Exploring the Quantum Mechanics of Dense Matter

2016 Stewardship Science Academic Programs (SSAP) Symposium
February 18, 2016

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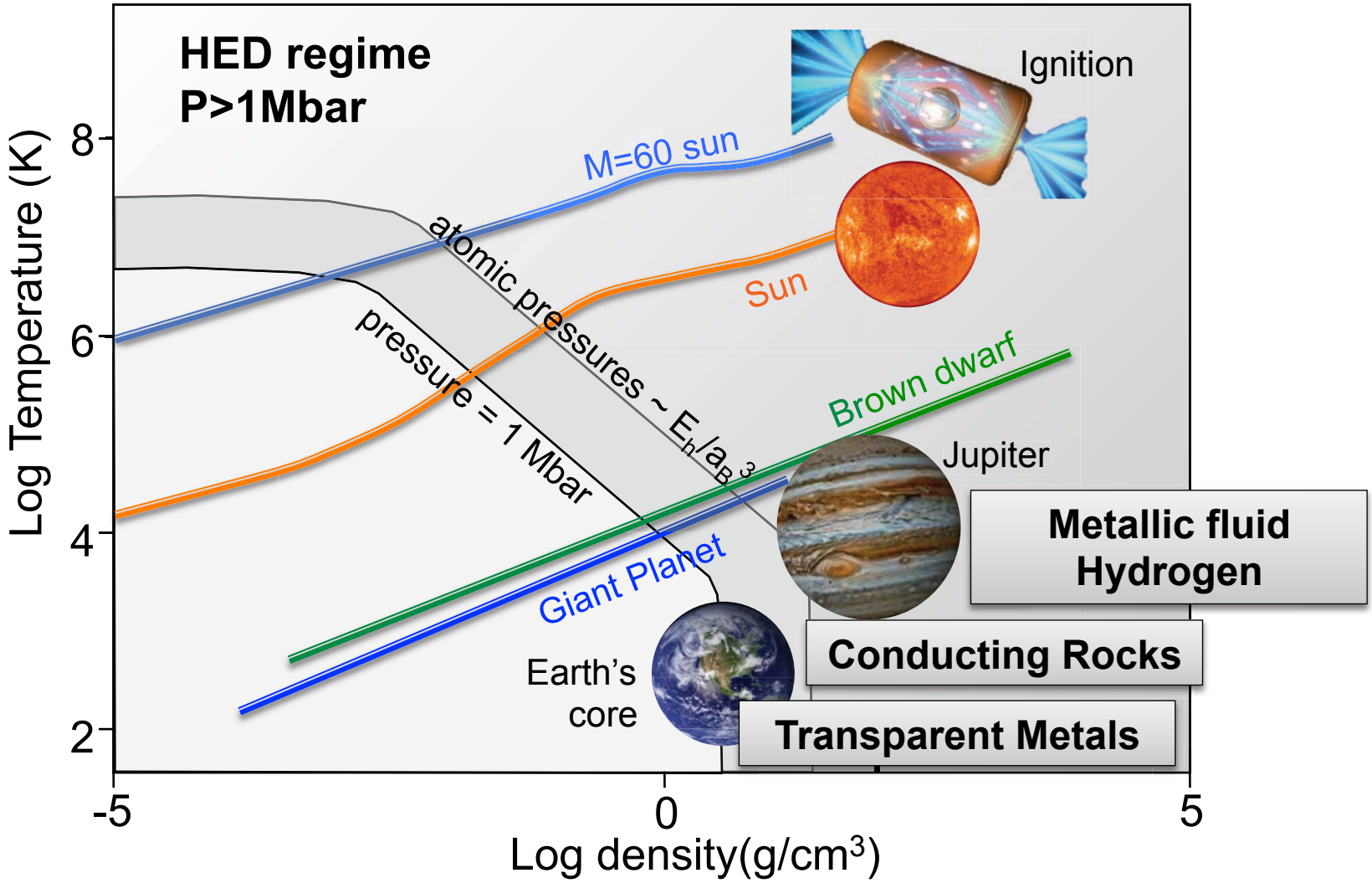
Marius Millot, Peter Celliers, Rip Collins, Jon Eggert, Dayne Fratanduono and Ryan Rygg – LLNL
Stephanie Brygoo and Paul Loubeyre – CEA
Tom Boehly – Laboratory for Laser Energetics, University of Rochester

LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

millot1@llnl.gov

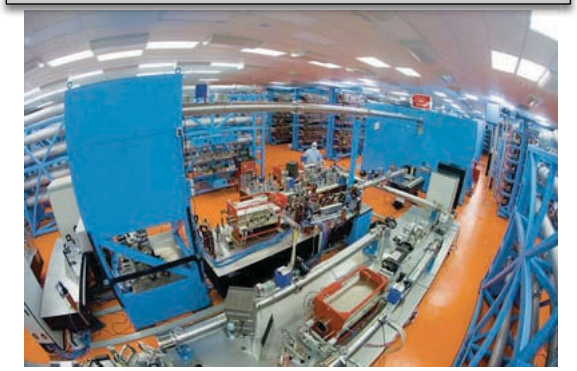
Lawrence Livermore National Laboratory

Extreme density modifies dramatically condensed matter properties



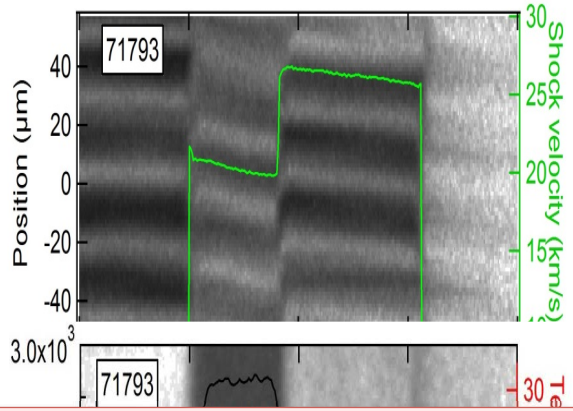
Large lasers can be used to study matter at extreme density with dynamic compression experiments

Omega and NIF Lasers



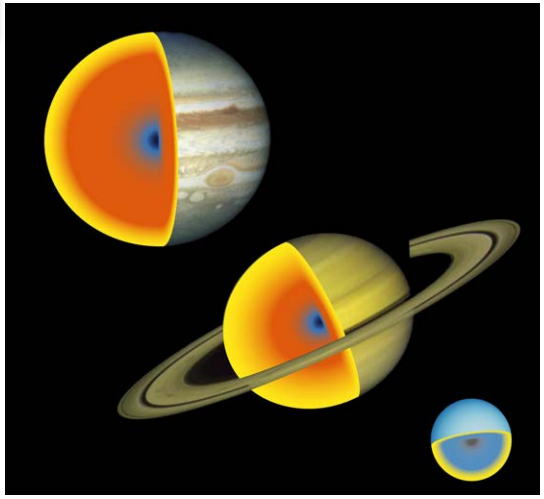
Laser "shot"

Smart Target Design + Ultrafast Optical Diagnostics

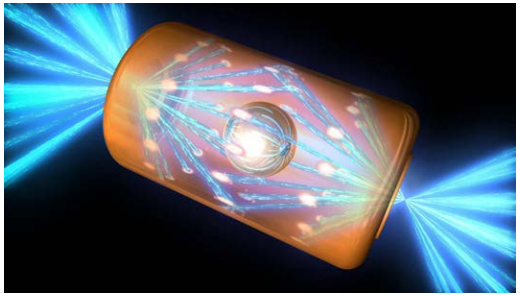


EOS, Optical Properties
Structure,…
P~0.5 - 50 Mbar
T~1000 - 50 000 K

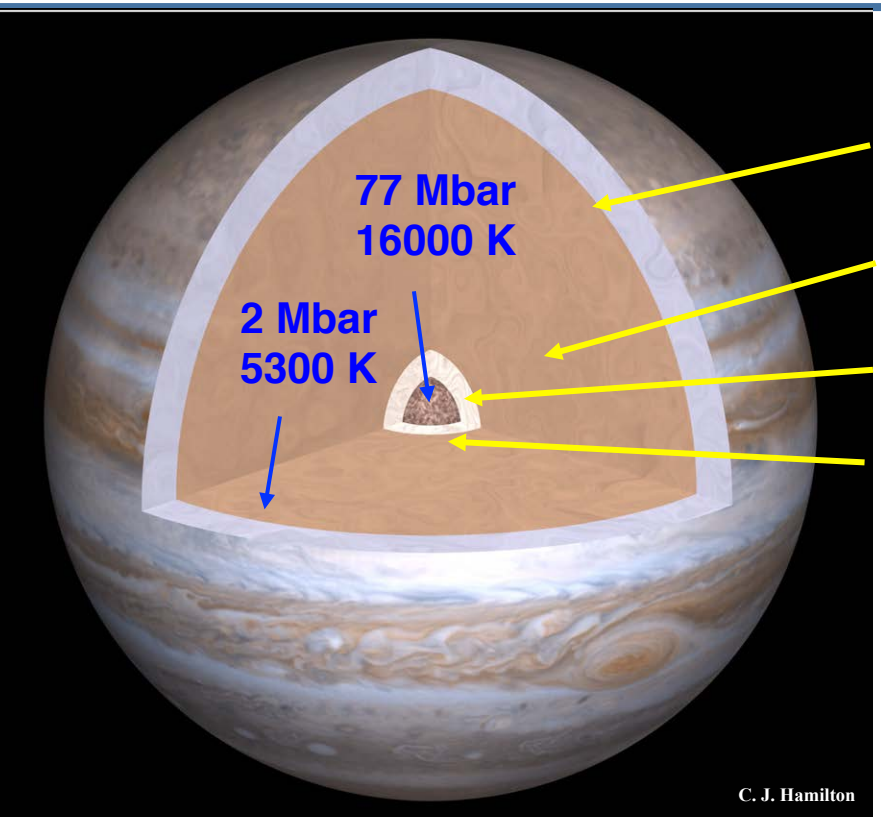
Planetary Interiors



NNSA Missions



Inside Saturn and Jupiter, hot dense helium and metallic fluid hydrogen might demix

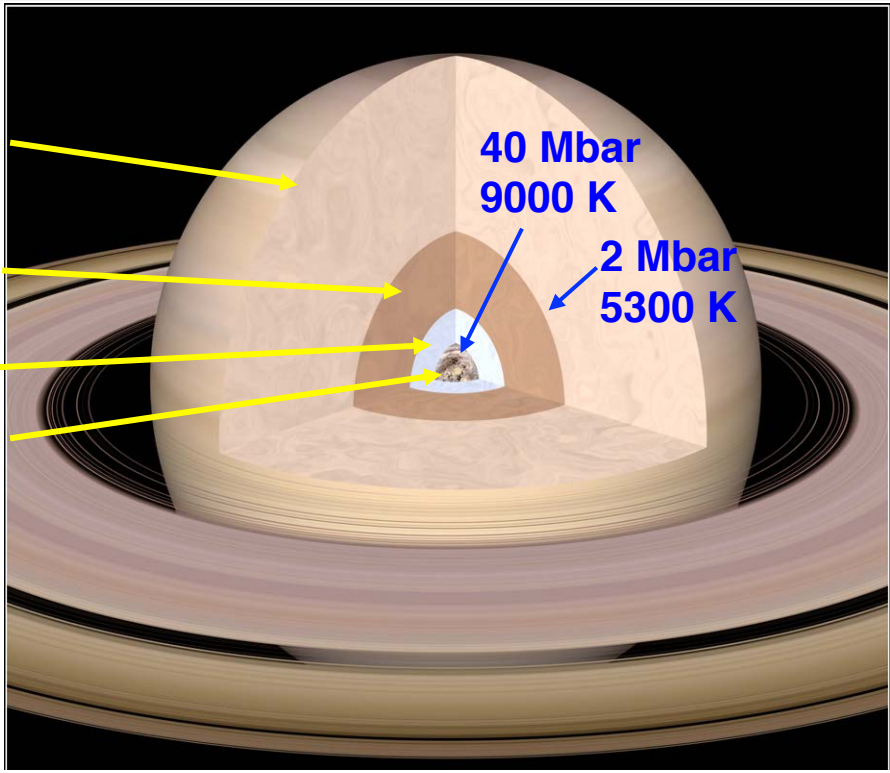


H_2+He

H^++He

Ices

rocks



Hubbard, 98

Theory (70s-2010s): demixing only inside Saturn explains its excess luminosity

Many theoretical studies for H-He mixing but no experimental data above ~10 GPa

Demixing is bounded by **metallic transition** at low P and competition of T vs **mixing energy** at high P

THEORY:

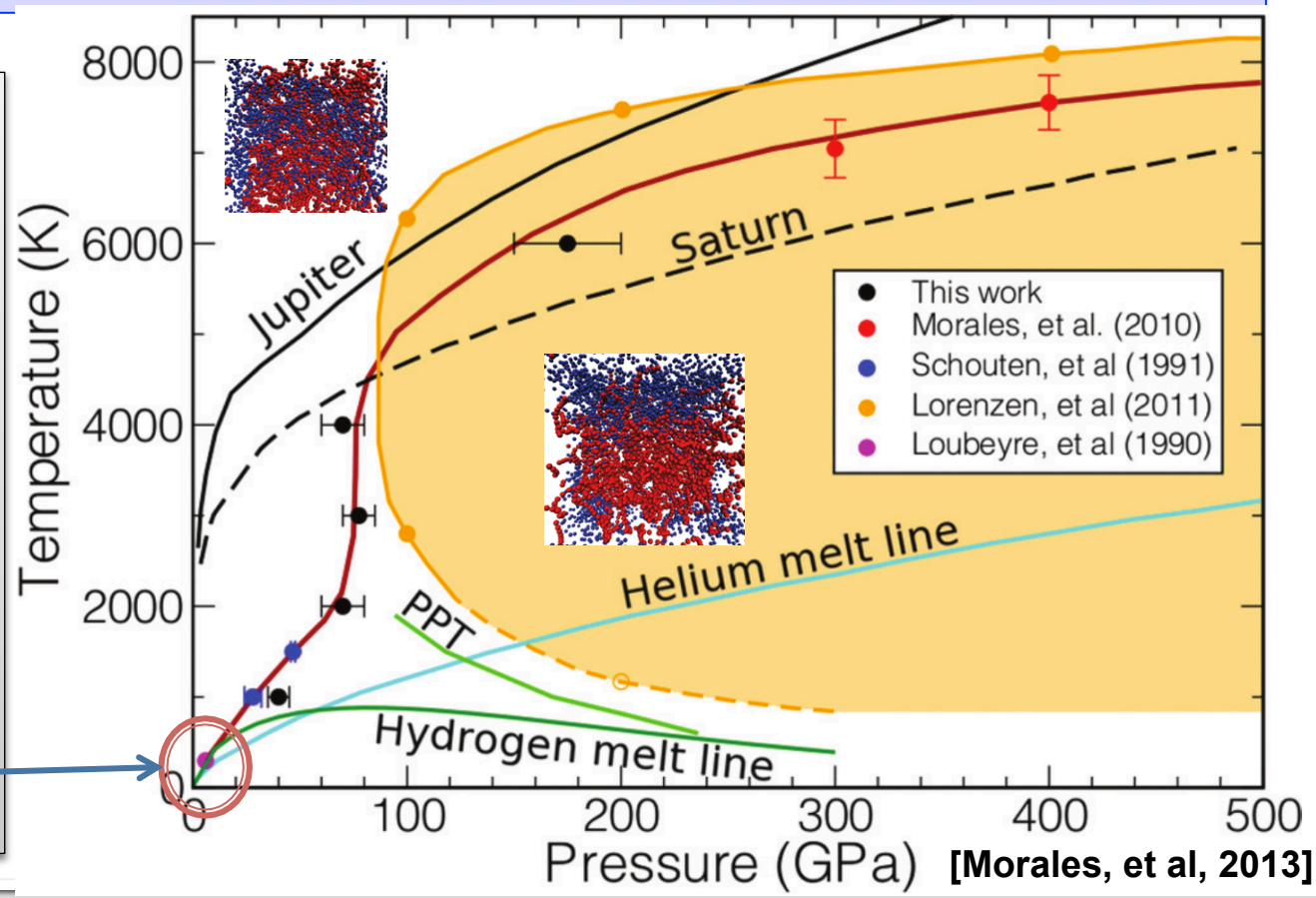
Chemical model:
Stevenson, *PRB, 1975*

Monte Carlo:
Schouten, PRB, 1991

Ab initio:
Kepleis, Science, 1991
Pfaffenzeller, PRL, 1995
Lorenzen, PRL 2009
Hamel: PRB, 2011
Morales, PRB, 2013
Soubiran, PRB, 2013

EXPERIMENTS

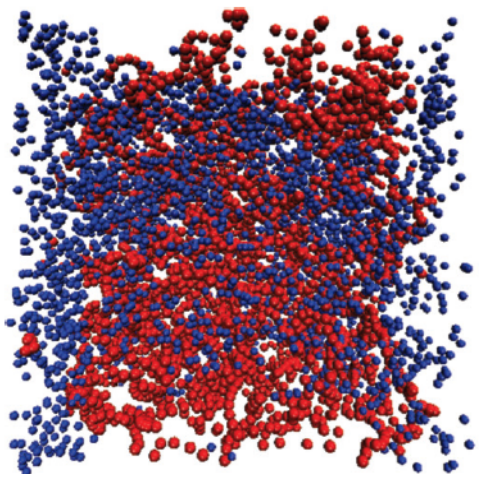
DAC Phase diagram:
Loubeyre 1990



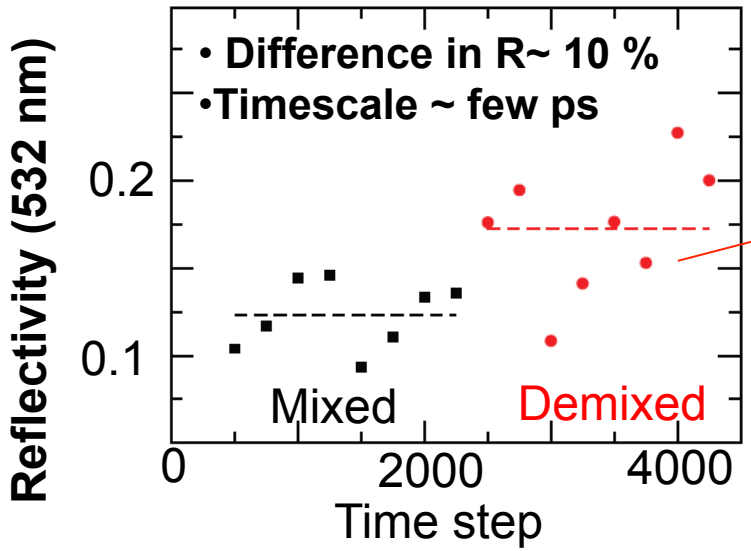
[Morales, et al, 2013]

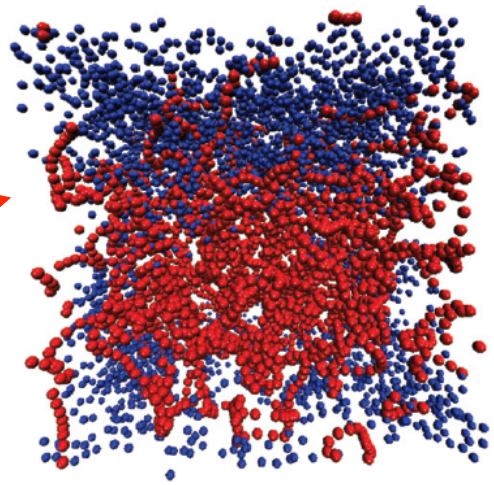
A change in reflectivity is expected upon demixing

- **Demixed fluid conducts well like pure metallic H**
- **Mixed fluid conducts less due to He "impurities"**



Mixed





Demixed

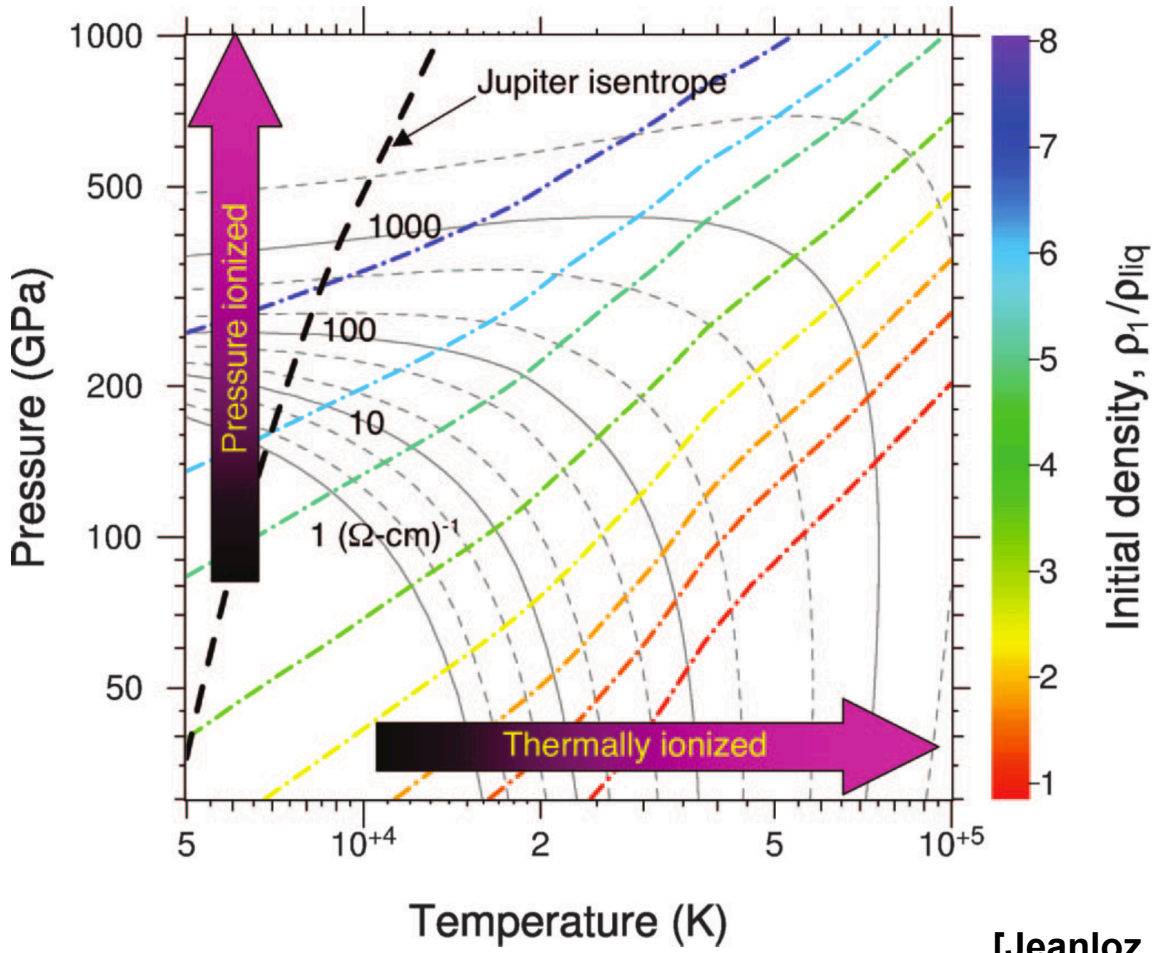
Lorenzen et al., PRB
Stevenson 2008,
Soubiran et al., PRB

Shock compression of precompressed samples allows to tune the P-T shock compression path

PNAS

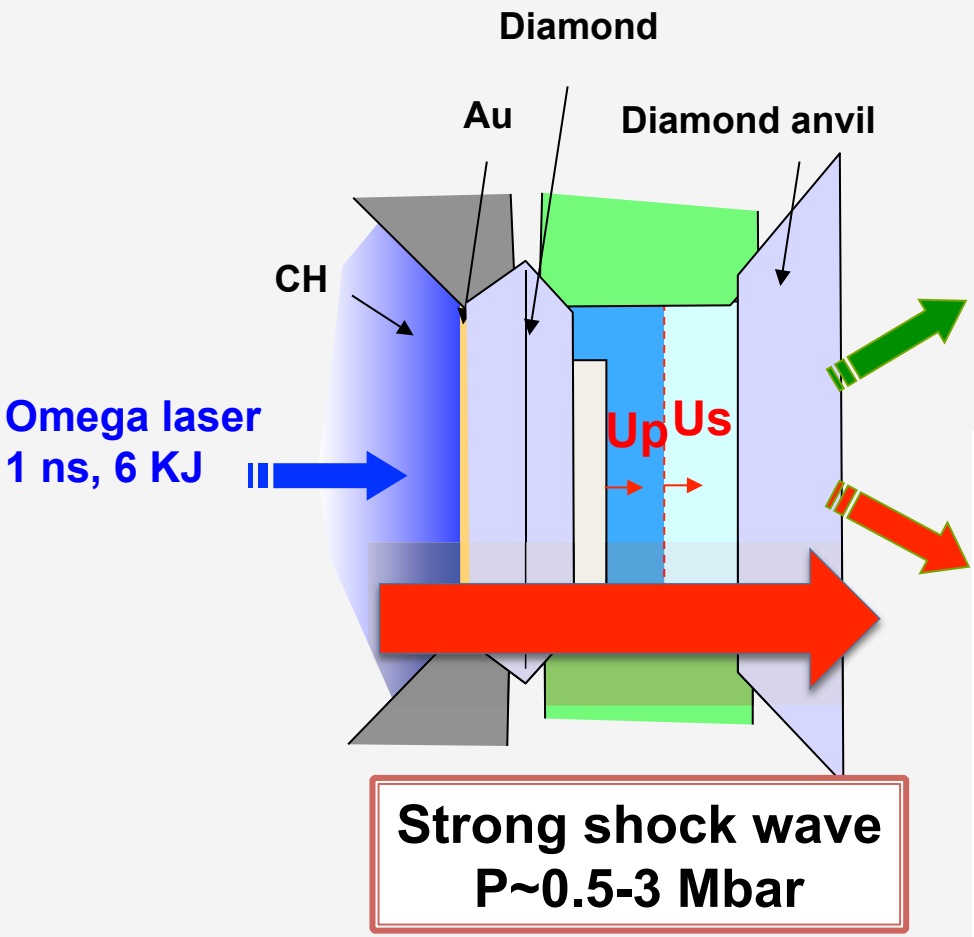
Achieving high-density states through shock-wave loading of precompressed samples

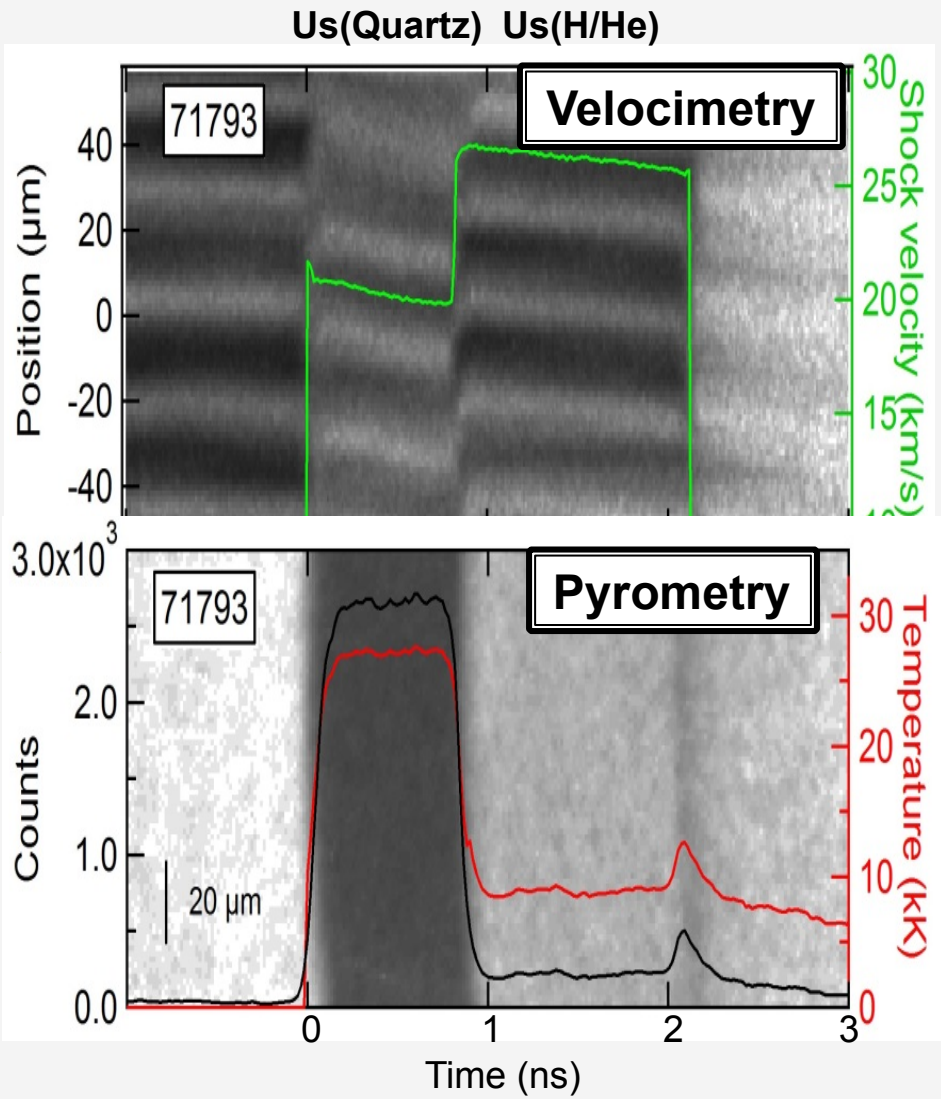
Raymond Jeanloz*†‡, Peter M. Celliers§, Gilbert W. Collins§, Jon H. Eggert§, Kanani K. M. Lee¶, R. Stewart McWilliams*, Stéphanie Brygoo‖, and Paul Loubeyre‖



[Jeanloz, et al, PNAS 2007]

High pressure properties of H-He mixtures are explored by shock loading precompressed targets





We continue to develop analysis methods and improve shocked quartz as a standard for dynamic compression

Science AAAS

Shock compression of stishovite and melting of silica at planetary interior conditions
M. Millot *et al.*
Science **347**, 418 (2015);
DOI: 10.1126/science.1261507

AIP | Physics of Plasmas
#1 JOURNAL IN 2014 GOOGLE SCHOLAR METRICS FOR THE PLASMA & FUSION CATEGORY

Optical and transport properties of dense liquid silica
Tingting Qi, Marius Millot, Richard G. Kraus, Seth Root, and Sebastien Hamel

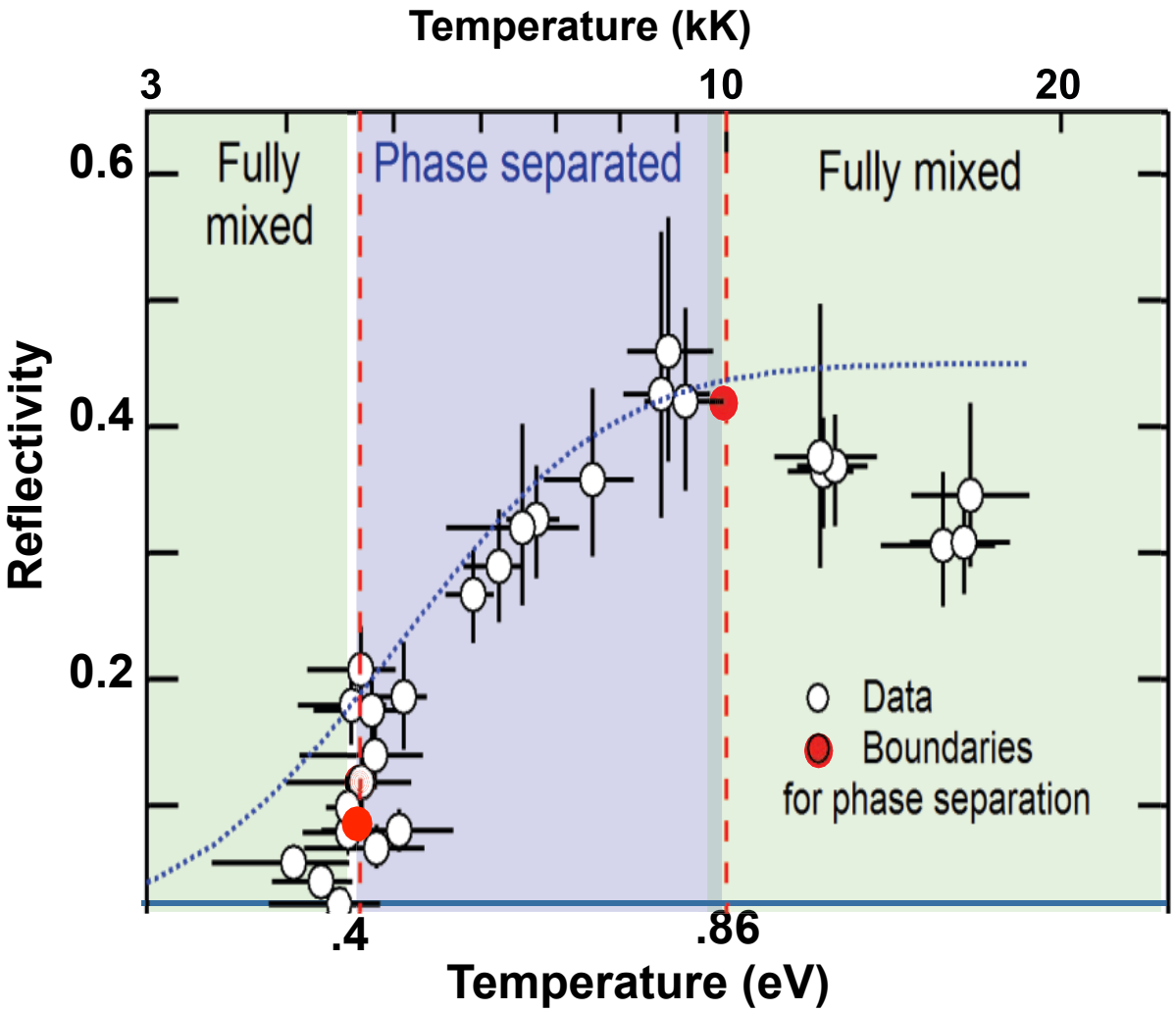
Citation: Physics of Plasmas **22**, 062706 (2015); doi: 10.1063/1.4922471

AIP | Journal of Applied Physics

Analysis of laser shock experiments on precompressed samples using a quartz reference and application to warm dense hydrogen and helium
Stephanie Brygoo, Marius Millot, Paul Loubeyre, Amy E. Lazicki, Sebastien Hamel, Tingting Qi, Peter M. Celliers, Federica Coppari, Jon H. Eggert, Dayne E. Fratanduono, Damien G. Hicks, J. Ryan Rygg, Raymond F. Smith, Damian C. Swift, Gilbert W. Collins, and Raymond Jeanloz

Citation: Journal of Applied Physics **118**, 195901 (2015); doi: 10.1063/1.4935295

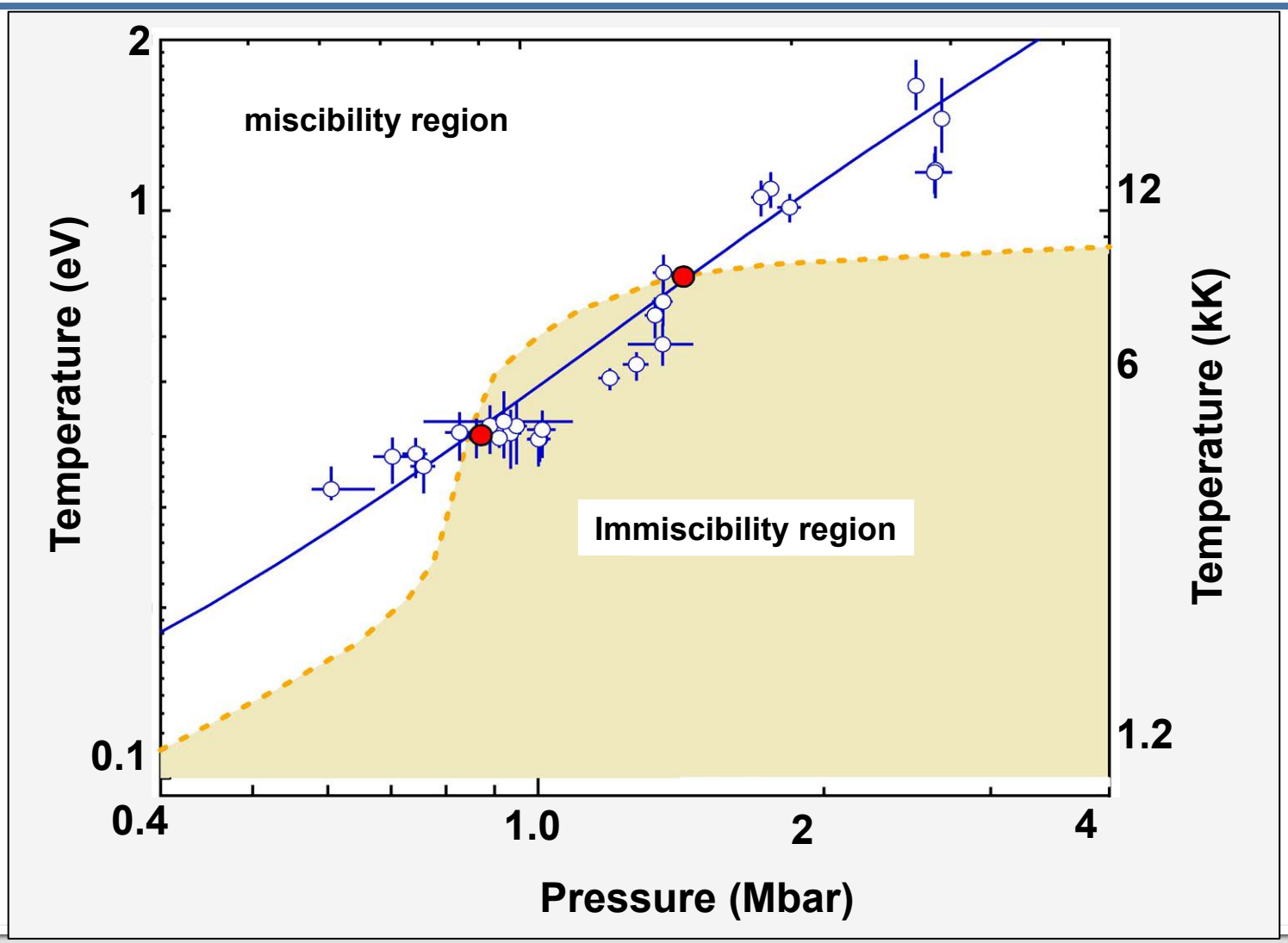
We discovered an anomaly in the onset of reflectivity for a ~protosolar He-H mixture (P_0=4 GPa)



Pure H or He and other P0 or He content mixtures have a monotonous onset

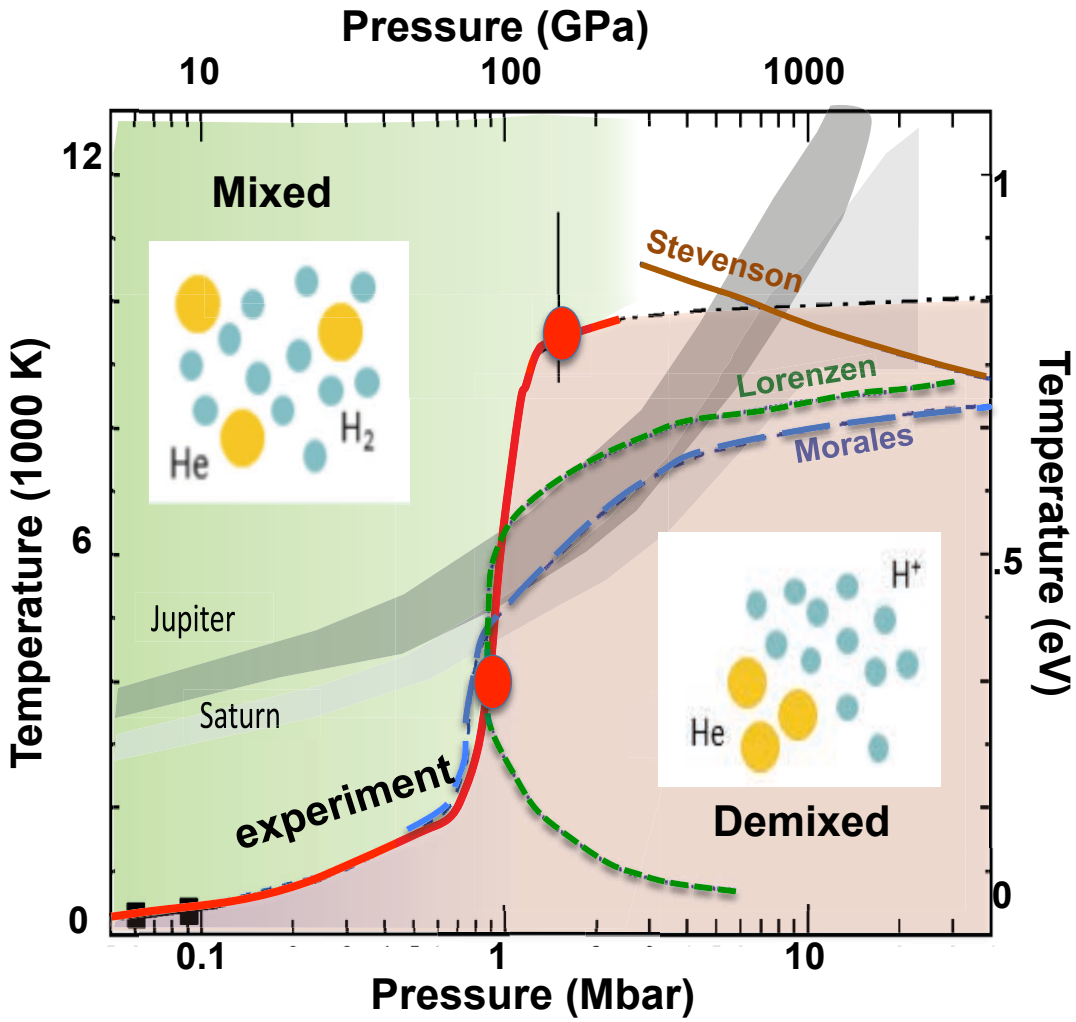
[Brygoo, Loubeyre, Millot et al, under review]

The same mixture has an anomalous shock heating curve, suggesting a phase transformation



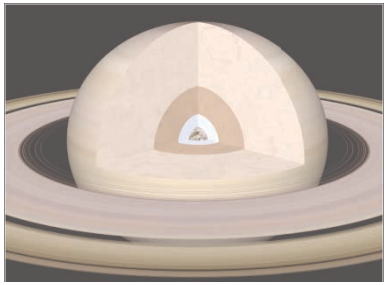
[Brygoo, Loubeyre, Millot et al, under review]

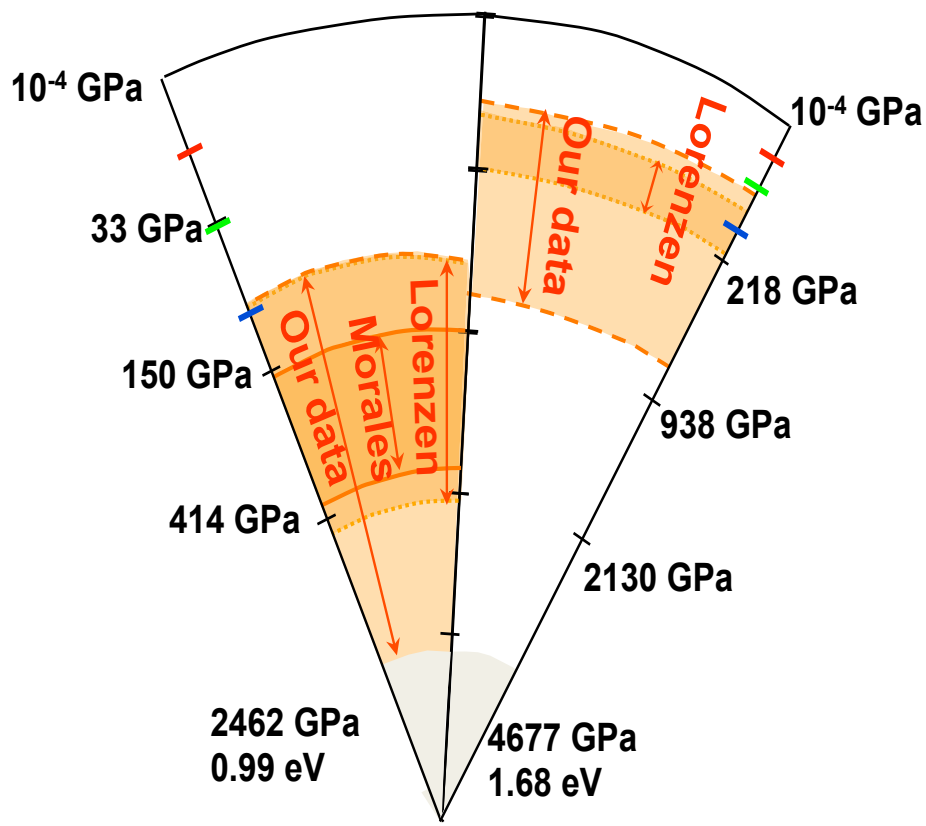
Our experiments suggest that the demixing region extends to higher temperature

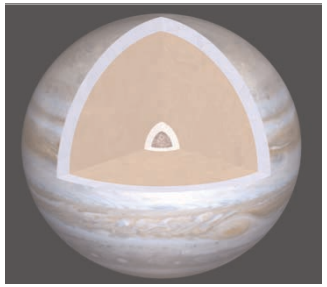


[Brygoo, Loubeyre, Millot et al, under review]

Demixing could occur in a large fraction of Saturn and Jupiter







[Brygoo, Loubeyre, Millot et al, under review]

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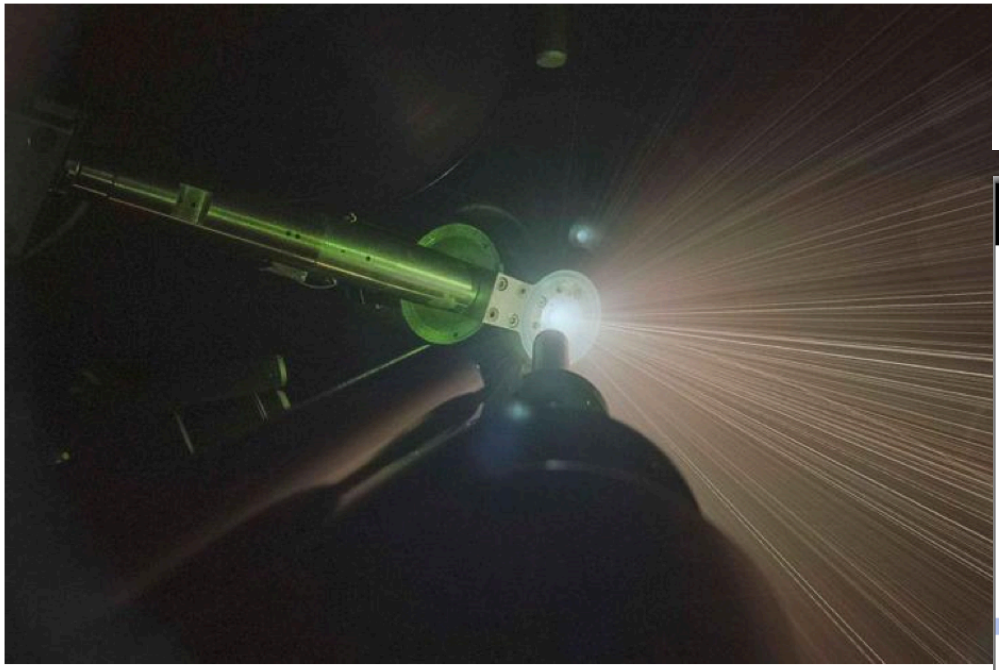

Laser shots strike a diamond anvil, driving a mixture of helium and hydrogen to the crushing pressures seen in Saturn's interior.

Physicists find new evidence for helium 'rain' on Saturn

By Eric Hand | Dec. 16, 2015 , 3:15 PM

Top 10 images of 2015

Tweet G+1 6

By Nala Rogers | 23 December 2015 2:45 pm | 1 Comment

2015 was a visual feast for science fans. Zombie beetles, sperm in a worm's head, and close-ups of Pluto's craggy surface are just a few of the sights that made us say "wow." Here are 10 of our favorite images, all published online in *Science* news stories over the past year.

Email Nala

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Helium rain on Saturn

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Unraveling the mysteries of dog domestication--one of our most popular features of 2015: scim.ag/22uHqQG pic.twitter.com/Aws5U3Msrg

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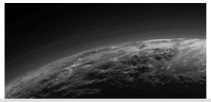
Compiling our top news stories of 2015: scim.ag/1NLDfhX pic.twitter.com/Wkx5ucnxdX



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Laboratory for Laser Energetics

a unique national resource

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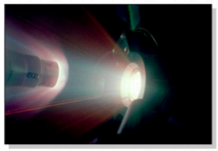
Welcome to LLE

The Laboratory for Laser Energetics (LLE) of the University of Rochester is a unique national resource for research and education in science and technology. LLE was established in 1970 as a center for the investigation of the interaction of intense radiation with matter. The National Nuclear Security Administration funds LLE as part of its Stockpile Stewardship Program.



OFFICE OF THE DIRECTOR

Laser's 50th Anniversary

Quick Shot

Physicists Find New Evidence for Helium "Rain" on Saturn

Research scientists Marius Adrien Millot (LLNL) and Stephanie Brygoo (CEA) are shown displaying a *Science* Magazine news article on their research at LLE. They used the OMEGA Laser System to demonstrate possible helium "rain" on Saturn to account for the unexpectedly high brightness for a normally cooling planet. The helium "rain," occurring at pressures and temperatures that can be created using OMEGA, unleashes gravitational potential energy that makes Saturn more luminous. In addition to LLNL and CEA, scientists come from around the world to take advantage of the facilities at LLE. The *Science* Magazine online article is available here.

Quick Links

ANOMALOUS ABSORPTION CONFERENCE

NLUF National Laser Users' Facility

Laboratory Basic Science FY17 Solicitation Coming Soon

FSC Fusion Science Center

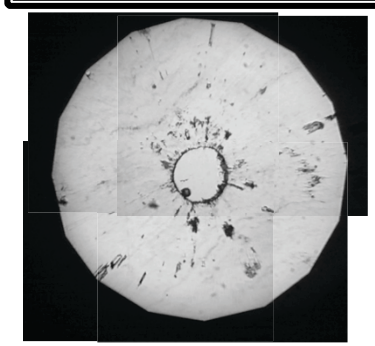
Omega Laser Facility Users Group

RSA SecurID SOFTWARE TOKEN DOWNLOAD

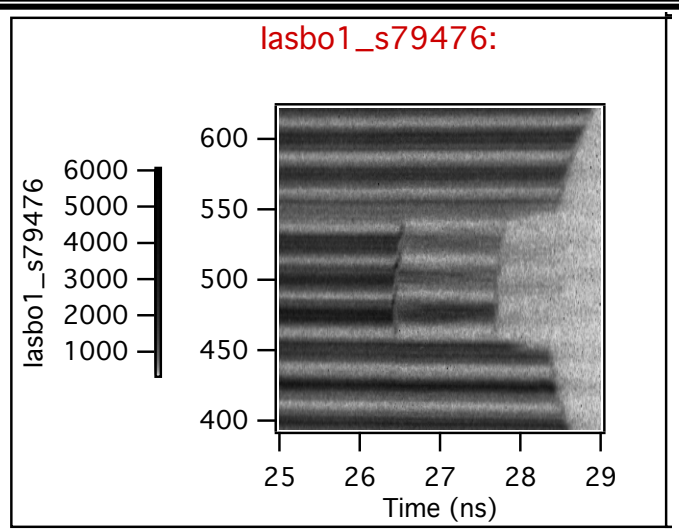
The Omega Laser Facility Users' Guide is now available for download here.

Exploring new ways to reach higher densities: higher pre-compression development

Solid Deuterium
P_0=120 kbar



Raw VISAR Data showing evidence of Metallic Hydrogen (Deuterium) near 150 GPa and 3000 K



2003 — 5-10 kbar

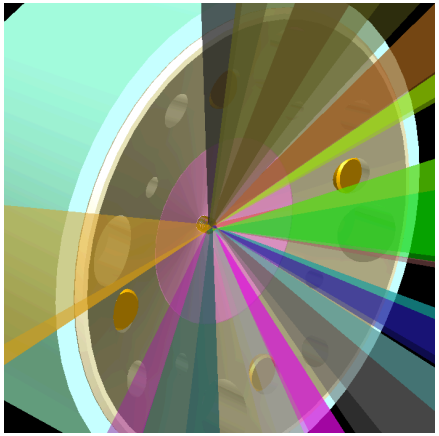
2009 — 15-20 kbar

2012 — 60 kbar

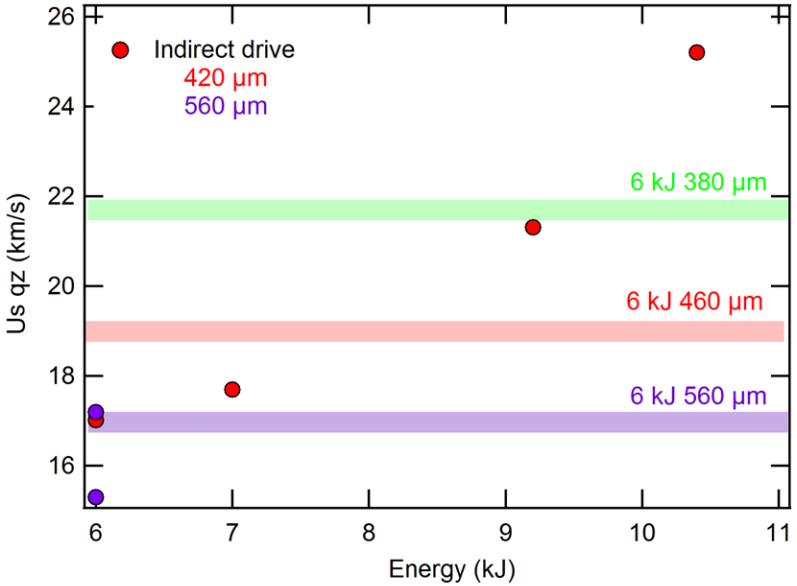
2016 — 120 kbar

Exploring new ways to reach higher densities: indirect drive platform development

- **Indirect Drive is promising**
  - **Higher shock pressure**
  - **Higher precompression P_0**
  - **Scalable to NIF**

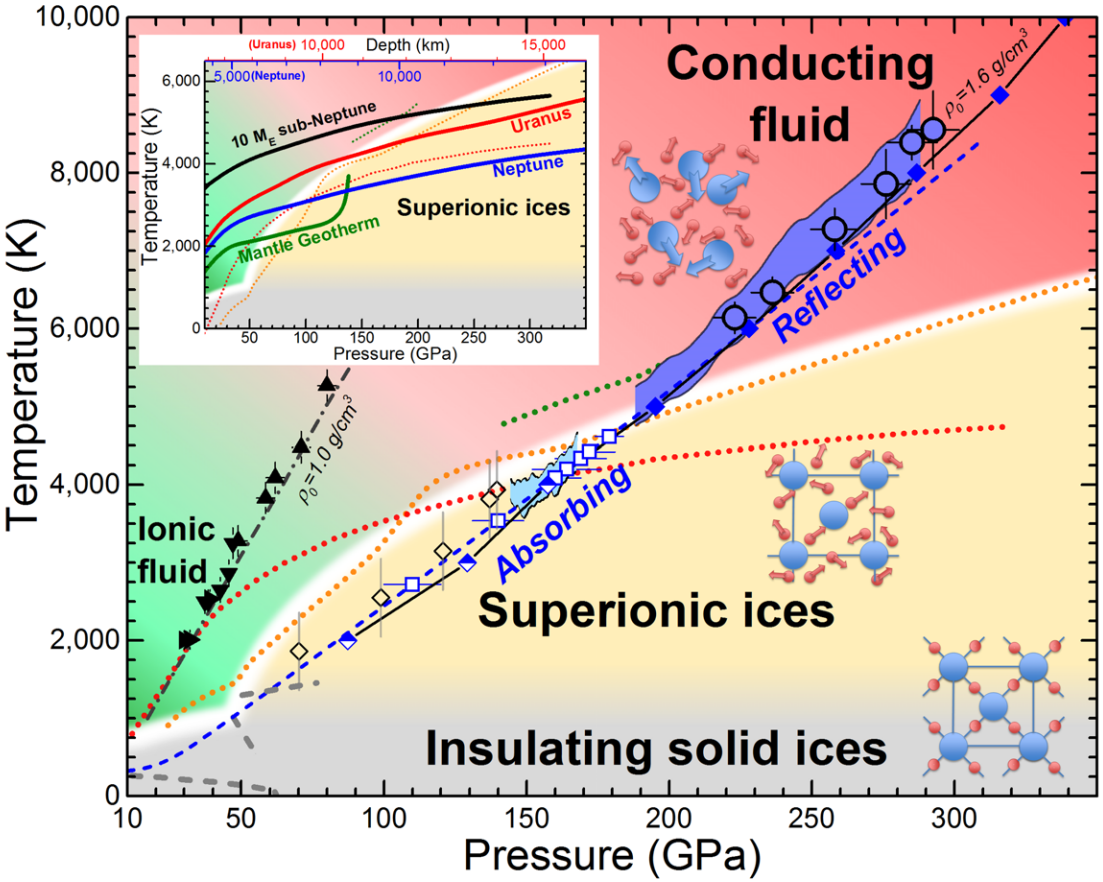


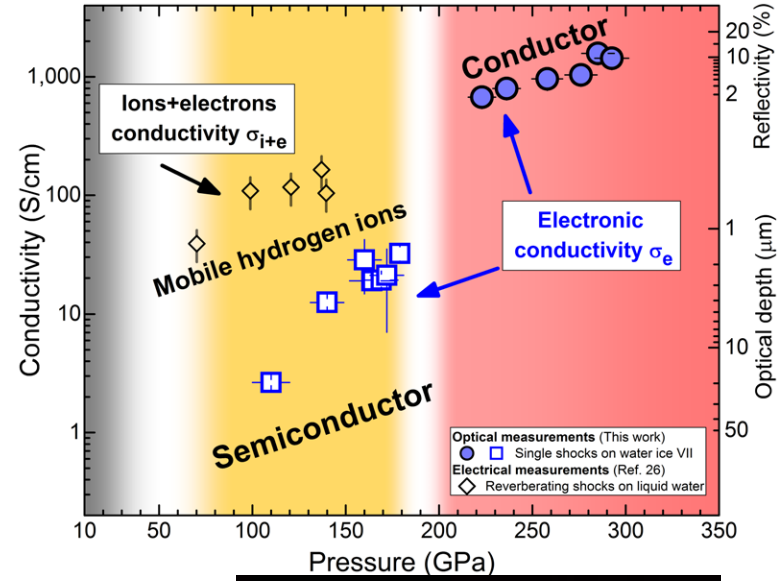
- **First Successful Campaign**
  - Target Preparation at LLNL
  - Fielding 7 shots
  - High T_{rad}> 220 eV
  - 50 % higher shock pressure at maximum drive energy

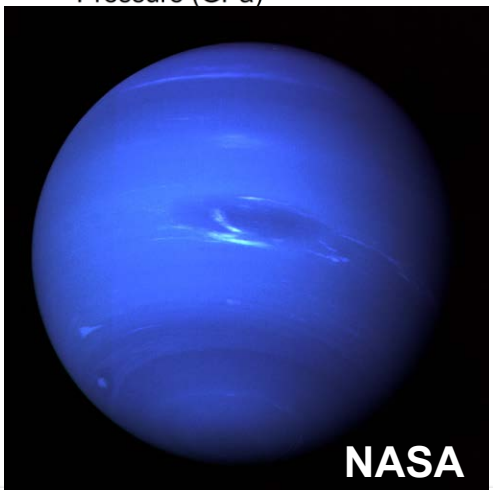


[Millot et al, in preparation]

Extending our technique to study H_2O, we obtained the first experimental evidence for Superionic water







LBS Shots, HEDLP Grant

[Millot et al, under review]

Acknowledgments

Funding and shots

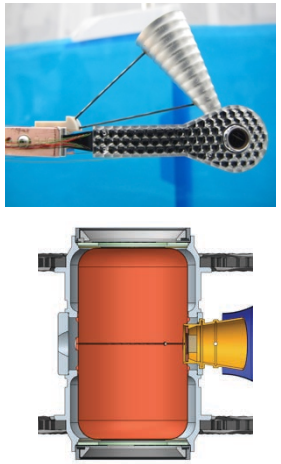
LDRD, HEDLP, LBS and NLUF programs.

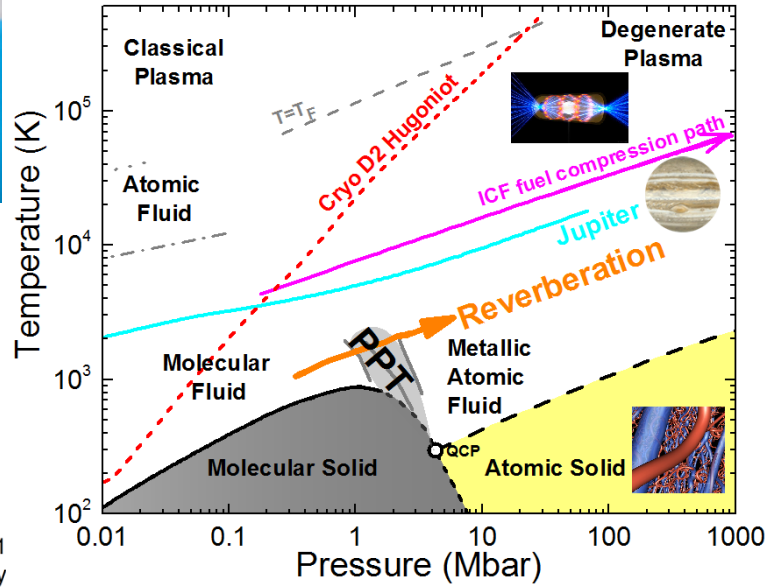
Engineering Support

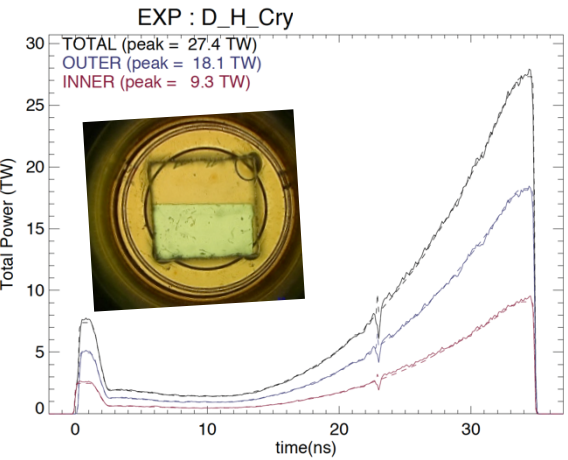
- LLNL Target Fab
- LLE Omega Laser Staff & Support Team

Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

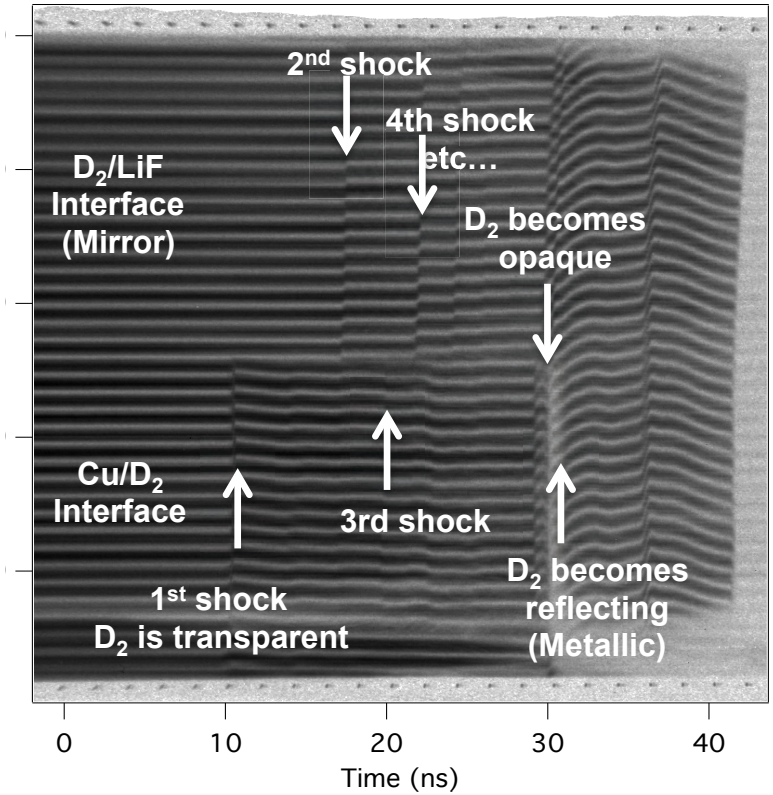
Our team conducted NIF Discovery Science Experiments to explore Hydrogen metallization near 2 g/cc







Exploring similar P-T than Knudson et al Science 2015
~10x faster timescale



- ✓ 4 cryogenic shots
- ✓ Successful reverberation compression to >3 Mbar
- ✓ Excellent quality VISAR data
- ✓ Signatures of changes in the hydrogen optical properties

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