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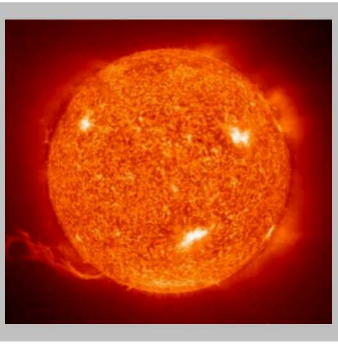

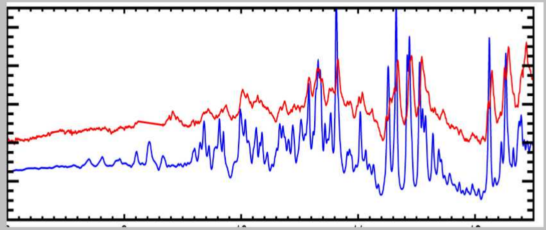

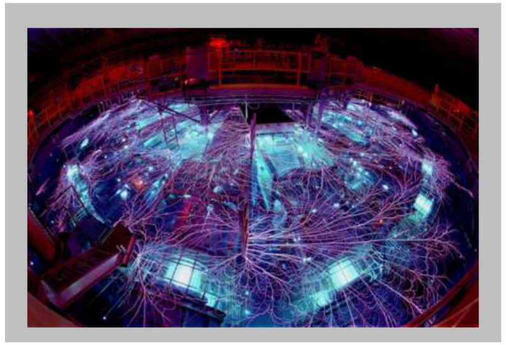

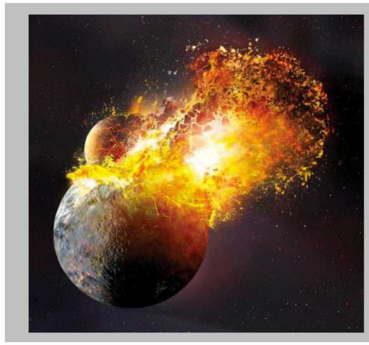

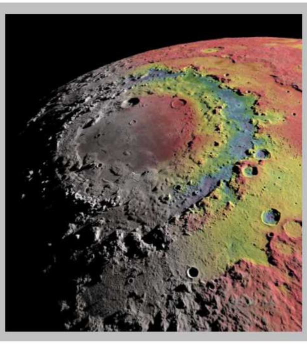

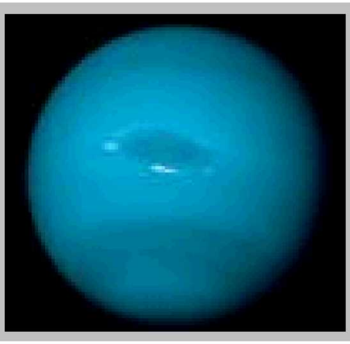

# Astrophysics within the Z Fundamental Science Program

Thomas R. Mattsson

NNSA/CEA-DAM Postdoc Workshop Paris, France, 5/16/2018

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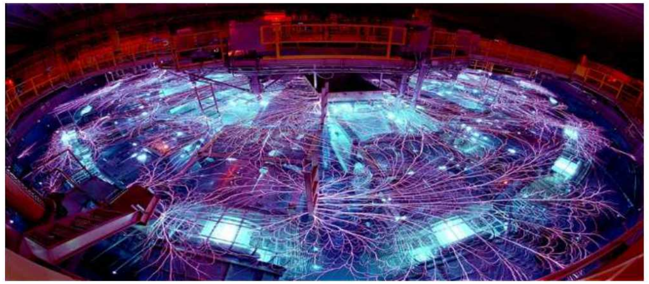
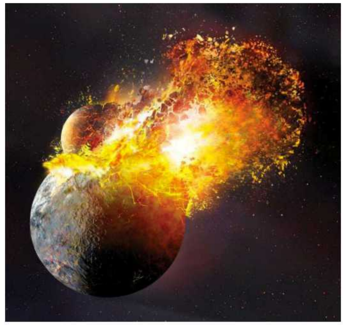
# Astrophysics / planetary science is a core part of the Z Fundamental Science Program

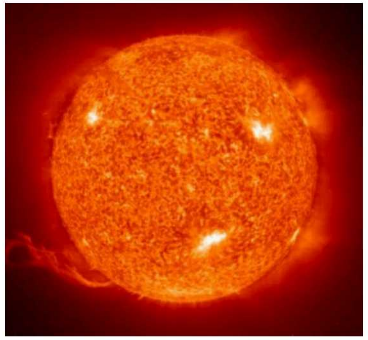
- Z – Machine
  - Pulsed Power, MHD Foundation, applications
- Z Fundamental Science Program
  - Planetary Science
  - Opacity of iron at solar conditions
- Summary



Z is the most powerful pulsed-power facility in the world



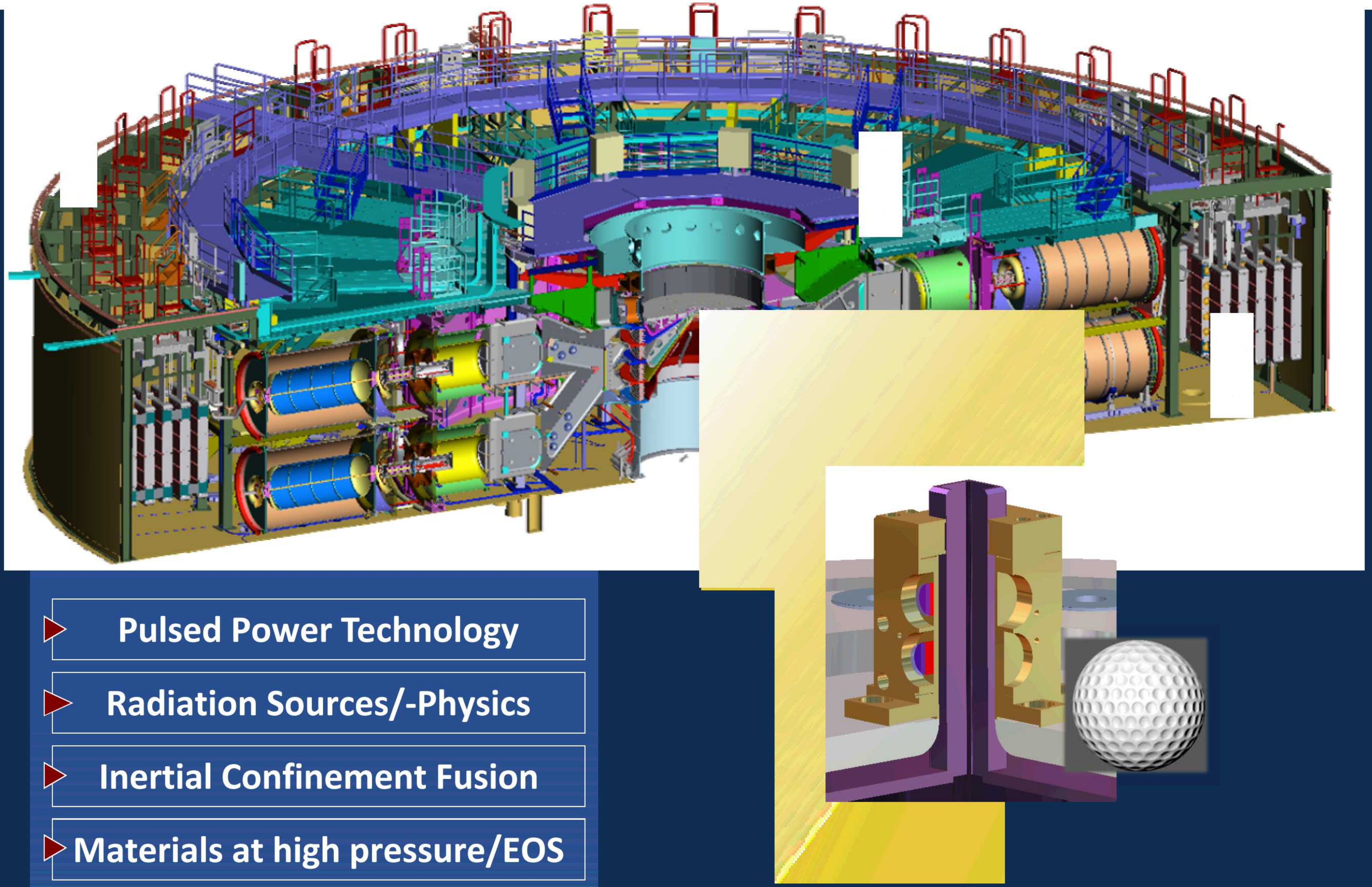
Direct measurement of iron vaporization at giant impact conditions – iron vaporizes earlier than ANEOS model.



Direct measurement of iron opacity at solar conditions – the opacity is significantly off compared to models

# Sandia's Z Machine is a unique platform for multi-purpose research on high energy density (HED) environments

Acknowledge teams:
Z operations, cryogenics, diagnostics, theory/ simulations, target design, engineering, and management



I ~ 26 MA,
τ ~100-1000 ns
X-ray power > 250 TW
X-ray energy > 2 MJ

- Pulsed Power Technology
- Radiation Sources/-Physics
- Inertial Confinement Fusion
- Materials at high pressure/EOS

# MHD: currents and the corresponding magnetic fields create matter and radiation in extreme conditions

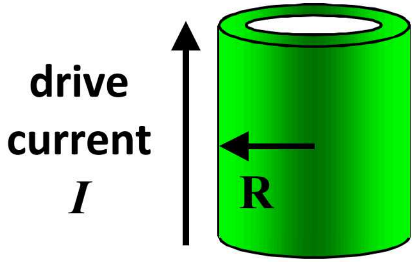
Current x magnetic field

Magnetic field as scalar pressure

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=\frac{\mathbf{J}\times\mathbf{B}}{c}-\nabla P\approx\frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B}-\nabla\left(P\;\text{[illegible]}\right)$$

Pressure

velocity field

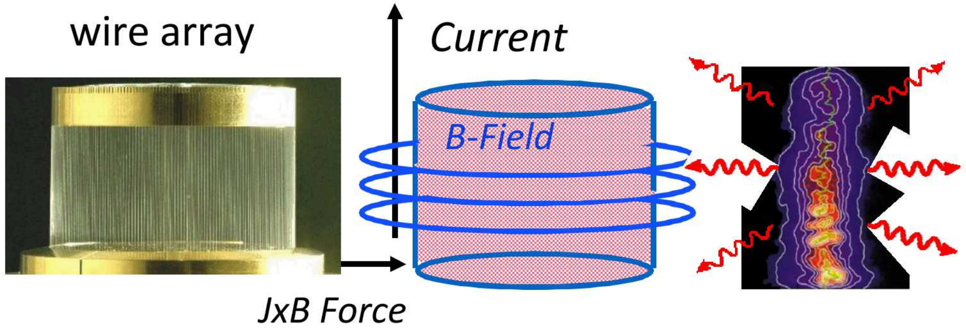


- 25 MA at 1cm radius is 1 Mbar
- 25 MA at 1mm radius is 100 Mbar

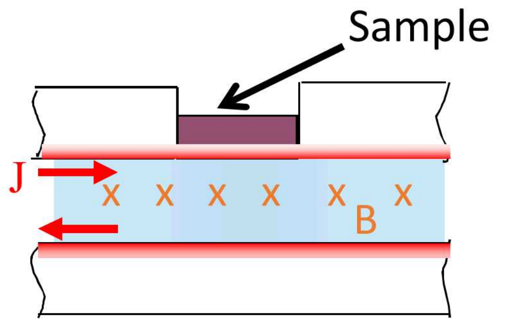
- Using pulsed power (current) as a source has advantages
  - *Can create high pressures without making material hot*
  - Generated over long time scales with control over the time history
  - Large samples and energetic sources (2 MJ to load of 20 MJ stored)
  - Low price - $4/Joule stored for refurbishment in 2007
- Integrated projects with theory/simulations/experiment
  - Develop, design, analyze, and optimize experiments

# We use magnetic fields to create HED matter in different ways for different applications

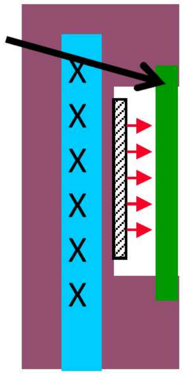
## Radiation physics from Z-Pinch X-ray Sources



## Materials Properties: EOS

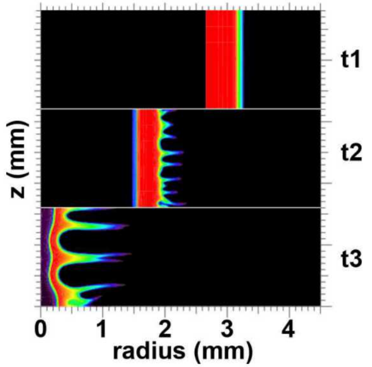


Isentropic Compression

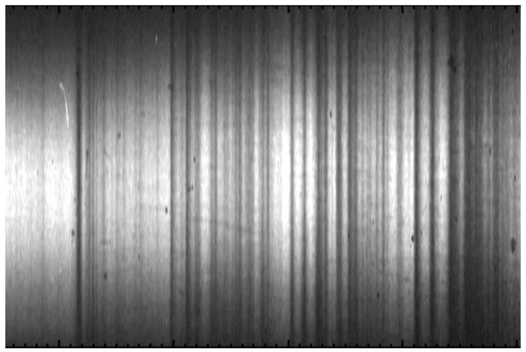


Flyer Plate

## Atomic- and plasma physics

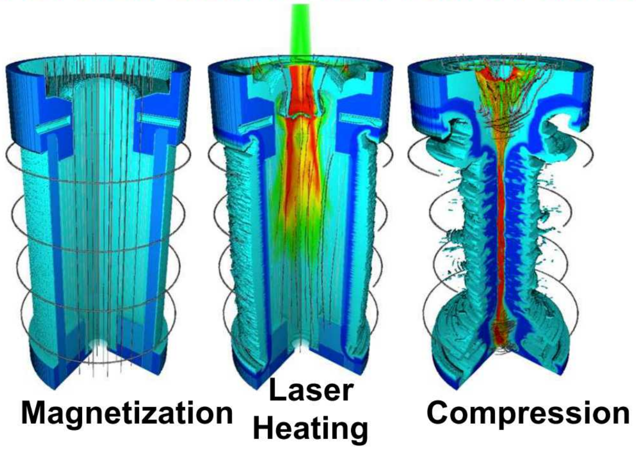


MRT instabilities



Iron spectrum

## Inertial confinement fusion

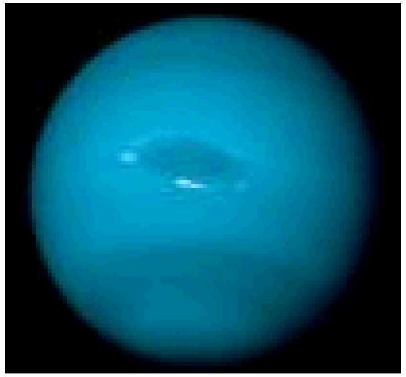


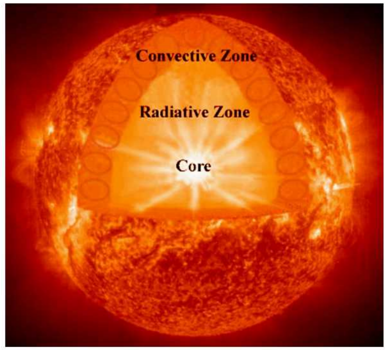
# Over the last 8 years, the Z Fundamental Science Program has developed into a key part of our research strategy

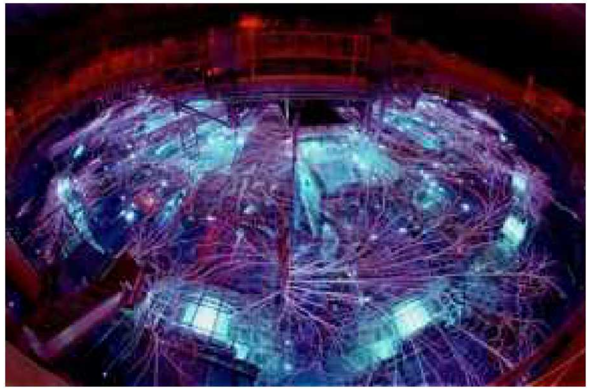
## Timeline for the program

- 2009 – 1st IHEDS workshop in Santa Fe
- 2010 – 1st call for proposals
- 2014 – Review, and extension for 2015
- 2015 – 2nd call for proposals (2016-17)
- 2017 – 3rd call for proposals (2018-19)

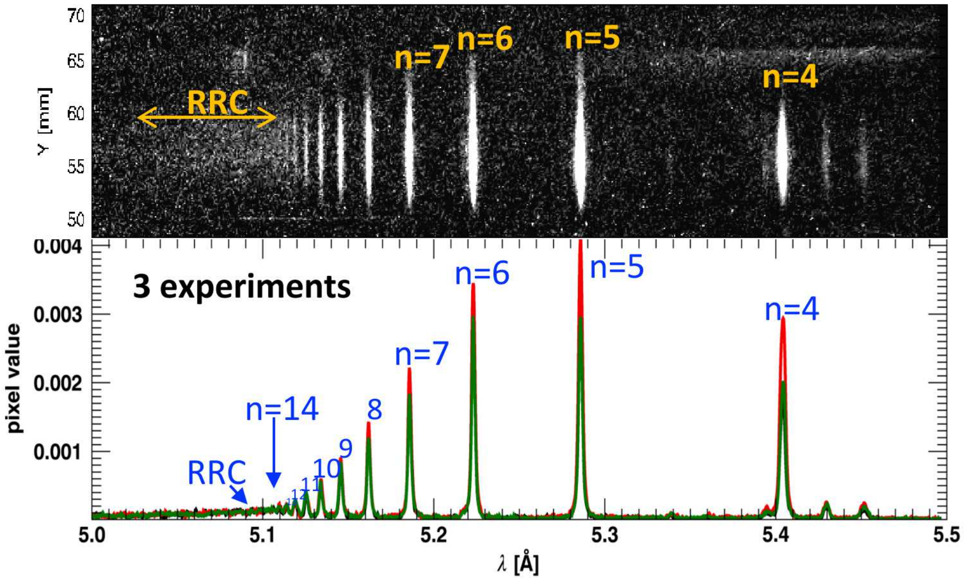
- **Workshops**
  - 2009 – 2011, Santa Fe
    - IHEDS SNL/UT Austin effort
  - 2012, 14 – 18, Albuquerque
    - *“Research opportunities and user meeting”*







# Four major discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program



**First observation of high-n He-like transitions and radiative recombination continuum in a photoionized plasma.**

Note the very high resolution in wavelength enabling the measurements.

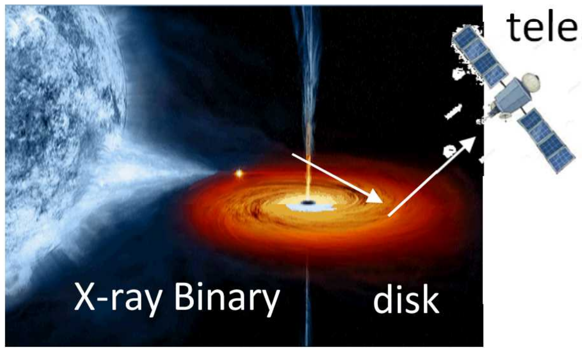
*Benchmark Experiment for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources*

G. P. Loisel, J. E. Bailey, et. al., Physical Review Letters **119**, 075001 (2017).

- Sandia, LLNL, LANL, NASA, UC Berkley, and UN Reno collaboration
- Created a low-density photo-ionized silicon plasma in conditions relevant to black hole accretion disks
- Demonstrated that Resonant Auger Destruction is not present in the photo-ionized spectra
- The findings are likely to affect how astrophysical objects like accretion disks are viewed

Black hole accretion

X-ray telescope



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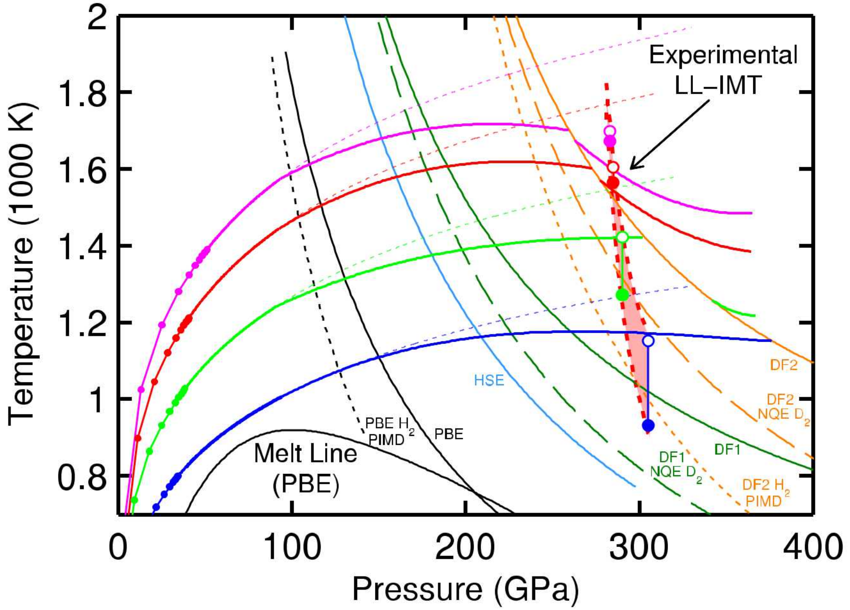
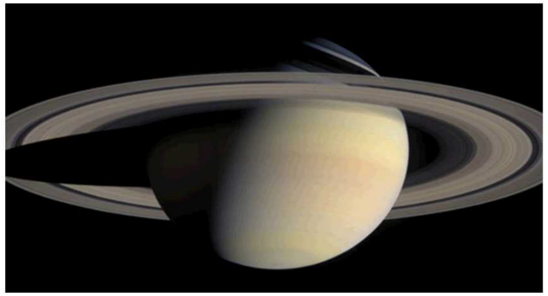


**Measured the predicted pressure-driven insulator-metallization transition in deuterium**

*Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium*

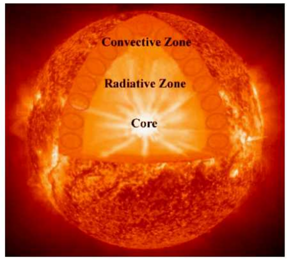
Marcus D. Knudson, Michael Desjarlais, et. al., SCIENCE **348**, 1455 (2015).

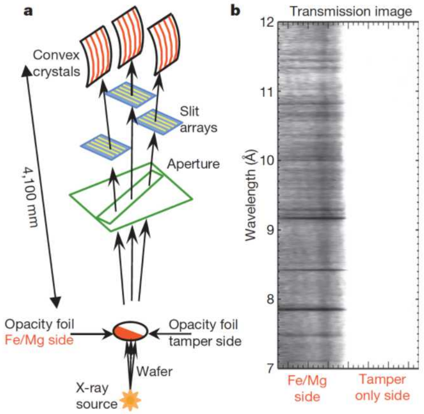
- Sandia and University of Rostock, Germany
- Experiments above ~250 GPa show clear evidence of metallization of deuterium
- Pressure is well above numerous first principles predictions
- Insensitivity to T suggests this is a density-driven transition



Implications for understanding Jupiter, Saturn, and thousands of exoplanets

# Four major discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program

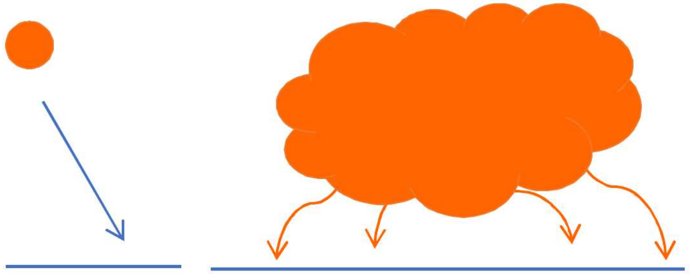




**A higher opacity of iron at solar conditions explains contradictions between helioseismic observations and established solar models**

*A higher-than-predicted measurement of iron opacity at solar interior temperatures*

- Jim Bailey, et. al., Nature 517, 14048 (2015)
- Sandia, Ohio State University, University of Nevada Reno, PRISM, LANL, LLNL, and CEA
- High-precision measurements at the almost unreachable conditions of the radiation/convection boundary in the sun

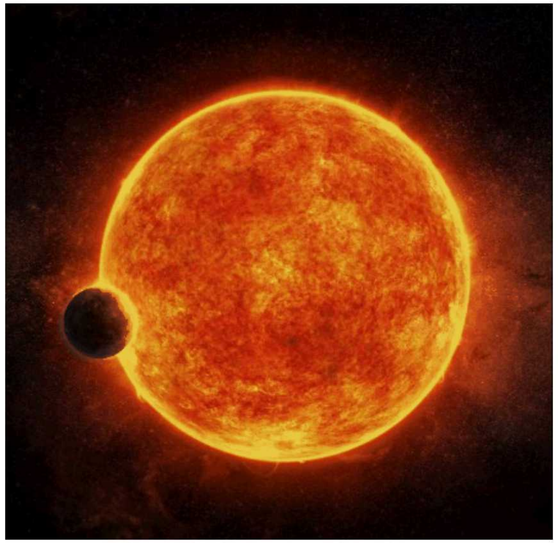


**Iron rain following a meteor impact explains the iron-enriched mantle of the earth and a key earth/moon difference**

*Impact vaporization of planetesimal cores in the late stages of planet formation*

- Richard D. Kraus, Seth Root, et. al., Nature Geoscience, DOI:10.1038/NGEO2369 (2015)
- Sandia, Harvard, UC Davis, and LLNL
- Multi-Mbar dynamical material experiments to measure properties of vaporized iron at conditions of planetary impacts

# Vaporization during planet formation and evolution is a key mechanism – large uncertainty in the onset of vaporization



- Giant impacts and the origin of the moon
- Addition and removal of planetary atmospheres
- Chemical evolution of planets
- Exoplanets! Wide range of interiors and atmospheres, mass-radius diagrams

***We aim to turn planetary science quantitative by high fidelity modeling and high-precision experiments***

# Giant impacts vaporize portions of planets

D. Crawford, 2011
CTH calculation

# Giant impacts vaporize portions of planets

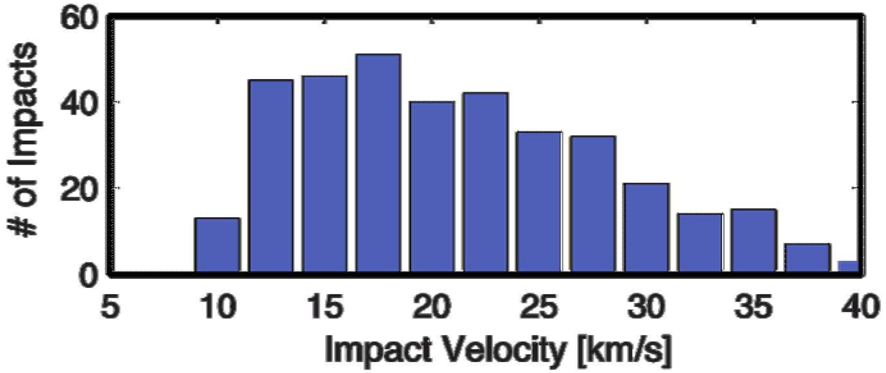
D. Crawford, 2011
CTH calculation

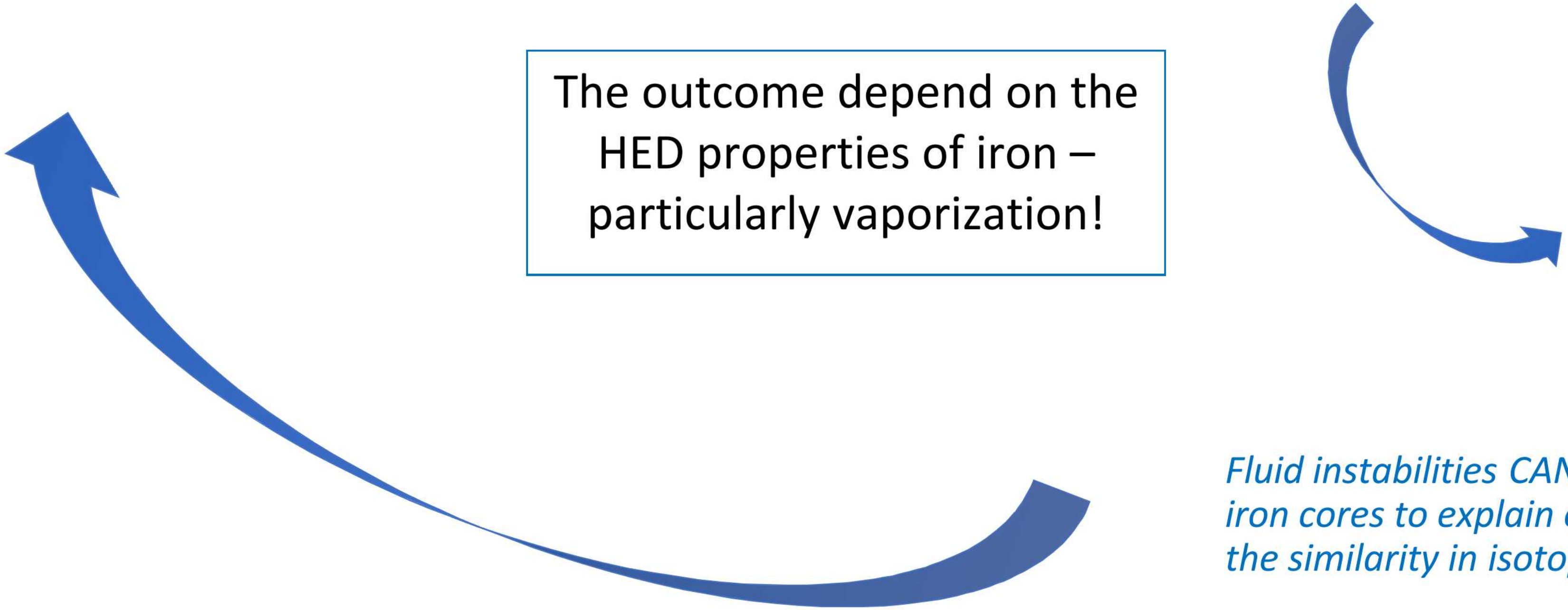
# Z experiments provide material properties in HED conditions to address the moon formation mystery

Does an iron meteor:

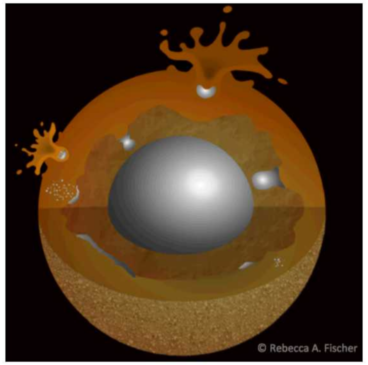
- plow into a planet as a bullet?
- splatter as a drop of rain?
- vaporize into a cloud of iron to return as iron rain?

Simulations of planetary dynamics suggest high impact velocities





The outcome depend on the HED properties of iron – particularly vaporization!

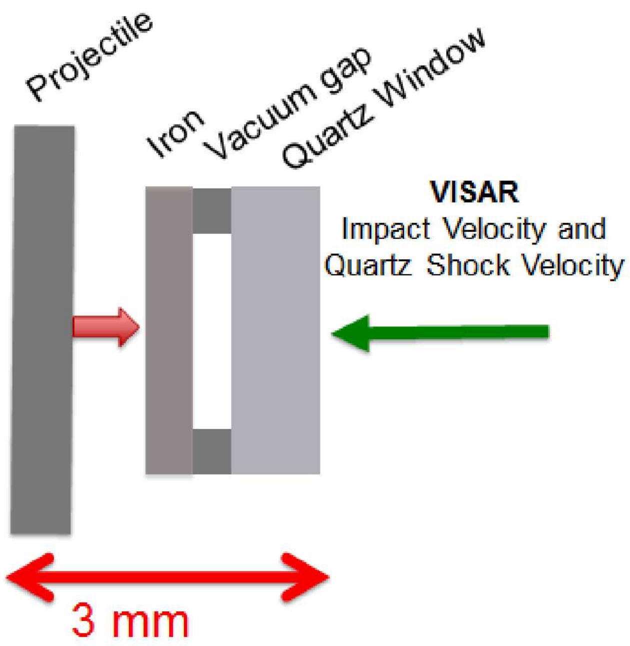


*Fluid instabilities CAN NOT sufficiently mix the incoming iron cores to explain observed iron content in the mantel or the similarity in isotopics between the earth and the moon.*

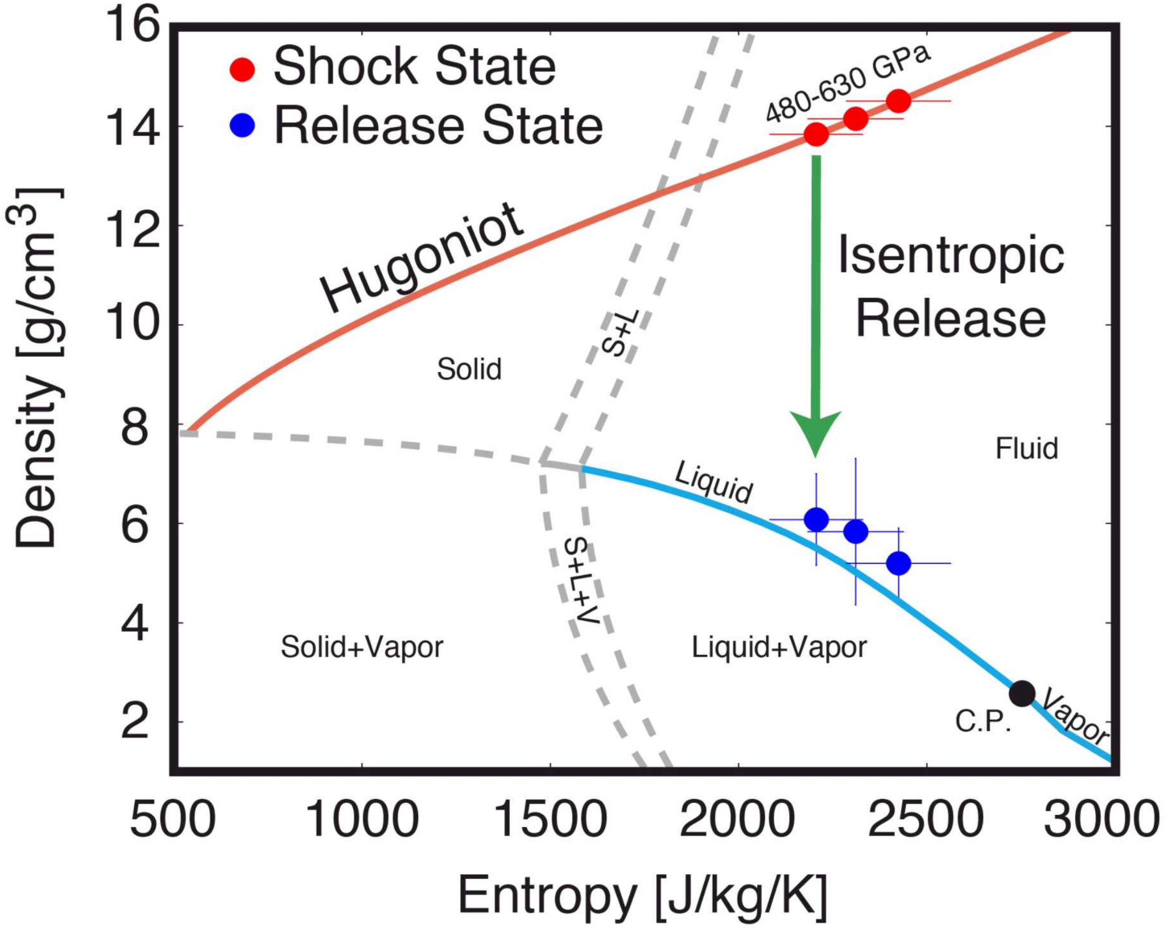
N-body simulations from Raymond et al. 2009

# Z can study vaporization for states produced by planet forming impacts

- On Z, we can launch flyer plates up to 40 km/s
- *It is possible to directly simulate all impact conditions*
- We locate the liquid-vapor dome as a function of entropy by a shock-release path

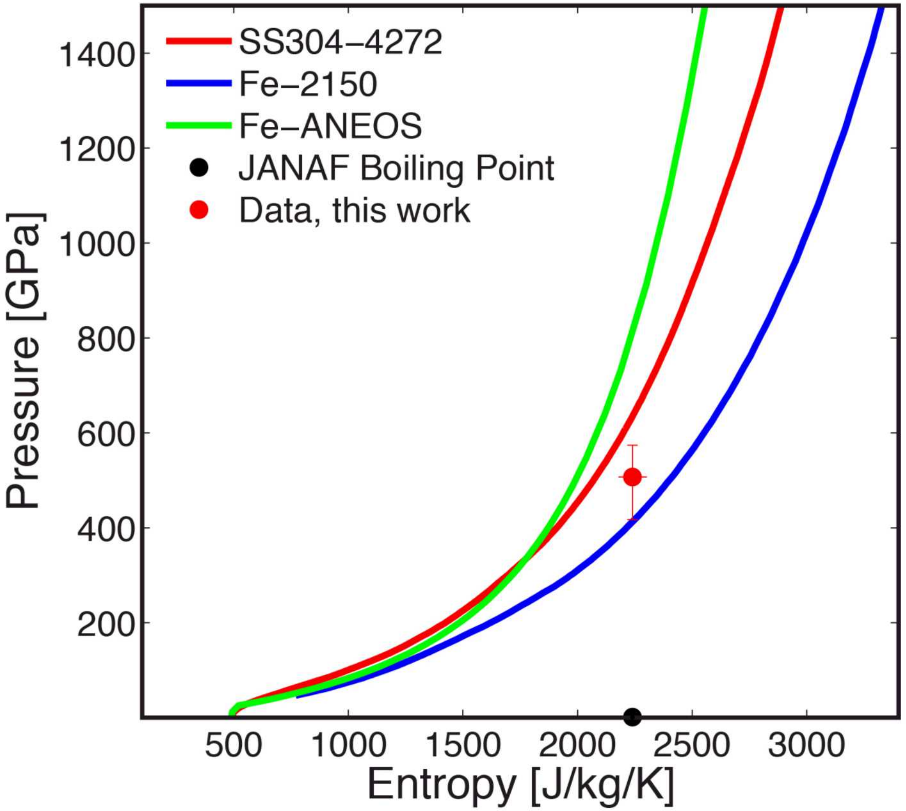


Iron Shock and Release Data



# This is one of the first determinations of the thermal state of an opaque material on the Hugoniot

*Quantitative knowledge of the behavior of matter under extreme conditions is crucial for improving our understanding of planetary physics*



- *Vaporization is significantly easier than ANEOS suggests – the most broadly used model*

- A project within the Z Fundamental Science Program
  - Stein Jacobsen, Harvard
  - Sarah Stewart at UC Davis
  - Rick Kraus, LLNL

*Impact vaporization of planetesimal cores in the late stages of planet formation*, R.G. Kraus, S. Root, R.W. Lemke, S.T. Stewart, S.B. Jacobsen, and T.R. Mattsson, Nature Geoscience 2015 DOI: 10.1038/NGEO2369

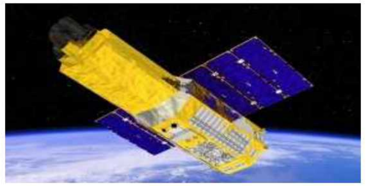
# We measure fundamental properties of atoms in plasmas to solve important astrophysical questions

- Astrophysics relies on *plasma spectral models*:
  - Spectral analysis of accretion disk radiation
  - Fundamental properties like opacity and equation of state
- ZAPP (= Z Astrophysical Plasma Properties) replicates and study astrophysics-relevant plasmas
- Laboratory astrophysics requires broad knowledge:
  - i) Astrophysical importance
  - ii) Model approximations and limitations
  - iii) Experimental feasibility

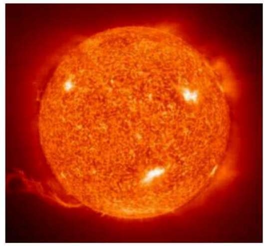
**Chandra - NASA**

**XMM-Newton - ESA**

**Suzaku – JAXA**



*Success of satellite missions require validated models, making benchmark experiments, and collaboration between fields*



Solar Fe opacity:

T=200 eV

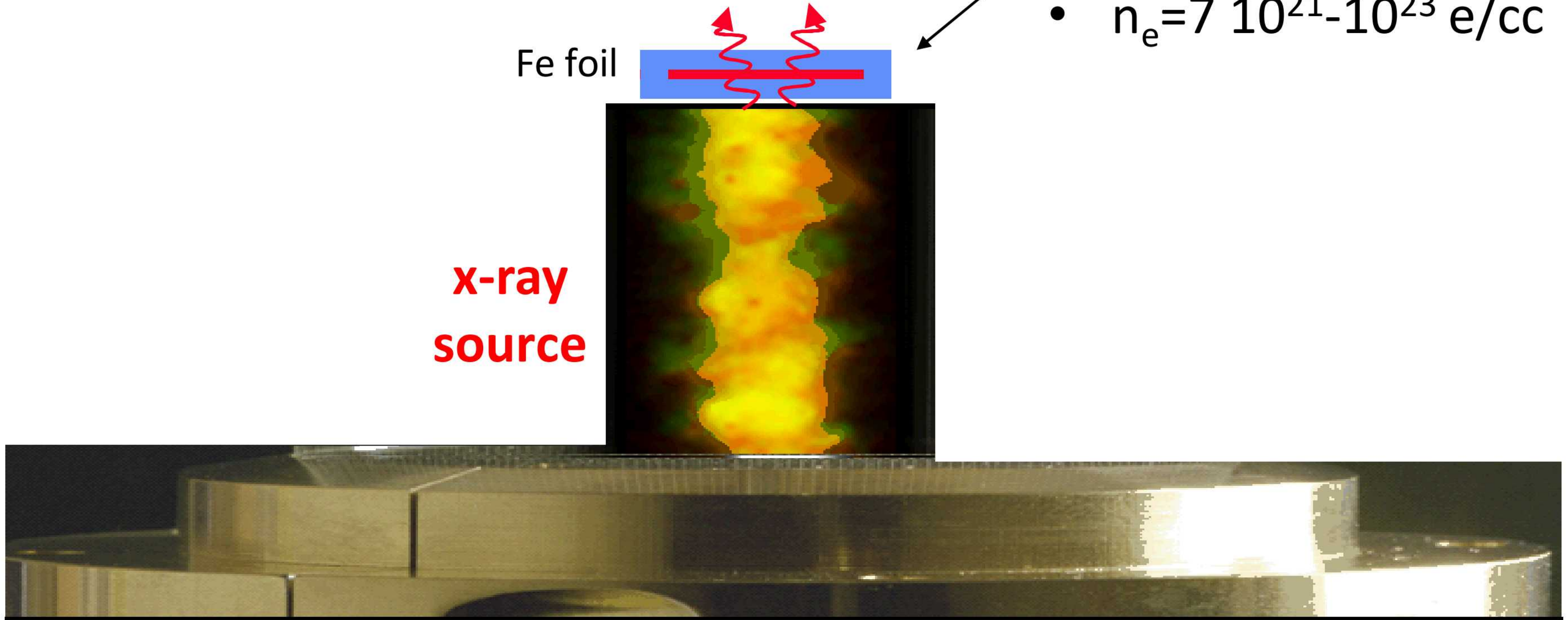
$n_e$=5 $10^{22}$ $cm^{-3}$

*P169 Stellar Interior Opacities*
*NNSA/CEA-DAM*

# The Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously

Solar opacity sample

- T=150-200 eV
- $n_e$=7 $10^{21}$-$10^{23}$ e/cc

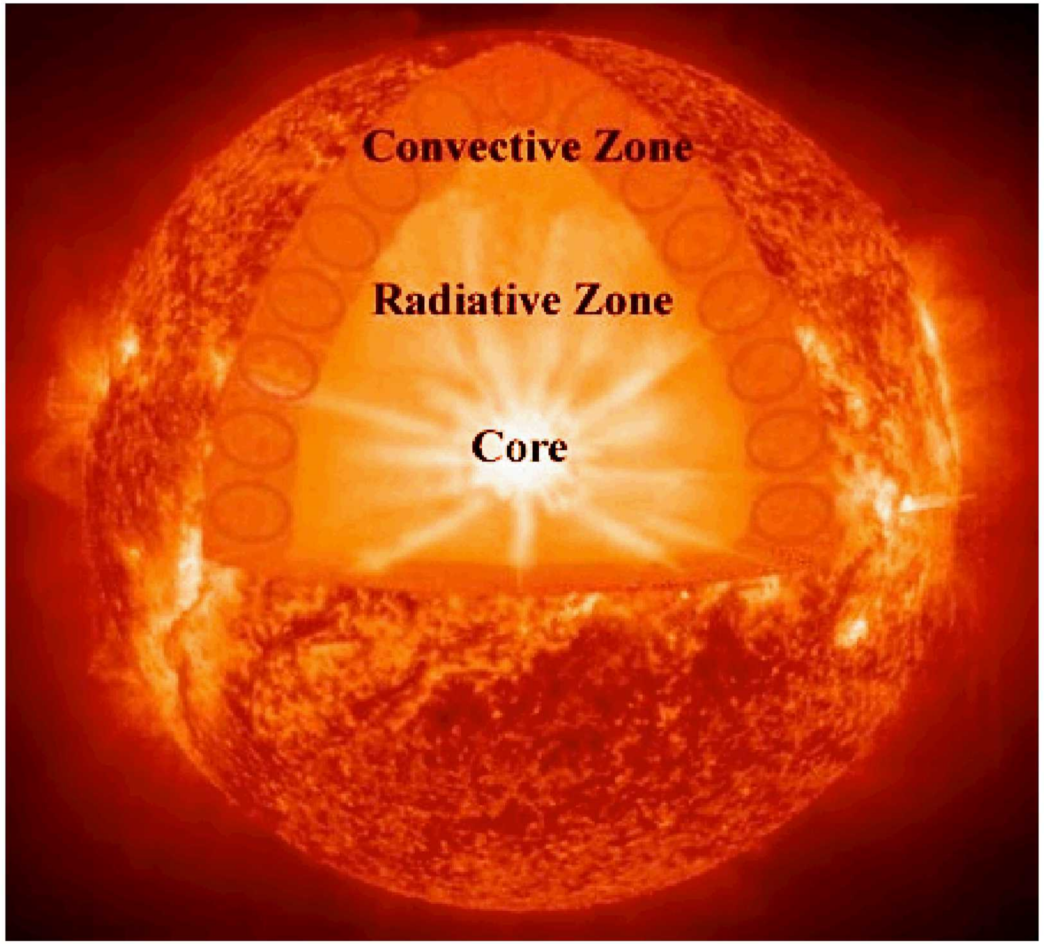


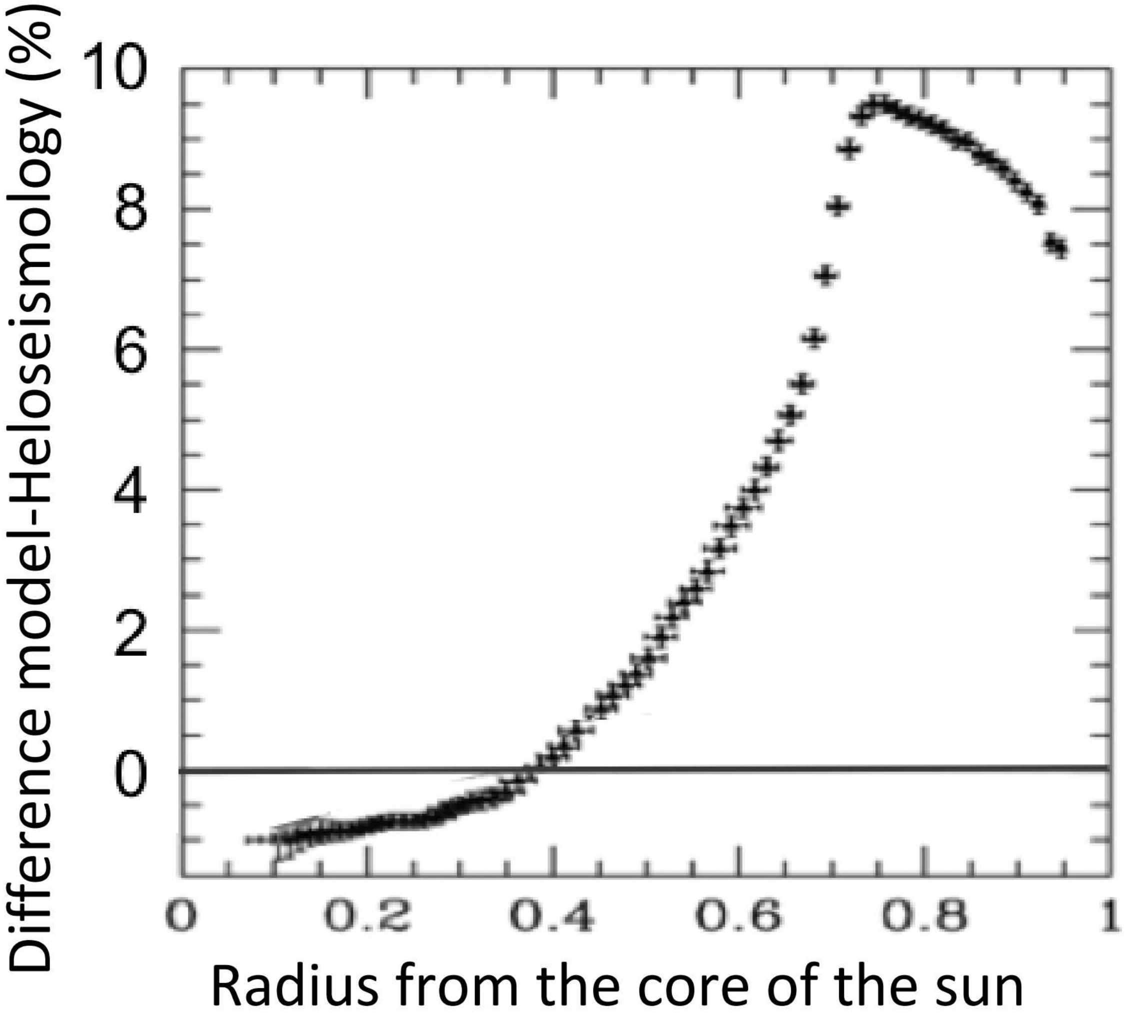
$P_{rad}$ ~ 220TW (±10%), $Y_{rad}$ ~ 1.6 MJ (±7%)

Single shot can perform multiple experiments at T=1-200 eV and $n_e$=5 $10^{16}$-$10^{23}$ e/cc

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

# Modeled solar structure disagrees with observations





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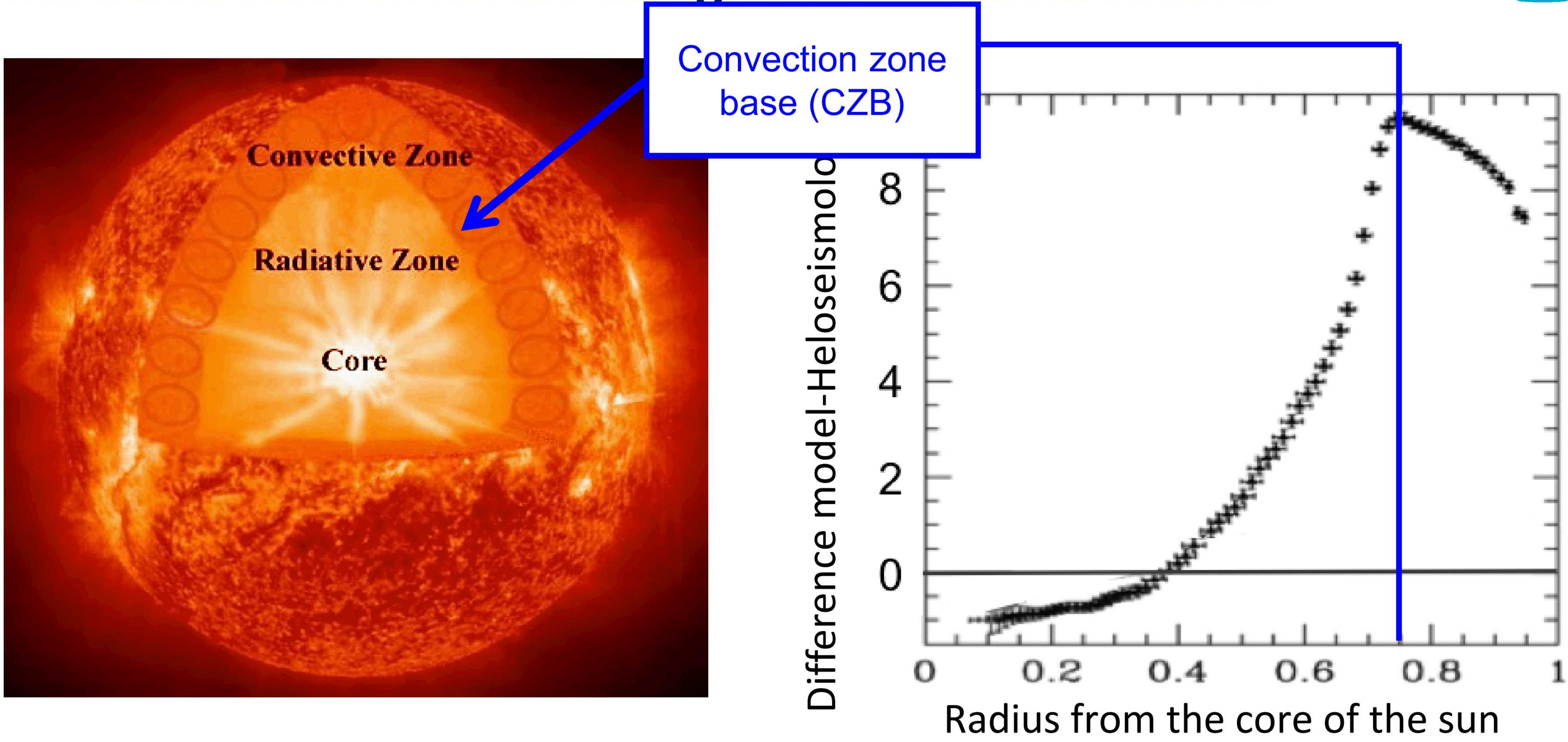

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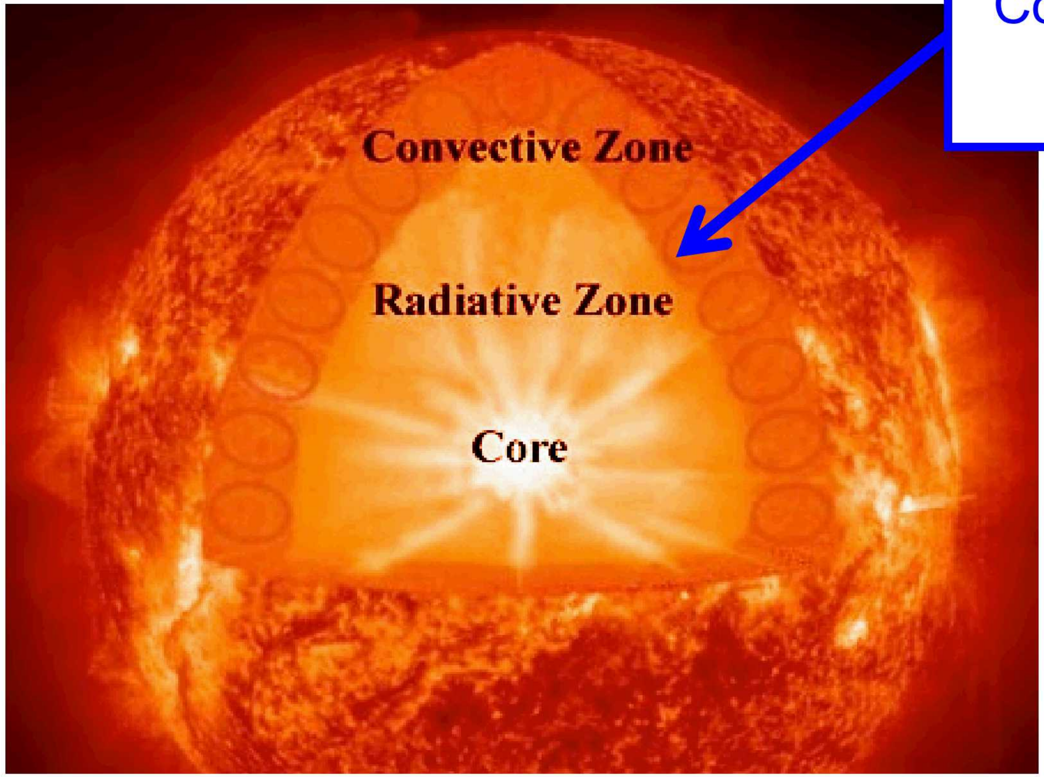
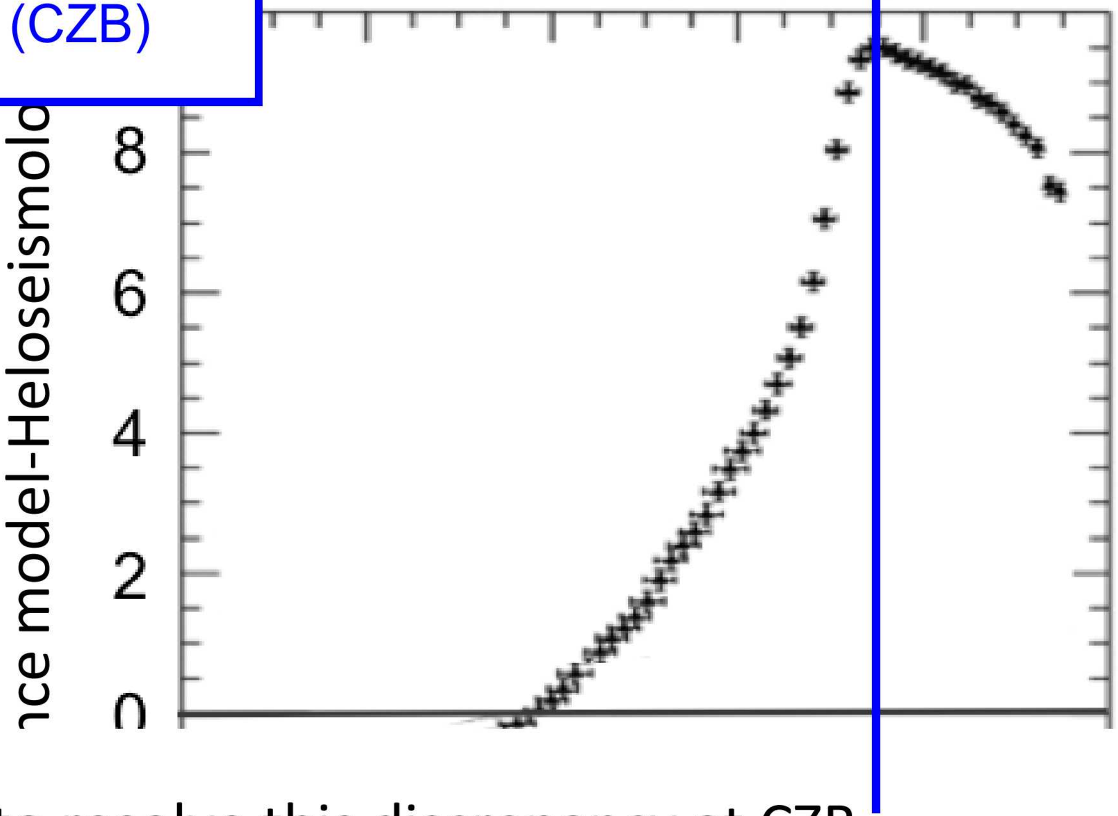


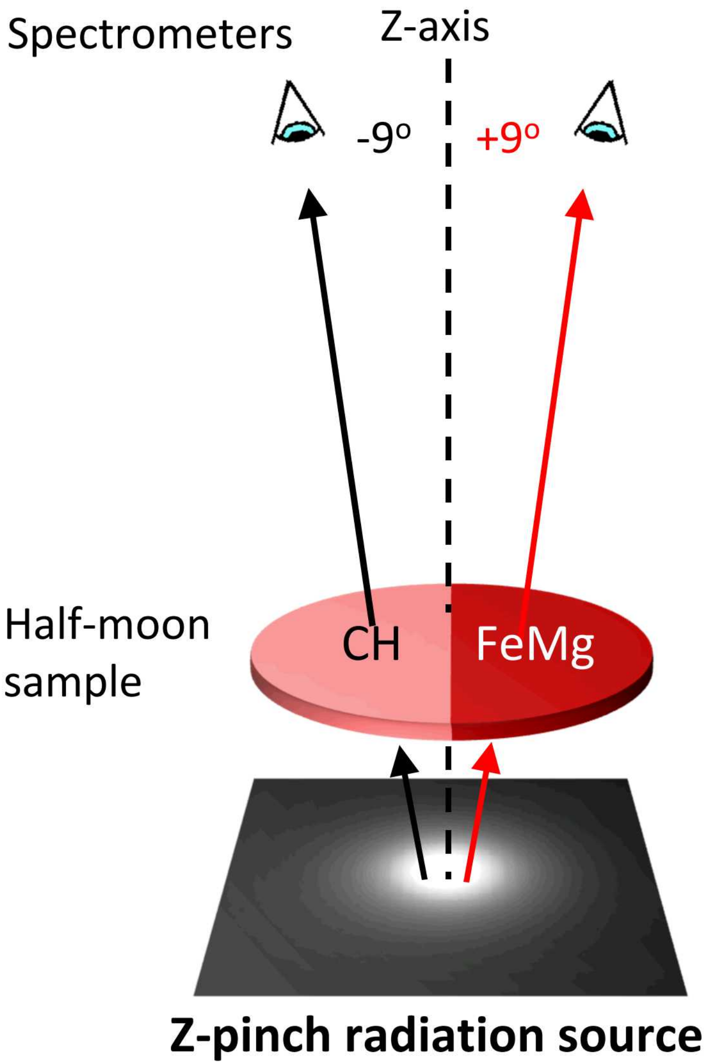
Convection zone base (CZB)



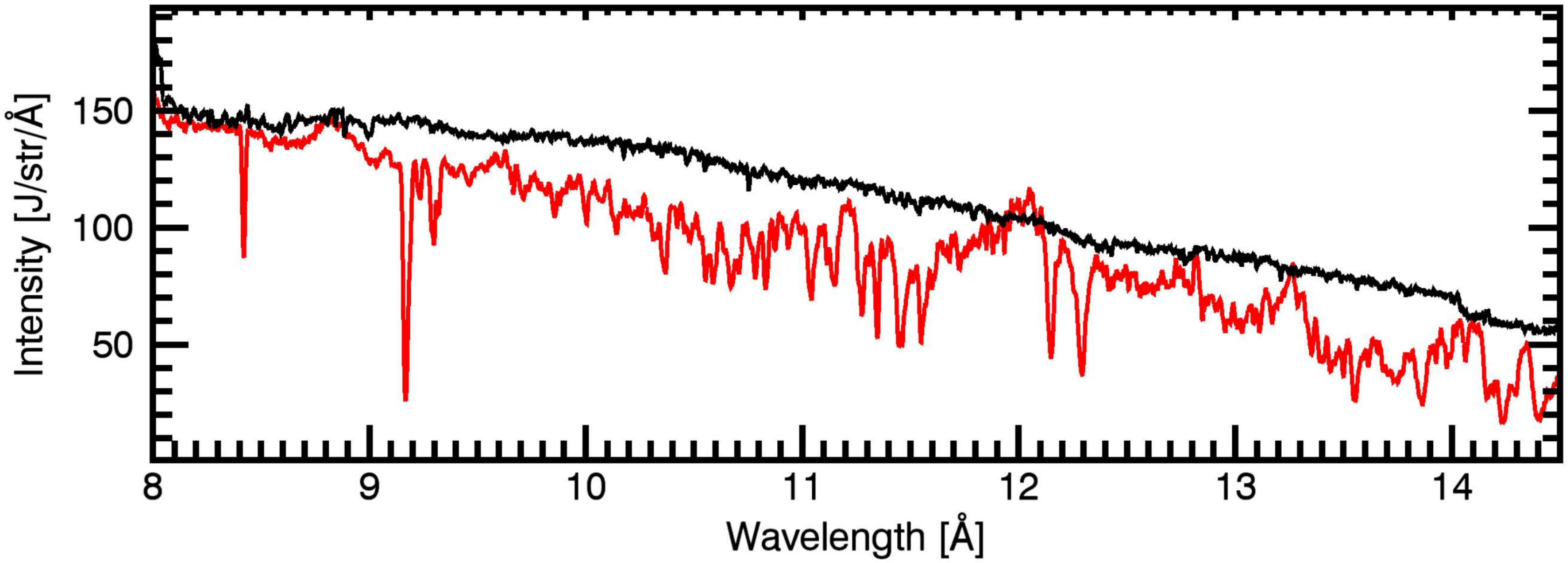
- 17% mean-opacity increase is needed to resolve this discrepancy at CZB
- Calculated opacity has never been tested at solar interior conditions

**Objective: Measure Fe opacity at CZB conditions ($T_e$=182 eV, $n_e = 9 \times 10^{22} cm^{-3}$)**

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



**Z-pinch radiation source**

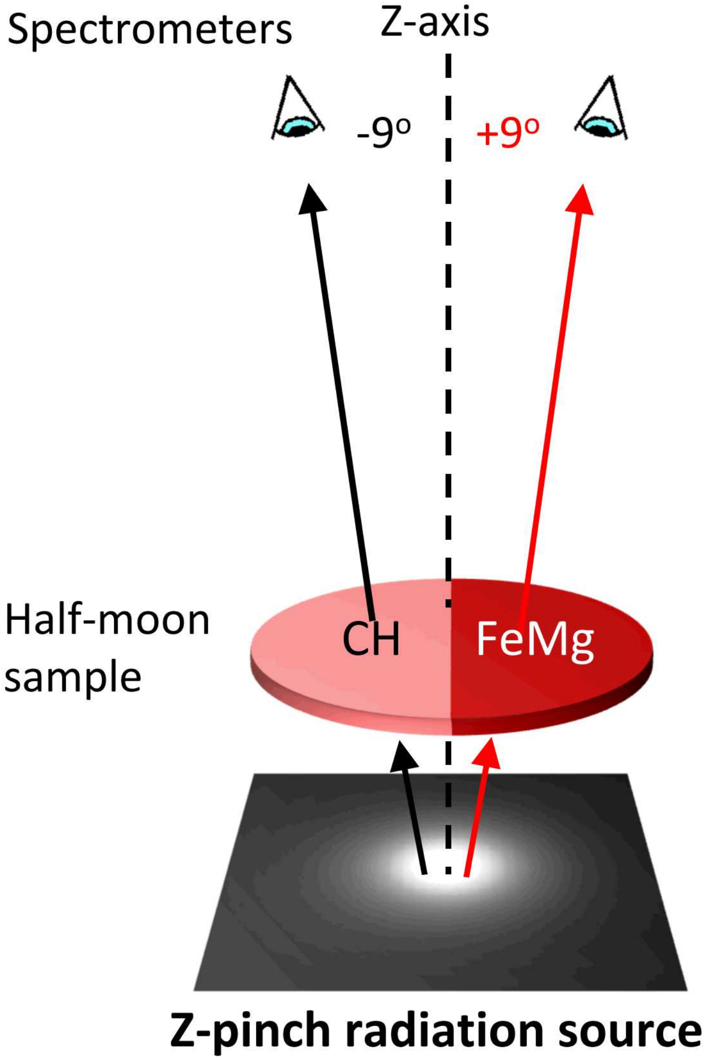


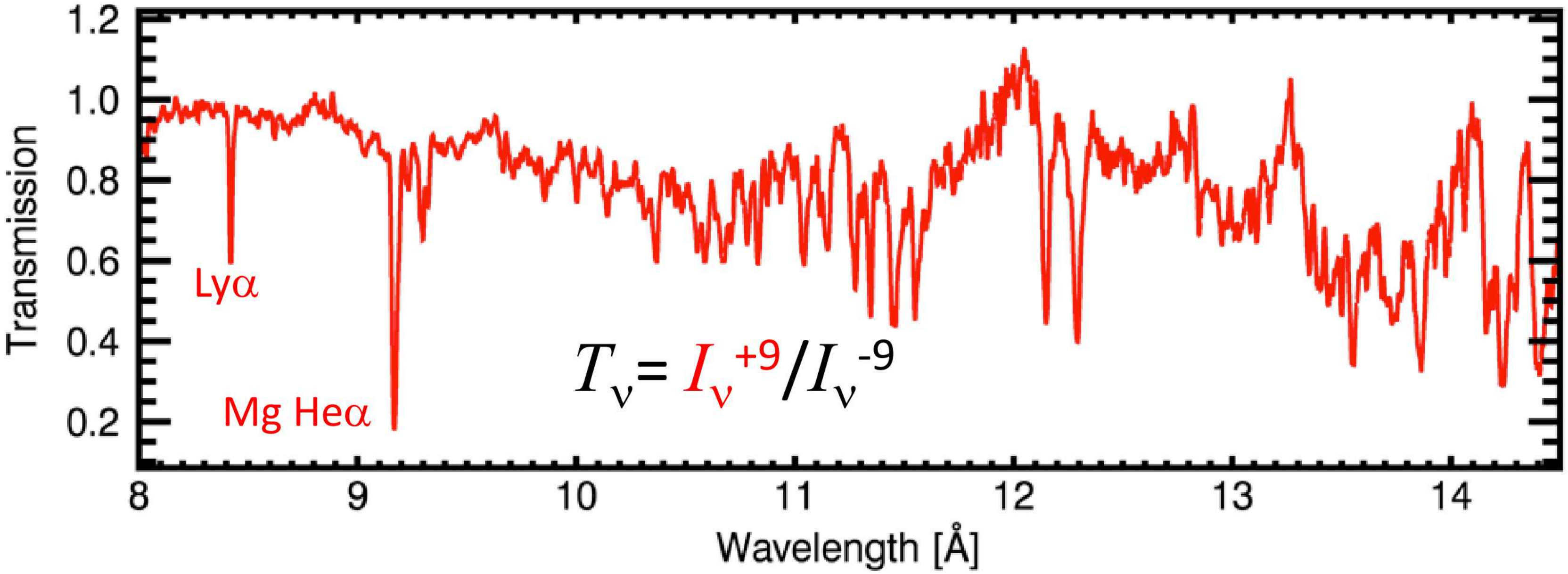
- Z-pinch energetic radiation provides uniform heating
- 350-eV Planckian backlight radiation mitigate sample self emission

[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

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





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- FeMg conditions inferred from Mg spectra

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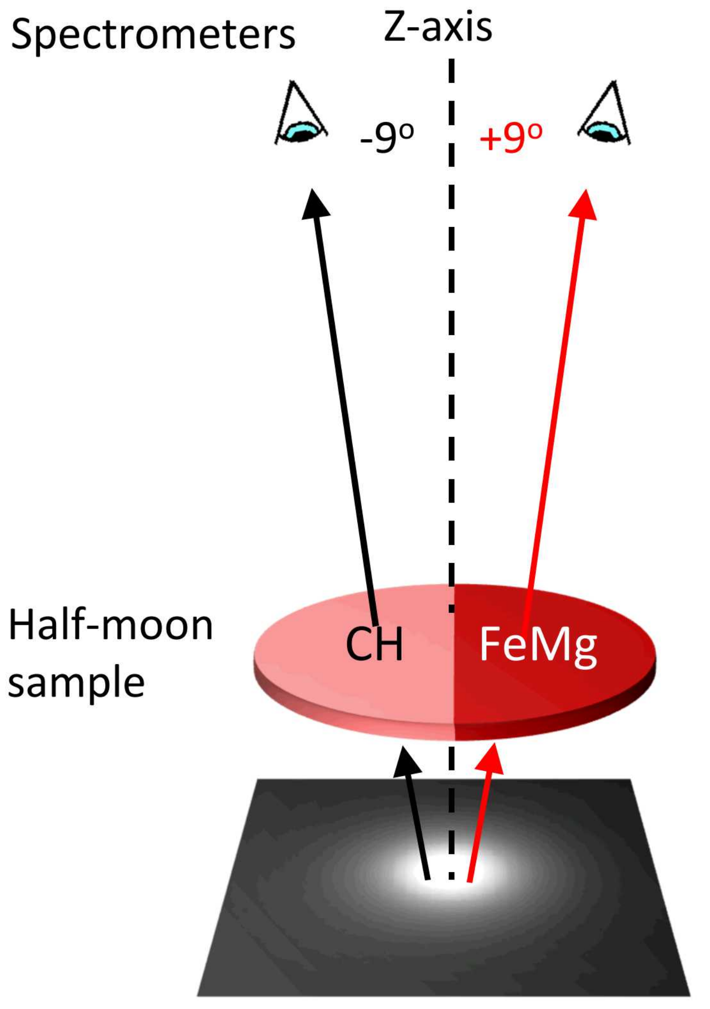
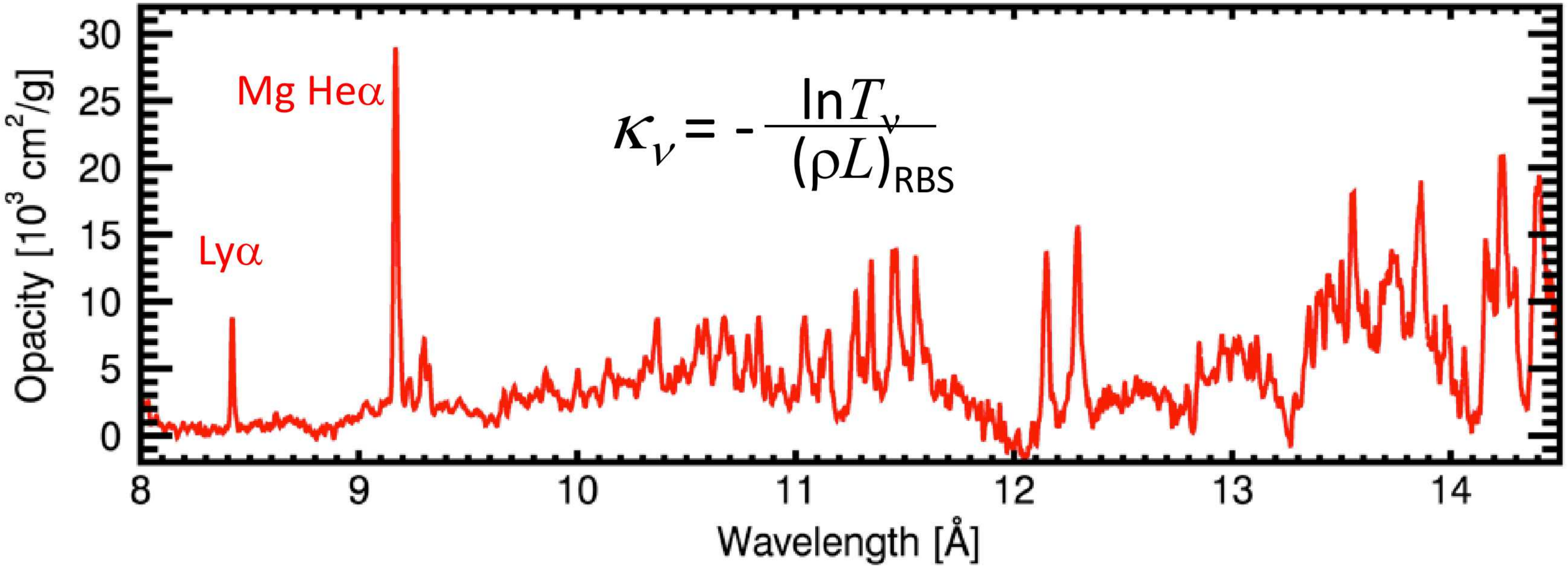


**Z-pinch radiation source**



$$\kappa_\nu = -\frac{\ln T_\nu}{(\rho L)_{\mathrm{RBS}}}$$

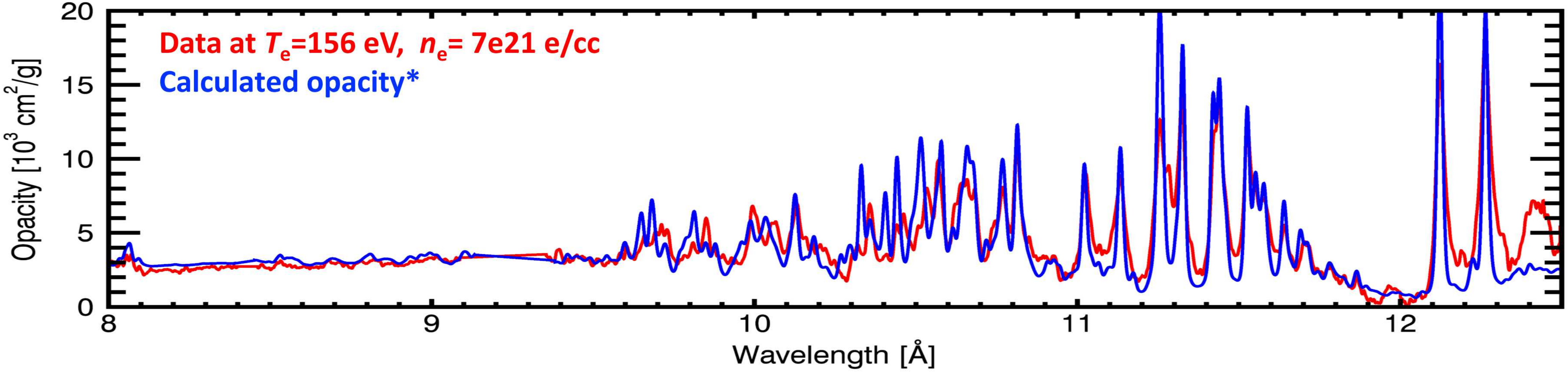
- Z-pinch energetic radiation provides uniform heating
- 350-eV Planckian backlight radiation mitigate sample self emission
- FeMg conditions inferred from Mg spectra

[1] Bailey et al., *Phys Plasmas* 16, 058101 (2009)

[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

# Initial measurements achieved lower $T_e$ and $n_e$, but model-data agreement is excellent

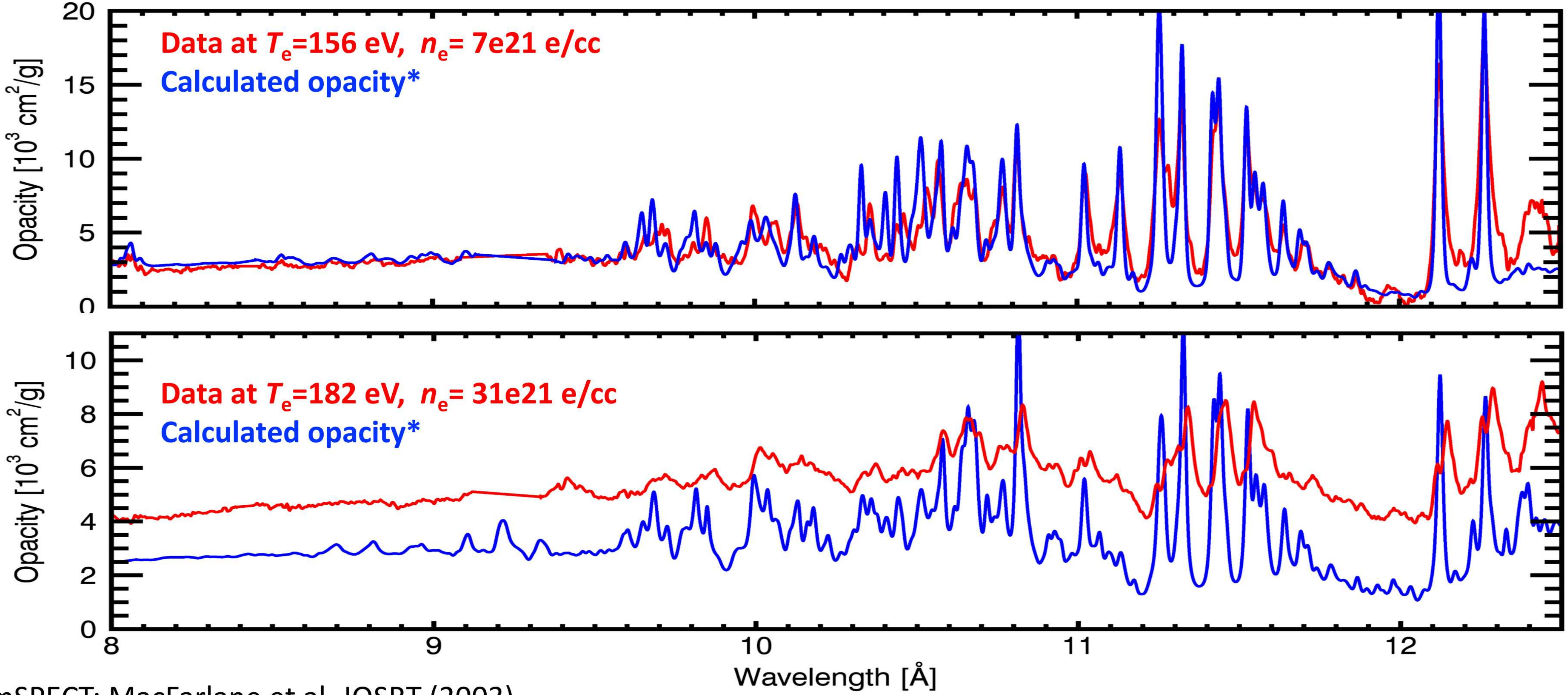
Convection Zone Base: $T_e$=182 eV, $n_e$ = 90e21 e/cc



* PrismSPECT: MacFarlane et al, JQSRT (2003)

# Modeled opacity shows severe disagreement as $T_e$ and $n_e$ approach solar interior conditions

Convection Zone Base: $T_e$=182 eV, $n_e$ = 90e21 e/cc

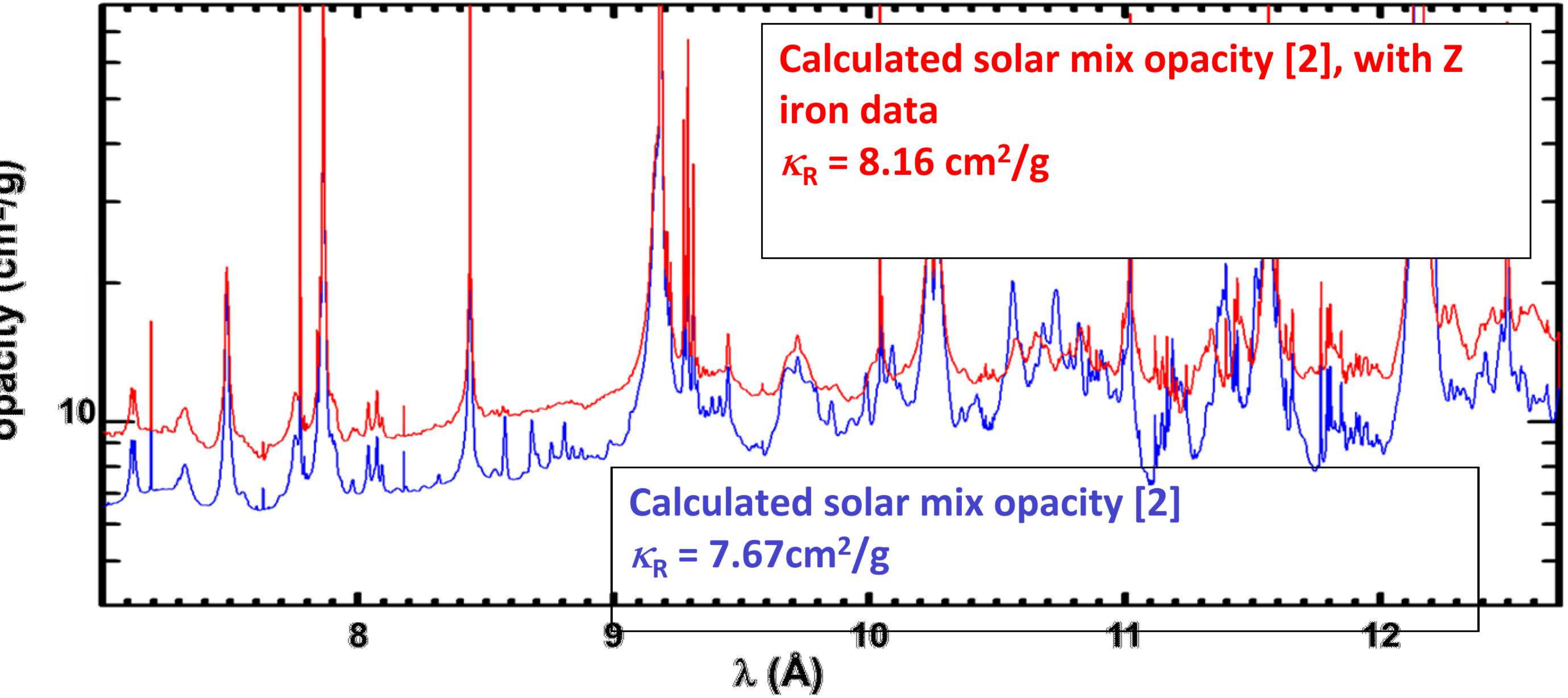


* PrismSPECT: MacFarlane et al, JQSRT (2003)

[1] Bailey et al., *Nature* 517, 56 (2015)

[2] Nagayama et al., *Phys Plasmas* 21, 056502 (2014)

# A solar mixture opacity using Z iron data has ~ 7% higher Rosseland-mean opacity than using calculated iron opacity[1]



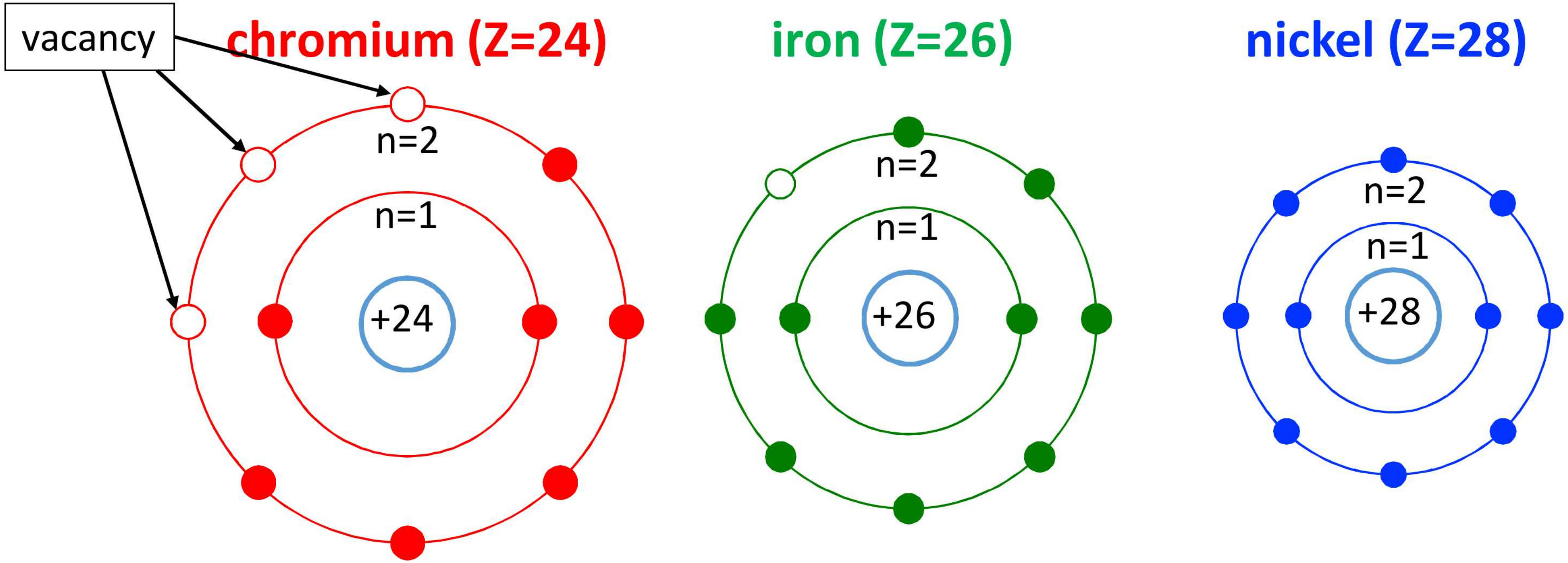
*Significant ongoing effort on the NIF to measure Fe opacity at similar conditions – making progress*

- A 7% Rosseland-mean increase partially resolves the solar problem
- Revision of opacity has significant impact on many astrophysical applications
- Ongoing work on Ni and Cr to identify source of discrepancies with theory

[1] Bailey et al., *Nature* 517, 56 (2015)

[2] OP: Seaton et al., *MNRAS* (1994)

# Experiments with different elements are a rich source of opacity model tests as well as experiment-platform test



*Main ongoing work – publication goal for 2018*

More ← L-shell vacancies — Less

More ← # of excited states — Less

More ← Density effects — Less

Challenges for Theory:

- Atomic data?
- Population kinetics?
- Density effects?
- Missing physics?

# The Z Fundamental Science Program engages a broad international community and has advanced HED science

- **10 teams won shots on the 18-19 allocation**
  - Carnegie Institution of Washington
  - Lawrence Livermore National Laboratory
  - Northwestern University
  - Sandia National Laboratories
  - UC Davis/ Harvard
  - University of Rostock, Germany
  - UN Reno
  - UT Austin x 2
  - Washington State University
- **12 students are currently involved**
  - Of former students: SNL (1) and LLNL (3)
- **Resources over 7 years**
  - 60+ dedicated ZFSP shots (5+ % of all Z shots)
  - Ride-along experiments on Z program shots, guns, DICE, and THOR

- Science with far-reaching impact
  - Nature, Nature Geoscience, SCIENCE
  - 5 Phys. Rev. Lett, 3 Physics of Plasmas, 5 Physical Review (A,B,E)
  - About 40 total peer reviewed publications and 10 conference proceedings
  - 70+ invited presentations

- Popular outreach
  - National Public Radio, “All things considered”, Joe Palca 3/6/2014
  - Discover Magazine
    - Reportage 9/16/2012
    - *Iron rain #62 in top 100 Science stories in 2015*
  - Albuquerque Journal Front Page 9/2017

# The ZFSP greatly benefits Sandia's and NNSA mission on both short- and long term

- **Direct recruiting**
  - Rick Kraus (Ph.D. Harvard) – Lawrence Fellow, now staff at LLNL
  - Ross Falcon (Ph.D. UT Austin) – postdoc at Sandia
  - Taisuke Nagayama (Ph.D. UN Reno) – staff at Sandia

- **Growth in the HED science community**
  - HEDLP funding to Harvard, UT Austin, UC SD/Davis
  - Active participation in the academic community of HED science – attracting new academic partners

- **Direct methods development**
  - The platform for shock experiments developed jointly with Harvard/UC Davis is now our standard setup for science campaign experiments
  - The work on Fe opacity has served an important role for platform development and provides international peer review benefitting research in science campaigns

- **Development of technical staff and postdocs**
  - An opportunity for Sandia staff and postdocs to do leading research and participate fully in the international research community
  - *Exciting opportunities for postdocs at Sandia, including at the Z – Machine*

# Pulsed power is exquisitely suited for HED science

- **Sandia's Z machine is ideal for Mbar material experiments**
  - Compression of solids and liquids
  - Obtain conditions of the interiors of gas giants and the Earth/ super earths, other exoplanets
- **The Z machine produces MJs of x-rays**
  - Radiation effects on materials
  - Fundamental properties of matter
- **Fundamental plasma physics**
  - Spectroscopy and plasma conditions: line broadening and opacity
- **Strong integration between experiments, theory, and simulations**
  - From quantum mechanics to MHD and beyond

- ***Well-defined path for the future – decades of exciting HED Science research lies ahead***