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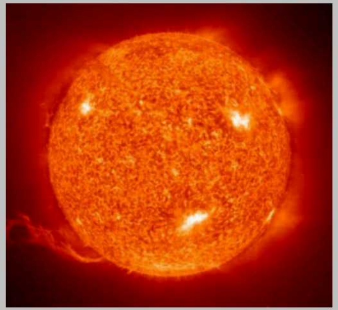

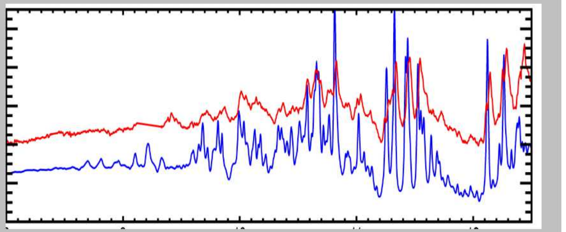

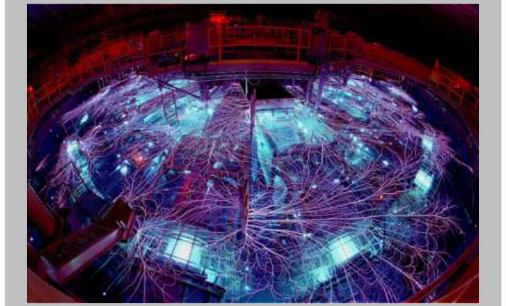

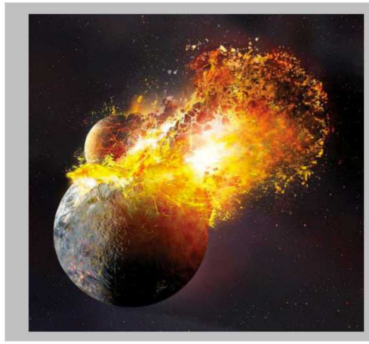

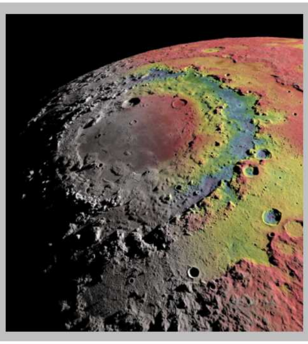

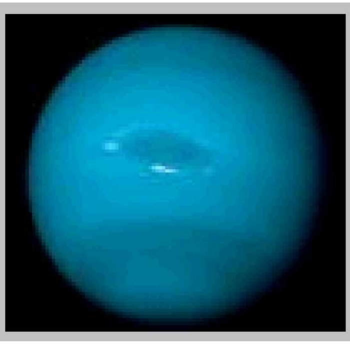

Planets and stars in the laboratory: the Z Fundamental Science Program

Thomas R. Mattsson and Marcus D. Knudson

Sandia National Laboratories

SCCM 2019, Portland, Oregon.

SAND2019 -

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

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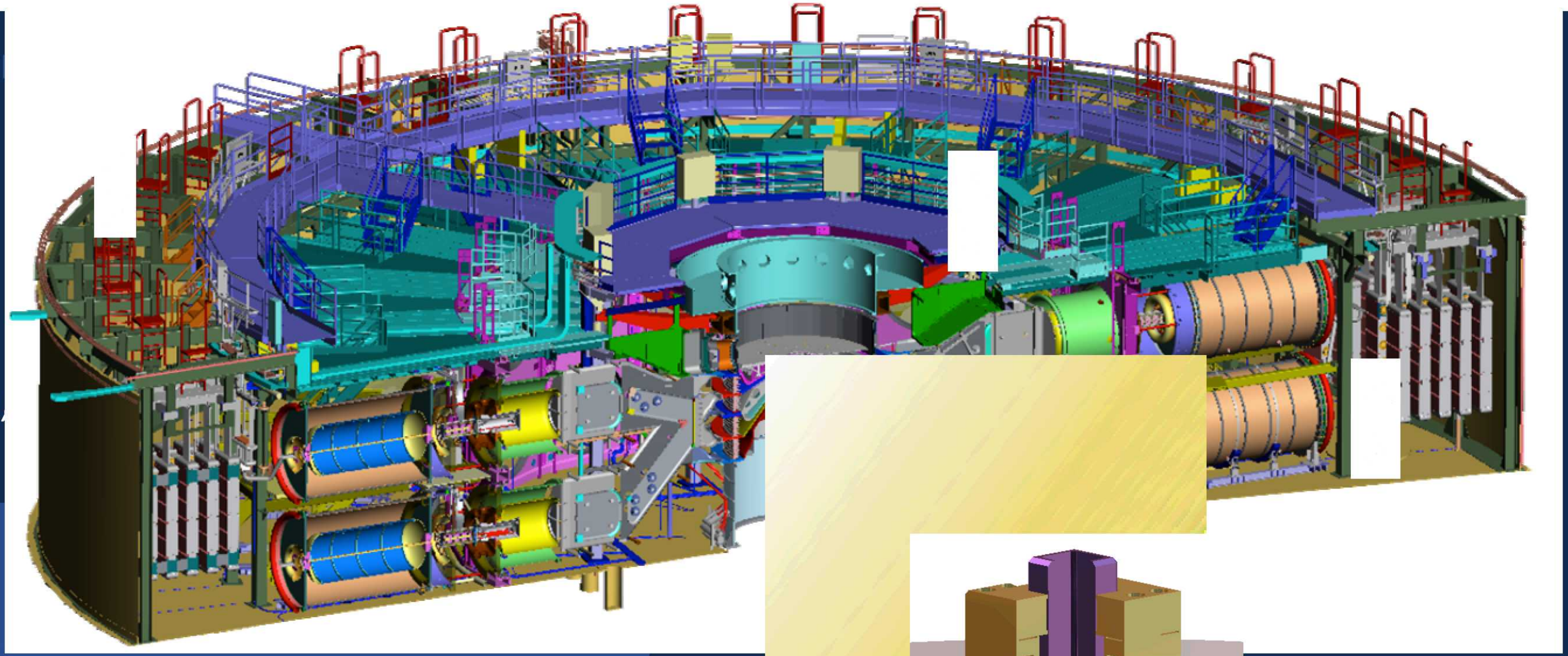
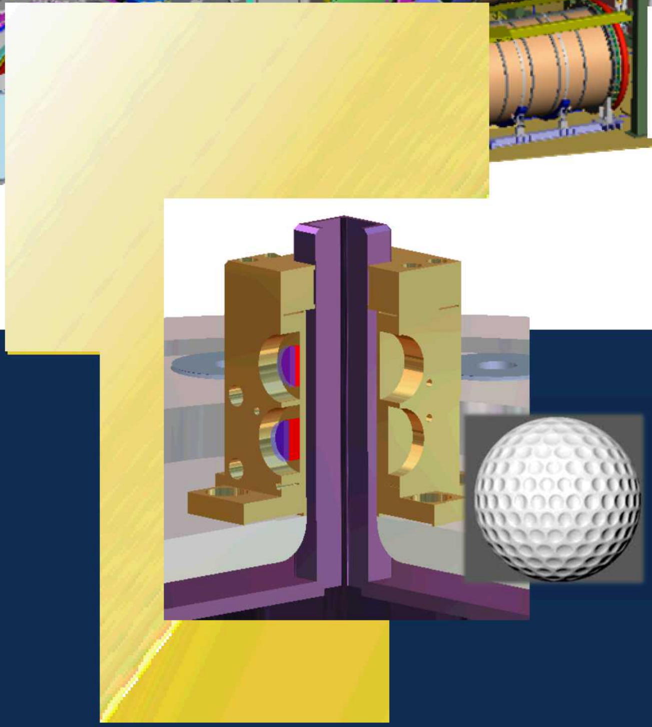
Acknowledge teams:
Z operations, cryogenics, diagnostics, theory/ simulations, target design and -fabrication, engineering, and management



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

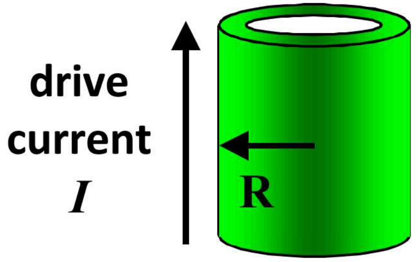
Current x magnetic field

Magnetic field as scalar pressure

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=\frac{\mathbf{J}\times\mathbf{B}}{c}-\nabla P\approx\frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B}-\nabla\left(P+\frac{B^2}{8\pi}\right)$$

Pressure

velocity field

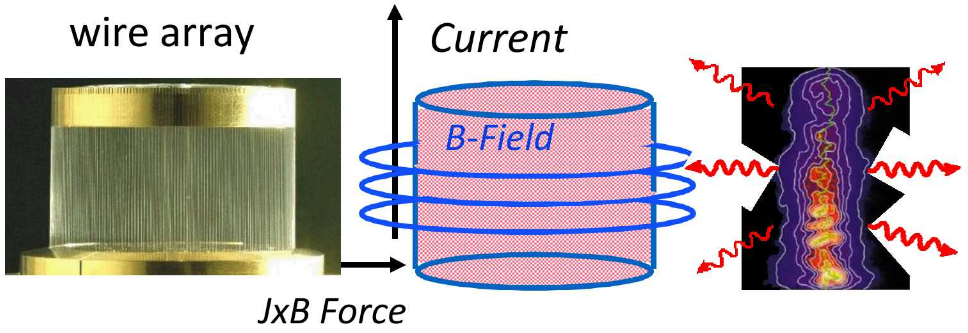


- 25 MA at 1cm radius is 1 Mbar
- 25 MA at 1mm radius is 100 Mbar

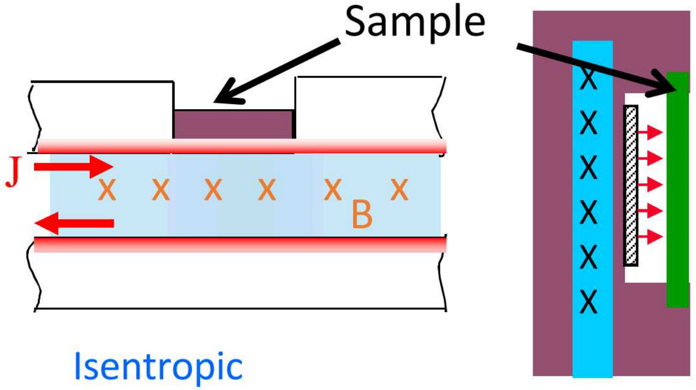
- Using pulsed power (current) as a source has advantages
  - *Can create high pressures without making material hot*
  - Generated over long time scales with control over the time history
  - Large samples and energetic sources (2 MJ to load of 20 MJ stored)
- Integrated projects with theory/simulations/experiment
  - 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



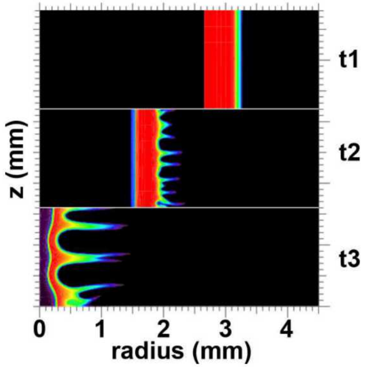
Materials Properties: EOS



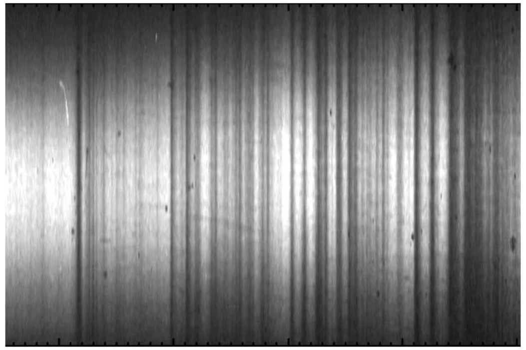
Isentropic Compression

Flyer Plate

Atomic- and plasma physics

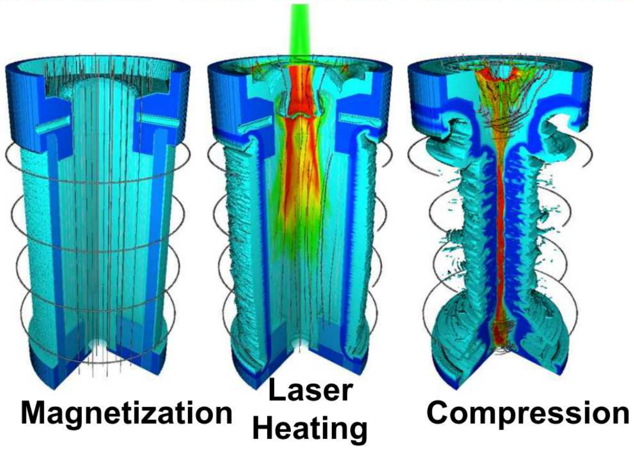


MRT instabilities



Iron spectrum

Inertial confinement fusion



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

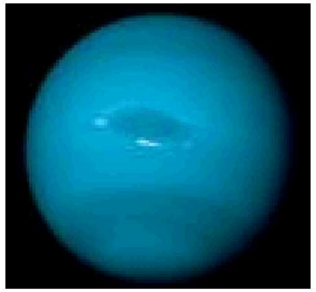
- **10 teams won shots on the 18-19 allocation**
  - Carnegie Institution of Washington
  - Lawrence Livermore National Laboratory
  - Northwestern University
  - Sandia National Laboratories
  - UC Davis/ Harvard
  - University of Rostock, Germany
  - UN Reno
  - UT Austin x 2
  - Washington State University
- **12+ students are currently involved**
  - Former students have found interesting positions
- **Resources over 8 years**
  - 100 dedicated ZFSP shots (5-7% of all Z shots)
  - Ride-along experiments on Z program shots, guns, DICE, and THOR

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

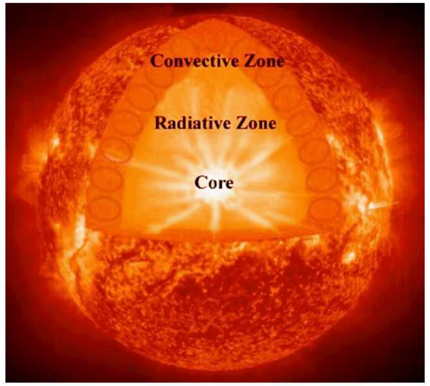
- **Popular outreach**
  - National Public Radio, “All things considered”, 2014
  - Discover Magazine
    - Reportage 9/16/2012
    - *Iron rain #62 in top 100 Science stories in 2015*
  - Albuquerque Journal Front Page 9/2017
  - Twice local TV coverage on planetary science

Properties of matter under HED (High Energy Density) conditions are important for a broad range of applications

- **Planetary science – Jupiter, Saturn, Uranus, Neptune, and exo planets [e.g. hot Neptunes]**
  - Water in 2005-2012: 2 Phys Rev Letts and 2 Phys Rev B
  - Metallization of hydrogen/deuterium: Science 2015



- **Planetary science – Earths and super-earths**
  - Silicates, MgO (Phys. Rev. Lett. 2015, Geophysics Research Letters 2018), and iron/iron alloys
  - Determining the vaporization threshold for iron – and implications for planetary formation, Nature Geoscience 2015.

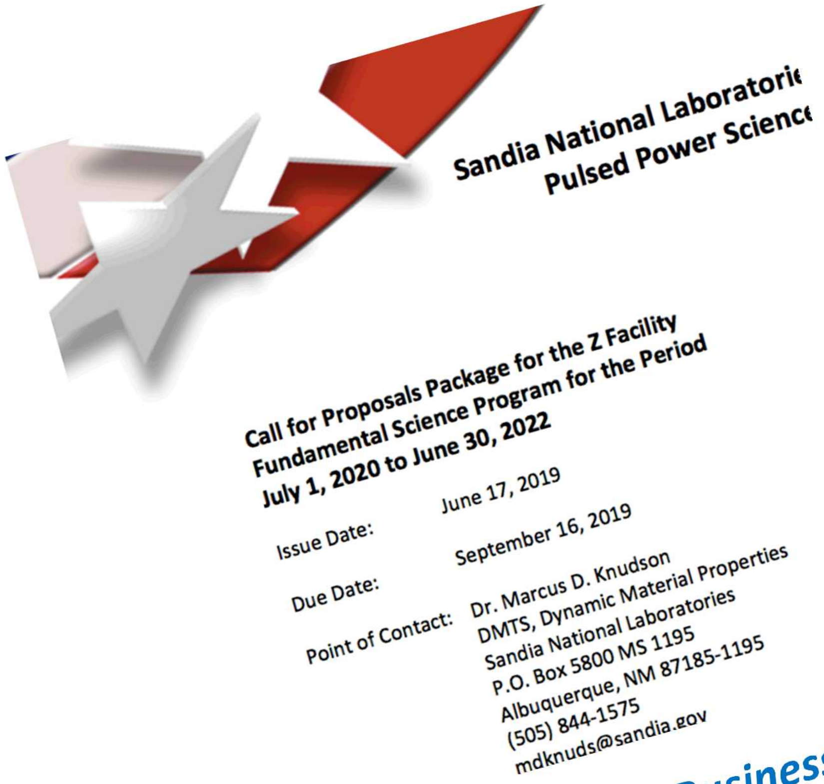


- **Physics of matter at the conditions in stars and around black holes (not scaled)**
  - Opacity of Fe, Nature 2015, Phys. Rev. Lett. 2019.
  - Photo-ionized plasmas, PRL 2018.

We aim to turn astrophysics quantitative by high fidelity modeling and high-precision experiments

The third call for proposals is open and will close on Sept 16: Shots during 7/1/2020 to 6/30/2022

- **ZFSP is a core part of our research strategy**
  - 100+ dedicated shots since the start in 2011
  - About 10% of the shots on Z, so 15 per year
  - 4 -7 independent projects
- **Proposal format**
  - 12 page research narrative
  - Shot plan, target- and diagnostics needs, etc
  - PI CV/resume
- **Review**
  - Facility review for safety and readiness (target, diagnostics)
  - Review of scientific relevance and impact by an independent review panel
- **ZFSP workshop 2019 August 11 – 14, Albuquerque**
  - Sunday Aug 11 (evening) – Wednesday Aug 14 (all day)
  - Hotel Andaluz, downtown ABQ
  - Wednesday afternoon dedicated to town-hall on NSF/NAS ?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Pulsed Power Science

Call for Proposals Package for the Z Facility Fundamental Science Program for the Period July 1, 2020 to June 30, 2022

Issue Date: June 17, 2019

Due Date: September 16, 2019

Point of Contact: Dr. Marcus D. Knudson
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Sandia National Laboratories
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… opportunities for US University, Business, and National Laboratory Scientists to perform experiments in high-energy-density (HED) physics …

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

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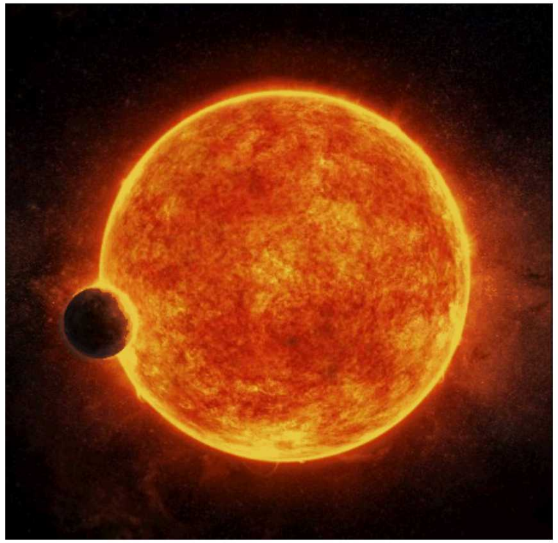
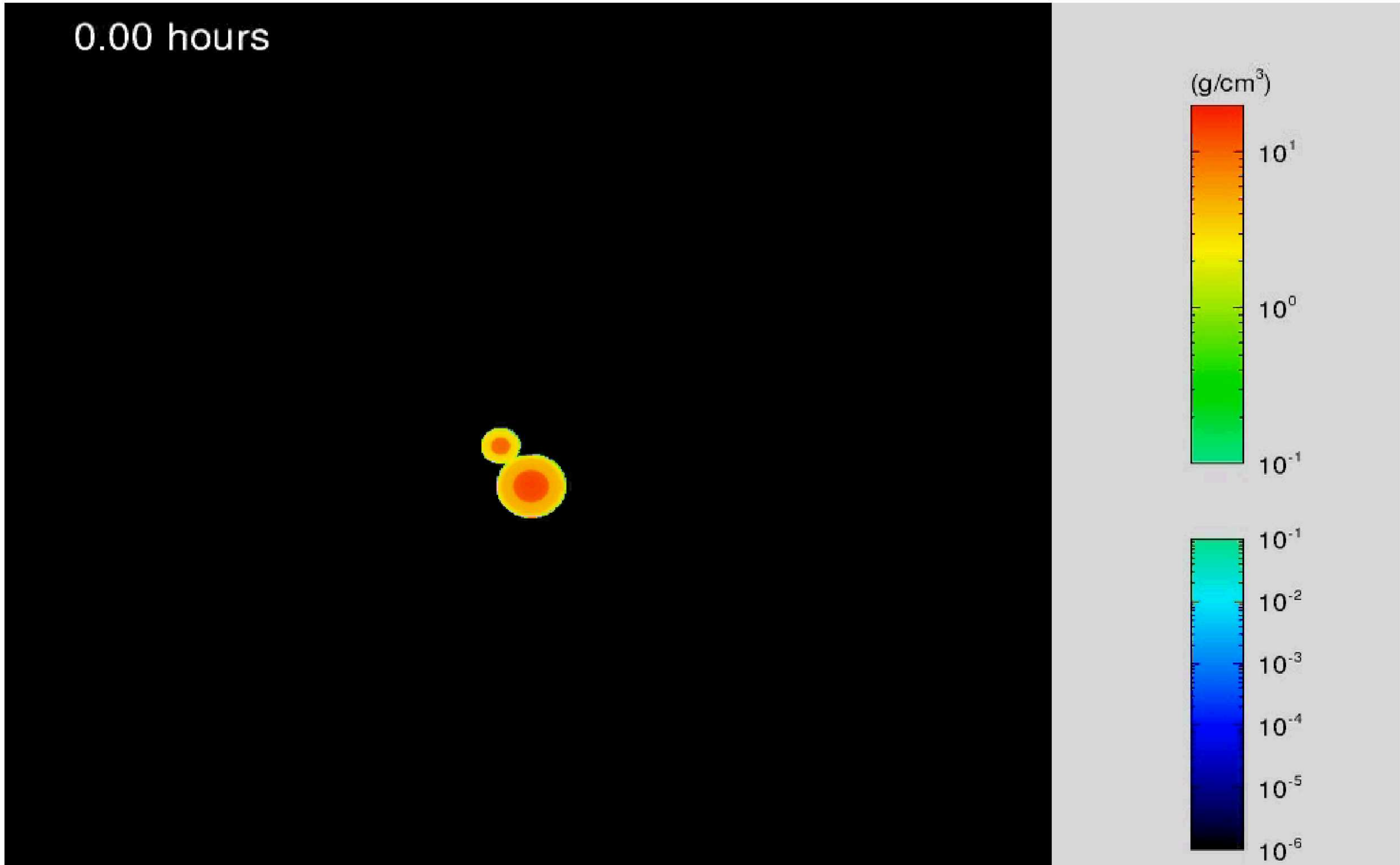
- Giant impacts and the origin of the moon
- Addition and removal of planetary atmospheres
- Chemical evolution of planets
- Exoplanets! Wide range of interiors and atmospheres, mass-radius diagrams



- Ted Talk by Professor Sarah T. Stewart “Where did the Moon come from? A new Theory”

Giant impacts bring matter to extreme conditions – melting and even vaporizing planets!

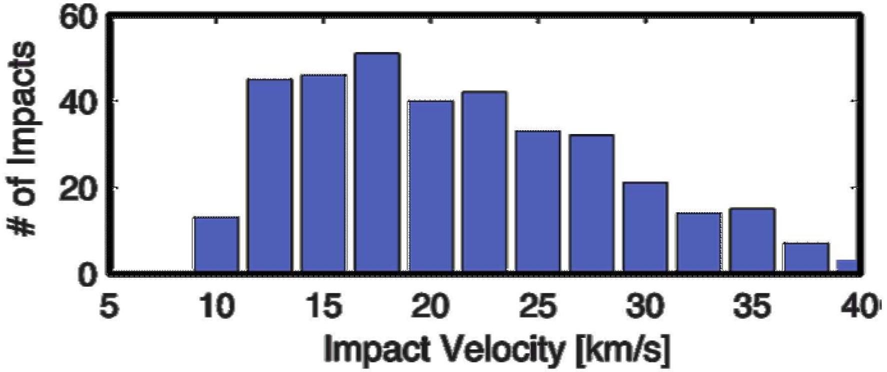


D. Crawford, 2011
CTH calculation

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?



We determined that vaporization is significantly easier than previously thought, changing the way we understand giant impacts.

See Sarah's TED talk for an example

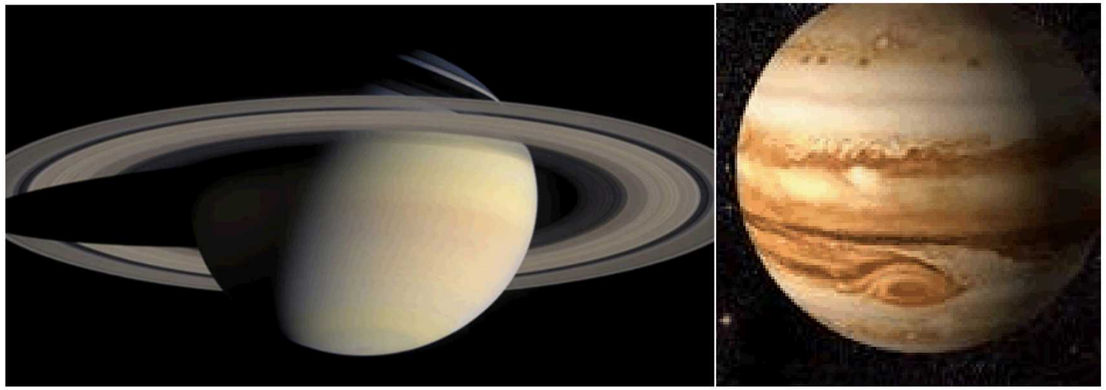
Simulations of planetary dynamics suggest high impact velocities.

These velocities are directly accessible on the Z-machine!

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

Observation of H2 metallization needed to address a planetary mystery

Why is Saturn hot?

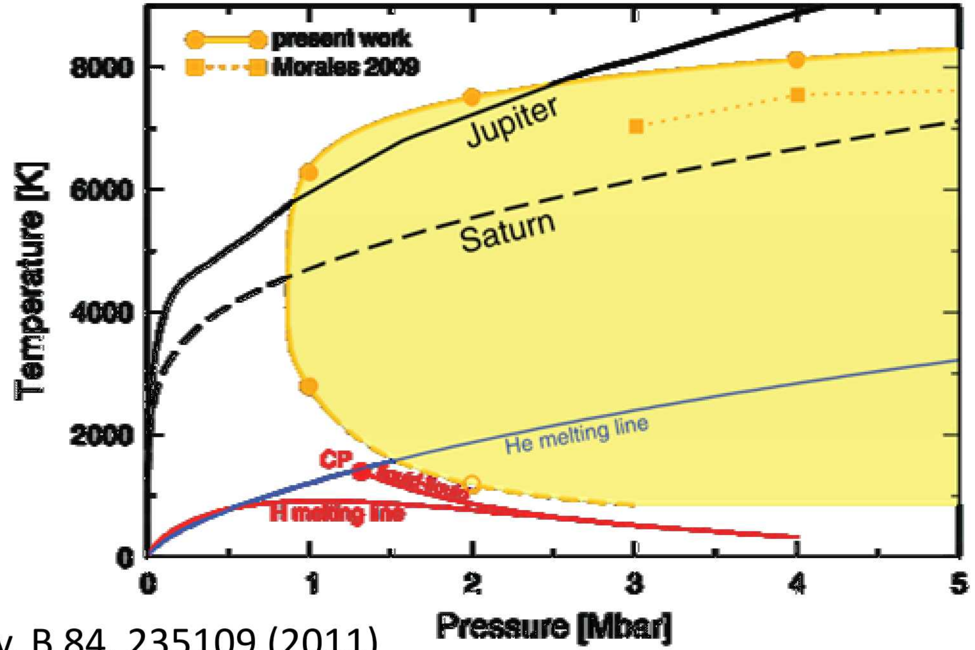


- Planets cool with age
- Saturn is much hotter than would be expected for it's age

- Two billion years problem using the same aging model as for Jupiter

- Hydrogen metallization, Wigner(1935), is linked to H-He de-mixing
- Formation of helium rain would generate heat

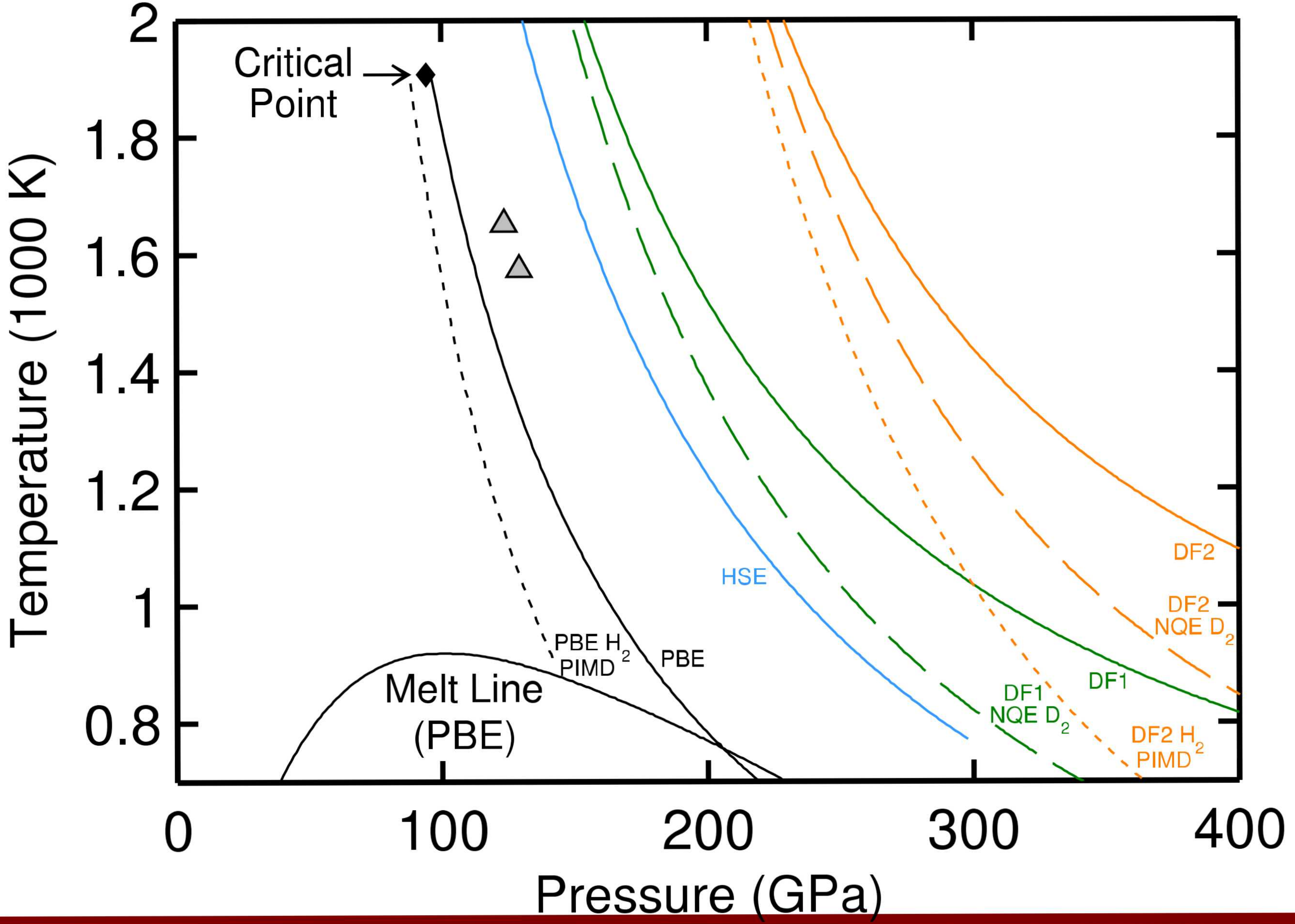
- BUT - Jupiter would also have He rain and excess heat according to models at the time



W. Lorenzen, B. Holst, and R. Redmer, Phys. Rev. B 84, 235109 (2011)

Recent Quantum predictions of the LL-IMT in hydrogen – quite a spread…

Hydrogen is particularly challenging for Density Functional Theory due to the self-interaction error – elements with more electrons show less spread



We have located the Liquid-Liquid Insulator-to-Metal Transition in deuterium to be a steep curve at 300 GPa

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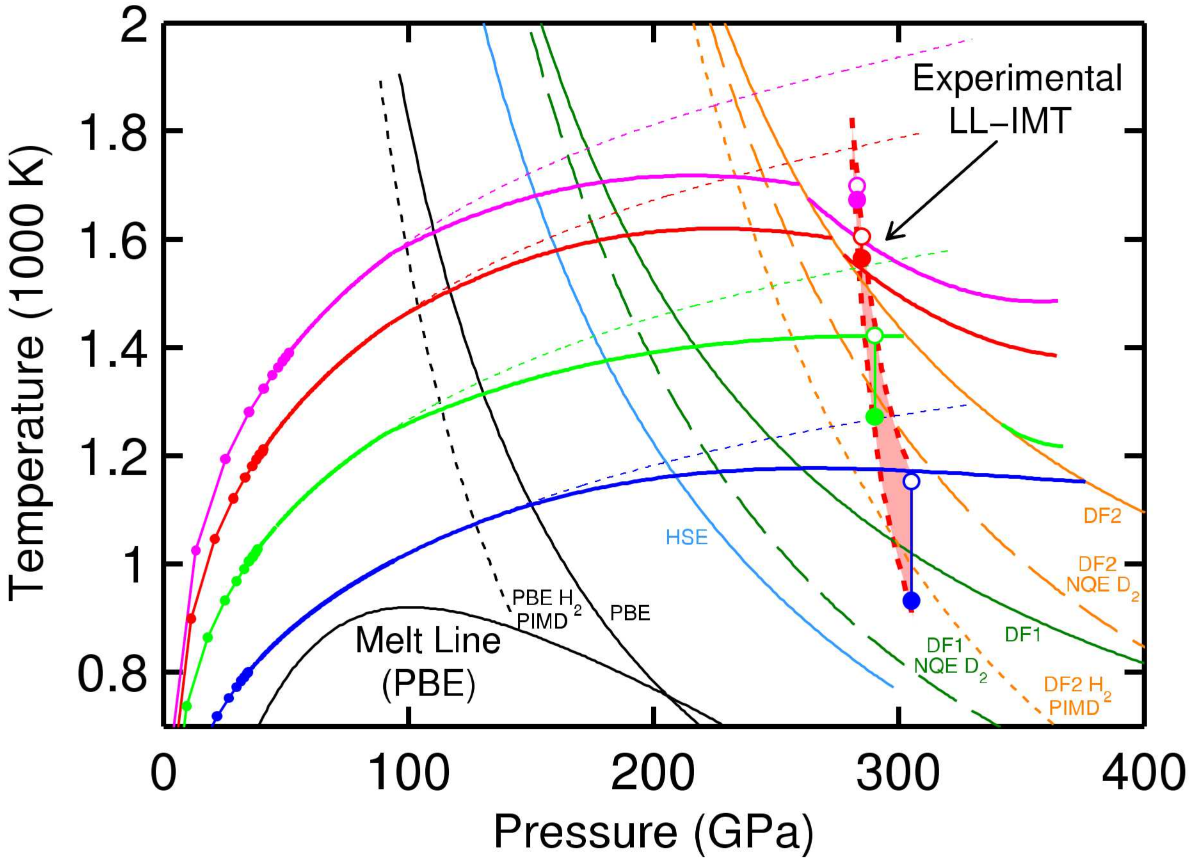


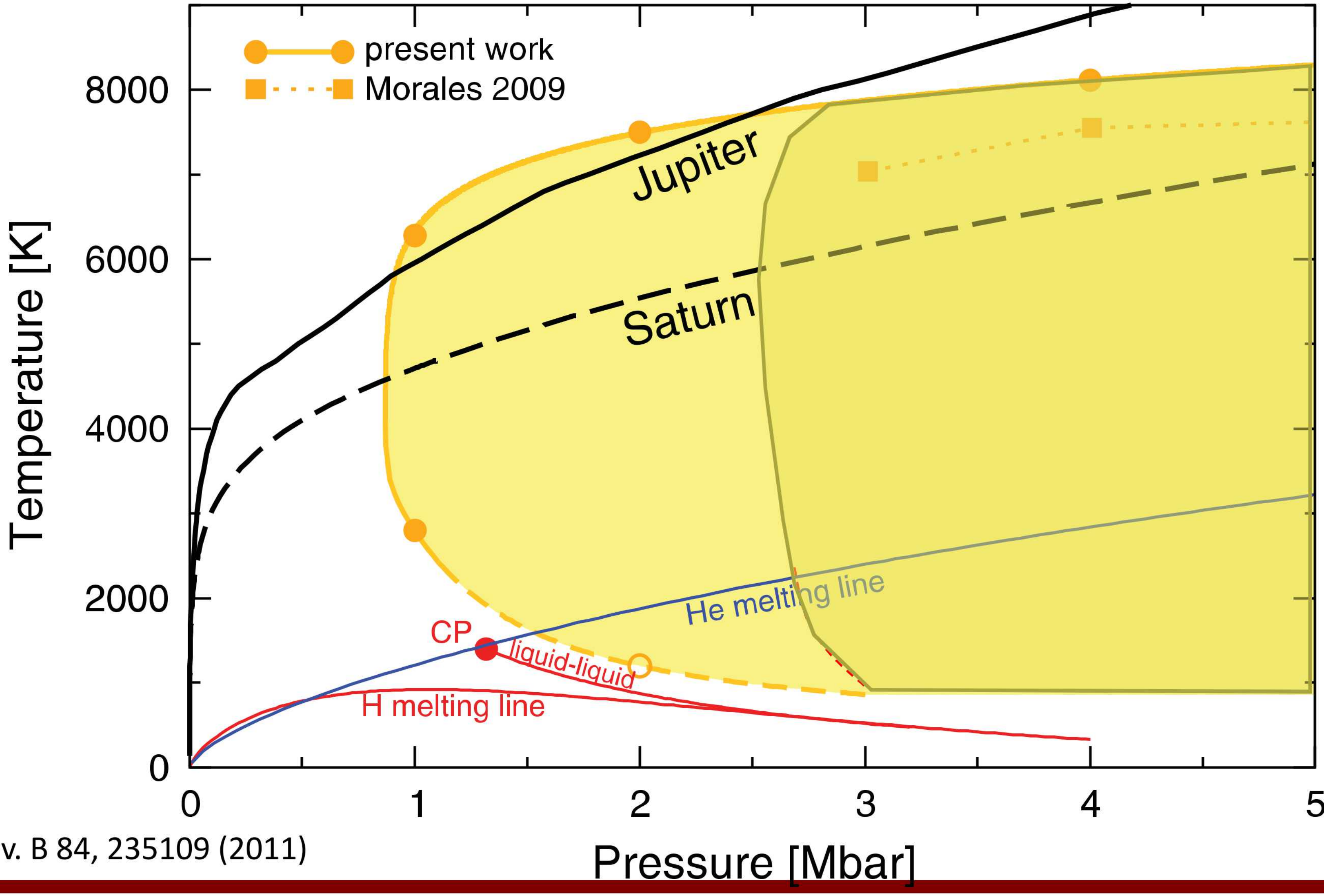
- *Insensitivity to T suggests this is a ρ-driven transition*
  - ρ at the transition is inferred to be ~2-2.1 g/cc in deuterium
  - Qualitatively different transition than in shock experiments (T driven)
- Broad team with expertise in diagnostics, pulse-shaping, experimental design, and first-principles simulations
- Sandia and University of Rostock, Germany

M.D. Knudson, M.P. Desjarlais, A. Becker, R.W. Lemke, K.R. Cochrane, M.E. Savage, D.E. Bliss, T.R. Mattsson, and R. Redmer, Science **348** 1455, 26 June 2015.

We expect the H-He demixing region to be shifted to higher pressure – possibly explaining the Jupiter/Saturn mystery

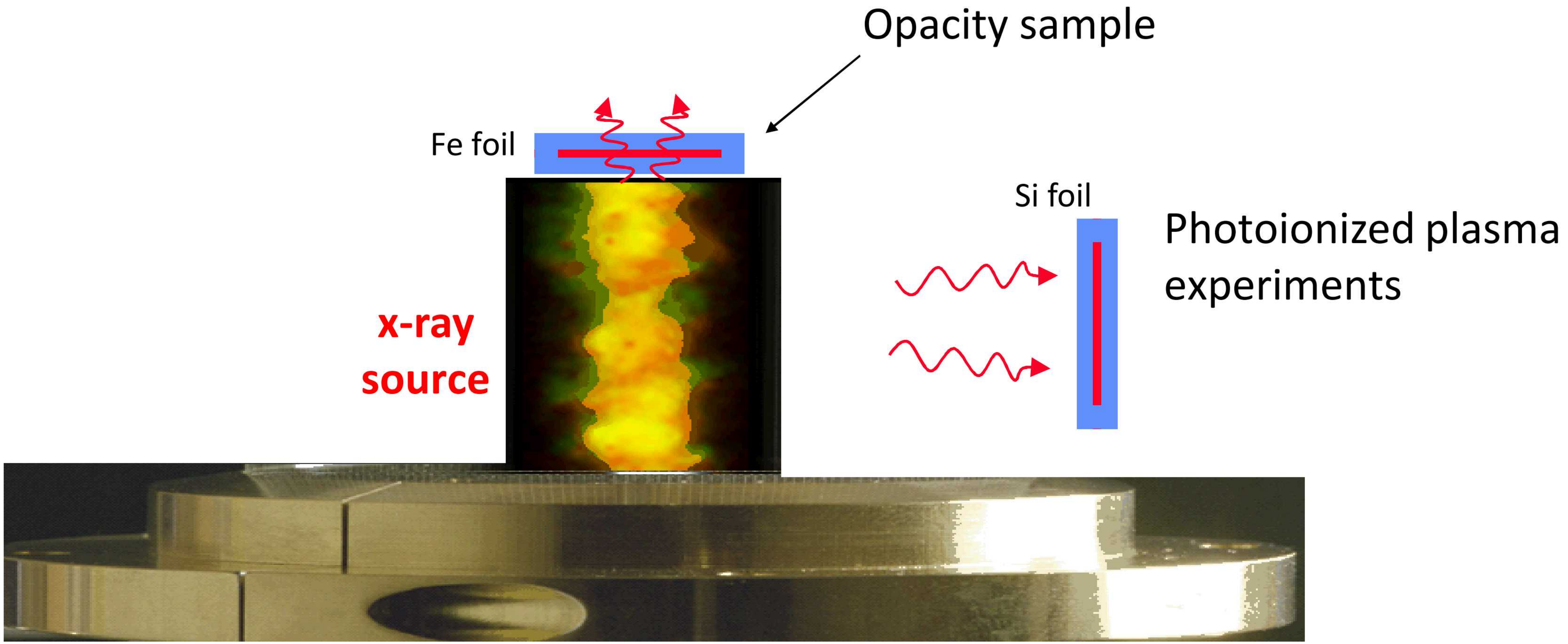
Quantitative knowledge of the behavior of matter under extreme conditions is crucial for improving our understanding of planetary physics.

Our results indicate that PBE is inadequate in describing H-He miscibility and our work prompted others to investigate H-He miscibility using vdW potentials (Schttler and Redmer PRL 2018).



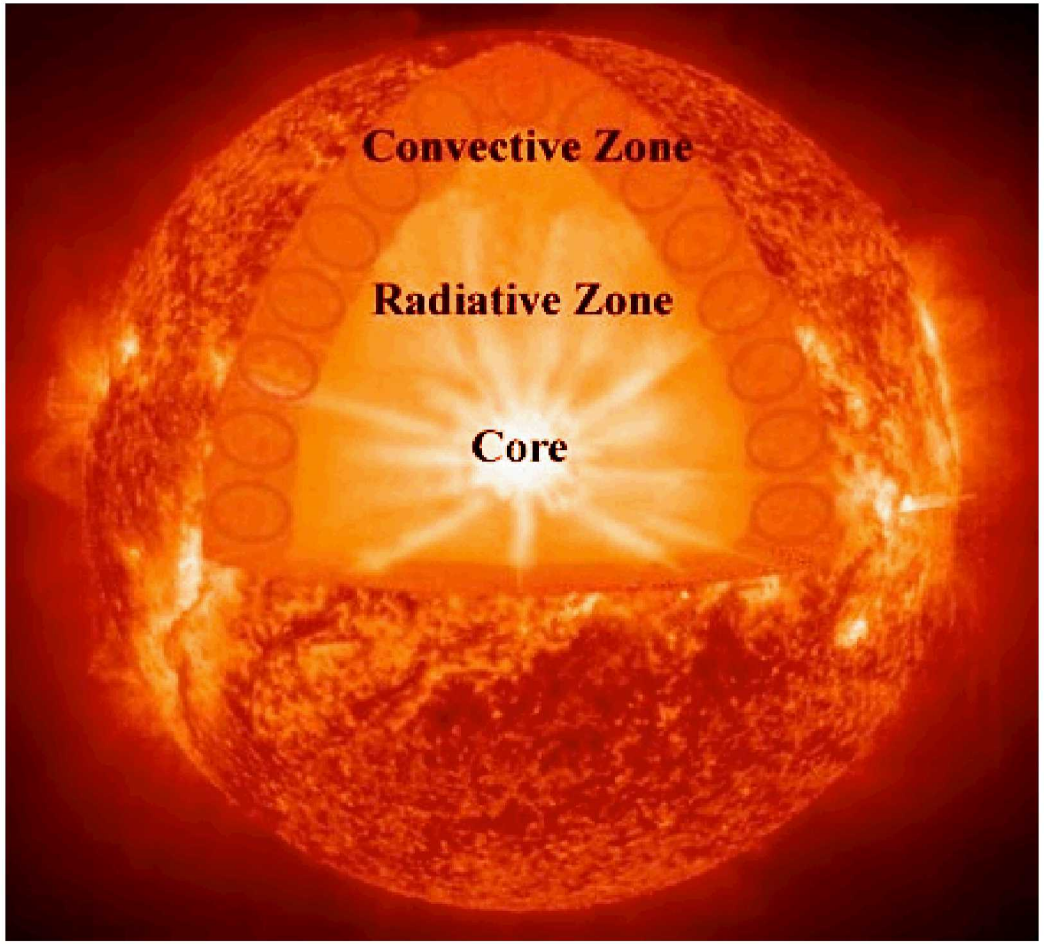
W. Lorenzen, B. Holst, and R. Redmer, Phys. Rev. B 84, 235109 (2011)

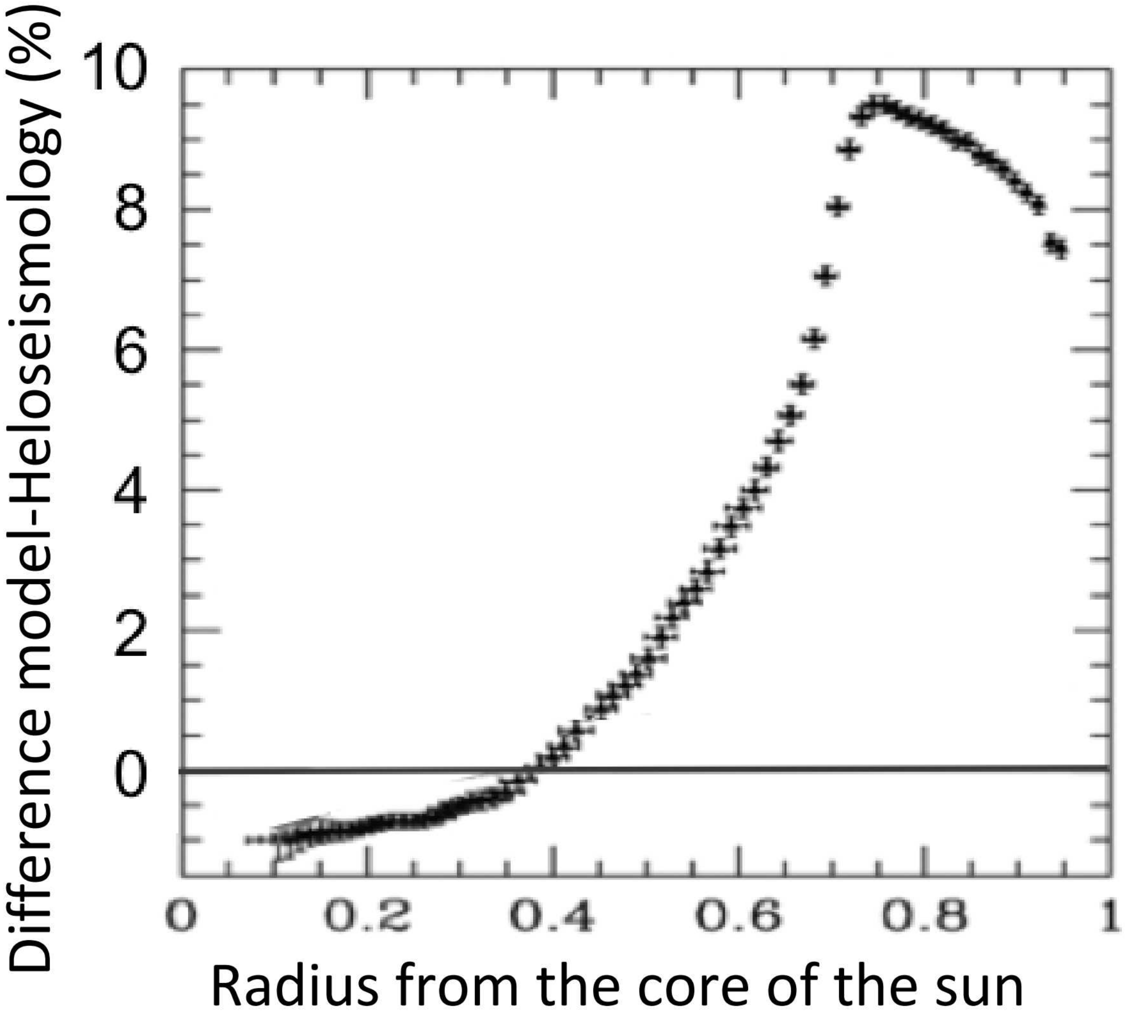
The Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously



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

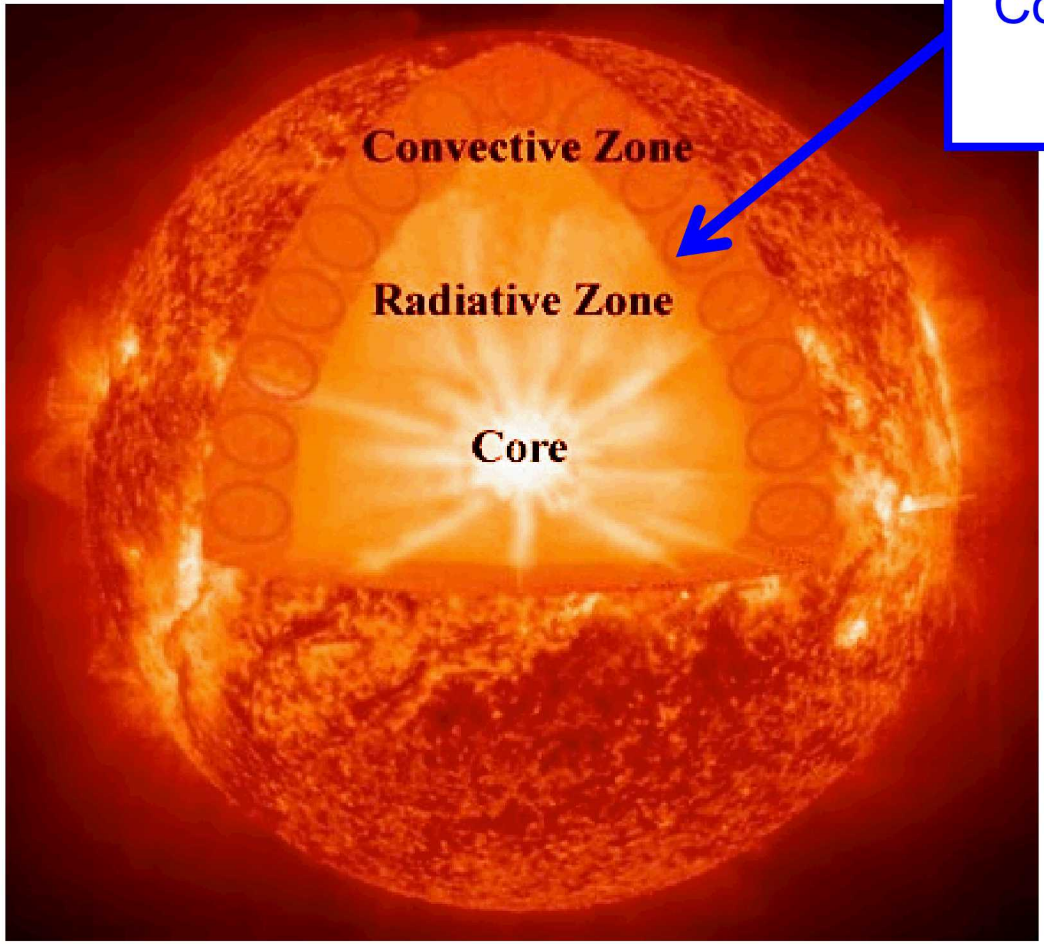
Modeled solar structure disagrees with observations

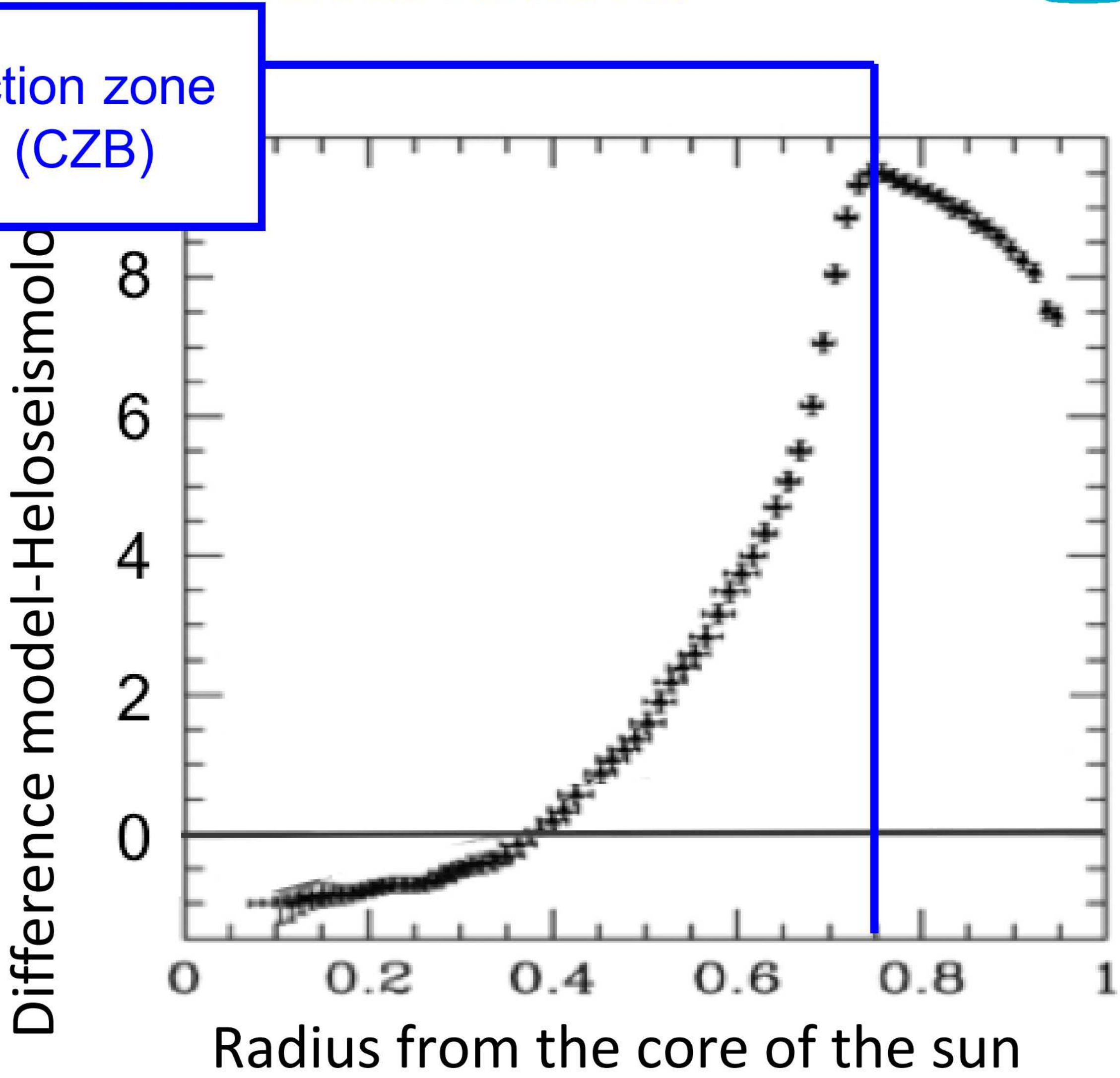




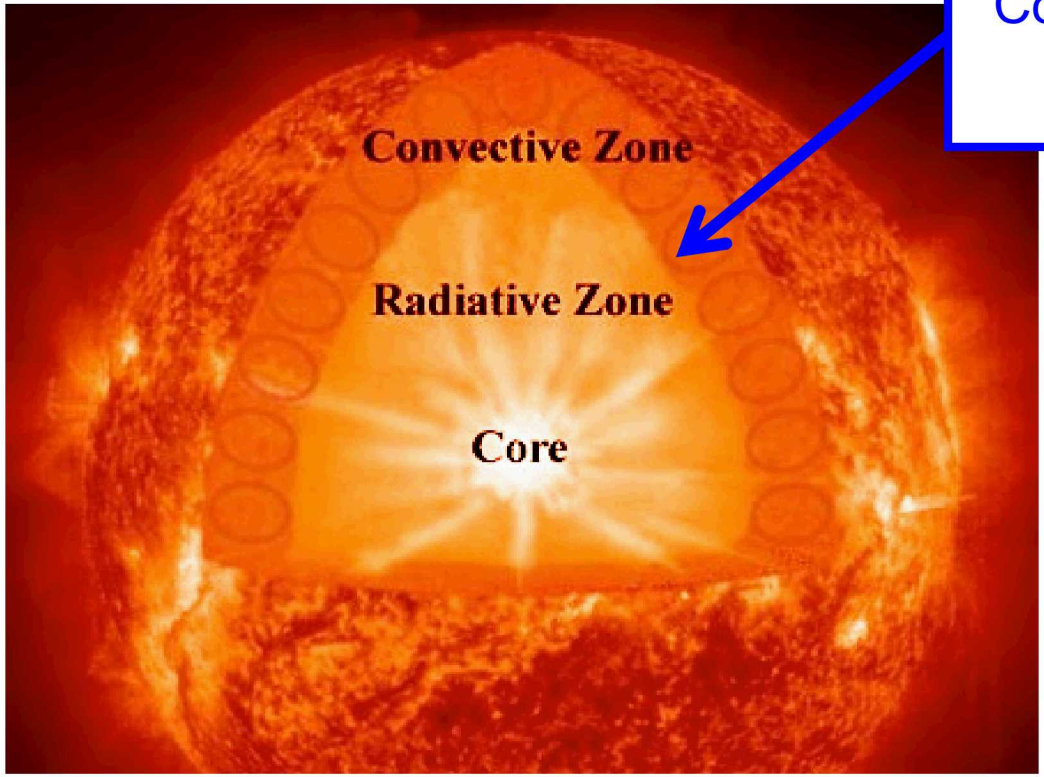
[1] S. Basu and H. M. Antia, Physics Reports 457, 217 (2008).

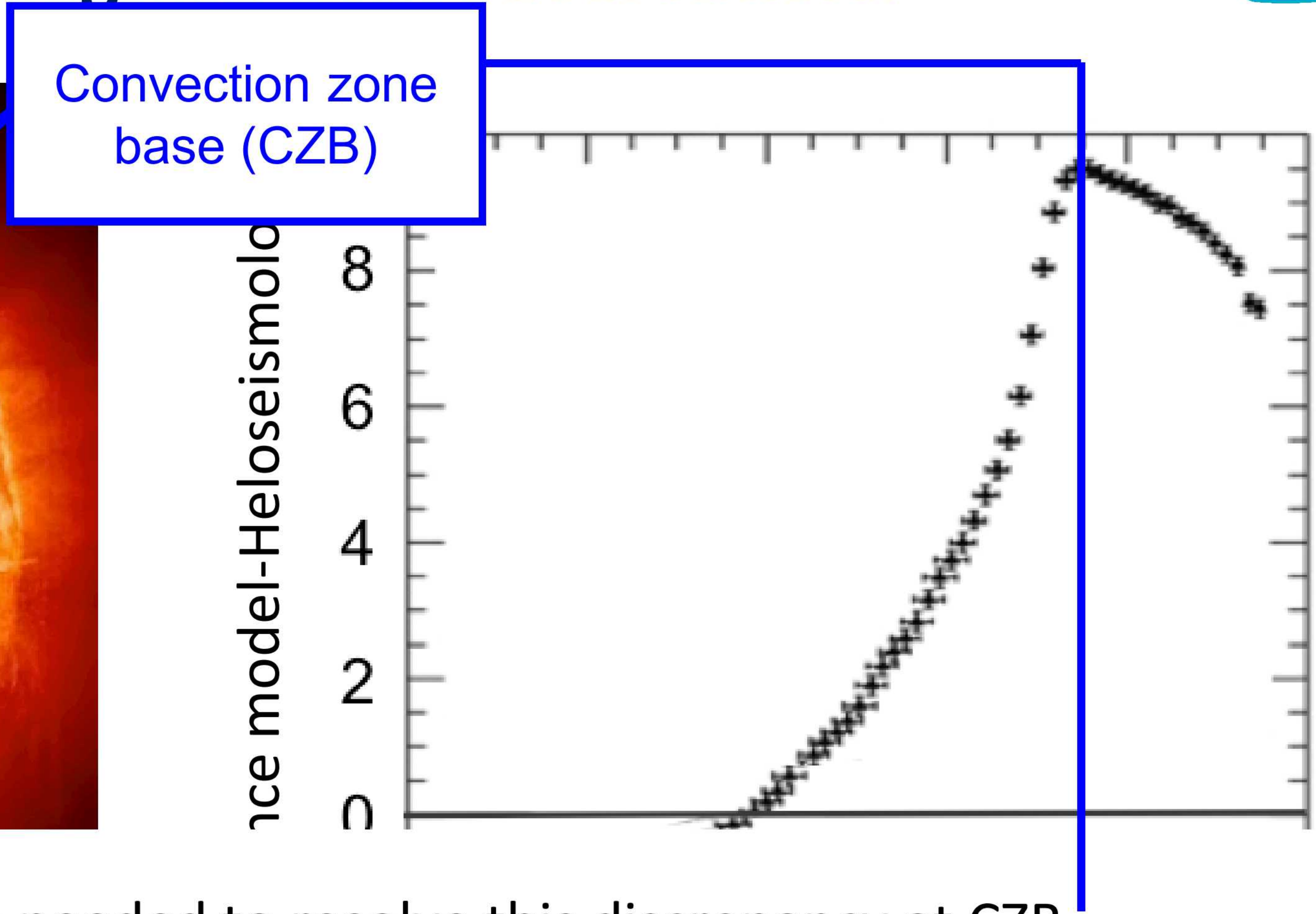
Modeled solar structure disagrees with observations





Modeled solar structure disagrees with observations



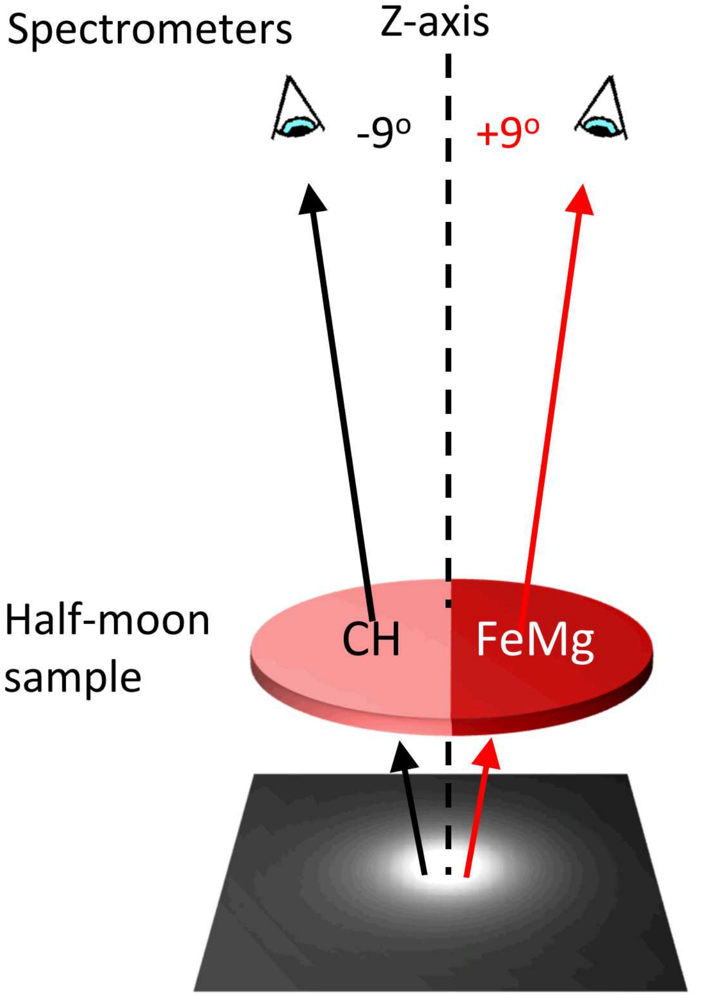


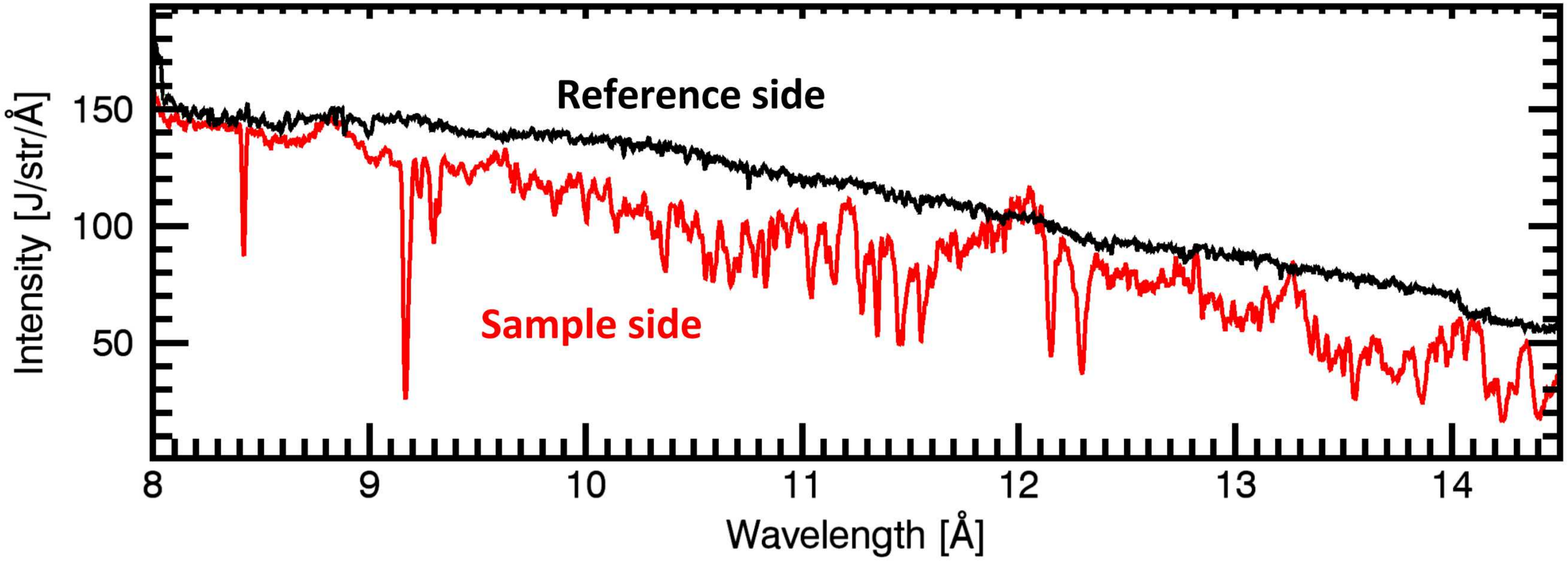
- 17% mean-opacity increase is needed to resolve this discrepancy at CZB
- Calculated opacity has never been tested at solar interior conditions

Objective: Measure Fe opacity at conditions approaching the CZB

[1] S. Basu and H. M. Antia, Physics Reports 457, 217 (2008).

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





Modeled opacity shows severe disagreement as conditions approach ones in the solar interior

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