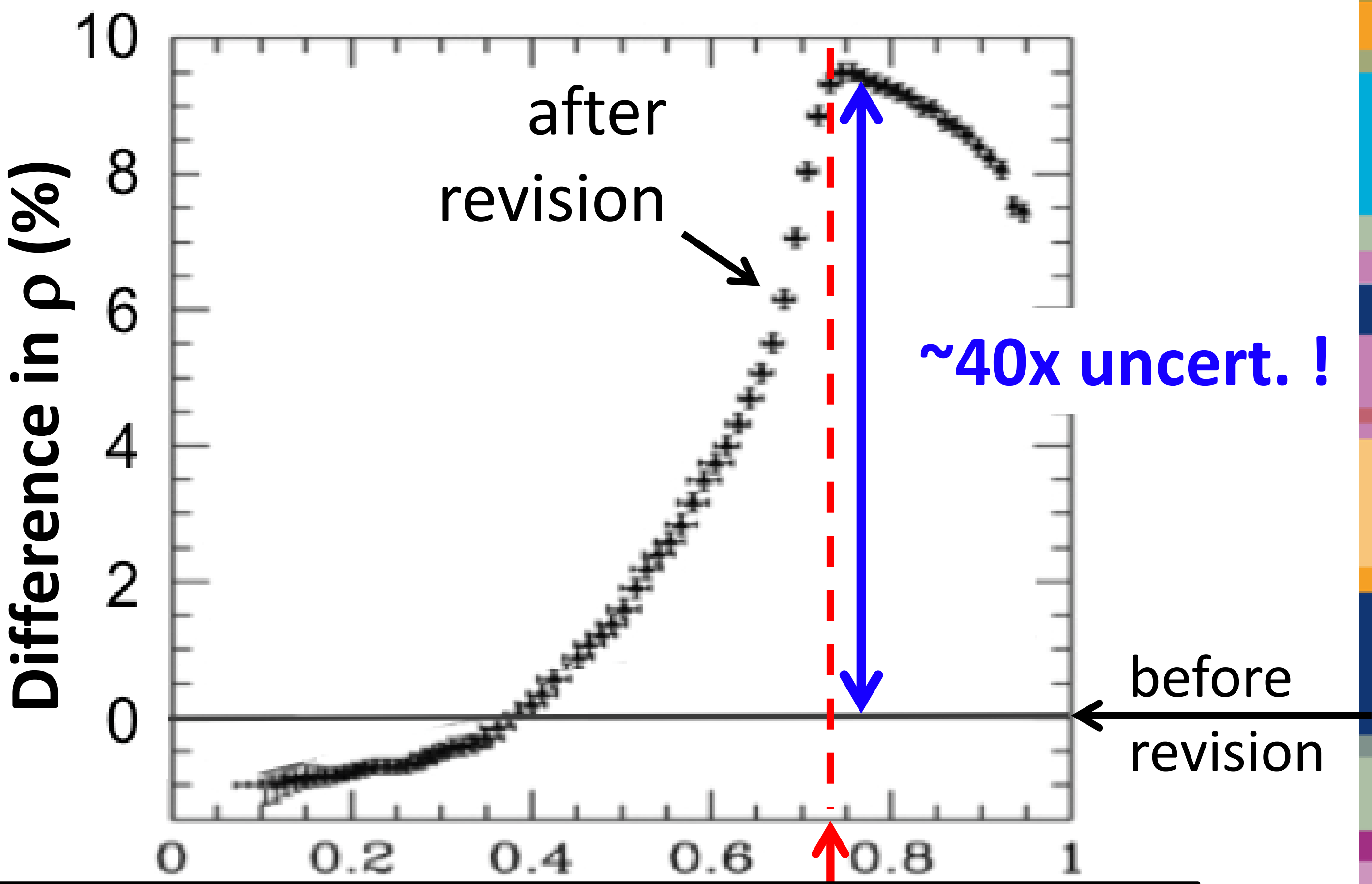


$T_e \simeq 182$ eV , $n_e \simeq 9\text{x}10^{22}$ e^-/cc

*Asplund *et al.*, Astron. Astrophys.(2004) , Basu, S. & Antia, H. M. *Physics Reports* 457 (2008)

An outstanding problem: structure disagree with models of the Sun after metal abundances were reduced two decades ago





Solar models need 10-30% higher mean opacity to resolve the structure problem [1]

[1] C. Dalsgaard et al., A&A (2009); Basu, S. & Antia, H. M. *Physics Reports* 457 (2008)

Debate on abundances to solve the solar problem is still active after two decades!

A&A 653, A141 (2021)
https://doi.org/10.1051/0004-6361/202140445

Astronomy & Astrophysics

The chemical make-up of the Sun: A 2020 vision

M. Asplund[1], A. M. Amarsi[2], and N. Grevesse[3,4]

...

Conclusions. Updated present-day solar photospheric and proto-solar abundances are presented for 83 elements, including for all long-lived isotopes. The so-called solar modelling problem – a persistent discrepancy between helioseismology and solar interior models constructed with a low solar metallicity similar to that advocated here – remains intact with our revised solar abundances, suggesting shortcomings with the computed opacities and/or treatment of mixing below the convection zone in existing standard solar models. The uncovered trend between the solar and CI chondritic abundances with condensation temperature is not yet understood but is likely imprinted by planet formation, especially since a similar trend of opposite sign is observed between the Sun and solar twins.

"Lower abundances are right!"

A&A 661, A140 (2022)
https://doi.org/10.1051/0004-6361/202142971

Astronomy & Astrophysics

Observational constraints on the origin of the elements

IV. Standard composition of the Sun

Ekaterina Magg[1], Maria Bergemann[1,5], Aldo Serenelli[2,3,1], Manuel Bautista[4], Bertrand Plez[7], Ulrike Heiter[6], Jeffrey M. Gerber[1], Hans-Günter Ludwig[8], Sarbani Basu[9], Jason W. Ferguson[10], Helena Carvajal Gallego[11], Sébastien Gamrath[11], Patrick Palmeri[11], and Pascal Quinet[11,12]

...

Results. We find an unprecedented agreement between the new estimates of transition probabilities, thus supporting our revised solar oxygen abundance value. We also provide new estimates of the noble gas Ne abundance. In addition, we discuss the consistency of our photospheric measurements with meteoritic values, taking into account the systematic and correlated errors. Finally, we provide revised chemical abundances, leading to a new value proposed for the solar photospheric present-day metallicity of $Z/X = 0.0225$, which we then employed in SSM calculations. We find that the puzzling mismatch between the helioseismic constraints on the solar interior structure and the model can be resolved thanks to this new chemical composition.

"Higher abundances are right!"

A&A 669, L9 (2023)
https://doi.org/10.1051/0004-6361/202245448

Astronomy & Astrophysics

LETTER TO THE EDITOR

Higher metal abundances do not solve the solar problem

G. Buldgen[1,2], P. Eggenberger[1], A. Noels[2], R. Scuflaire[2], A. M. Amarsi[3], N. Grevesse[2,4], and S. Salmon[1]

...

Results. When high-metallicity solar models are calibrated to reproduce the measured solar lithium depletion, tensions arise with respect to helioseismology and neutrino fluxes. This is yet another demonstration that the solar problem is also linked to the physical prescriptions of solar evolutionary models and not to chemical composition alone.

Conclusions. A revision of the physical ingredients of solar models is needed in order to improve our understanding of stellar structure and evolution. The solar problem is not limited to the photospheric abundances if the depletion of light elements is considered. In addition, tighter constraints on the solar beryllium abundance will play a key role improving of solar models.

"Abundances alone cannot resolve the problem!"

Debate on abundances to solve the solar problem is still active after two decades!

A&A 653, A141 (2021)
https://doi.org/10.1051/0004-6361/202140445

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"Abundances alone cannot resolve the problem!"

→ Benchmark HED opacities even more relevant

The first HED opacity measurements began in the 1980s, but measurements at solar interior conditions had to wait for the advent of MJ class HED facilities.

Eddington
"The Internal Constitution of the Stars"

Cox
bound-bound ~1.5x
opacity increase

Rogers & Iglesias
OPAL
2-3x opacity increase for Cepheid
OP

1905
Barkla

1925
Siegbahn
X-ray spectroscopy

1965

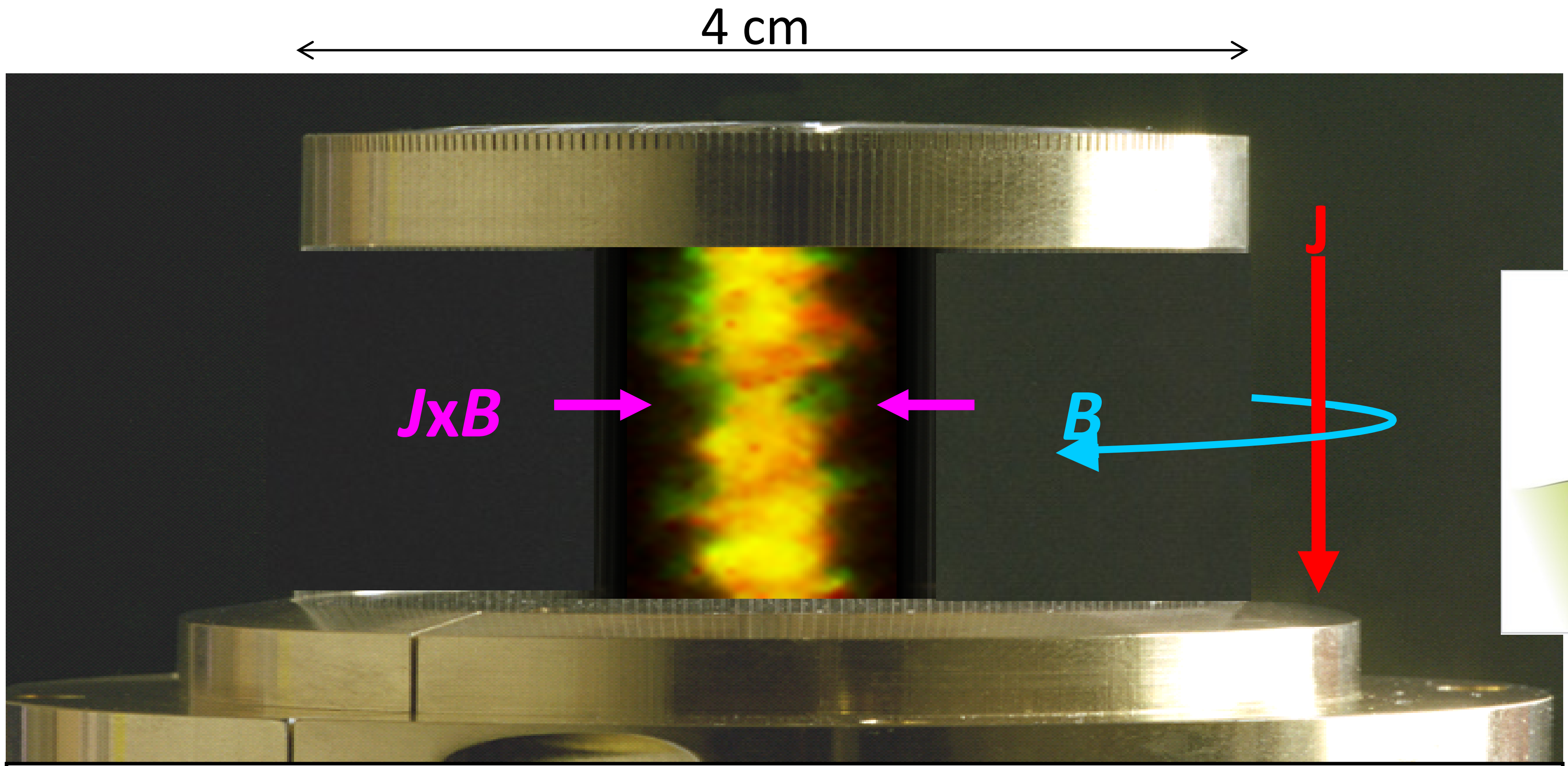
only bound-free and free-free absorption

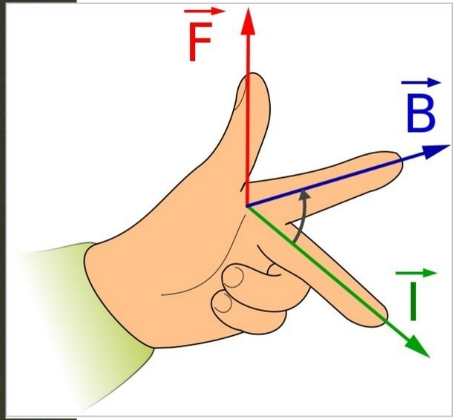
1988 1995
Davidson *et al.*
Perry *et al.*
hot dense plasma opacity
20-70 eV

2015
156-195 eV

Stellar interior opacity measurements are now possible for the first time

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



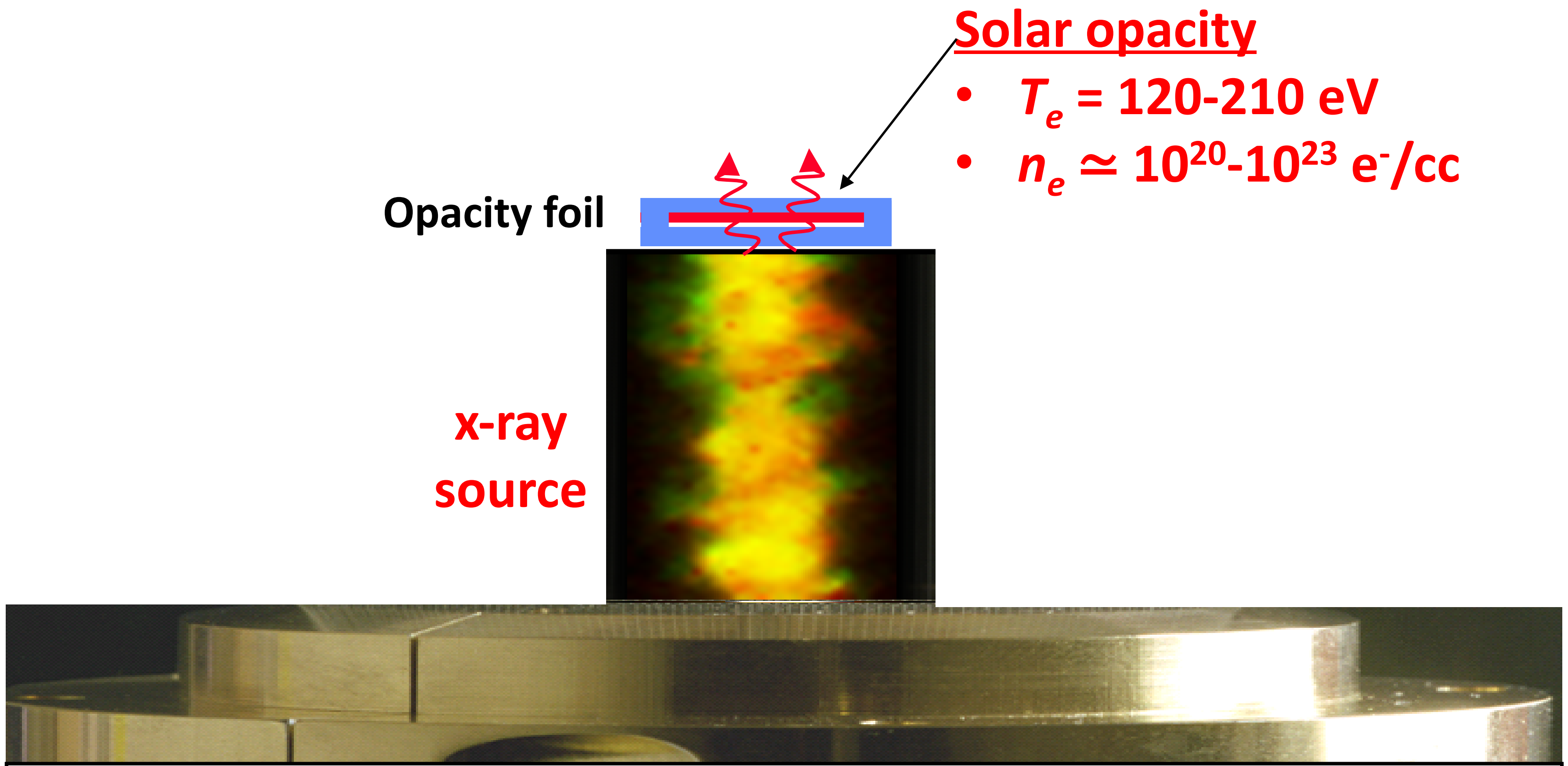


Lorentz force

X-ray yield ~ 1.6 MJ (±7%)

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

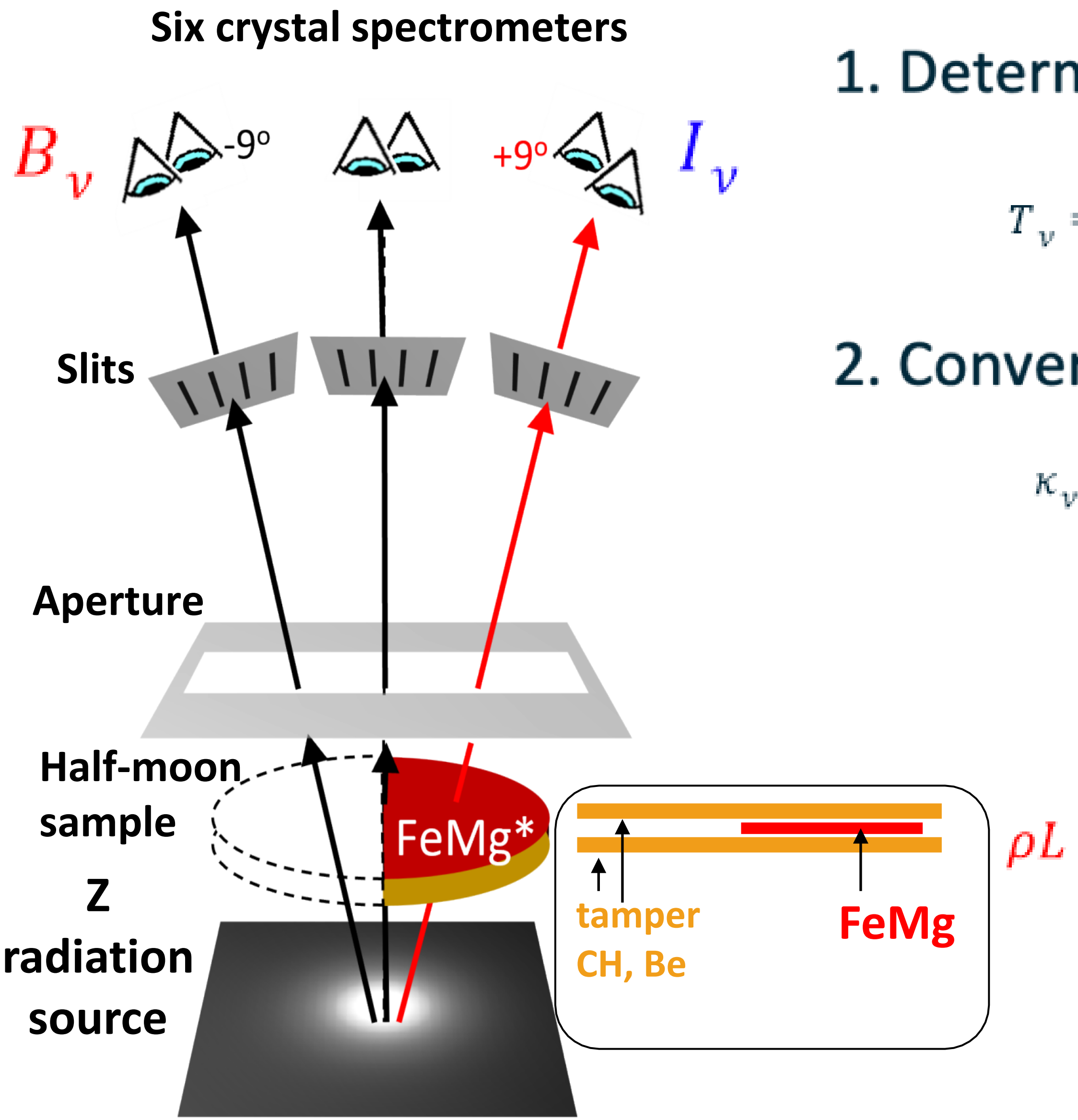
The Z machine uses 27 million Amperes to create x-rays, and drive a sample to solar interior conditions



X-ray yield ~ 1.6 MJ (±7%)

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

We infer opacity by measuring transmission of a very bright backlight through a sample uniformly heated using six space-resolving spectrometers



1. Determine transmission T_ν

$$T_\nu = \frac{I_\nu - \epsilon_\nu}{B_\nu - \epsilon_\nu}$$

2. Convert T_ν to opacity κ_ν

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

Sources of uncertainty

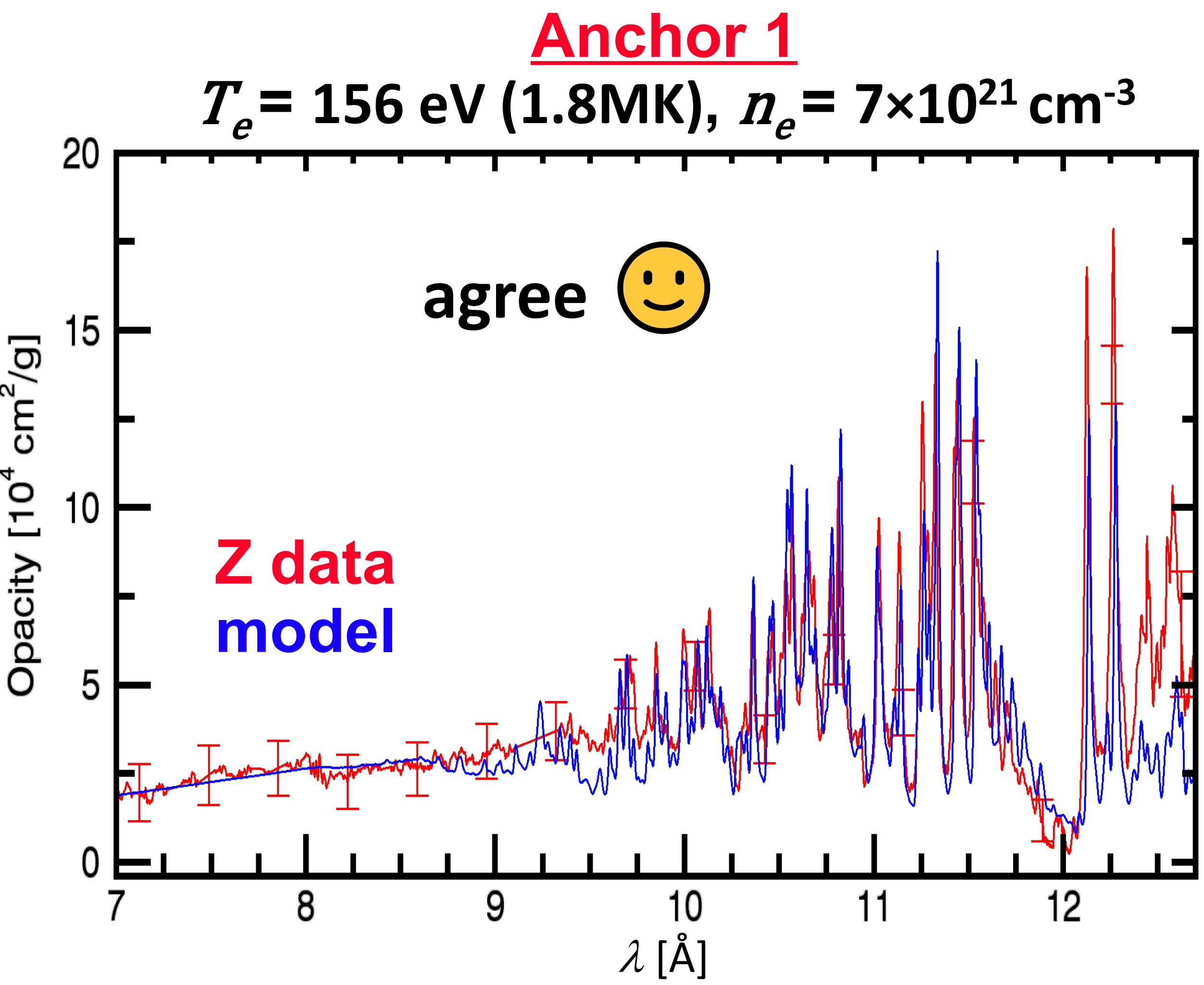
- **Unattenuated B_ν**
- **Background ϵ_ν**
- **Sample thickness ρL**

Requirements:

- Uniformly heat the sample to LTE
- Independent plasma diagnostics
- Bright backlight
- All sources of uncertainties need to be measured

Bailey et al Nature 2015; Nagayama et al, Phys Rev Lett 2019

Modern best-effort models agree very well with the Z iron data at T_e ~ 156 eV (1.8MK), n_e=7x10^{21} cm^{-3}

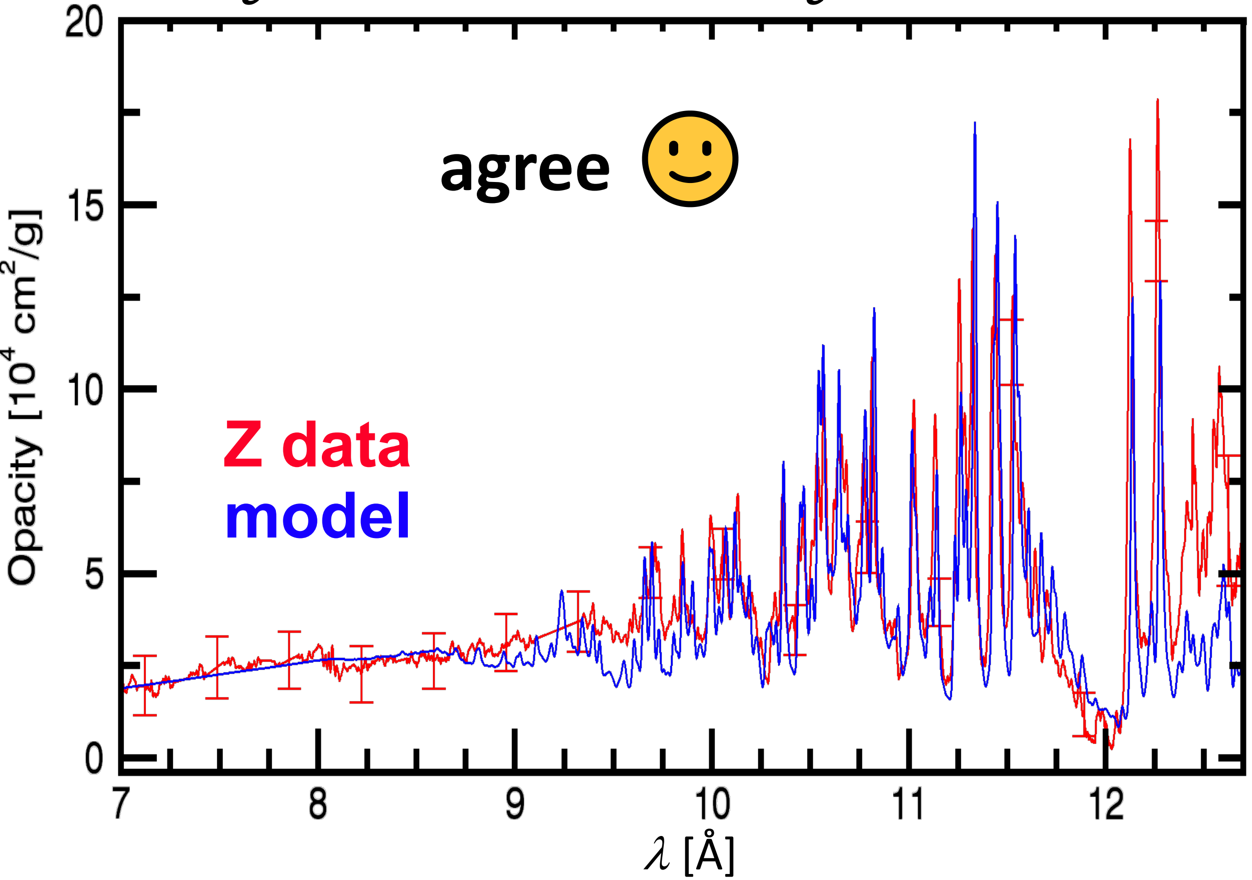


Bailey *et al.*, *PRL*, **99**, (2007)

… but disagree at near CZB conditions

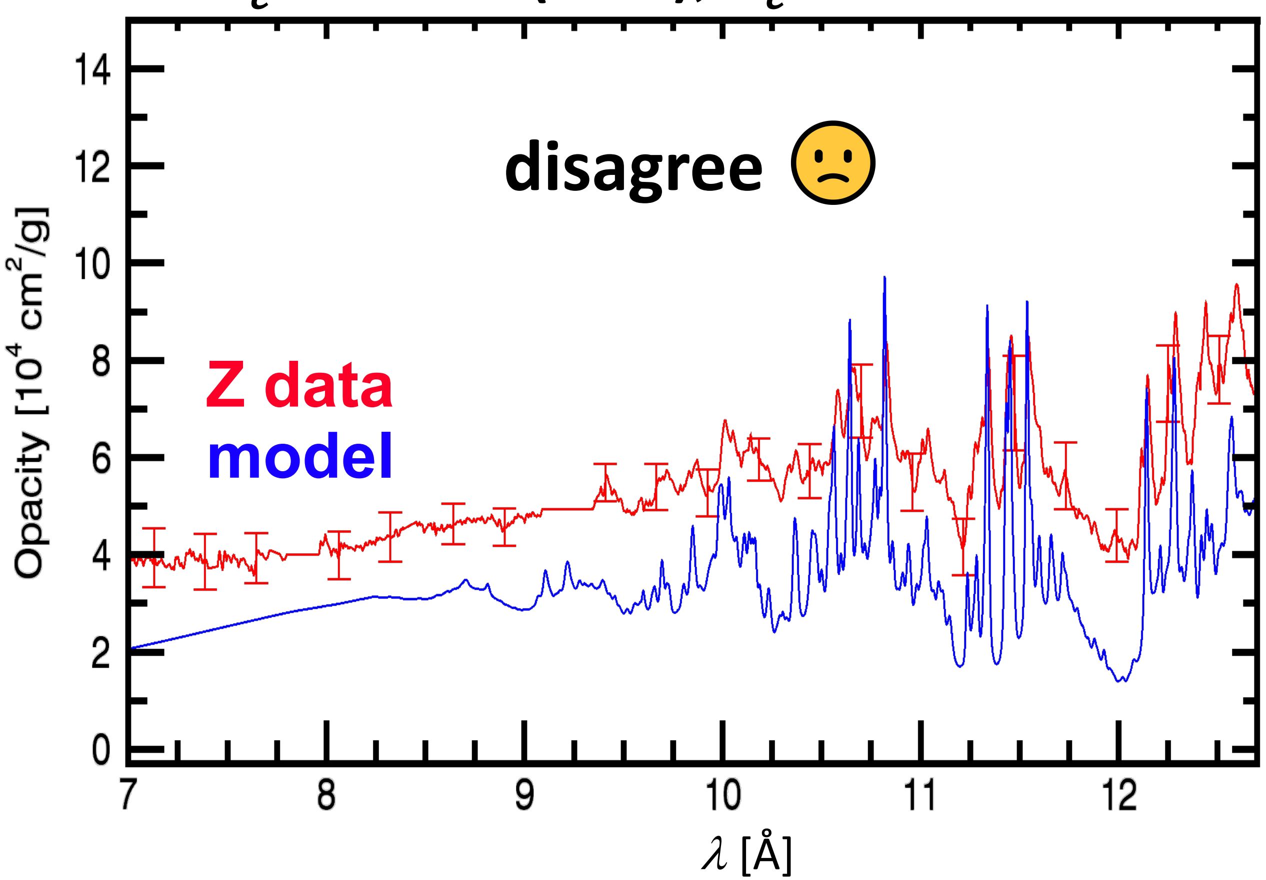
Anchor 1

T_e = 156 eV (1.8MK), n_e = 7×10^{21} cm^{-3}



Anchor 2 ~ solar CZB

T_e = 182 eV (2MK), n_e = 3×10^{22} cm^{-3}



- The difference accounts for roughly half the opacity change needed (+7%) 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)

The theory community has advanced and investigated several hypotheses to explain the discrepancy, but so far no widely accepted resolution is at hand.

Two-photon absorption

High Energy Density Physics 24 (2017) 44–49
Contents lists available at ScienceDirect
High Energy Density Physics
journal homepage: www.elsevier.com/locate/hedp

Opacity from two-photon processes☆

Richard M. More[a,1], Stephanie B. Hansen[b], Taisuke Nagayama[b,*]
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[b] Sandia National Laboratories, Albuquerque NM, USA

SNL [USA]

High Energy Density Physics 31 (2019) 38–46
Contents lists available at ScienceDirect
High Energy Density Physics
journal homepage: www.elsevier.com/locate/hedp

Two-photon absorption framework for plasma transmission experiments

Michael K.G. Kruse*, Carlos A. Iglesias
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LLNL [USA]

Transient spatial localization

SCIENCE CHINA
Physics, Mechanics & Astronomy
CrossMark
• Article •
March 2022 Vol. 65 No. 3: 233011
https://doi.org/10.1007/s11433-021-1812-1

U. Of Defense Technology [China]

Electron localization enhanced photon absorption for the missing opacity in solar interior

JiaoLong Zeng[1,3*], Cheng Gao[3], PengFei Liu[3], YongJun Li[3], CongSen Meng[3], Yong Hou[3], DongDong Kang[3], and JianMin Yuan[2,3*]
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[2] Graduate School of China Academy of Engineering Physics, Beijing 100193, China;
[3] Department of Physics, College of Liberal Arts and Sciences, National University of Defense Technology, Changsha 410073, China

Simultaneous electron-photon absorption

PHYSICAL REVIEW LETTERS 125, 145002 (2020)

Imperial College [UK]

Calculating Opacity in Hot, Dense Matter Using Second-Order Electron-Photon and Two-Photon Transitions to Approximate Line Broadening

R. A. Baggott,* S. J. Rose, and S. P. D. Mangles
Plasma Physics Group, Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom

Satellite lines

atoms
MDPI
Article

CEA [France]

Detailed Opacity Calculations for Astrophysical Applications

Jean-Christophe Pain *, Franck Gilleron and Maxime Comet
CEA, DAM, DIF, F-91297 Arpajon, France; franck.gilleron@cea.fr (F.G.); maxime.comet@cea.fr (M.C.)

Line broadening

PHYSICAL REVIEW LETTERS 127, 235001 (2021)

SNL, U Texas, LANL [USA, Australia]

All-Order Full-Coulomb Quantum Spectral Line-Shape Calculations

T. A. Gomez,[1,*] T. Nagayama,[1] P. B. Cho,[2] M. C. Zammit,[3] C. J. Fontes,[3] D. P. Kilcrease,[3] I. Bray,[4] I. Hubeny,[5] B. H. Dunlap,[2] M. H. Montgomery,[2] and D. E. Winget[2]
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[2] Department of Astronomy, University of Texas, Austin, Texas 78712, USA
[3] Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[4] Curtin Institute of Computation and Department of Physics and Astronomy, GPO Box U1987 Perth, Western Australia 6845, Australia
[5] Department of Astronomy, University of Arizona, Tucson, Arizona 85721, USA

Density

The Astrophysical Journal, 824:98 (6pp), 2016 June 20
doi:10.3847

Hebrew University [Israel]

LINE BROADENING AND THE SOLAR OPACITY PROBLEM

M. Krief, A. Feigel, and D. Gazit
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Received 2016 March 7; revised 2016 April 18; accepted 2016 April 21; published 2016 June 17

Experimental scrutiny is also warranted to seek potentially missed systematic errors

1) Refinement of data analysis

→ More accurate T_e and n_e (e.g. new line shapes)

→ More accurate transmission analysis

2) Systematic L-shell opacity investigation

→ Opacity of Cr (Z=24) and Ni (Z=28) powerful hypothesis constraints

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

Systematic Study of *L*-Shell Opacity at Stellar Interior Temperatures

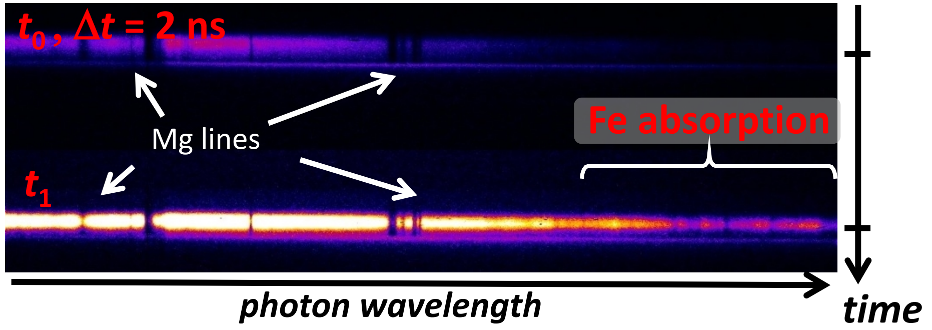
T. Nagayama,[1] J. E. Bailey,[1] G. P. Loisel,[1] G. S. Dunham,[1] G. A. Rochau,[1] C. Blancard,[2] J. Colgan,[3] Ph. Cossé,[2] G. Faussurier,[2] C. J. Fontes,[3] F. Gilleron,[2] S. B. Hansen,[1] C. A. Iglesias,[4] I. E. Golovkin,[5] D. P. Kilcrease,[3] J. J. MacFarlane,[5] R. C. Mancini,[6] R. M. More,[1,*] C. Orban,[7] J.-C. Pain,[2] M. E. Sherrill,[3] and B. G. Wilson[4]

3) Time-resolved measurements

→ Temporal gradients

→ Achieve higher temperature and/or density

→ Multiple plasmas conditions in a single experiment

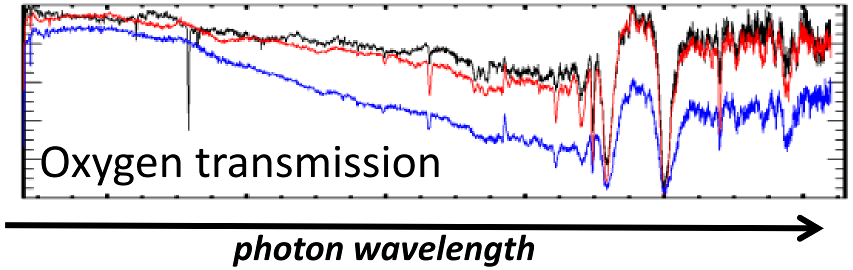


4) Oxygen opacity

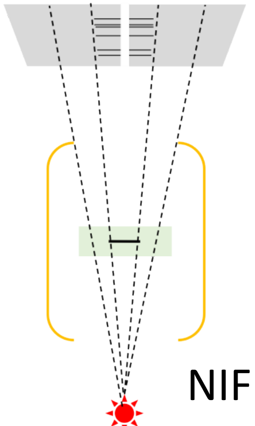
→ Simpler K-shell absorption although un-tested at CZB

→ Highest contributor to solar opacity at CZB

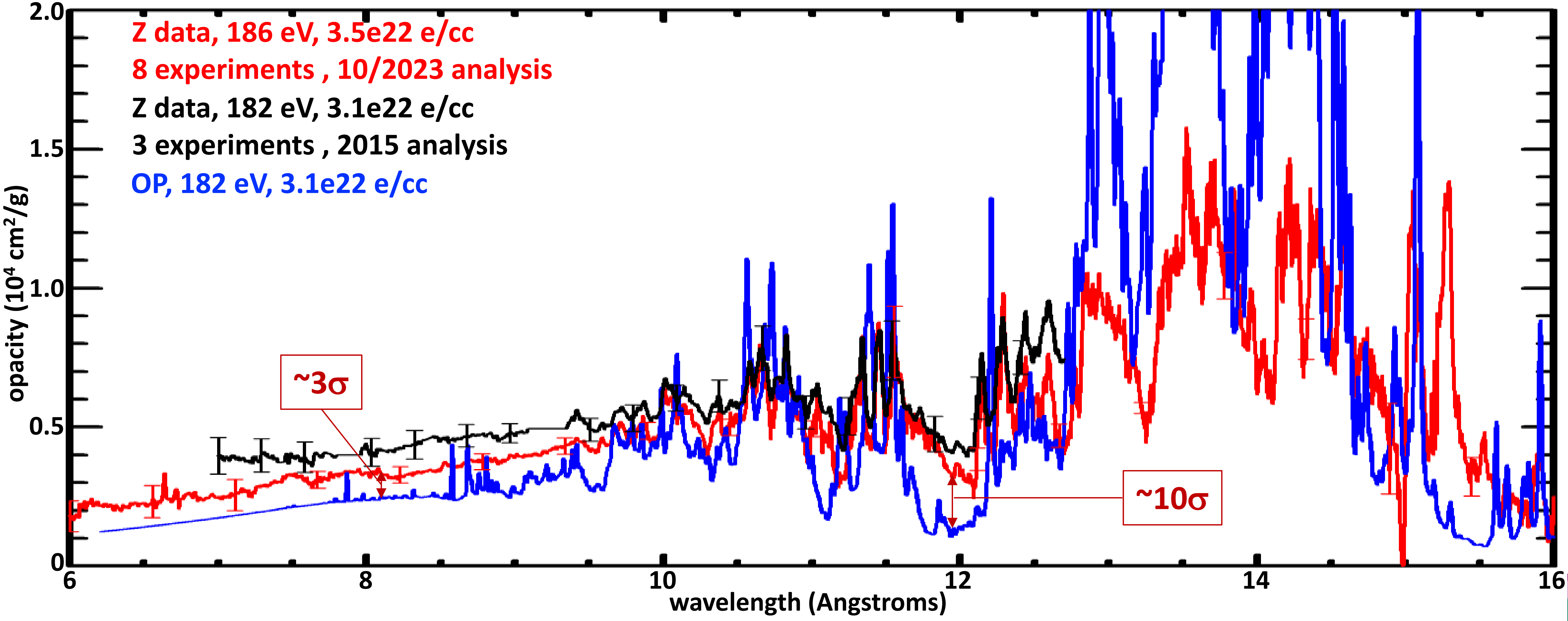
→ Experiments and analyses are underway



5) Cross-comparison with opacity from NIF facility (Fe, O)



Z iron opacity measurements have been refined over nearly a decade, but model-data discrepancies remain



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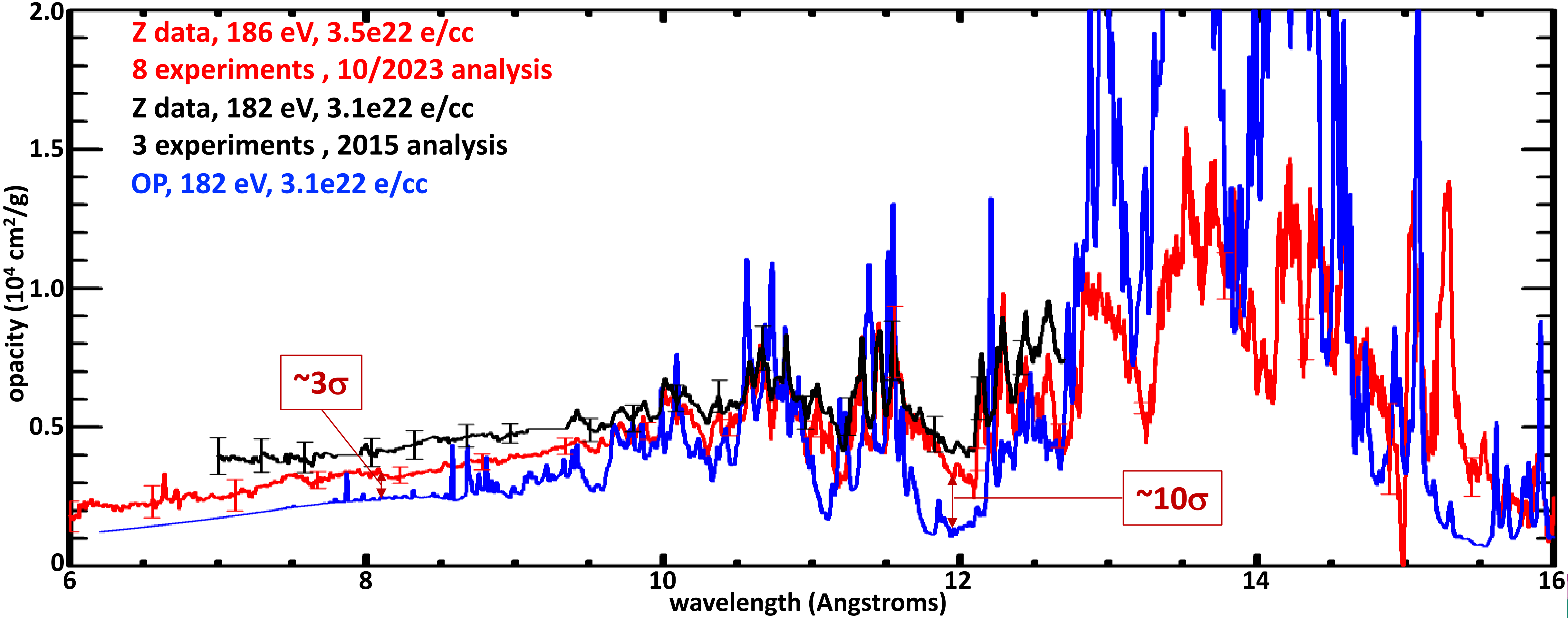
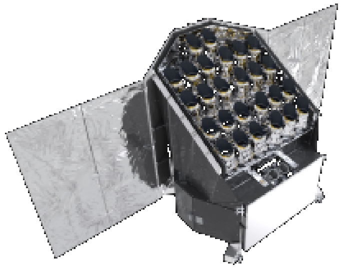


Scrutiny of both models and measurements must continue since this discrepancy affects all sun-like stars…
… and exoplanet parameter inference too! (E.g. ESA Plato mission 2026)



Temporal gradients 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

⋮

PHYSICAL REVIEW E **95**, 063206 (2017)

Numerical investigations of potential systematic uncertainties in iron opacity measurements at solar interior temperatures

T. Nagayama,* J. E. Bailey, G. P. Loisel, and G. A. Rochau
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

J. J. MacFarlane and I. E. Golovkin
Prism Computational Sciences, Madison, Wisconsin 53711, USA
(Received 23 February 2017; published 26 June 2017)

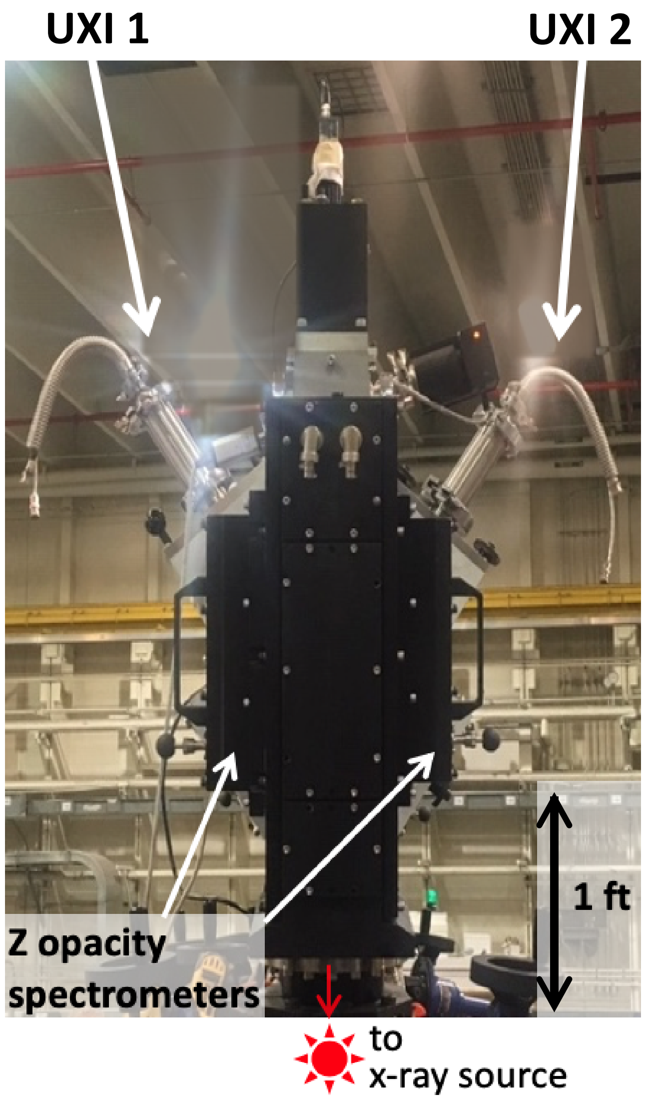
Temporal gradients were studied with simulations but not measured until now

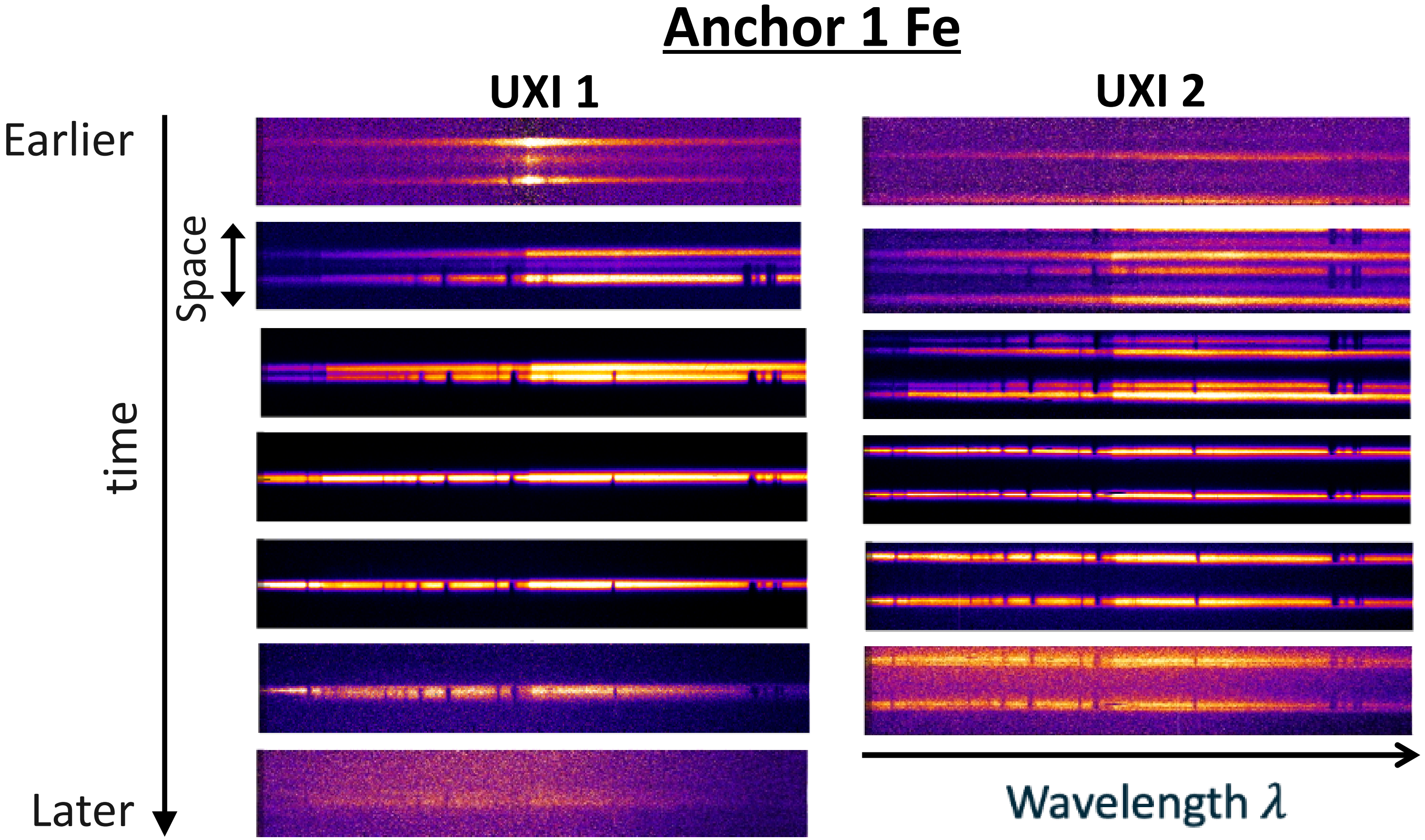
- Film-based spectra so far integrate 3.3 ns backlighter.
- *But,* T_e and n_e change over that duration. Does that affect our film-based measurements?

→ 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)

The Z spectrometers now returns nominal high-quality time-gated spectral images[1]

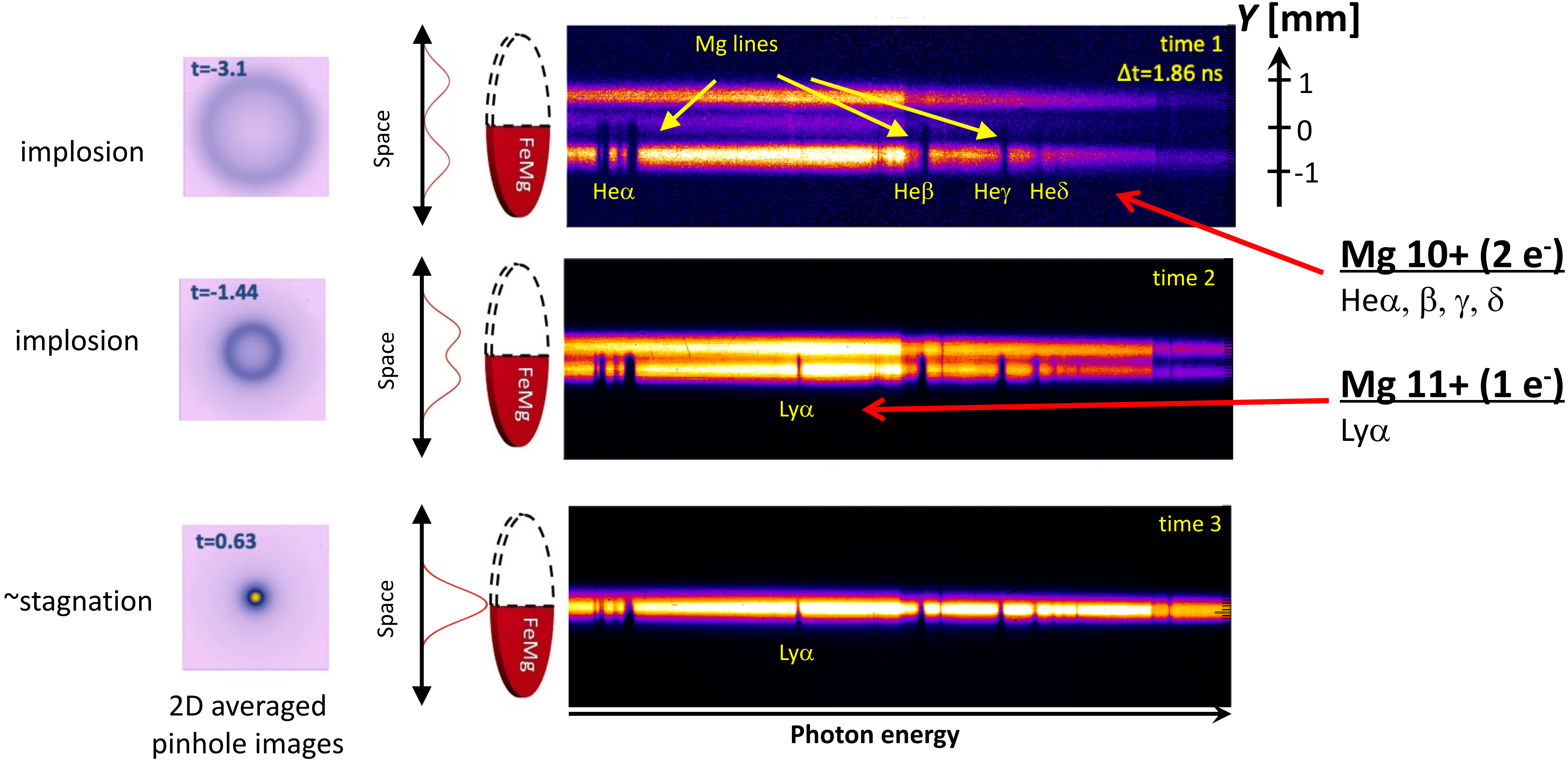




- Single photon detection → 12-14 ns of observations
- At peak ~50 signal-to-noise ratio

[1]UXI = Ultra-fast X-ray Imager: Claus *et al.*, *Proc. SPIE*, (2015, 2017), Looker *et al.*, *RSI*, **91**, 043502 (2020)

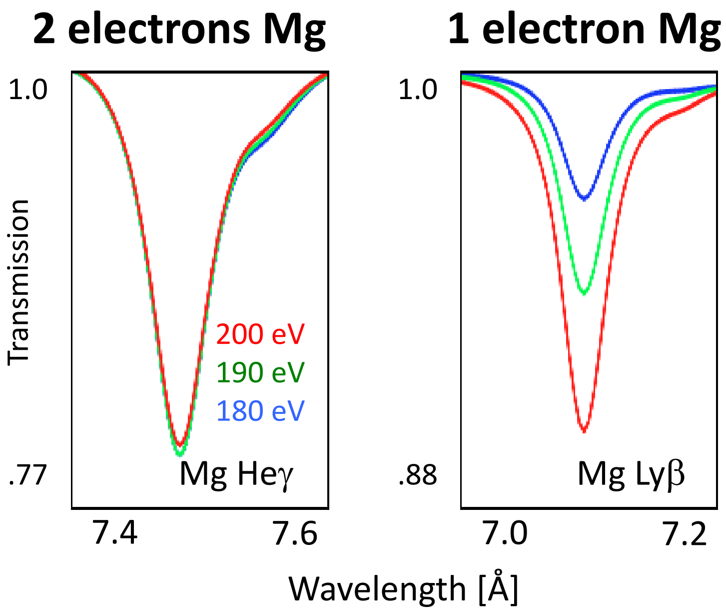
These images are *temporally* and *spectrally* resolved ... and also *1-D spatially* resolved



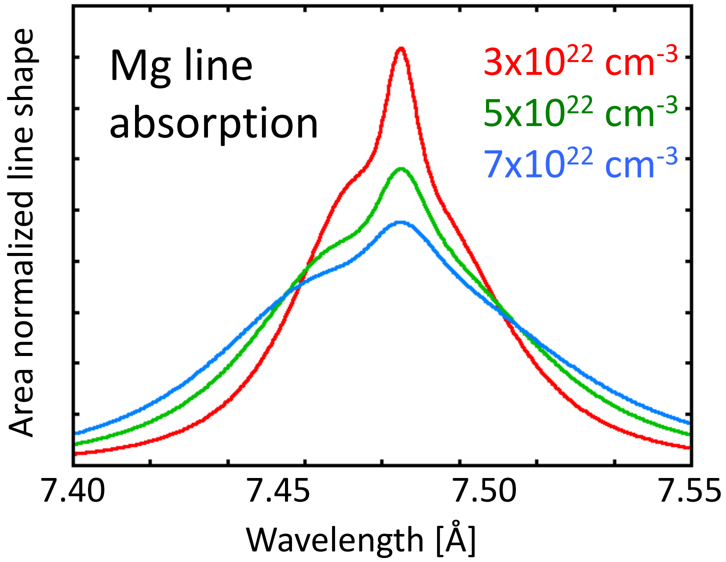
G. Rochau *et al.*, *PRL*, **100** (2008)

n_e and T_e are inferred from measured magnesium (Mg, tracer) line absorption spectrum[1]

- Line ratio: sensitive to electron temperature, T_e



- Line shape: sensitive to electron density, n_e

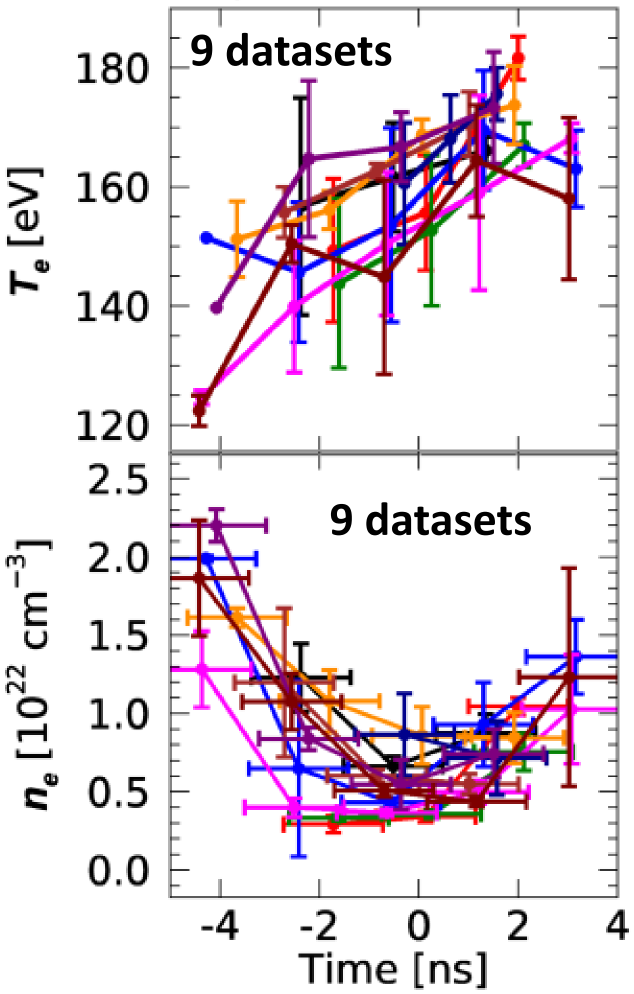


Plasma T_e and n_e can be extracted by reproducing measured spectra with spectral models

[1]Bailey, *et al. RSI* **79**,3104 (2008), Nagayama *et al.*, *PoP* 2**1**, 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).

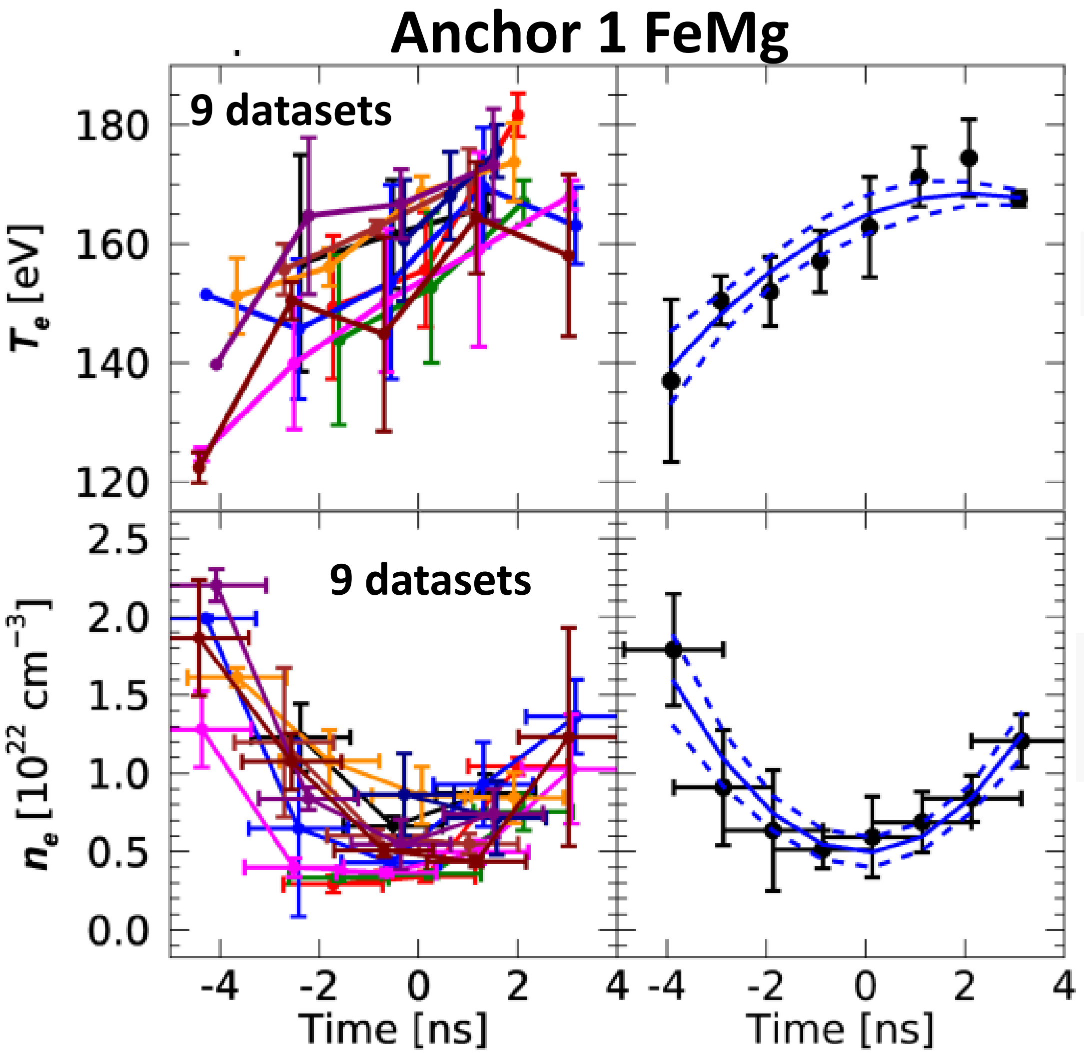
Fe opacity sample evolution are now obtained routinely near established anchor 1, 2 (T_e, n_e)

Anchor 1 FeMg



➢ **Multiple datasets show reliable trends**

Fe opacity sample evolution are now obtained routinely near established anchor 1, 2 (T_e, n_e)

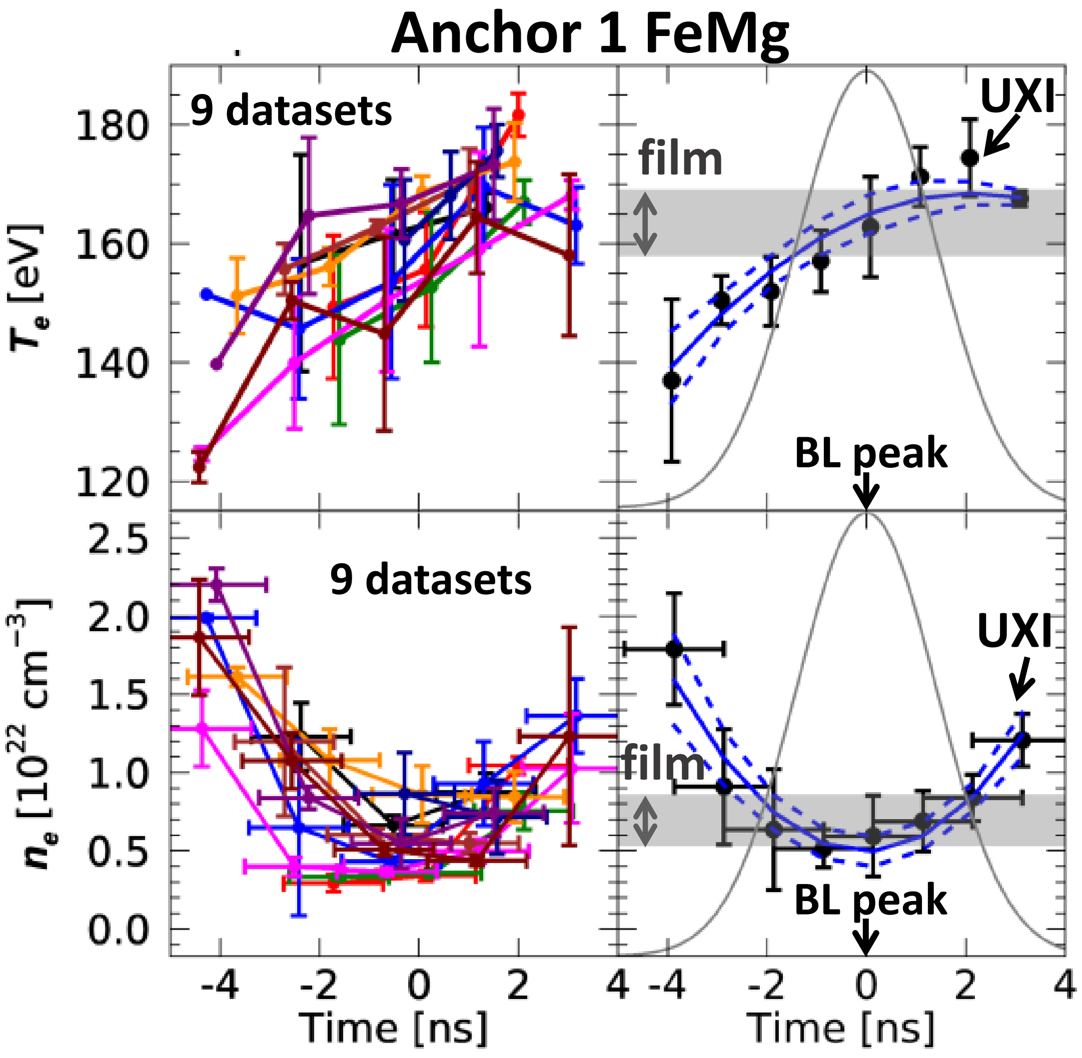


130 → 170 eV

Convex density
5–22 ×10^{21} e^-/cm^3

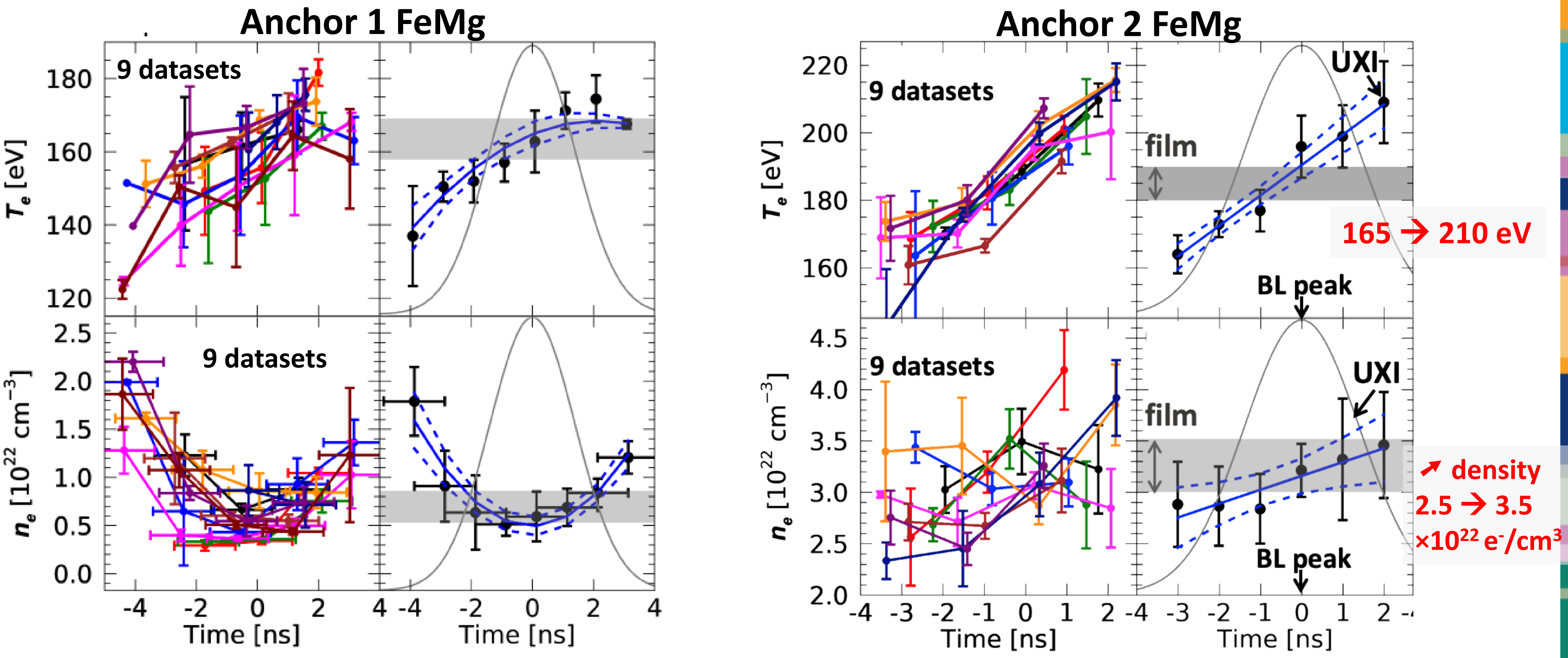
➢ Multiple datasets show reliable trends

Fe opacity sample evolution are now obtained routinely near established anchor 1, 2 (T_e, n_e)

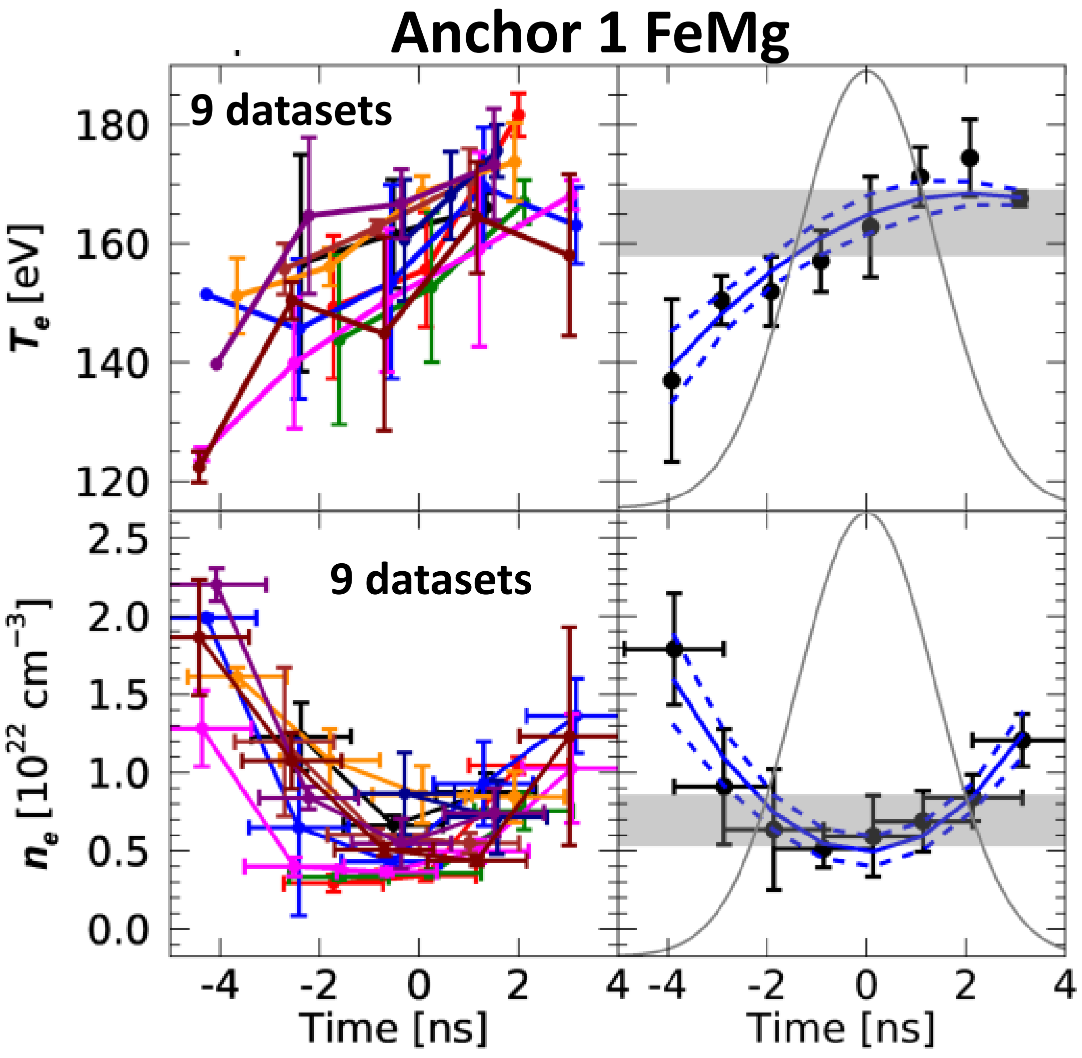


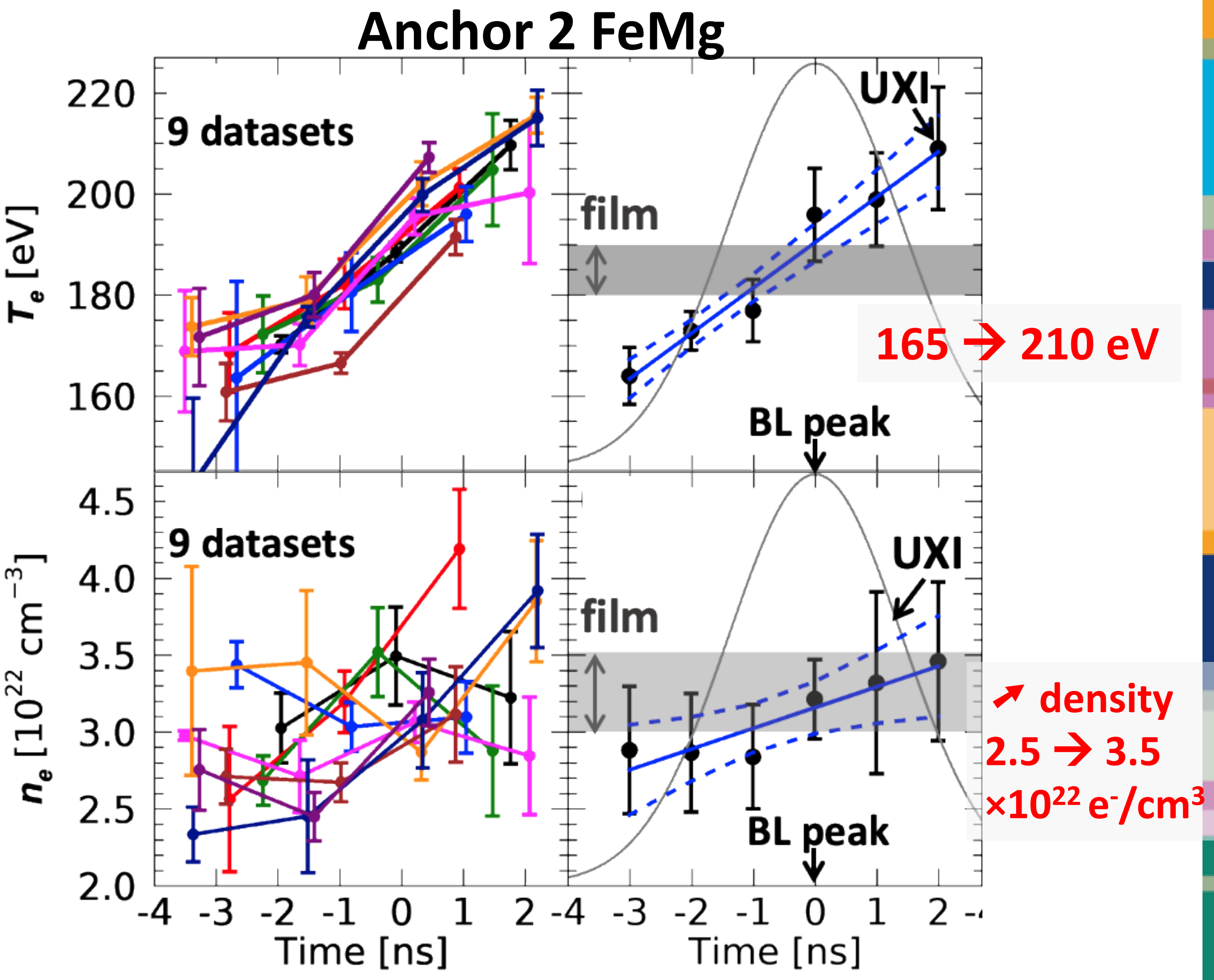
Film opacity = @ backlighter peak

Fe opacity sample evolution are now obtained routinely near established anchor 1, 2 (T_e, n_e)



Fe opacity sample evolution are now obtained routinely near established anchor 1, 2 (T_e, n_e)



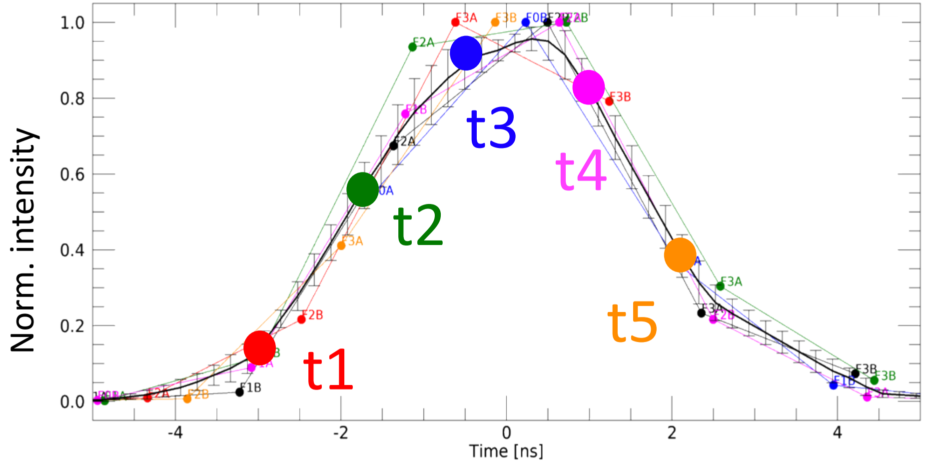


➢ T_e, n_e measurements independent from Fe opacity measurements (benchmark requirement)

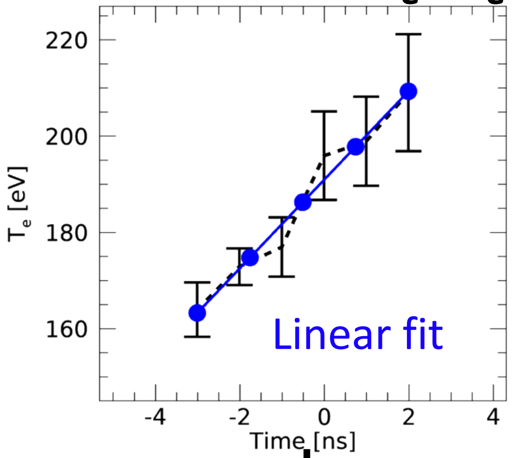
Could the observed gradient explain the anchor 2 model-data discrepancy? Let's investigate!

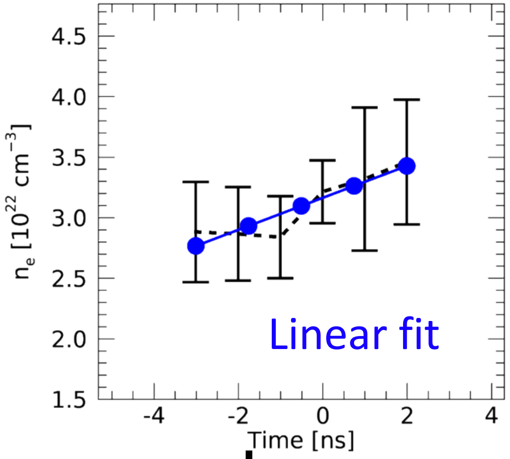
We need:

1) Measure BL history

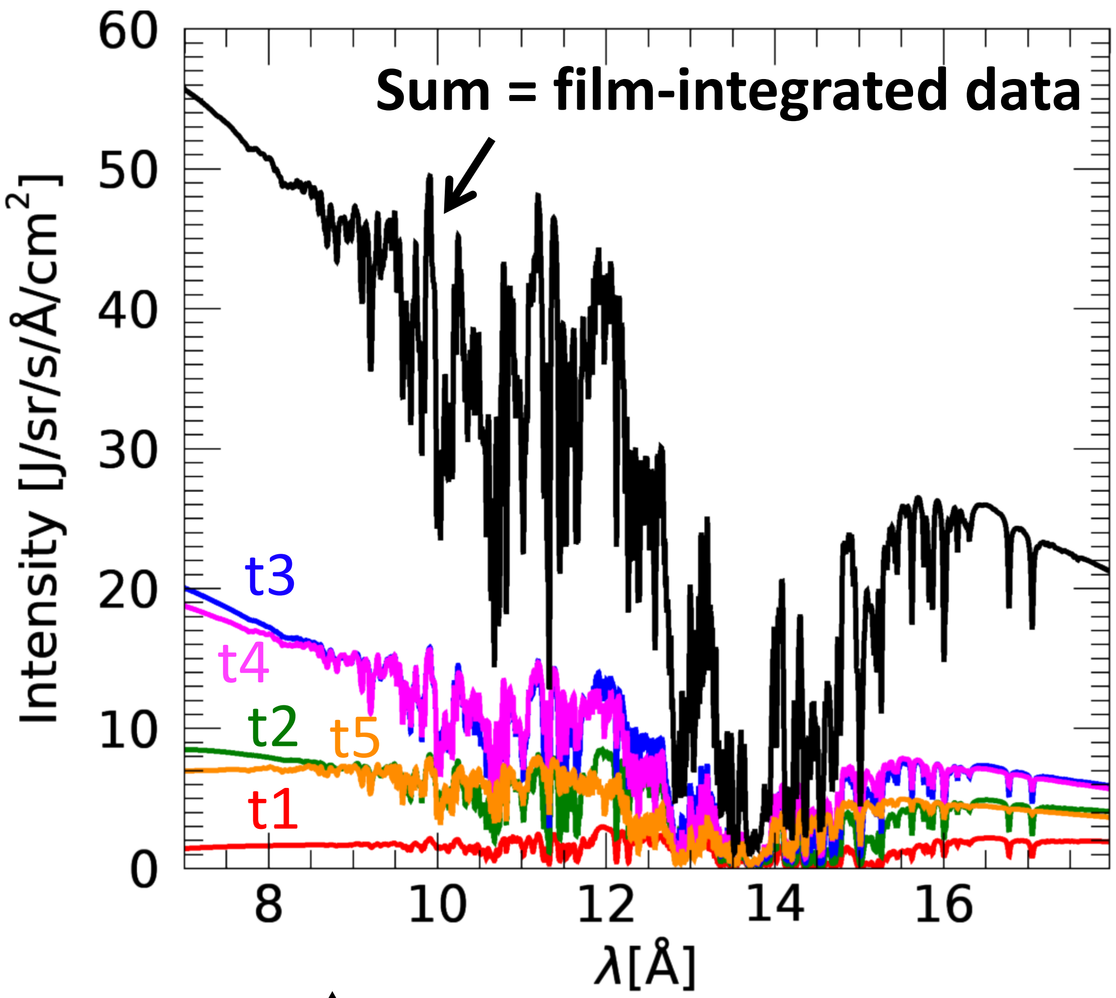


2) Measured T_e, n_e for opacity models





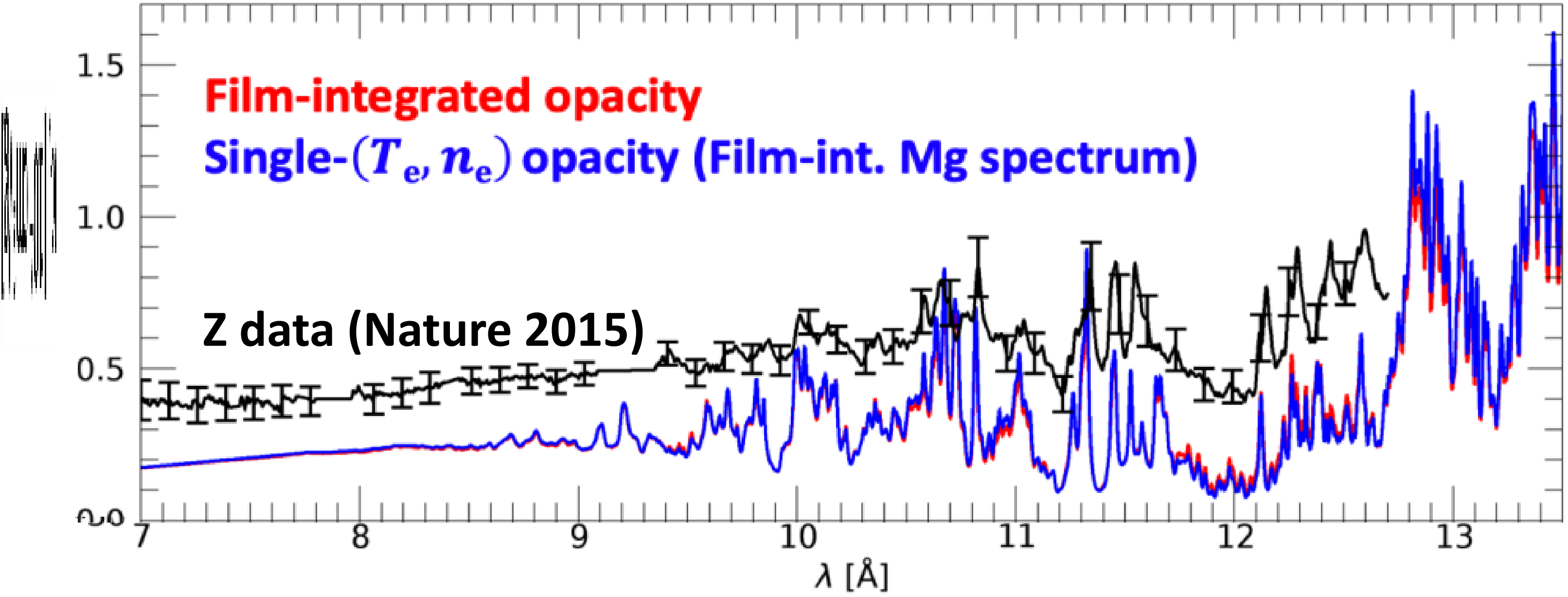
BL[1] × transmission[2]



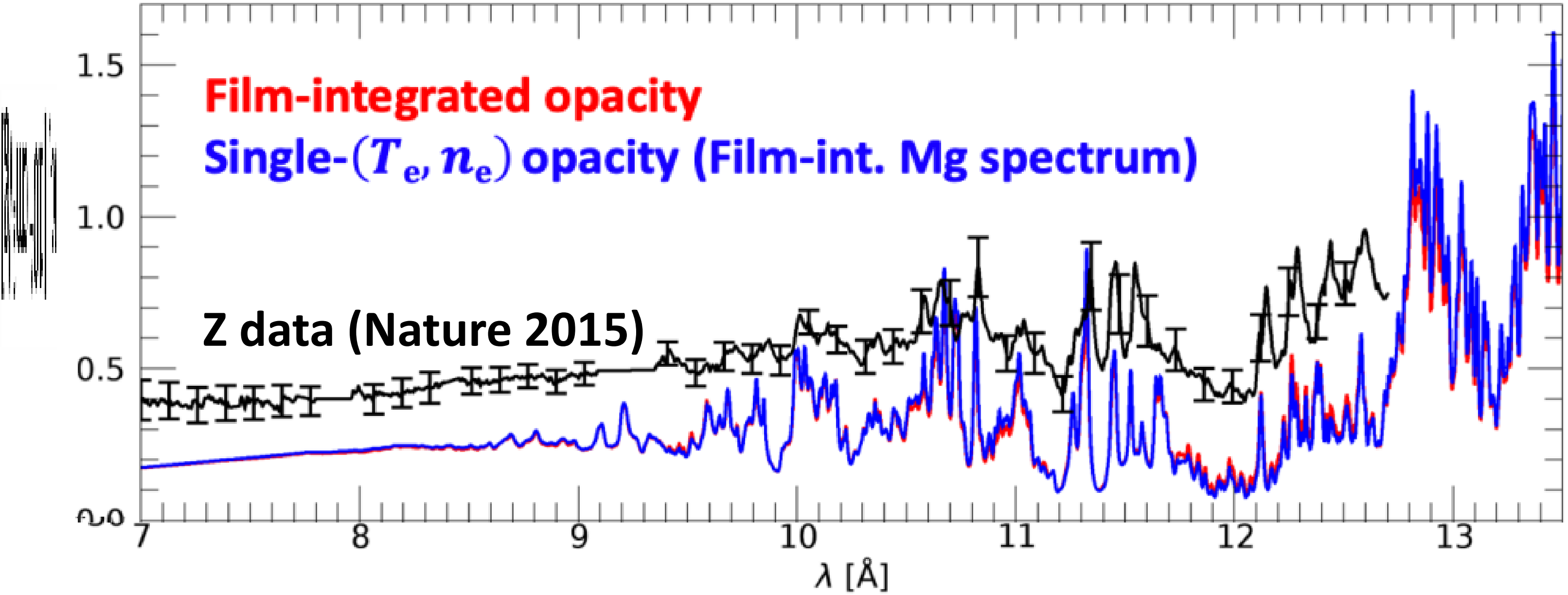
[1]Planckian shape assumed

[2]PrismSPECT, MacFarlane *et al.*, HEDP, (2007)

Film-integrated opacity compared to single-(T_e,n_e) opacity = temporal integration effects

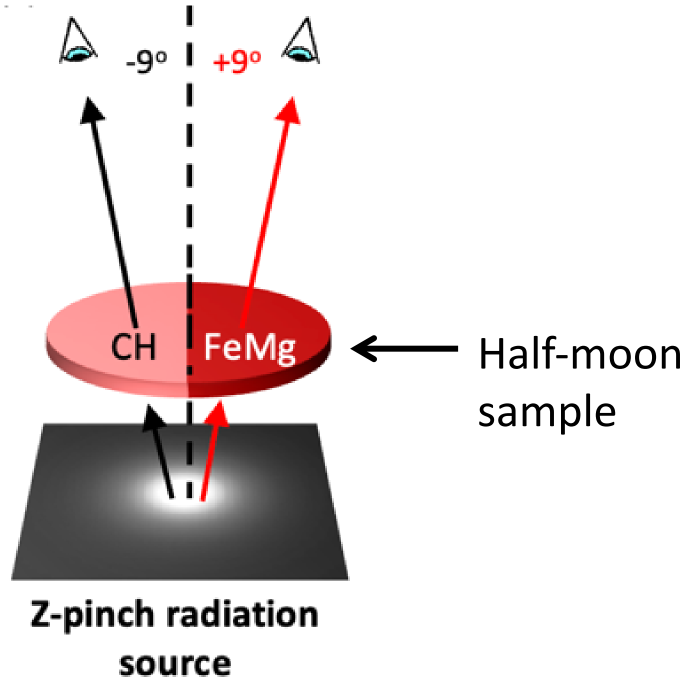


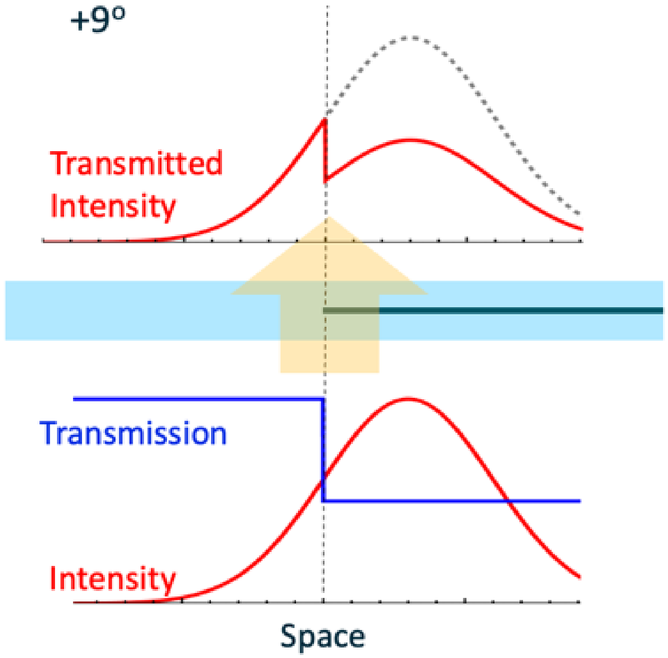
Film-integrated opacity compared to single-(T_e,n_e) opacity = temporal integration effects

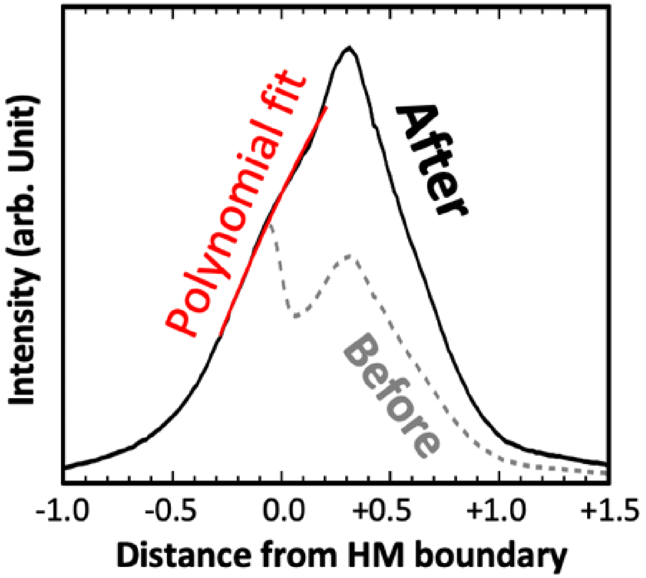


- Less than 5% difference in quasi-continuum (reported discrepancy)
- Uses measured conditions and BL history *but* modeled opacity
  → Need absolute opacity measurements to avoid this approximation (now!)

First time-resolved opacity is obtained using a statistical method

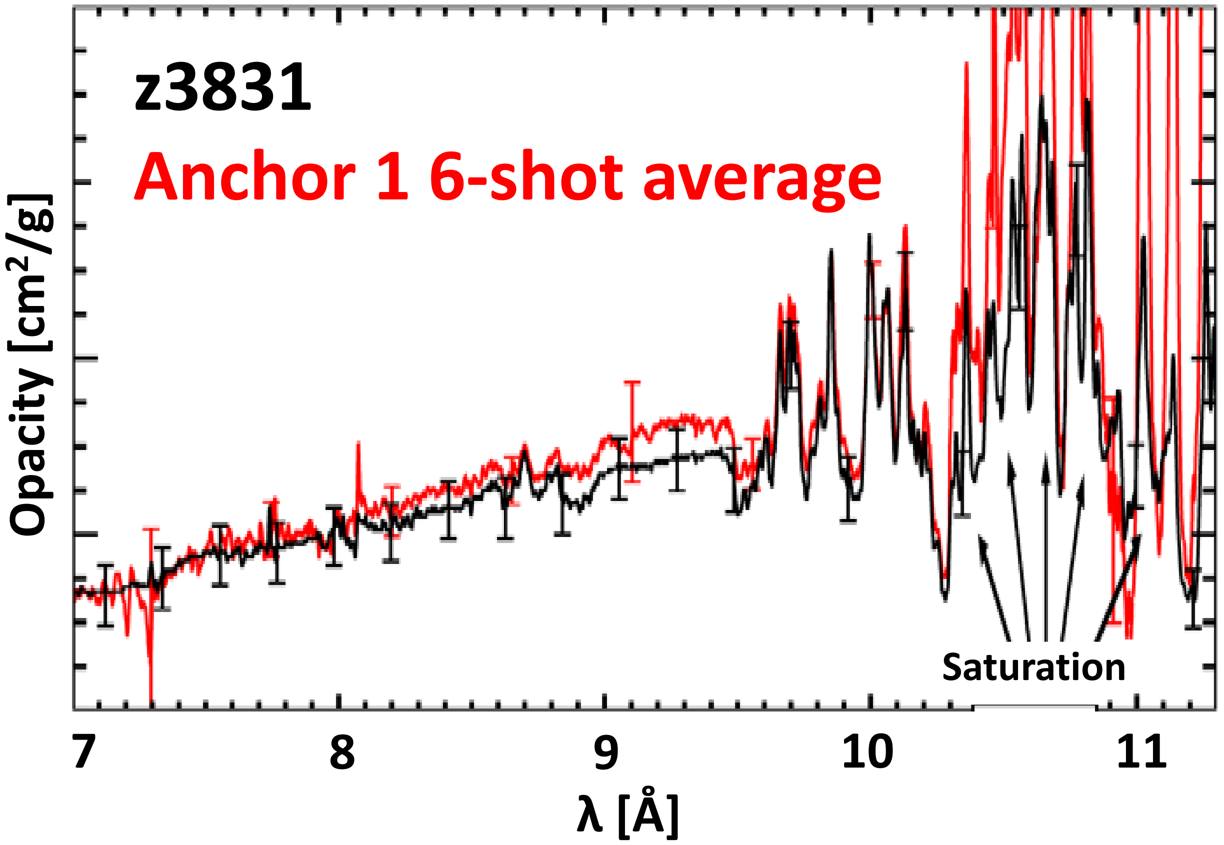




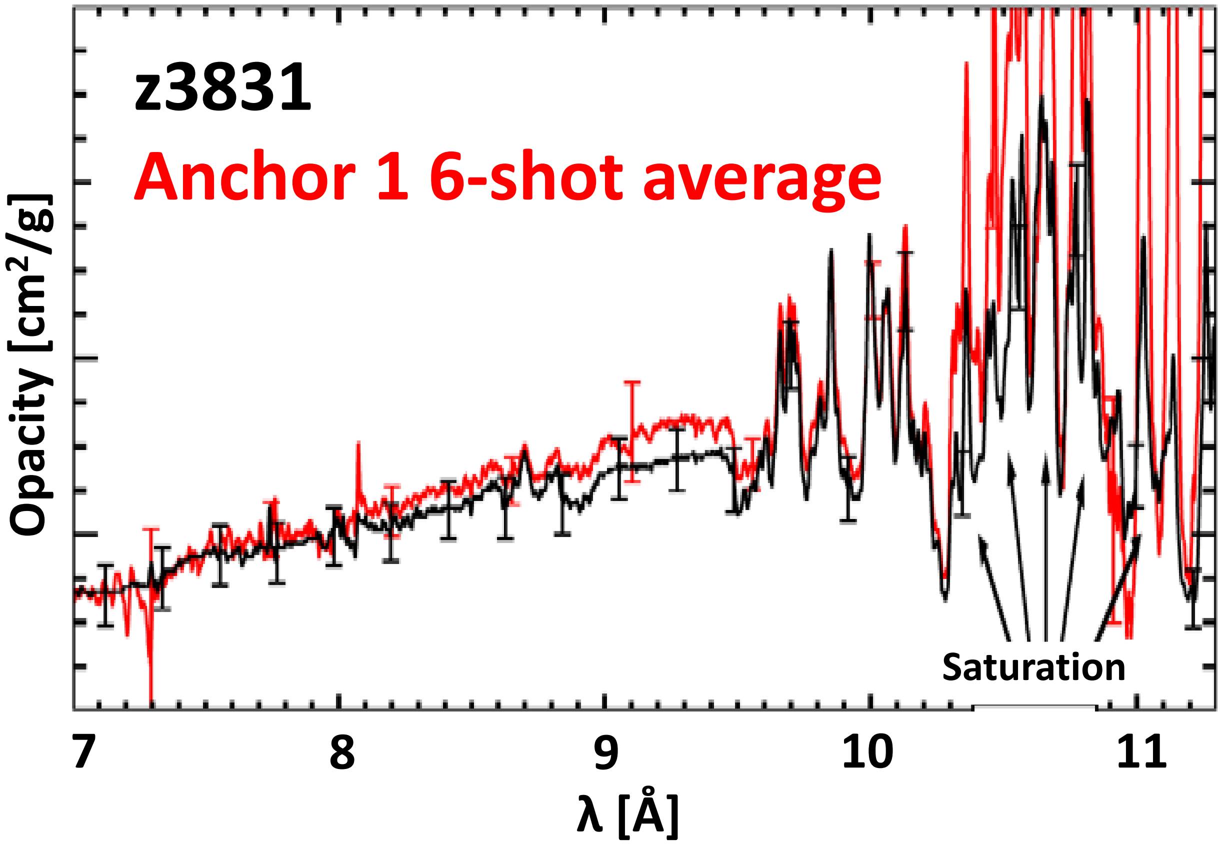


- **Transmission is obtained through minimizing slope discontinuity across half-moon boundary**

First anchor 1 with time-resolution agrees very well with reported Anchor 1 measurements

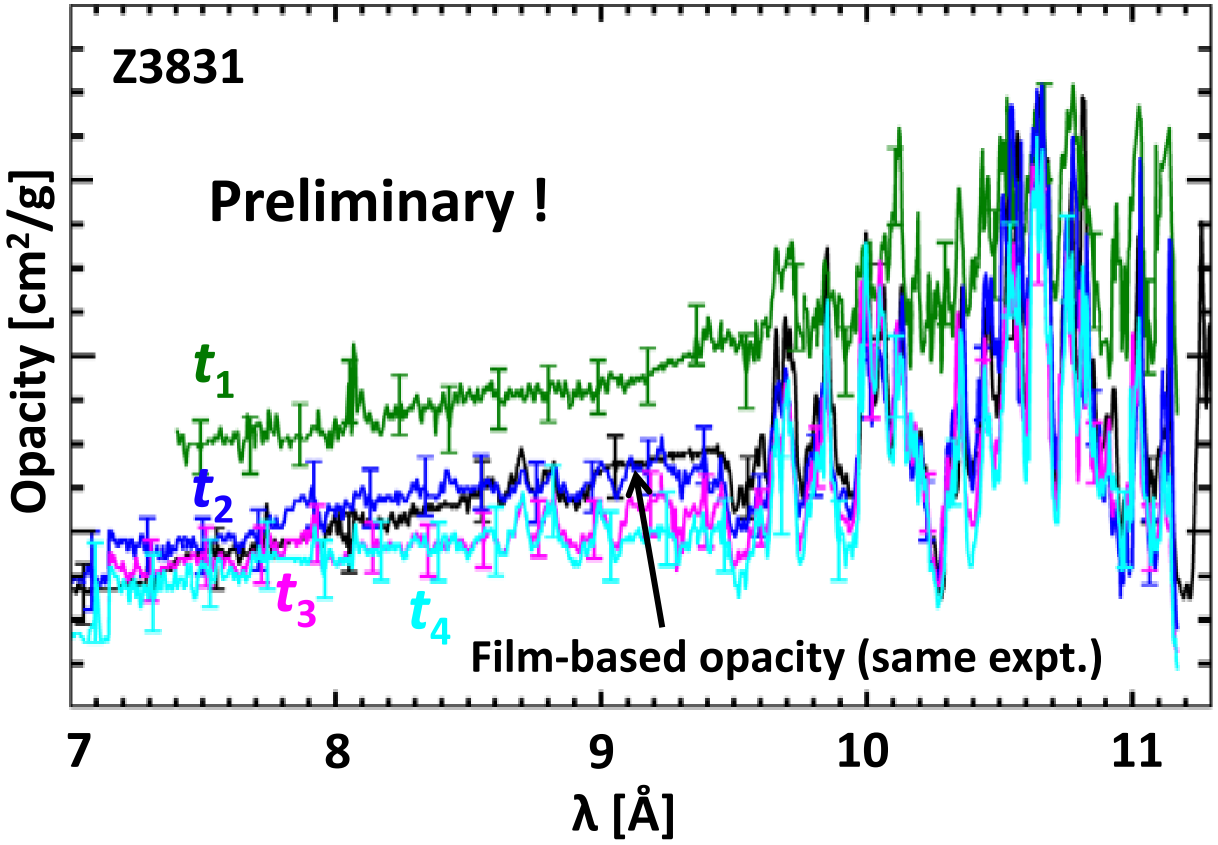


First anchor 1 with time-resolution agrees very well with reported Anchor 1 measurements



- Anchor 1 is an opacity-calibration point for Z
- Support confidence in time-resolved measurements to benchmark models

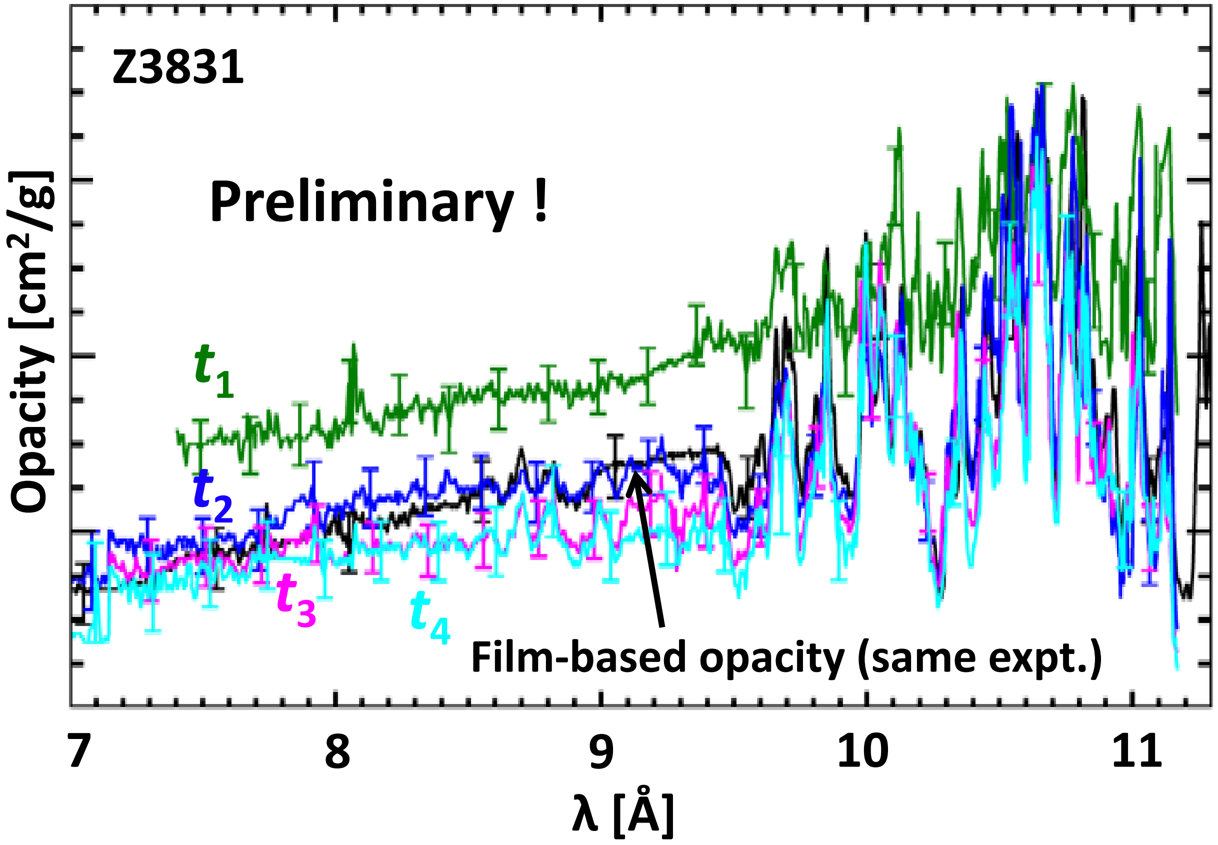
We applied transmission-corrected profile technique at *4* separate times

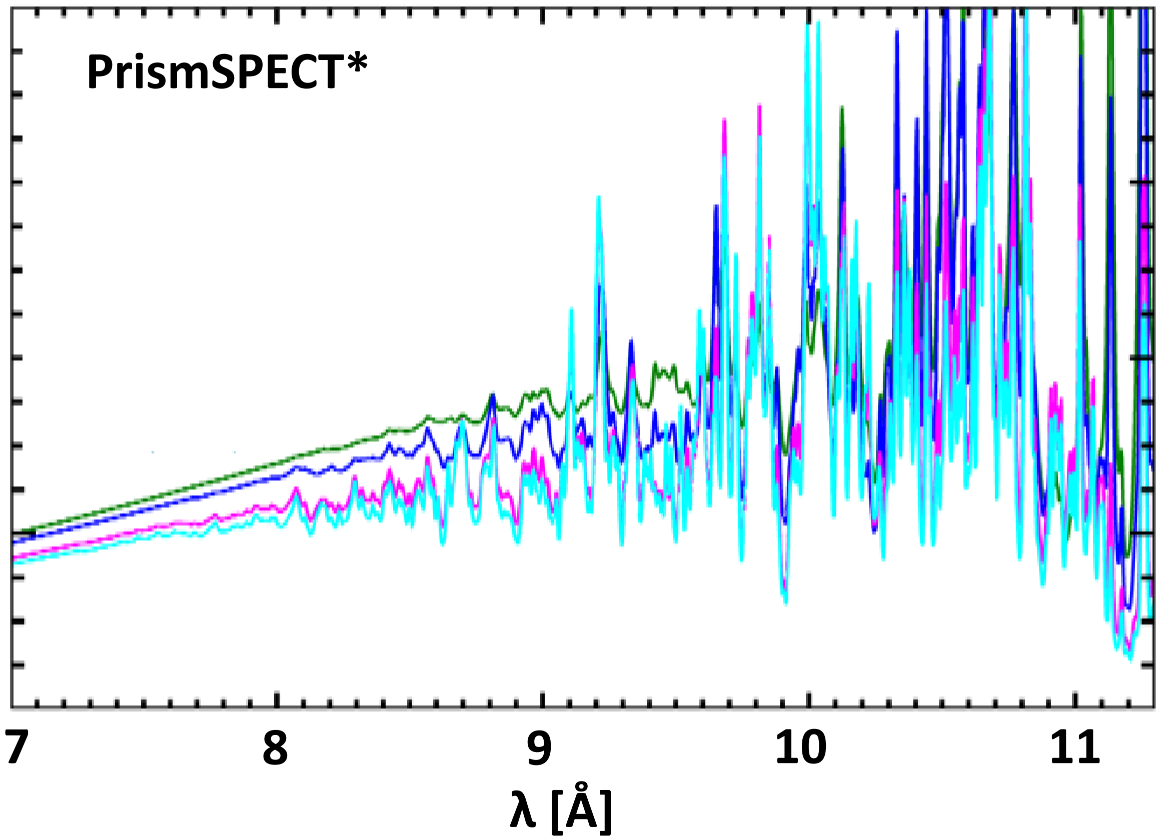


	$T_e(t)$ [eV]	$n_e(t)$ [10^{22} e^-/cm^3]
t_1	151	1.6
t_2	156	1.1
t_3	171	0.9
t_4	174	0.8

This is the first *absolute* time-resolved opacity on Z

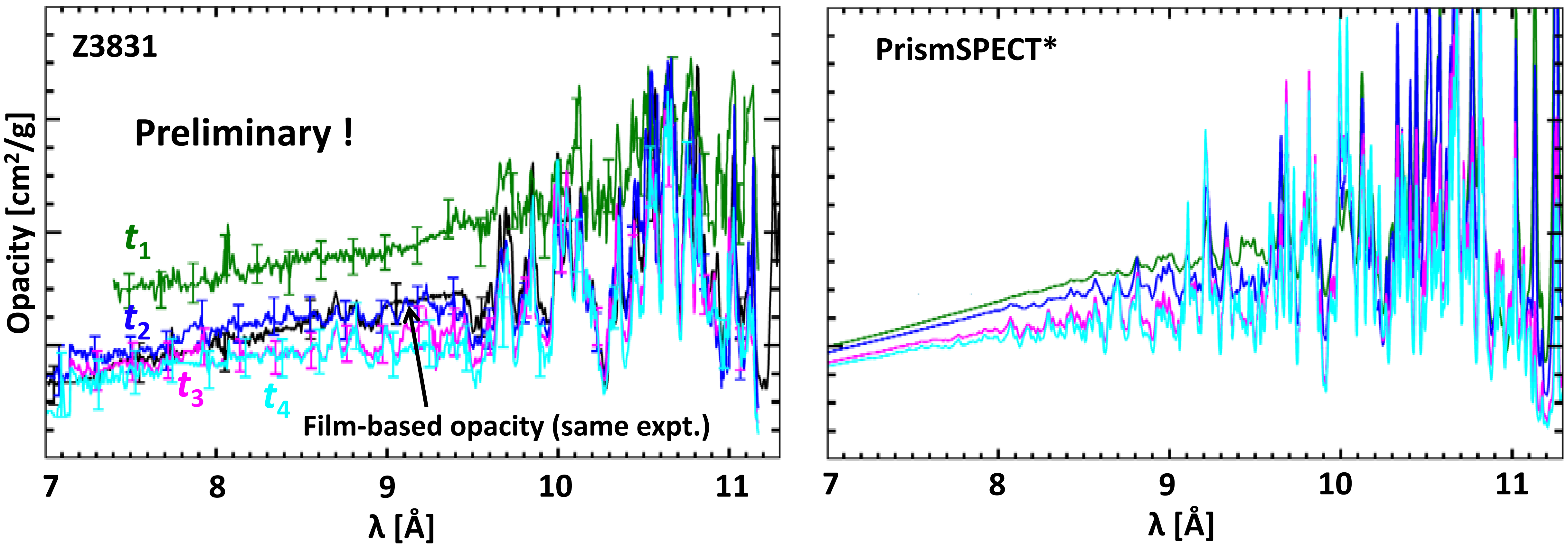
Opacity model* show similar trend vs time than Z data





*PrismSPECT, MacFarlane *et al.*, HEDP, (2007)

Opacity model* show similar trend vs time than Z data



- But t_1 opacity (high n_e, low T_e) is much larger than model!
- Similarly observed previously for Anchor 1+ (150 eV, 2×10^{22} cm^{-3}) on both Z & NIF, although not definitive

Exciting future work: Time-resolution advances Z opacity research beyond hypotheses testing

Advancement 1: Increase Z shot throughput

Advancement 2: Increase platform understanding

→ Density low at early times

→ Highest n_e

Advancement 3: Better control of conditions

→ Test single change in density

→ Increased overlap with NIF

Advancement 4: Optimized design for hypothesis testing

→ Reveal how density affects opacity

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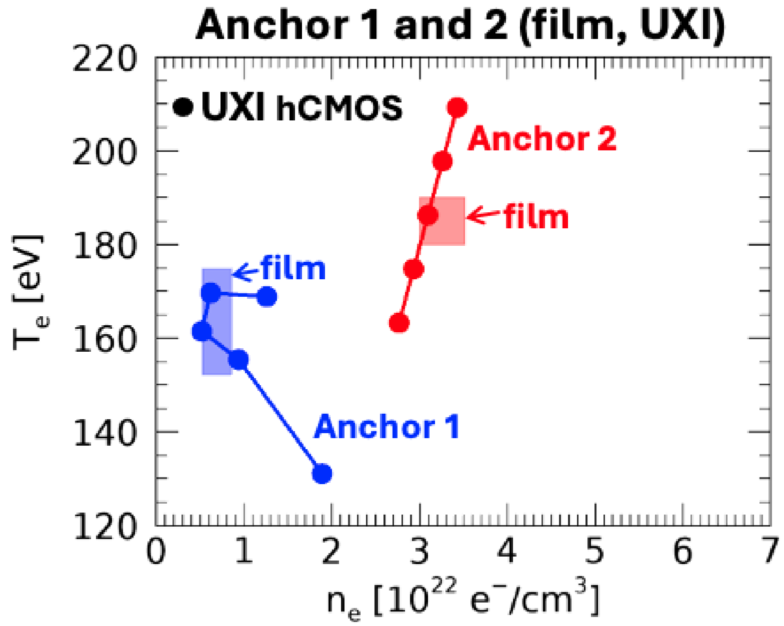


Exciting future work: Time-resolution advances Z opacity research beyond hypotheses testing

Advancement 1: Increase Z shot throughput

Advancement 2: **Increase platform understanding**

→ **Density low at early times**

→ **Highest n_e**

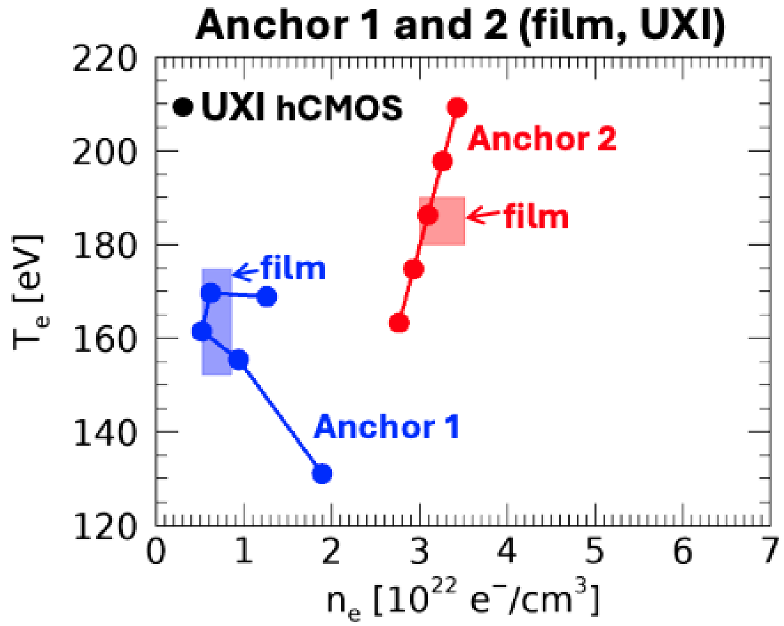
Advancement 3: Better control of conditions

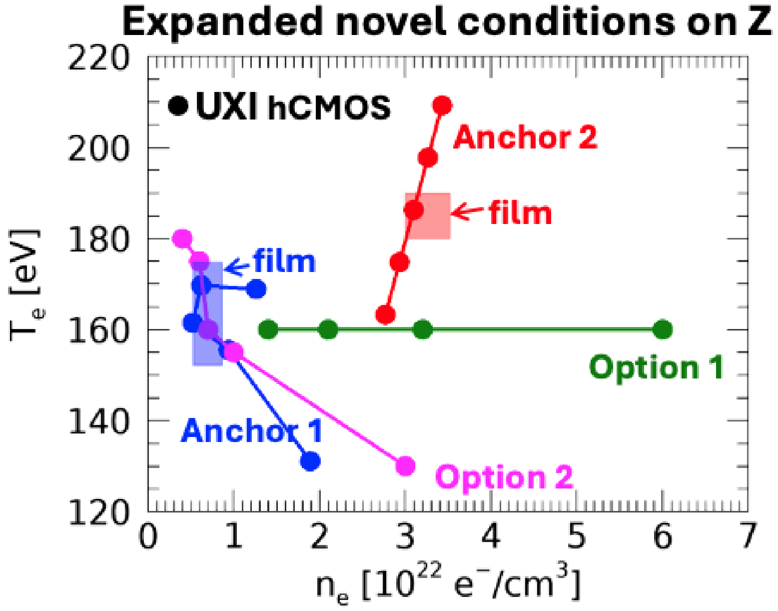
→ Test single change in density

→ Increased overlap with NIF

Advancement 4: Optimized design for hypothesis testing

→ Reveal how density affects opacity





Exciting future work: Time-resolution advances Z opacity research beyond hypotheses testing

Advancement 1: Increase Z shot throughput

Advancement 2: Increase platform understanding

→ Density low at early times

→ Highest n_e

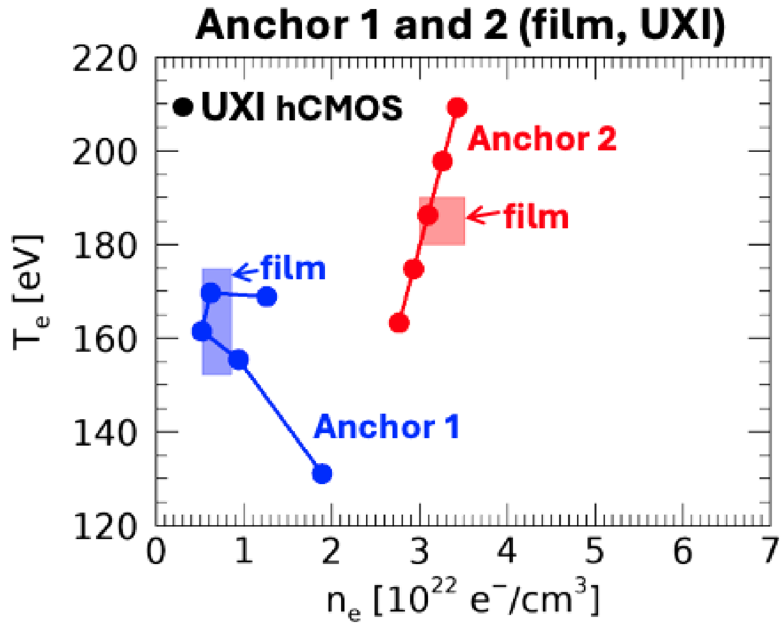
Advancement 3: **Better control of conditions**

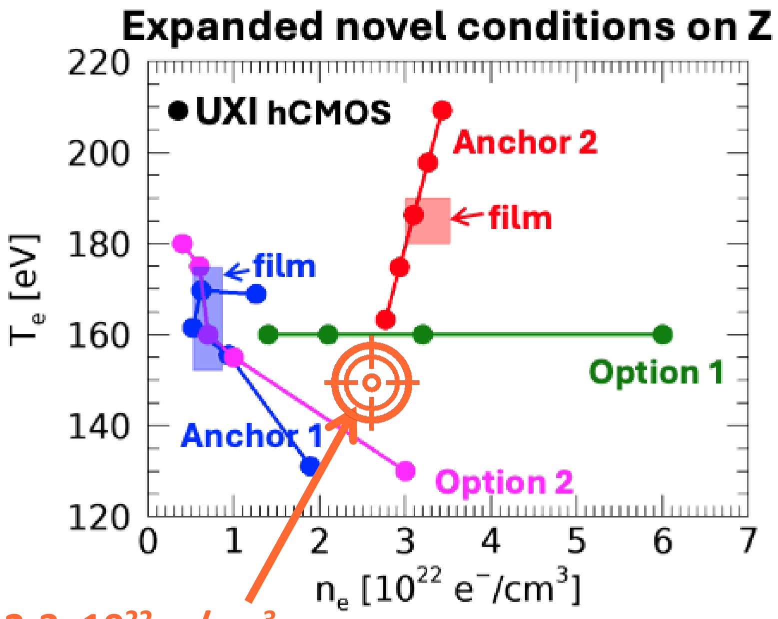
→ **Test single change in density**

→ **Increased overlap with NIF**

Advancement 4: Optimized design for hypothesis testing

→ Reveal how density affects opacity





Anchor 1+

T_e=150-160eV, n_e=2-3×10^{22} e^-/cm^3

Exciting future work: Time-resolution advances Z opacity research beyond hypotheses testing

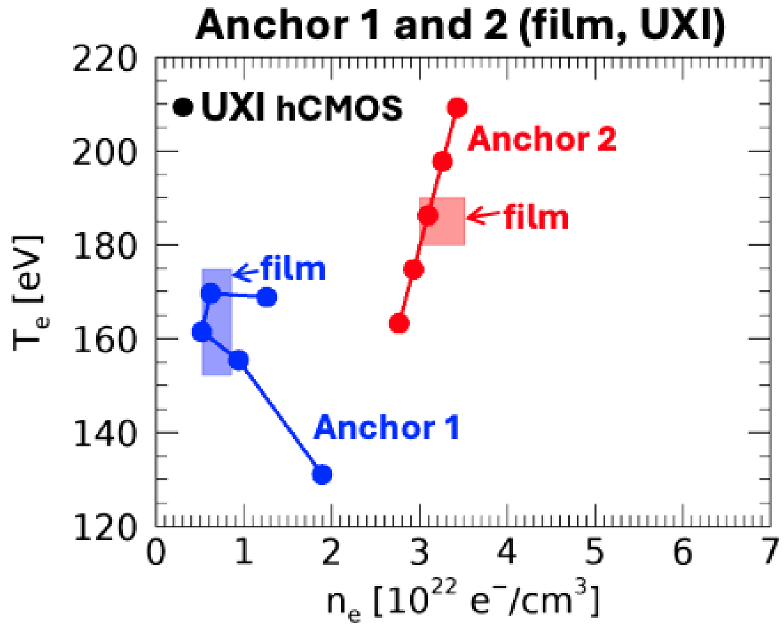
Advancement 1: Increase Z shot throughput

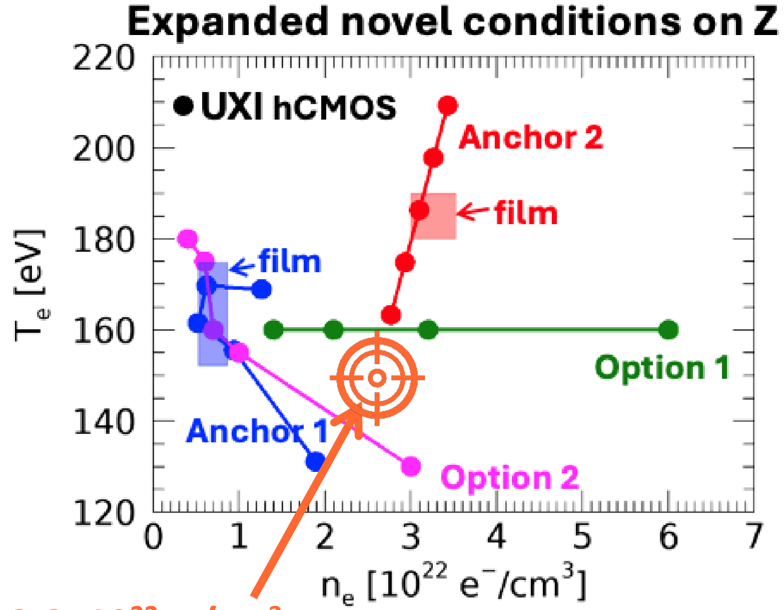
Advancement 2: Increase platform understanding
→ Density low at early times
→ Highest n_e

Advancement 3: Better control of conditions
→ Test single change in density
→ Increased overlap with NIF

***Advancement 4*: Optimized design for hypothesis testing**
→ Reveal how density affects oxygen opacity

Dan Mayes' talk





Anchor 1+
T_e=150-160eV, n_e=2-3×10^{22} e^-/cm^3

Summary: Advancing stellar opacity testing with novel time-resolved spectroscopy on Z

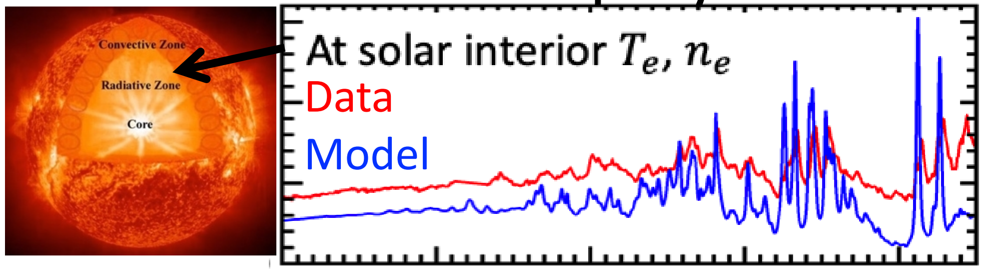
- **Puzzle:** the modeled and measured solar structure disagree
  - → *Is calculated iron opacity underestimated?*
  - → ***Initial Z experiments raised controversy***

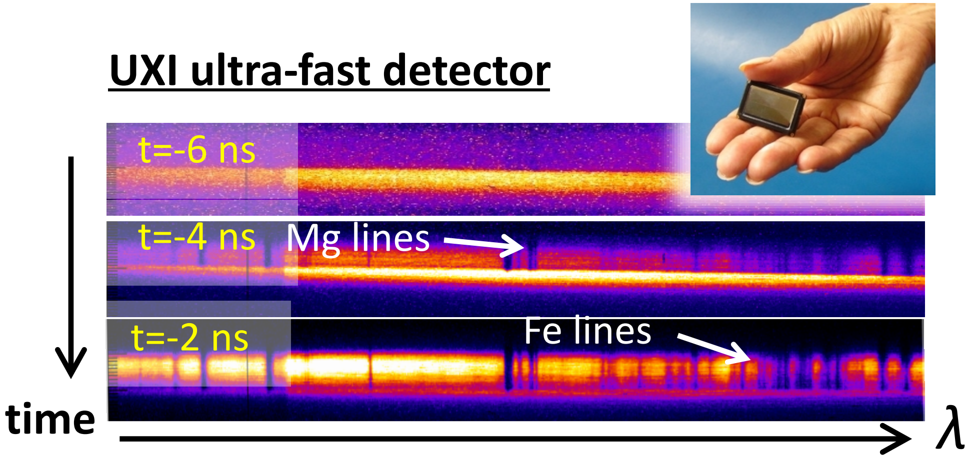
- **Experimental scrutiny:**
  - **Refining data analyses**
    - T_e, n_e analysis
    - Opacity analysis
  - **Time resolved measurements**
    - Tested temporal gradient effects → Found negligible

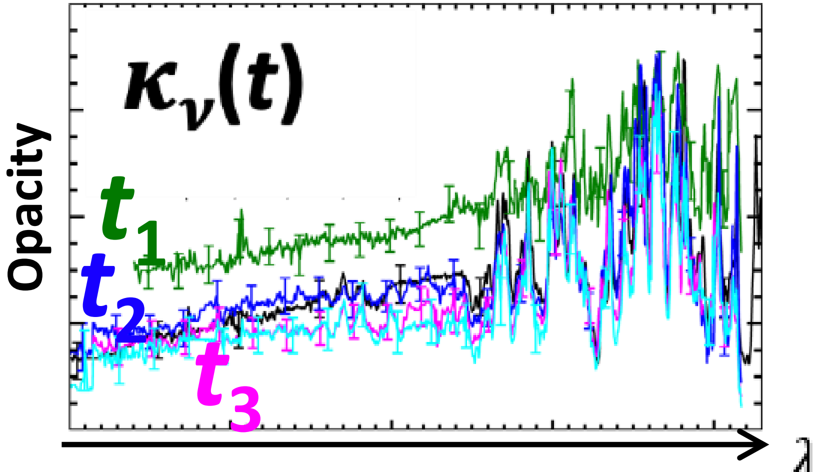
  → Transform experiments in 4 significant ways
    - Progress towards absolute time-resolved opacity measurements

Continued experimental and theoretical scrutiny are underway to answer this astrophysical puzzle

Anchor 2 Fe opacity

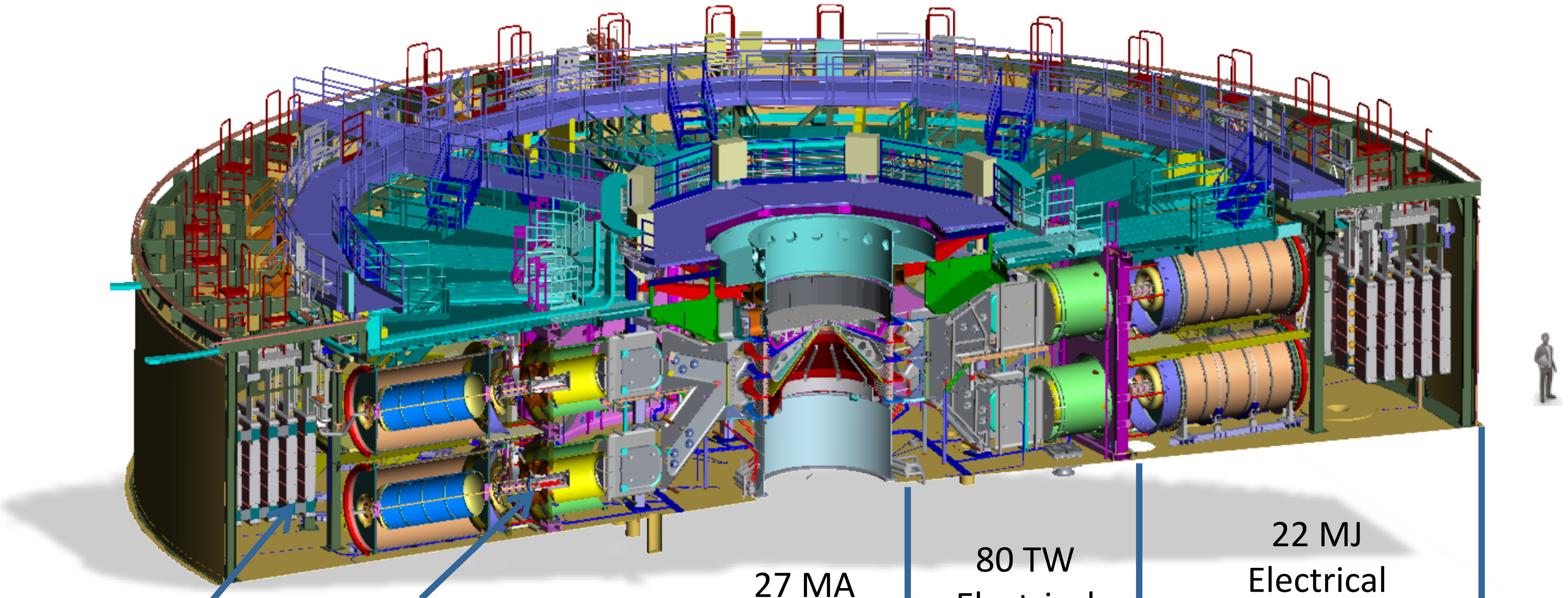






Extra slides

The Z facility at Sandia National Laboratories is the world's most powerful pulsed power machine

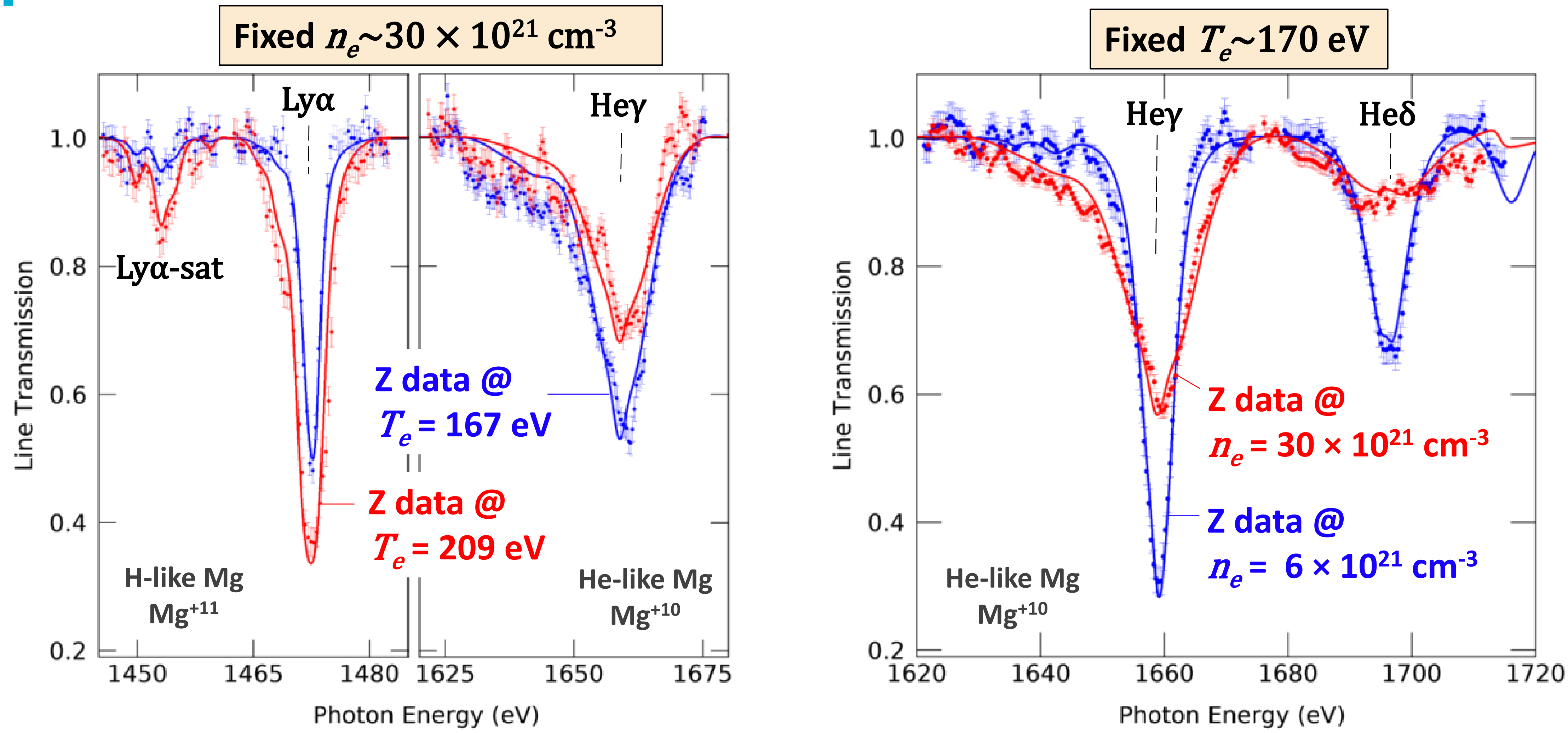


machine ⌀ = 108 ft
chamber ⌀ = 10 ft

1. **X-ray energy > 2 MJ**
2. **X-ray powers > 300 TW in 2 ns (2 billionth of a second)**

D. Sinars et al., Phys. Plasmas, 27 (2020)

Conditions were inferred successfully from UXI spectra



- **Increased control in Z platform: single T_e, n_e can be varied at a time!**

*T. Gomez *et al.*, *Phys. Rev. Letters*, **127**, (2021)