Structure of Solid Matter Under Super-Earth Conditions

Kavli Institute for Theoretical Physics, Santa Barbara, 2/23/2015

Physics of Exoplanets: From Earth-sized to Mini-Neptunes

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1 Mbar = 100 GPa = 0.1 TPa

We have built a broad base of academic collaborators

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  - C. Bolme
- **University of California, Berkeley**
  - R. Jeanloz
- **Princeton University**
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- **University of Rochester**
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- **Stanford University**
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- **University of Oxford, UK**
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- **National Research Council of Canada**
  - D. Klug, Y. Yao
- **Additional Collaborators / Consultants**
  - Andrew Comley, Brian Maddox, Chris Wehrenberg, Hye-Sook Park, and Bruce Remington
- **Plus farget fabrication, Omega and NIF facility and diagnostic teams.**

*Currently, Washington State University
**Currently, University of Edinburgh
***Currently, Harvard University
****Currently, DESY

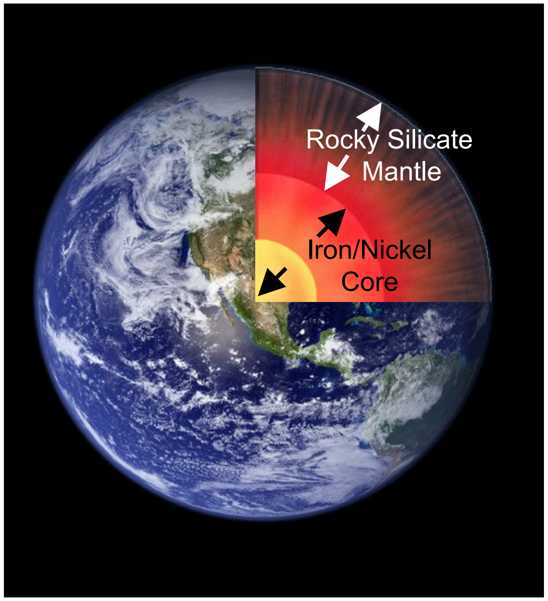
1 Mbar = 100 GPa = 0.1 TPa

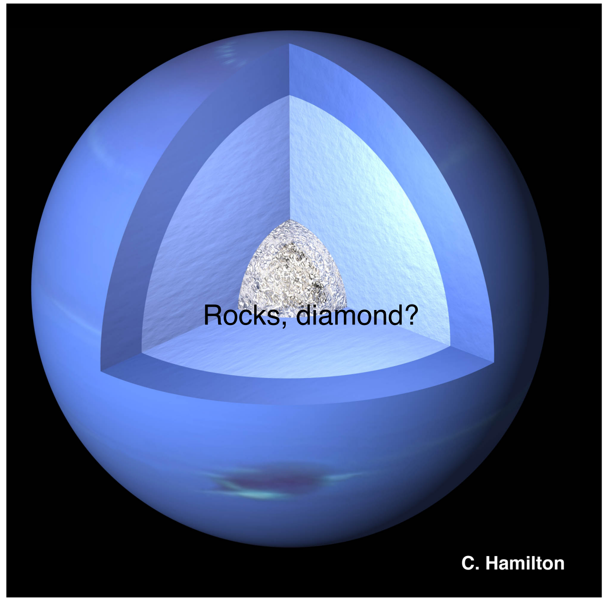
Outline

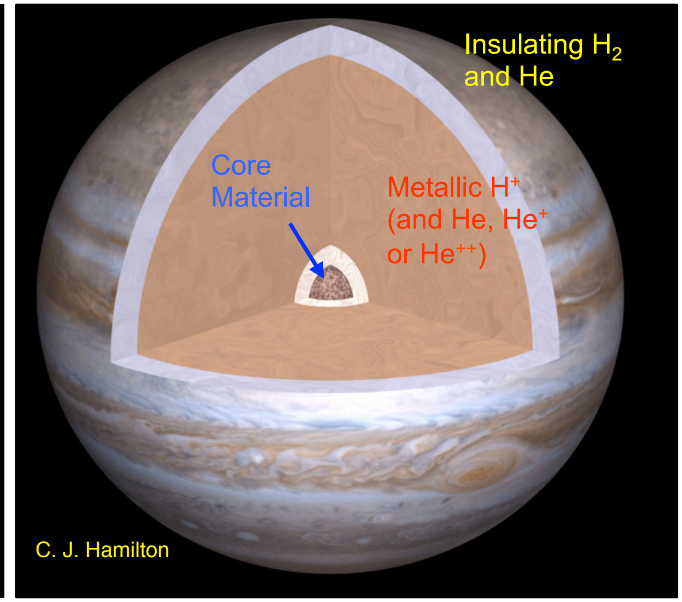
- Introduction
- Ramp-Compression Stress-Density EOS
- X-Ray Diffraction at Omega and NIF
- Future Experiments

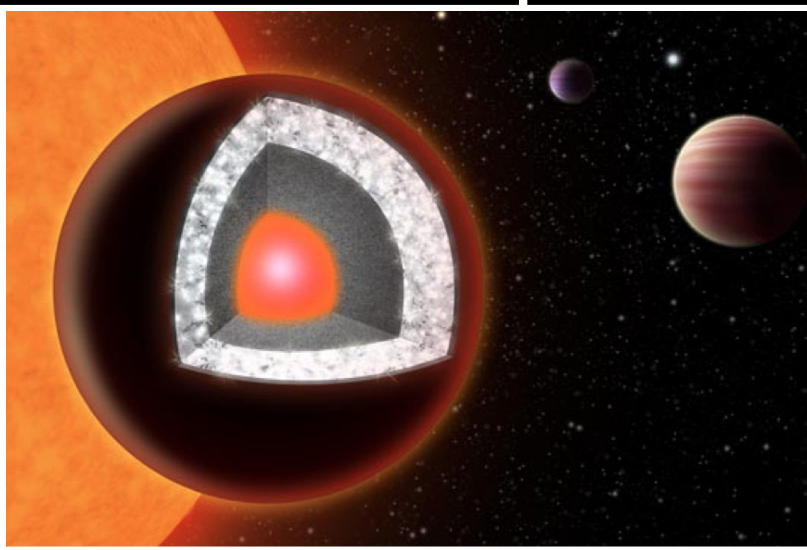
1 Mbar = 100 GPa = 0.1 TPa

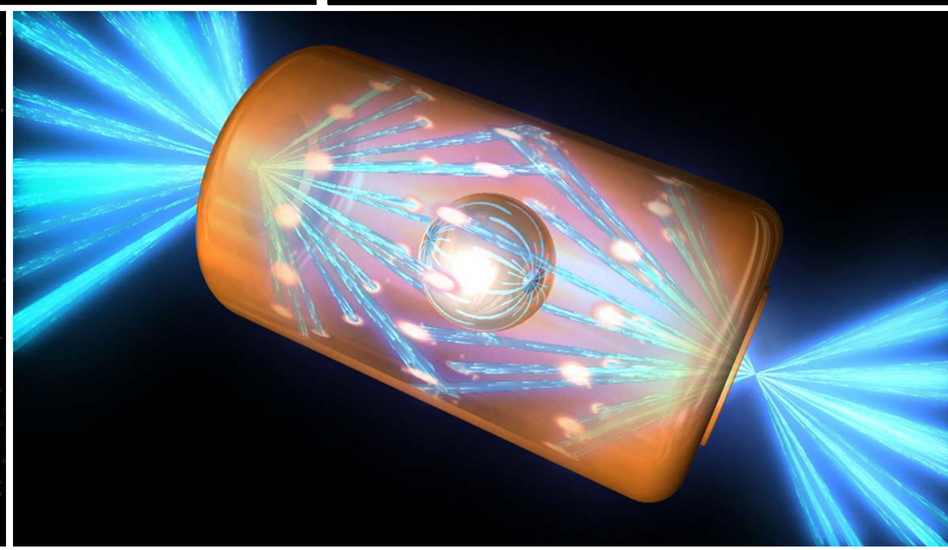
Matter at High Energy Density (HED) is found throughout our universe





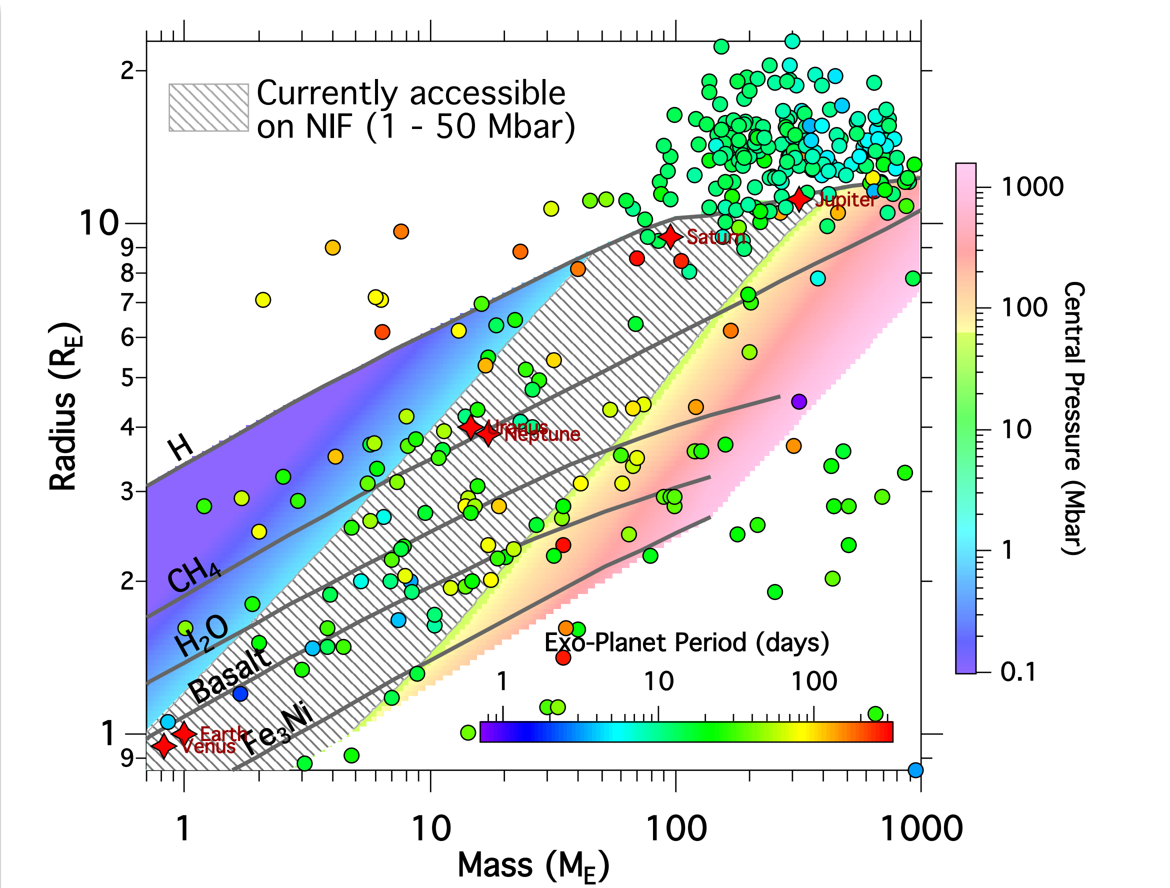






High pressures have particular relevance to the interiors of planets

1 Mbar = 100 GPa = 0.1 TPa



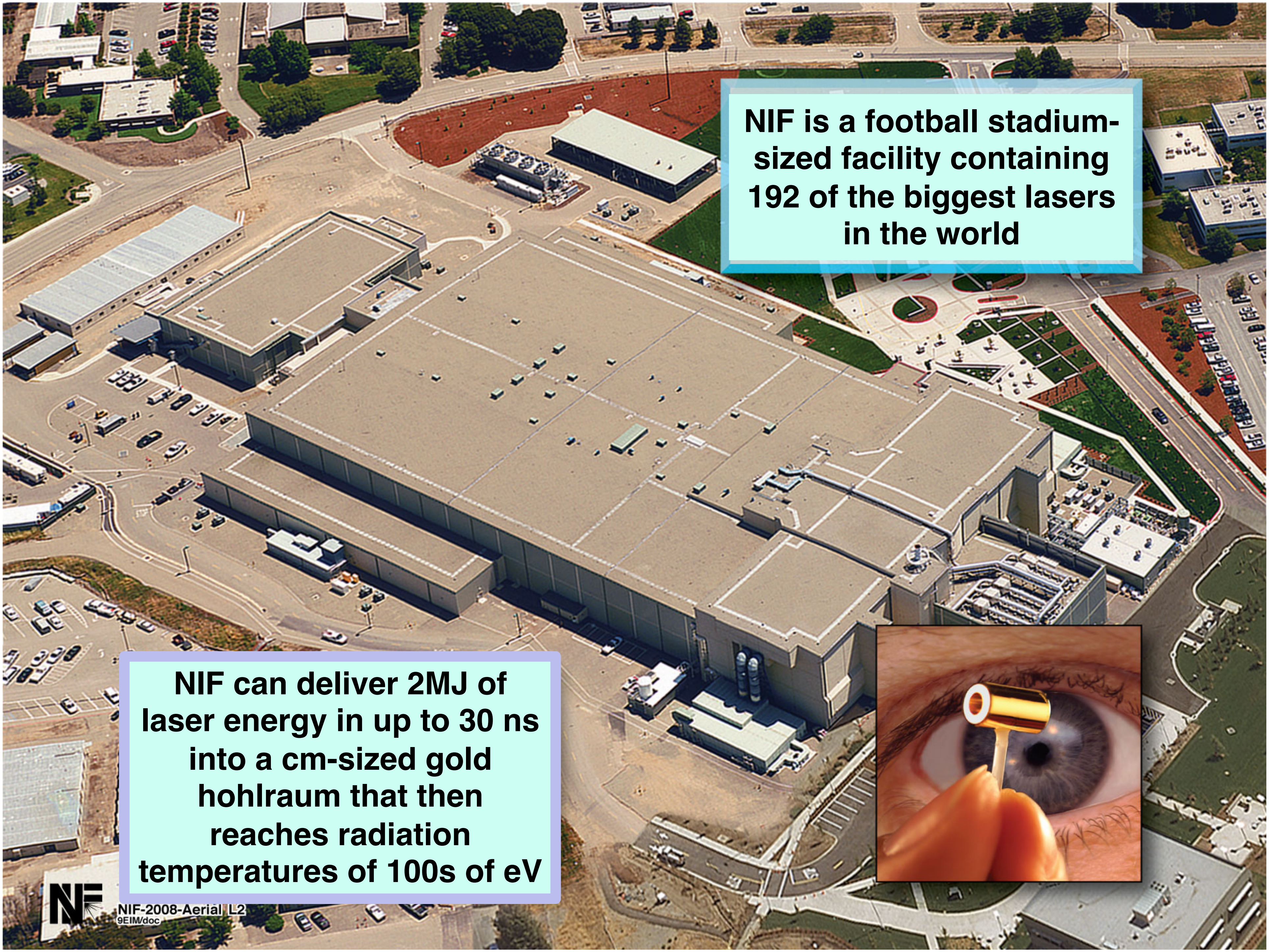
As of February 21, 2015:
1890 planets
1189 planetary systems
477 multiple planet systems
(http://exoplanet.eu)

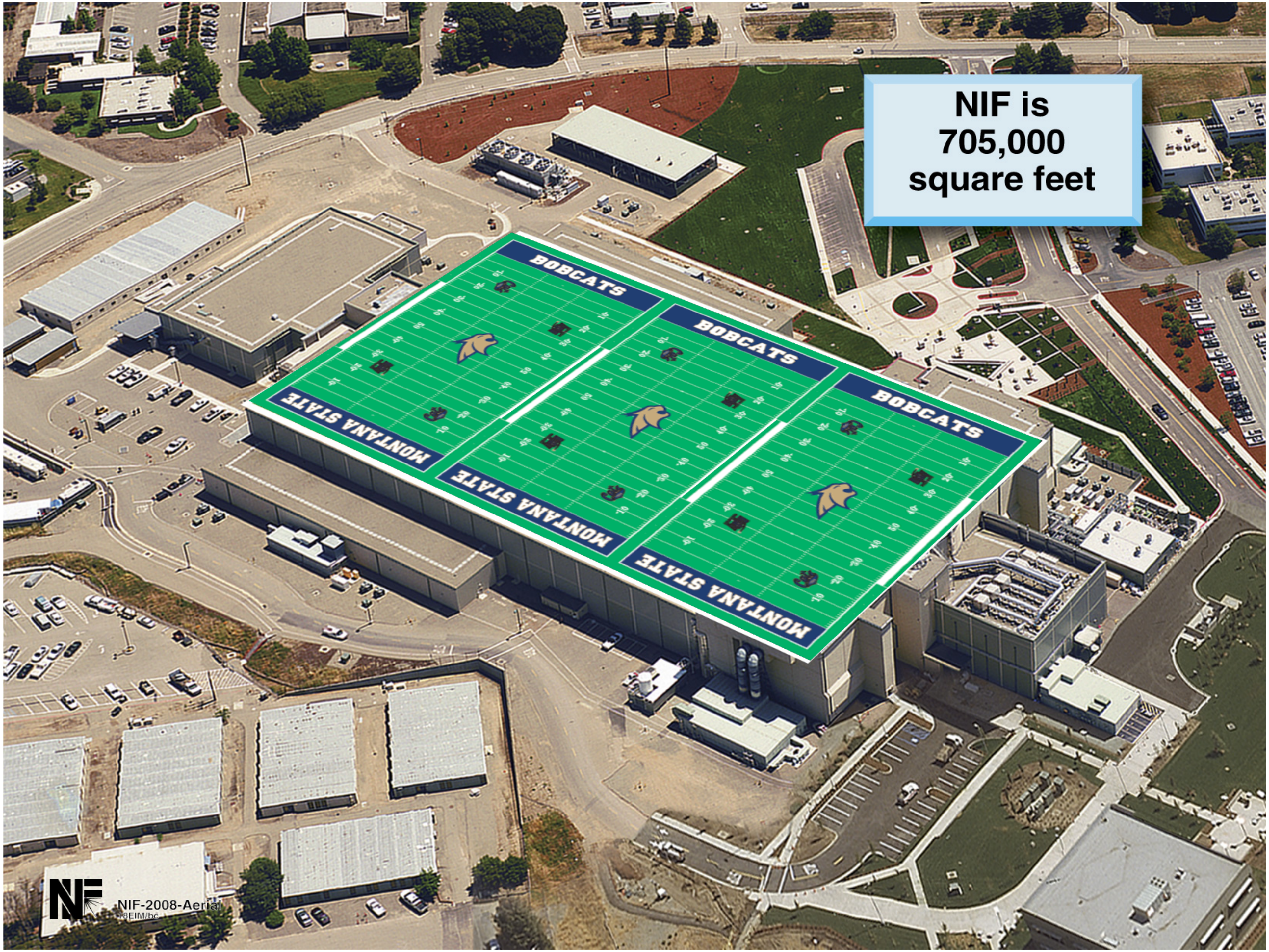
1189 transiting exo-planets have been confirmed ~405 with known mass and radius.

The mass-radius plot is our best way to constrain the interior make-up of the planets.

We can study materials at rocky-planet cores pressures for 0.5—20 earth masses in the laboratory

Pressures from, *Mass-radius relationships for exoplanets,* D. C. Swift, et al., **Astrophys. J.**, **744**:59 (2012).


NIF is a football stadium-sized facility containing 192 of the biggest lasers in the world
NIF can deliver 2MJ of laser energy in up to 30 ns into a cm-sized gold hohlraum that then reaches radiation temperatures of 100s of eV
NIF-2008-Aerial_L2
9EIM/doc

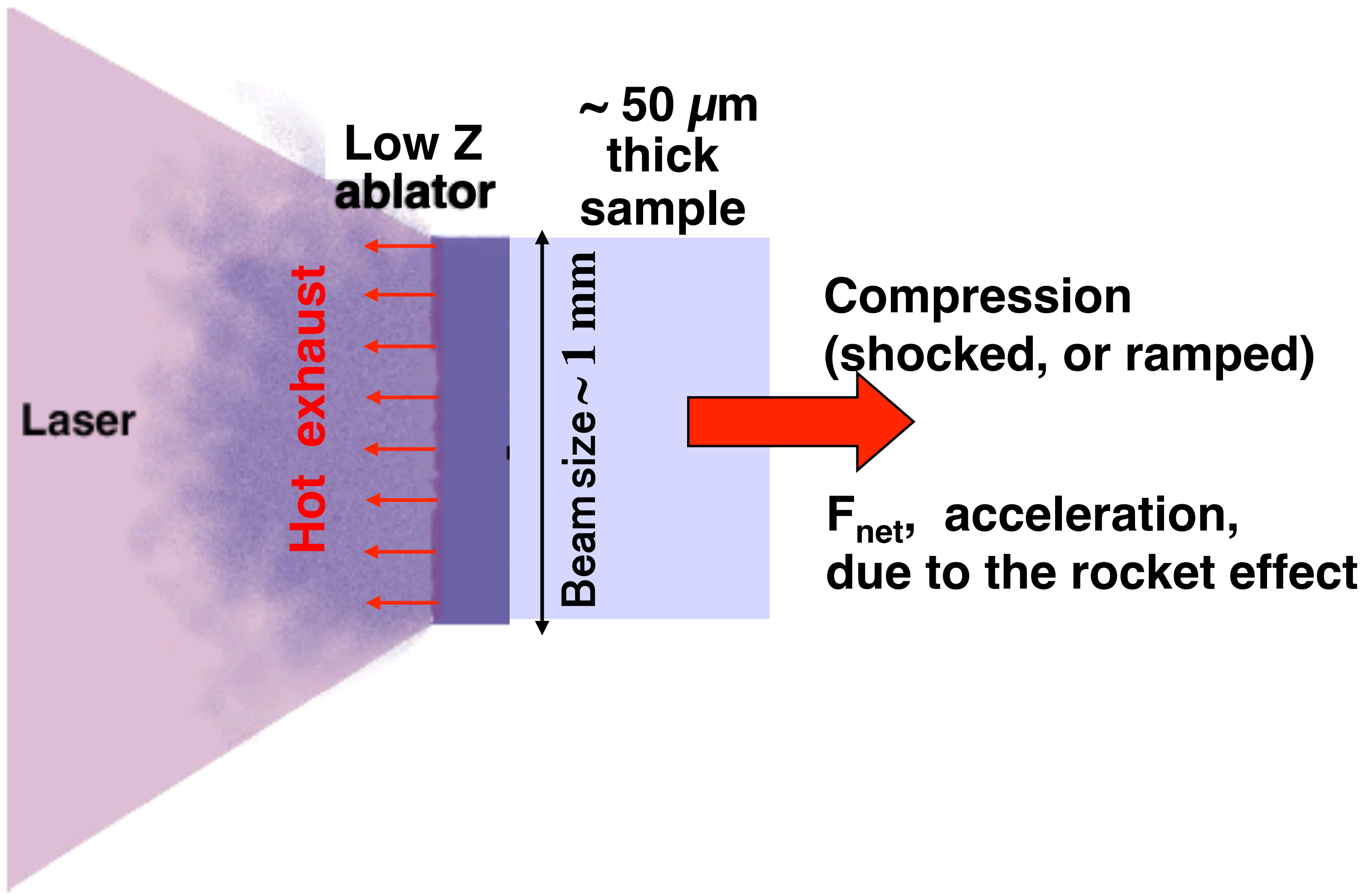

NIF is 705,000 square feet
BOBCATS
MONTANA STATE
NIF-2008-Aerial


Finished LB2
Installation Qualification
March 31, 2008
NIF-0508-14729
12EIM/cls


Inside the Target Chamber

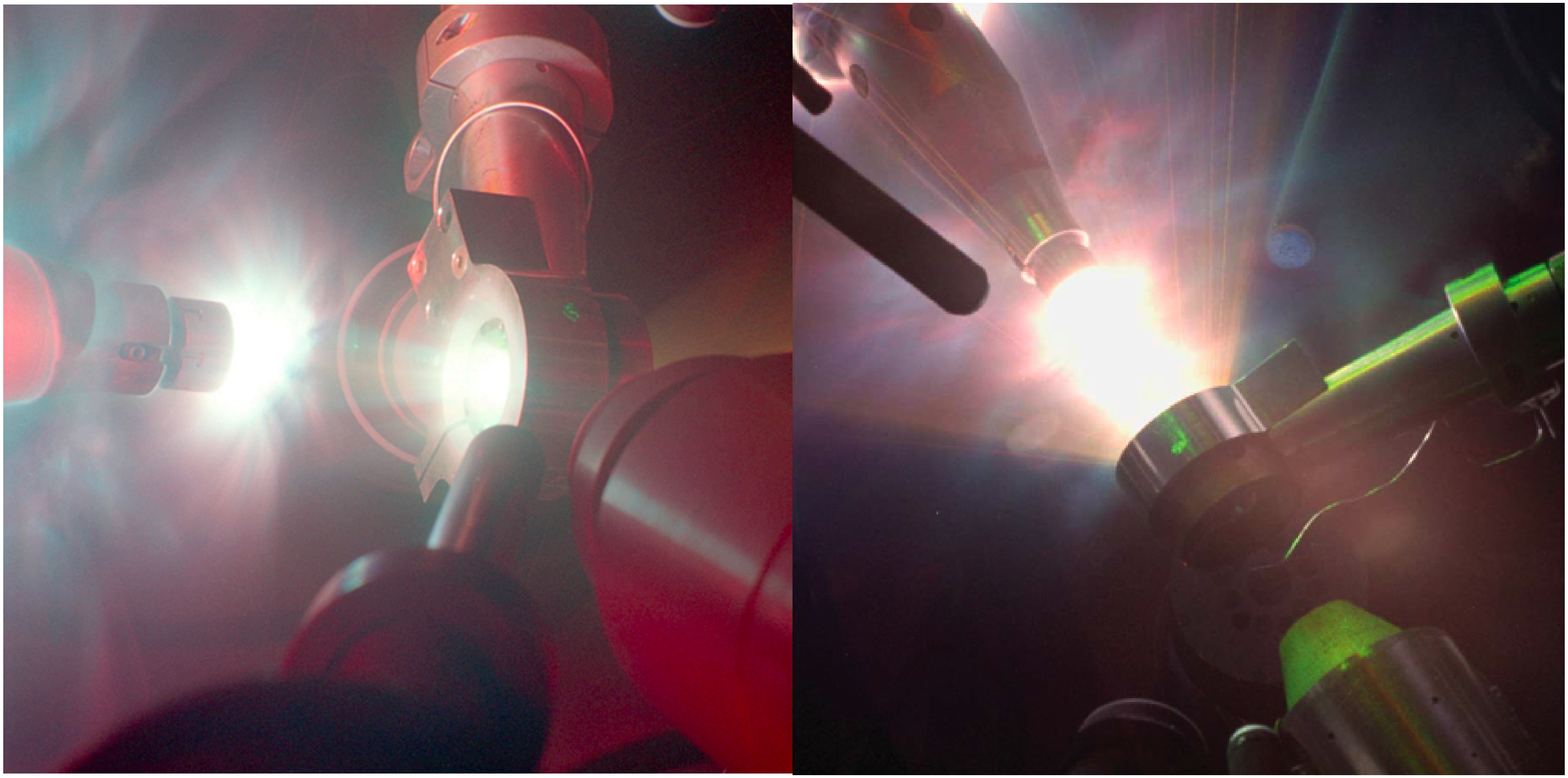
1 Mbar = 100 GPa = 0.1 TPa

Laser Ablation Drive



1 Mbar = 100 GPa = 0.1 TPa

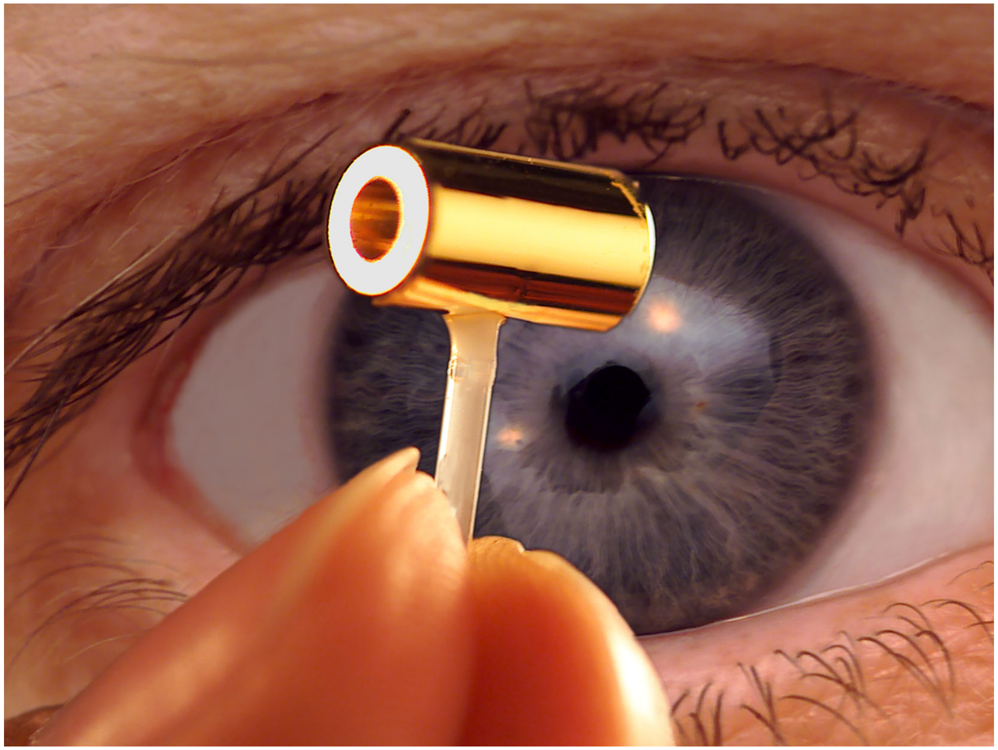
High pressures result from the rocket effect generated by laser-induced ablation.

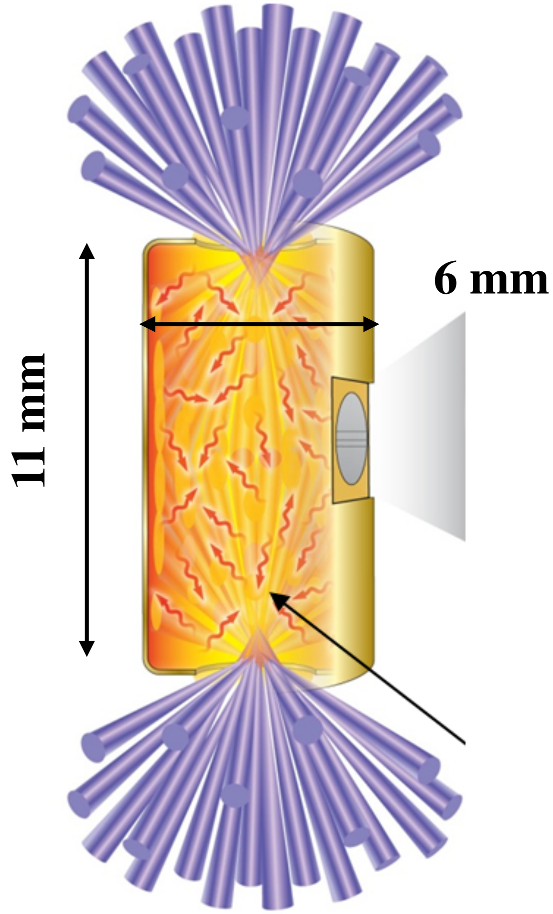


Time-integrated photos of shots at the Omega laser (60 beams, 30 kJ) at University of Rochester

1 Mbar = 100 GPa = 0.1 TPa

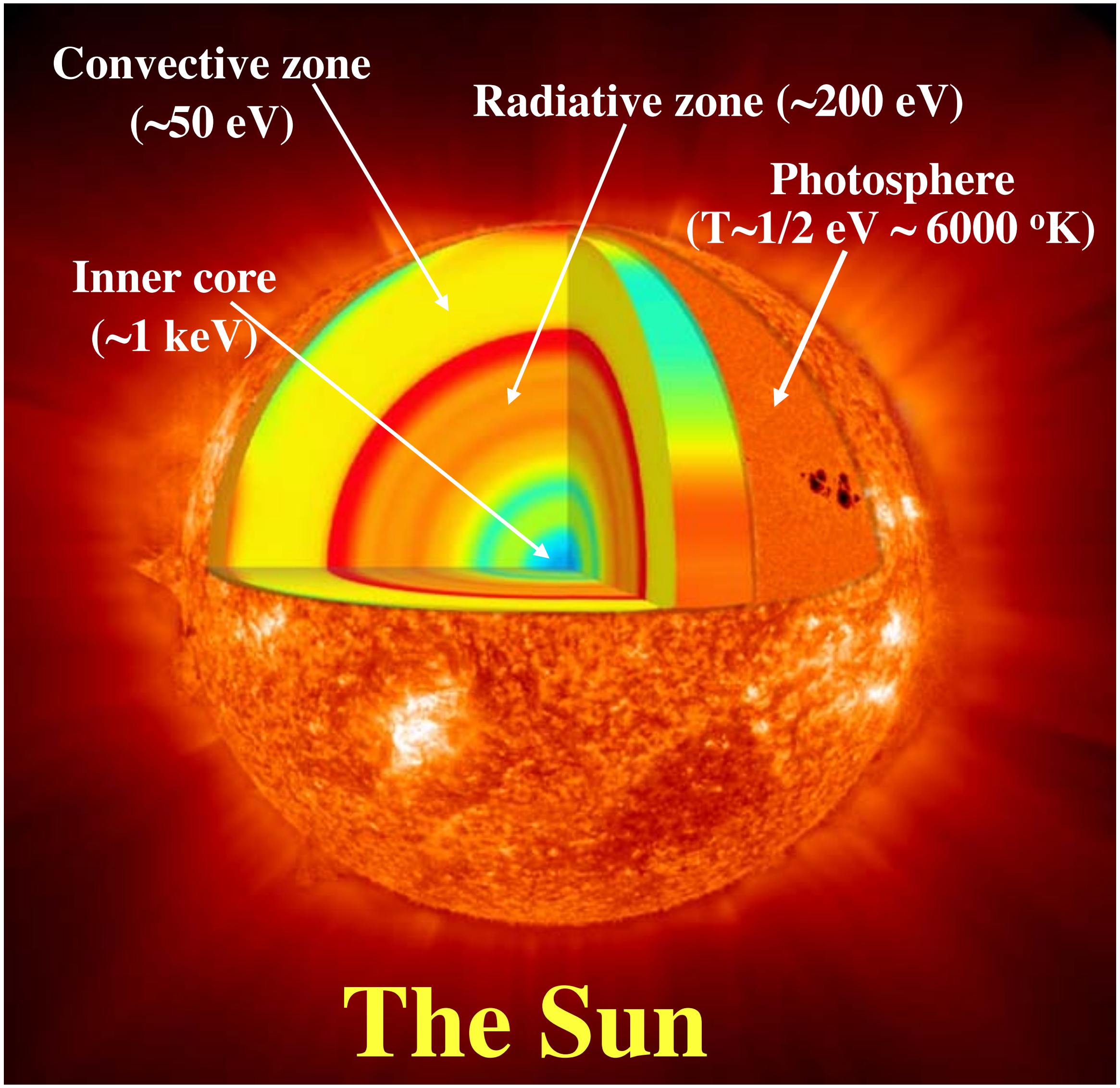
A uniform photon field supplied by a gold radiation cavity or *Hohlraum* ensures good drive planarity





Typical T_{rad} of 200 eV will generate pressures of about 40 Mbar

How hot is 200 eV?



- 200 eV = 2 million degrees
- 200 eV = 400 x temperature at the surface of sun
- 200 eV = the temperature about half way to the center of the sun, in the radiative zone

1 Mbar = 100 GPa = 0.1 TPa

Using the NIF we will explore Extreme Compression Science

We want to measure:

Stress-Density

Temperature

Melting

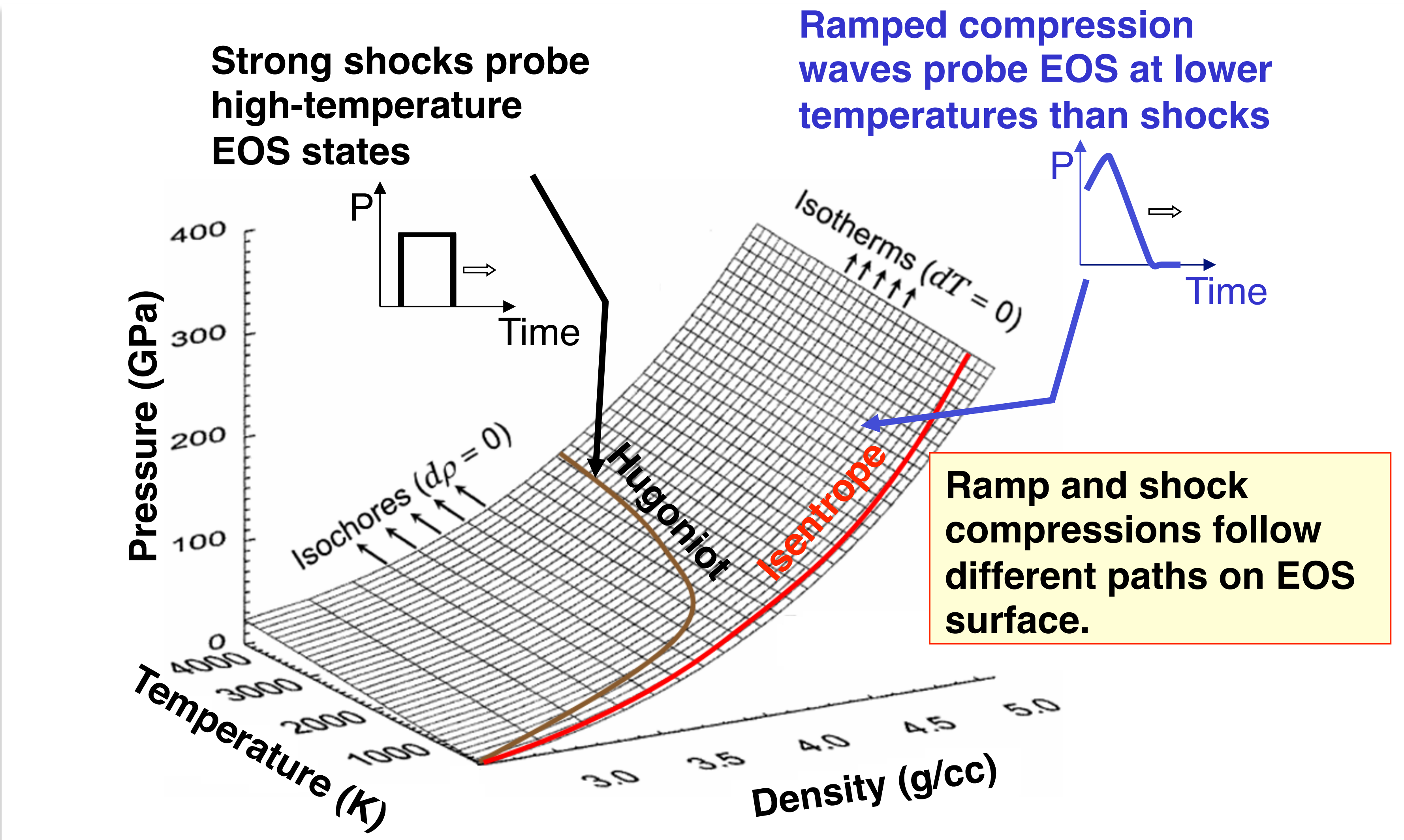
Solid-Solid Phase Transitions

Structure

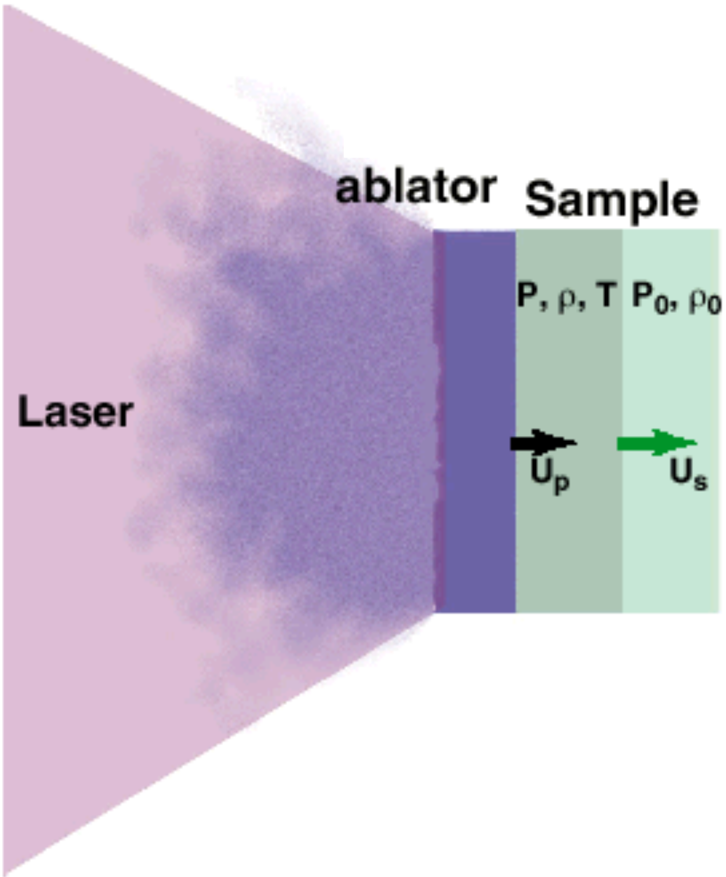
Texture

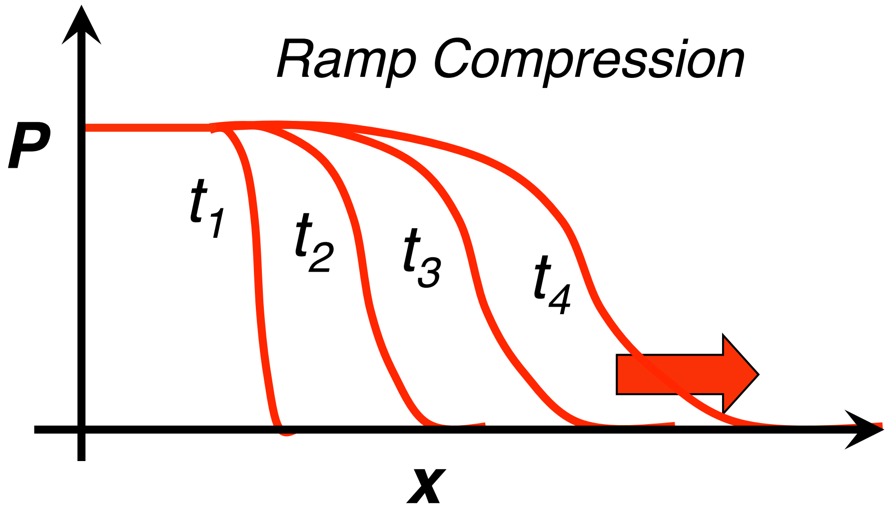
Strength

Equilibrium thermodynamics is described by an equation-of-state (EOS) surface



Ramp compression by variable drive intensity

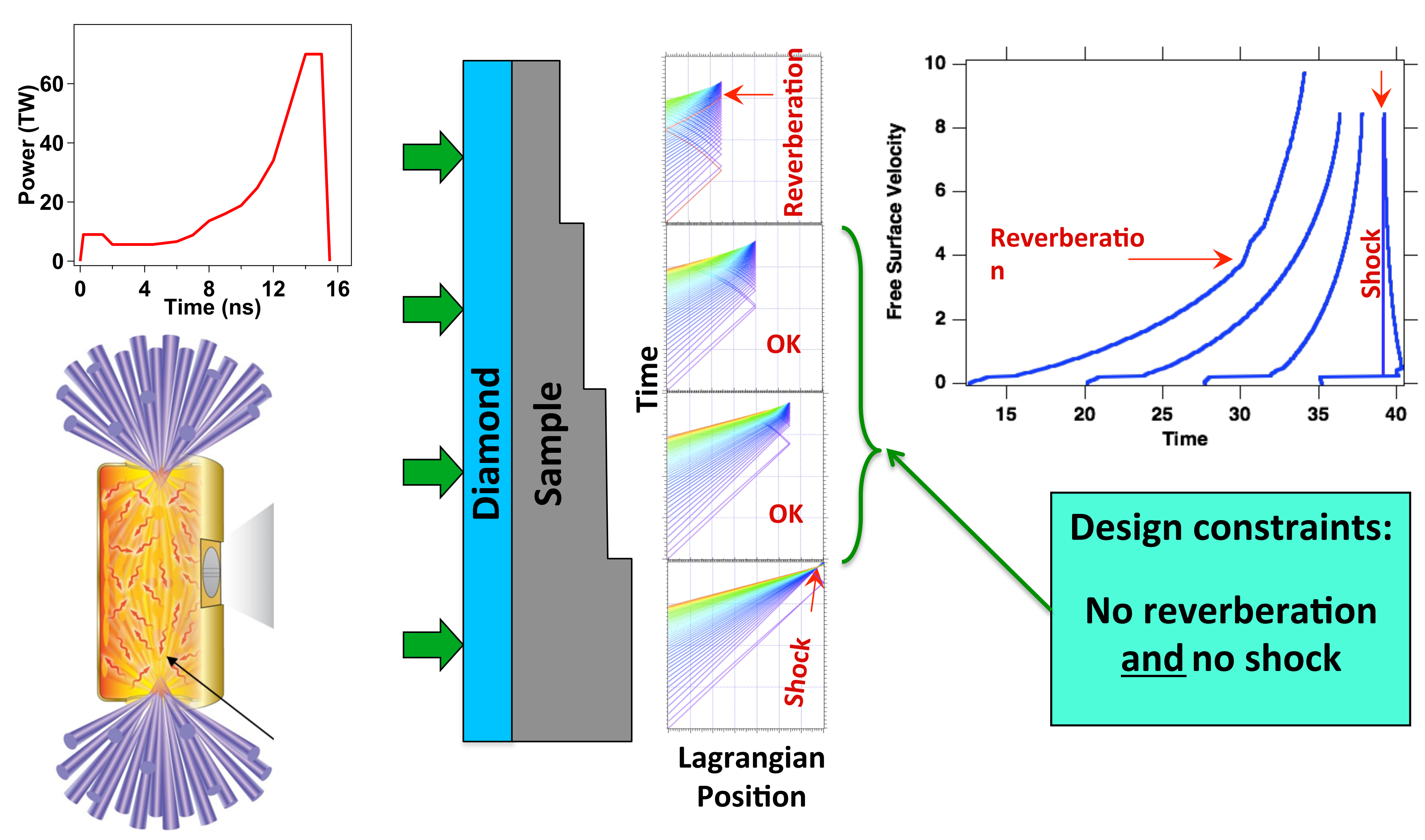




Ramp Compression -> Lower Temperature

1 Mbar = 100 GPa = 0.1 TPa

Ramp loading, EOS (stress-density) determined from free-surface velocity measurements

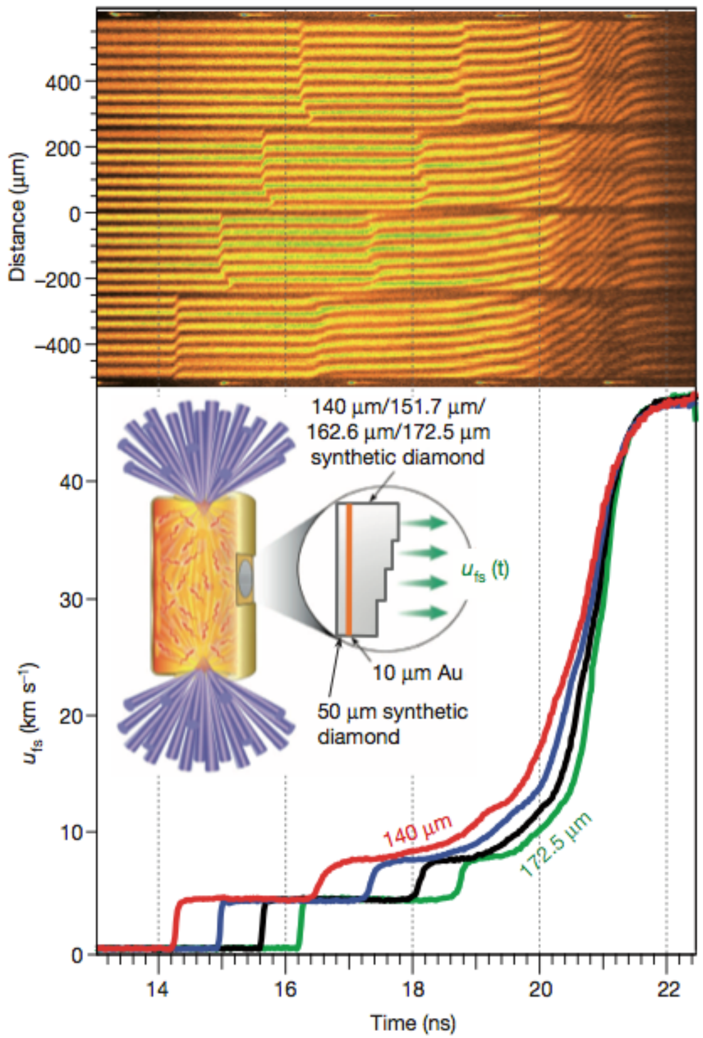


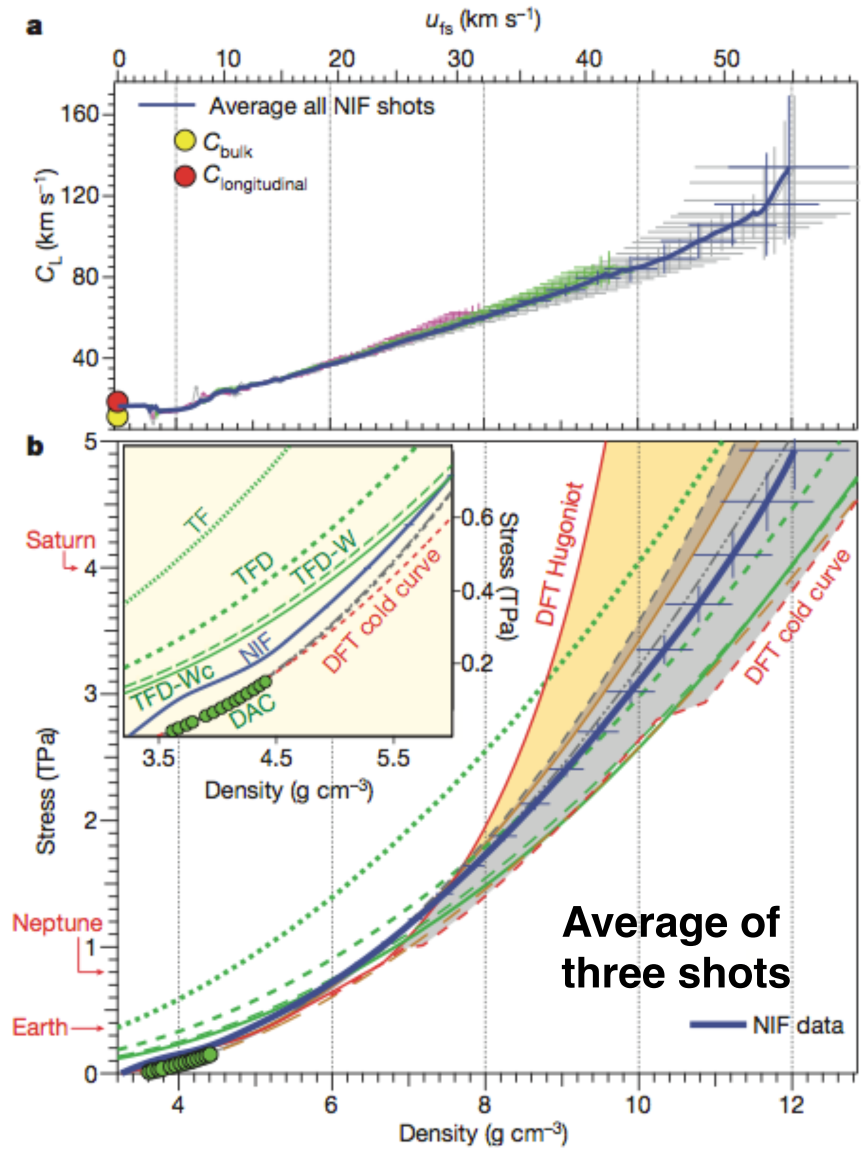
Design constraints:

No reverberation <u>and</u> no shock

1 Mbar = 100 GPa = 0.1 TPa

Ramp-compression EOS of nano-crystalline diamond to 50 Mbar.

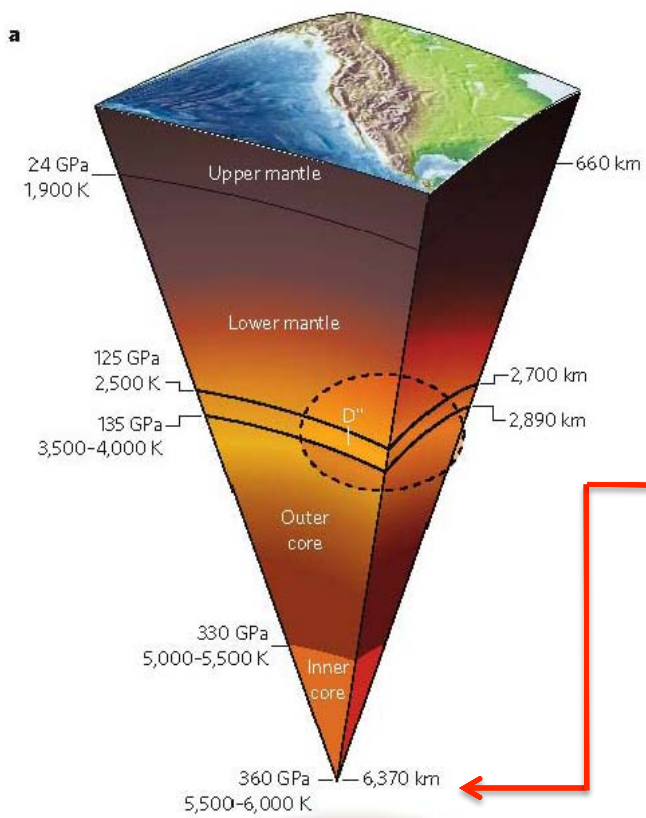




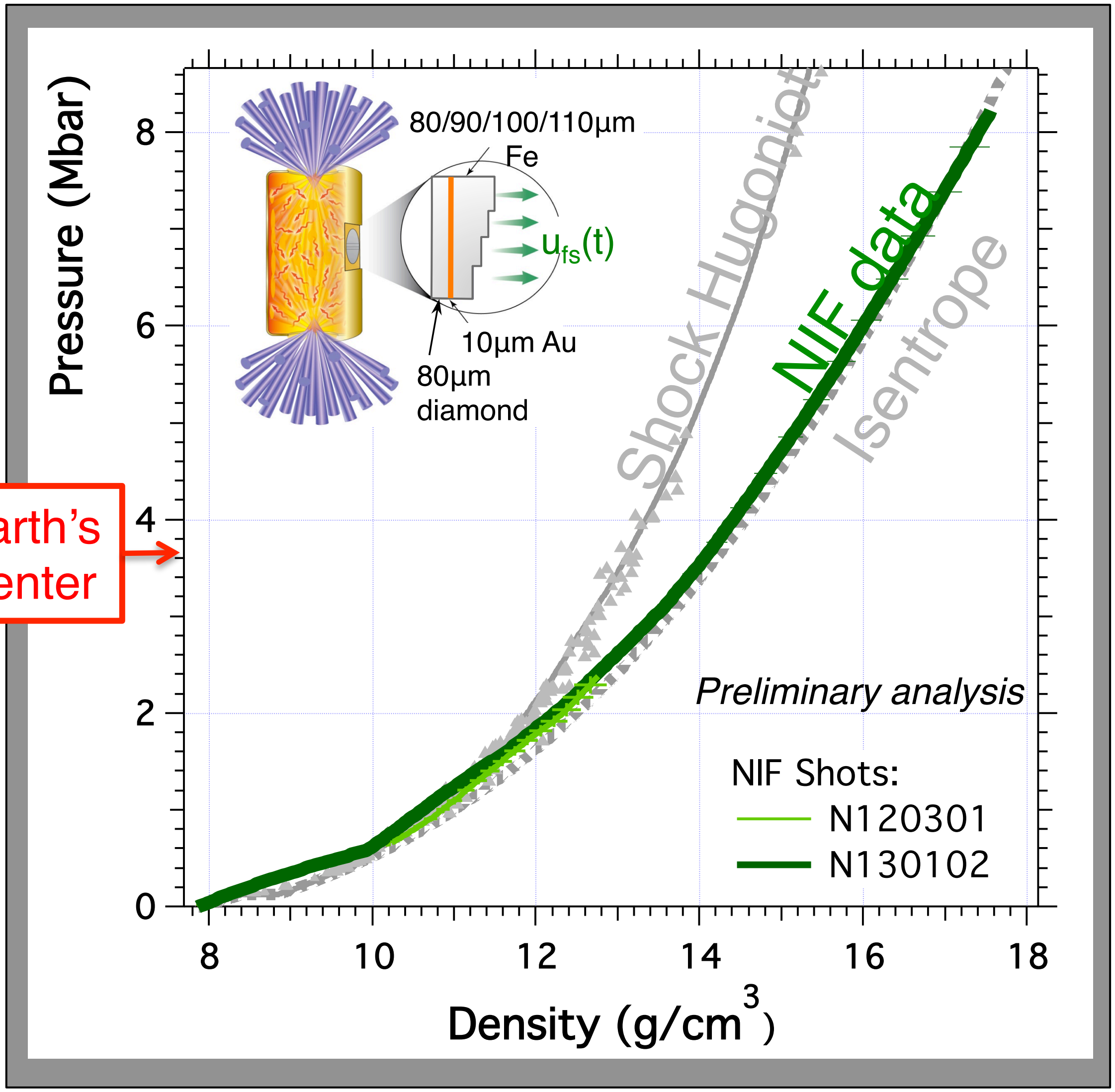
(Smith, et al., Nature, 2014)

1 Mbar = 100 GPa = 0.1 TPa

Recent shots on NIF have measured the equation of state of Fe at 8 Mbar, >2x pressure of Earth's core



Earth's Center



But, we wanted to measure…

Stress-Density

Temperature

Melting

Solid-Solid Phase Transitions

Structure

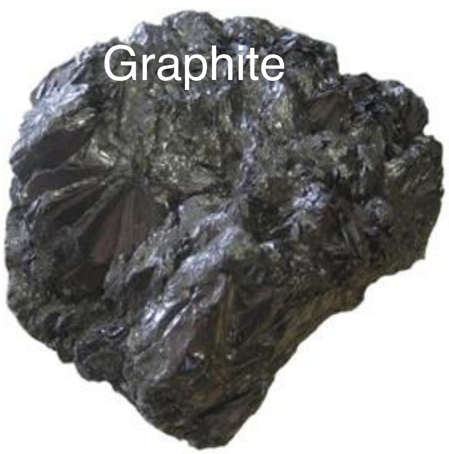
Texture

Strength

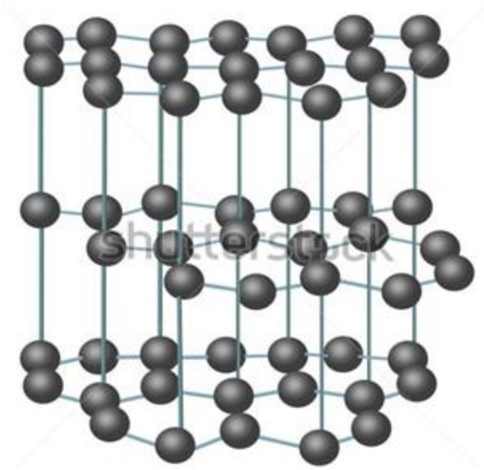
So we developed an X-ray diffraction platform for Omega and NIF

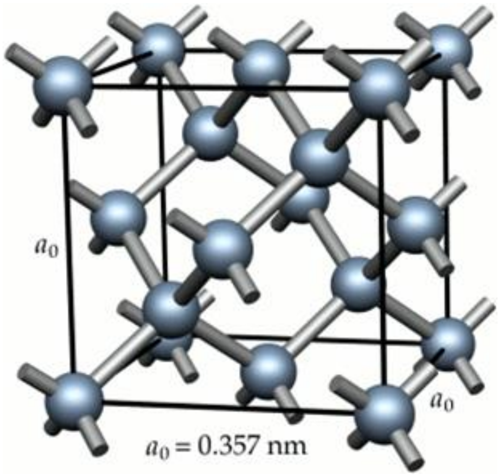
1 Mbar = 100 GPa = 0.1 TPa

Thermo-mechanical properties can vary significantly between structures



Atomic Structure





Physical Properties

	Graphite	Diamond
Density (g/cm^3)	2.2	3.51
Bulk Modulus (GPa)	34	440
Coefficient of Thermal Expansion (K^{-1})	7.8×10^{-6}	1.1×10^{-6}
Strength (GPa)	< 0.2	>110

Structure difference leads to:

1.6x difference in density

10x difference in compressibility

500x difference in strength

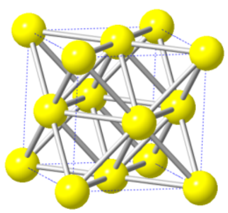
1 Mbar = 100 GPa = 0.1 TPa

Surprising phases have been discovered at high compression

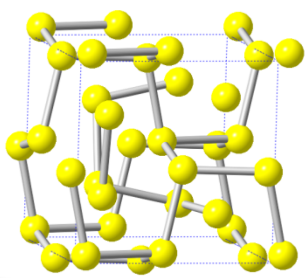
Traditional view that *all* materials become simple at high pressure is incorrect!

". . . what the present results most assuredly demonstrate is the importance of pressure in revealing the limitations of previously hallowed models of solids"
–Neil Ashcroft (2009).

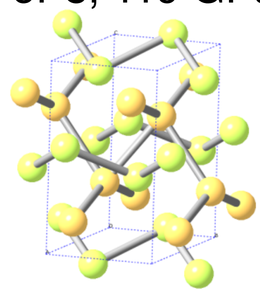
FCC, 65 GPa



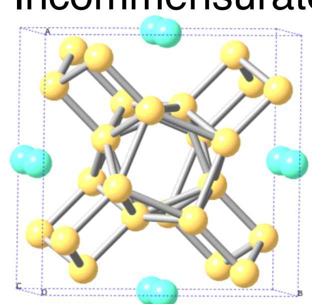
cI16, 108 GPa



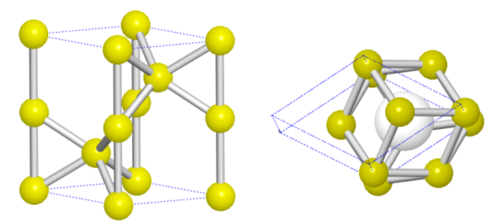
oP8, 119 GPa



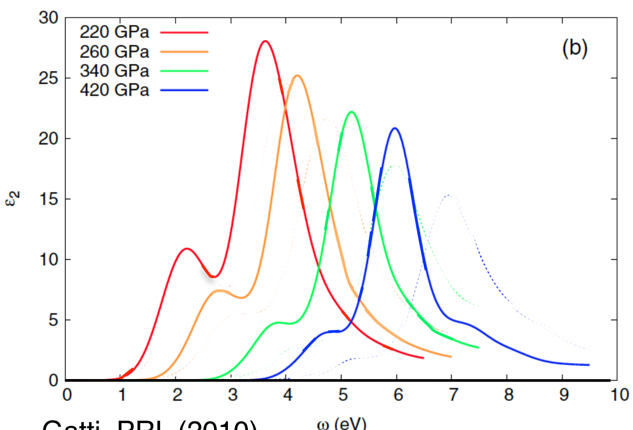
tI19, 147 GPa
Incommensurate



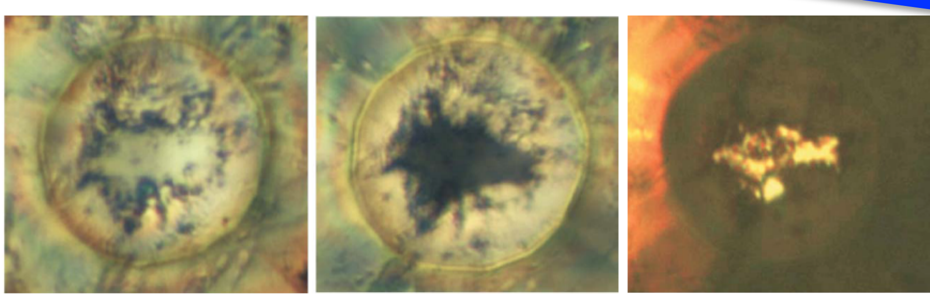
hP4, 190 GPa
Insulating, Transparent
Electride



Increasing Structural Complexity



Gatti, PRL (2010)



120 GPa 156 GPa 199 GPa

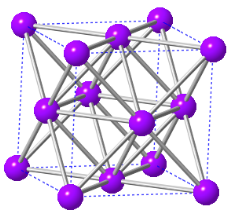
Ma, Nature (2009)

1 Mbar = 100 GPa = 0.1 TPa

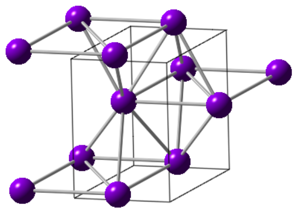
High pressure phases of aluminum are also predicted to be complex

Pickard and Needs, Nature Materials (2010).

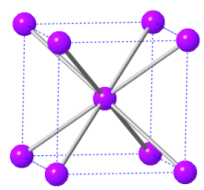
FCC



HCP
2.17 Mbar

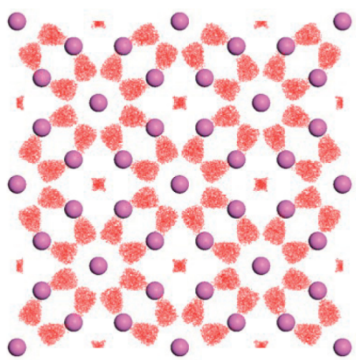


BCC
3.8 Mbar



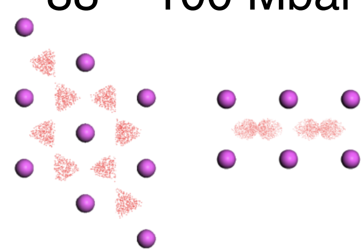
ΔV~2.8%

Host-Guest structure of Ba-IVa (Incommensurate Electride)
32-88 Mbar

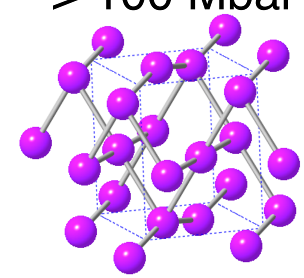


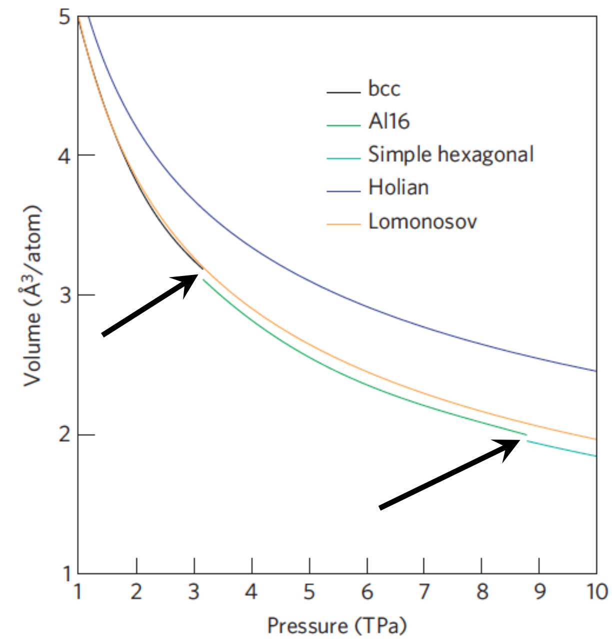
ΔV~1.8%

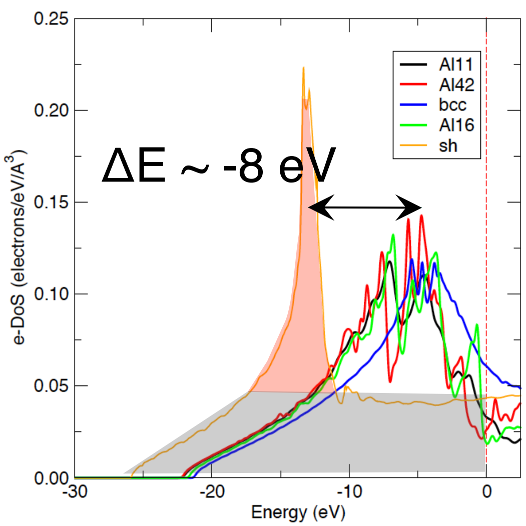
Simple Hexagonal Electride
88 – 100 Mbar



CMMA Electride
> 100 Mbar

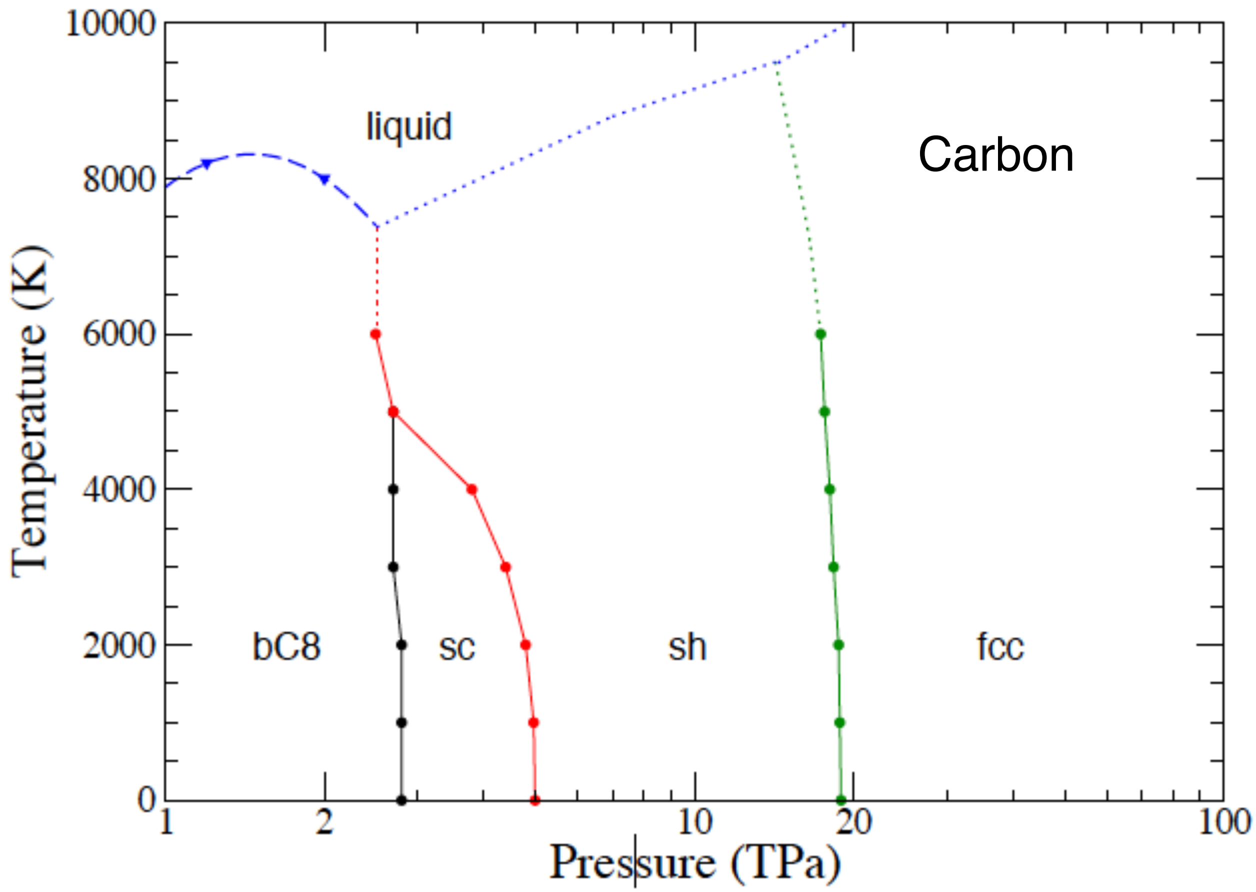




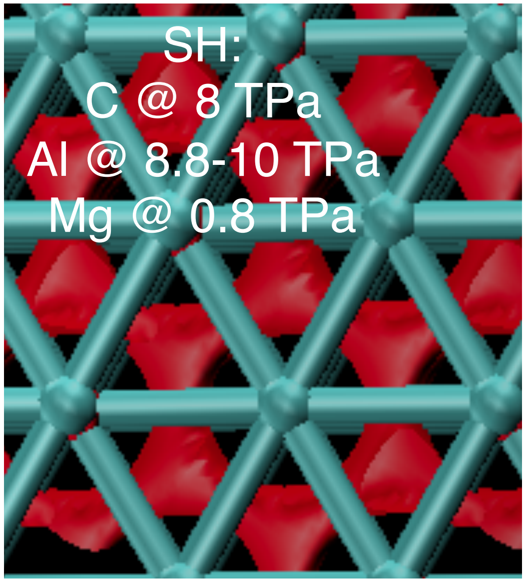


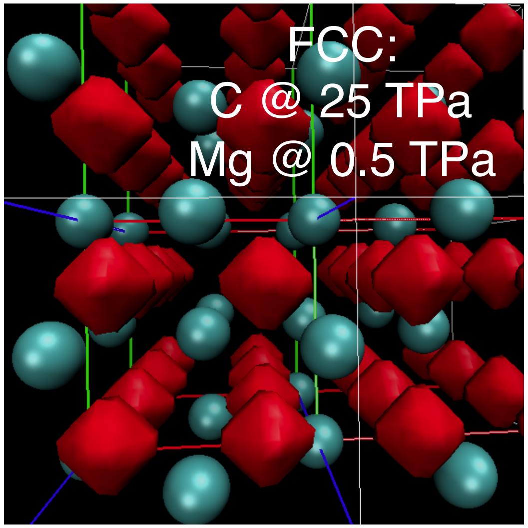
"All structures near 300 Mbar are far from close packed"

At even higher pressures carbon is also predicted to adopt electride phases.



Canales, Pickard, Needs, Phys. Rev. Lett. 108, 045704 (2012)



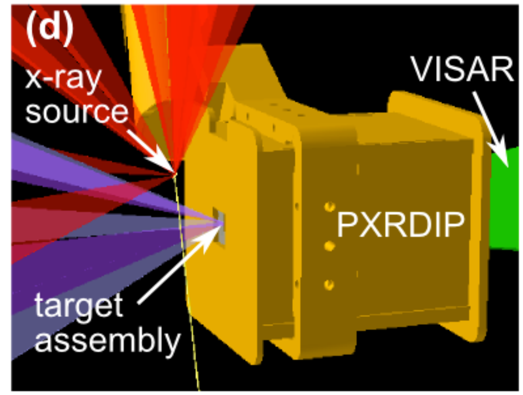


1 Mbar = 100 GPa = 0.1 TPa

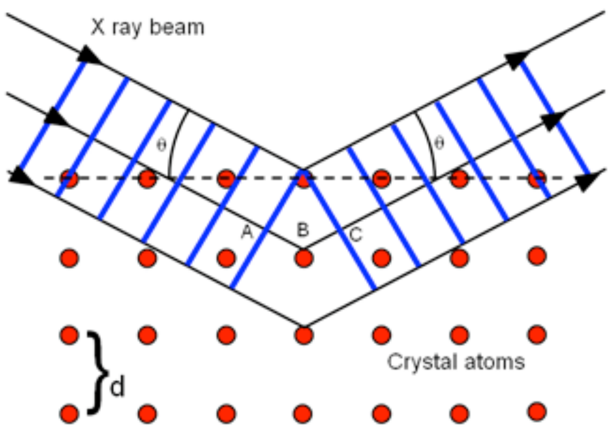
In situ diffraction gives critical data:

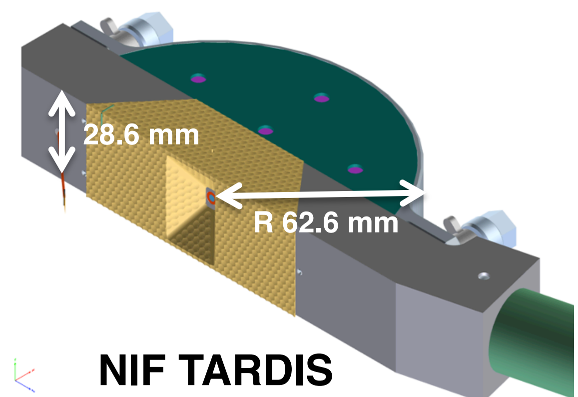
- -Crystal structure / phase diagram
- -EOS
- -Phase-transition mechanisms
- -Deformation texture / microstructure
- -Potential to determine liquid structure

➢ **Target and diagnostics are simple**
➢ **We have done 22 NIF TARDIS shots**



Demonstrated at Omega, PXRDIP
(Powder X-Ray Diffraction Image Plates)



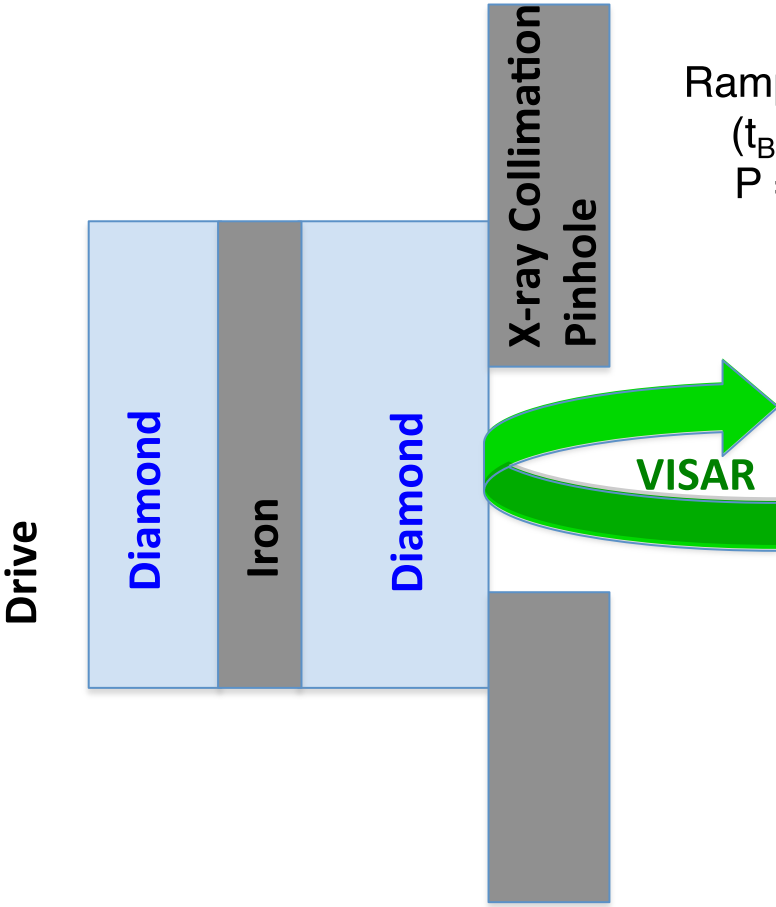


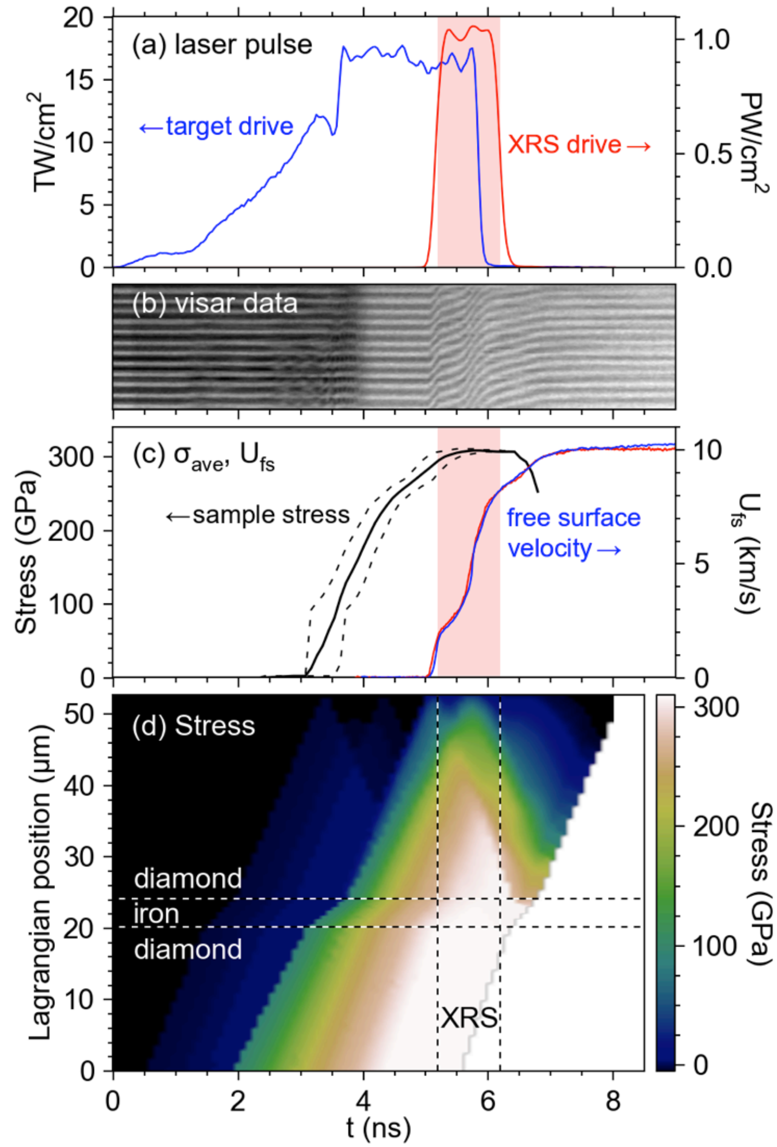
NIF TARDIS
(TARget Diffraction In Situ)

1 Mbar = 100 GPa = 0.1 TPa

We use diamond-sandwich targets to obtain uniform stress density conditions after ramp compression

Ramp drive: 197J
(t_{BL} = 5.0 ns)
P = 3.2Mbar

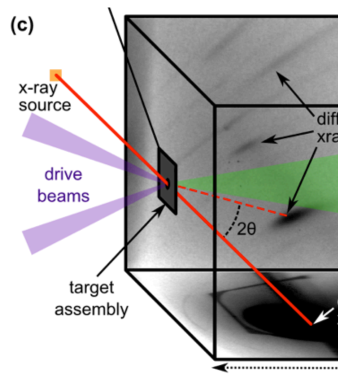


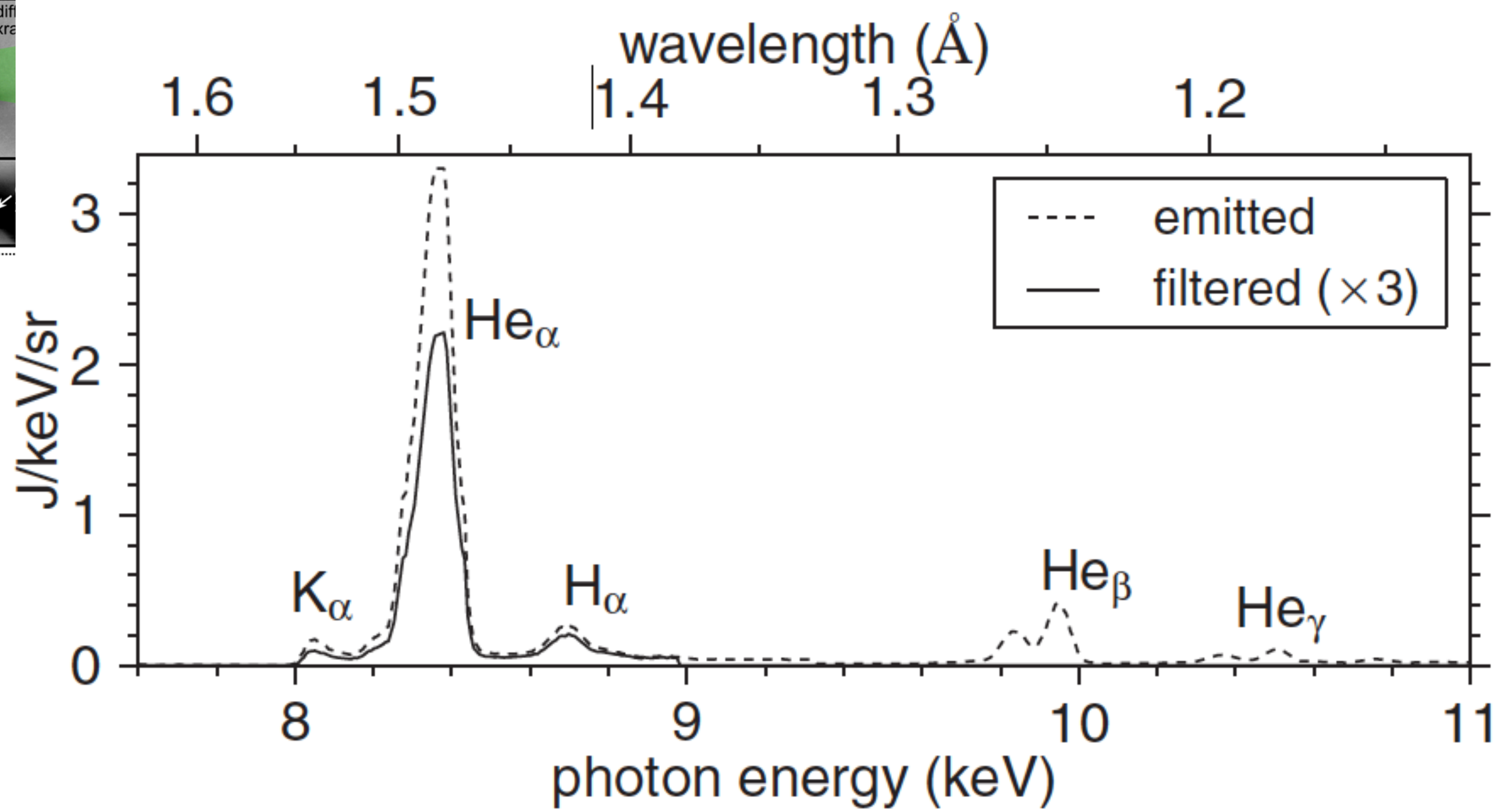


We determine stress by backward propagation of the diamond free-surface velocity, assuming that we know the EOS of diamond.

Rygg, et al., RSI, **83,** 113904 (2012)

Quasi-monochromatic beam by thermal emission of Cu He-α line.



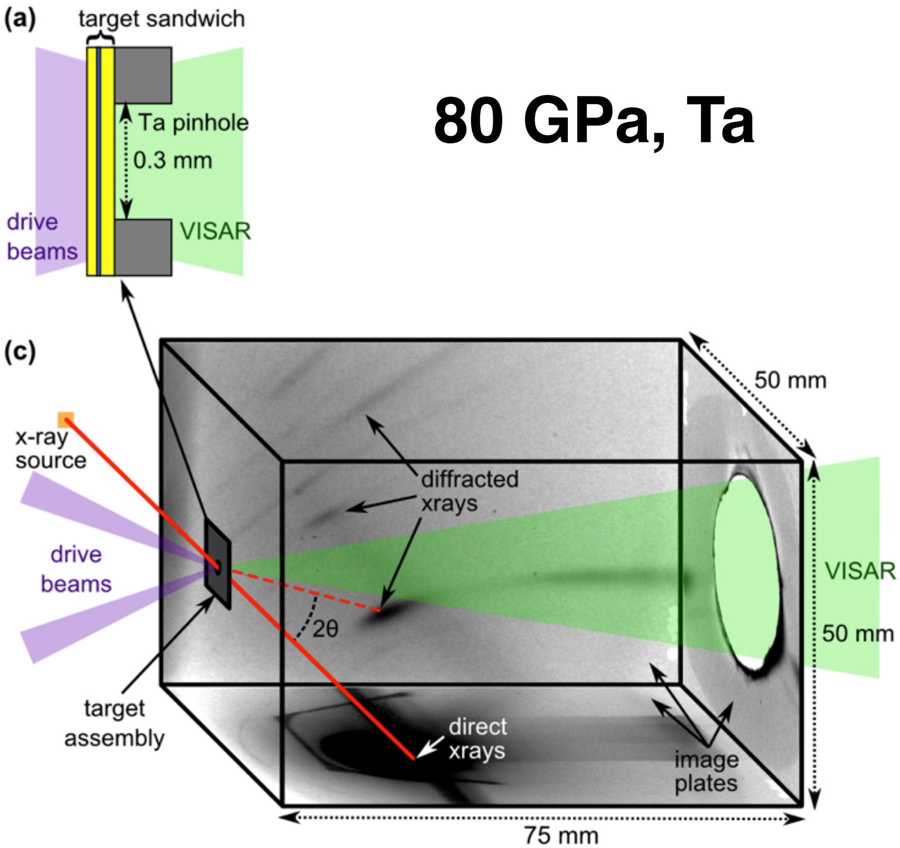


10^{11} - 10^{12} photons incident on sample
3.5% bandwidth

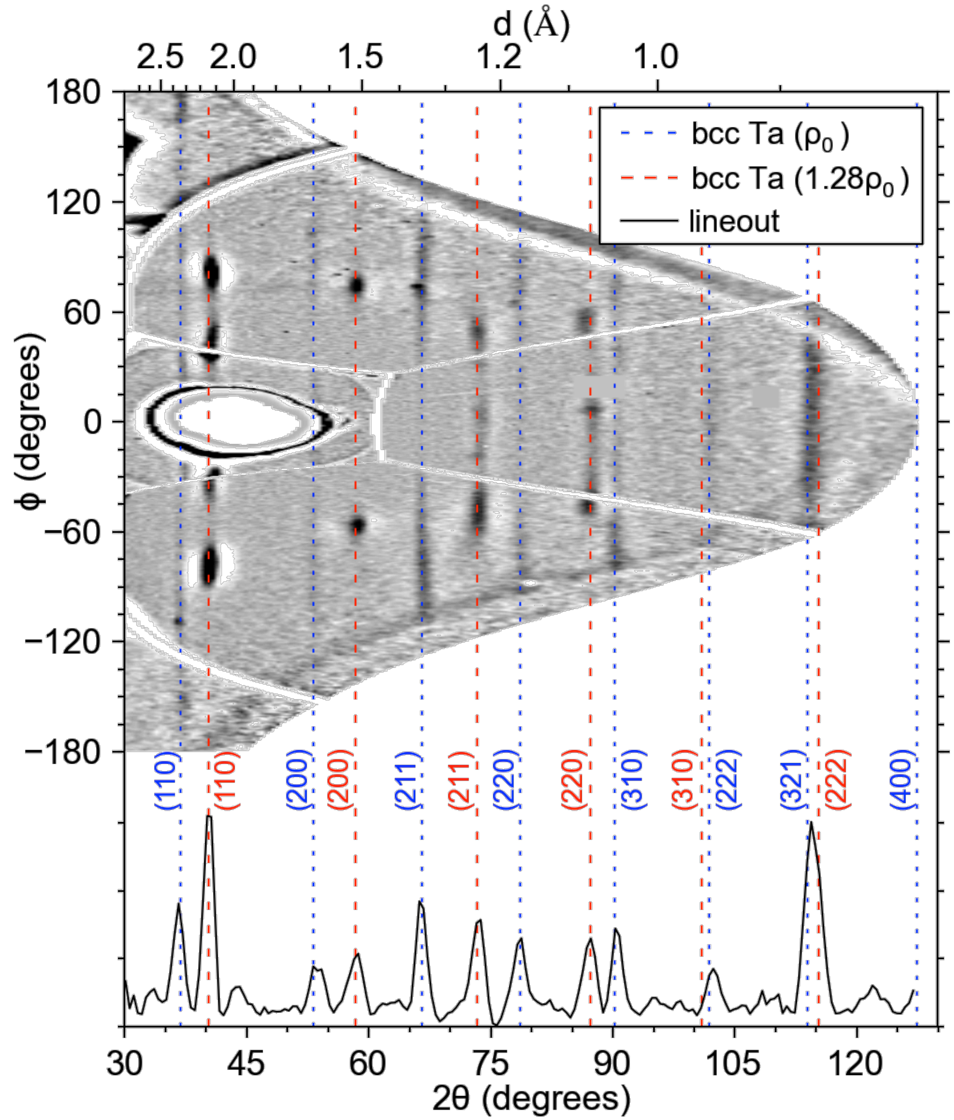
1 Mbar = 100 GPa = 0.1 TPa

In situ diffraction provides crystal structure. Demonstrated at Omega

80 GPa, Ta

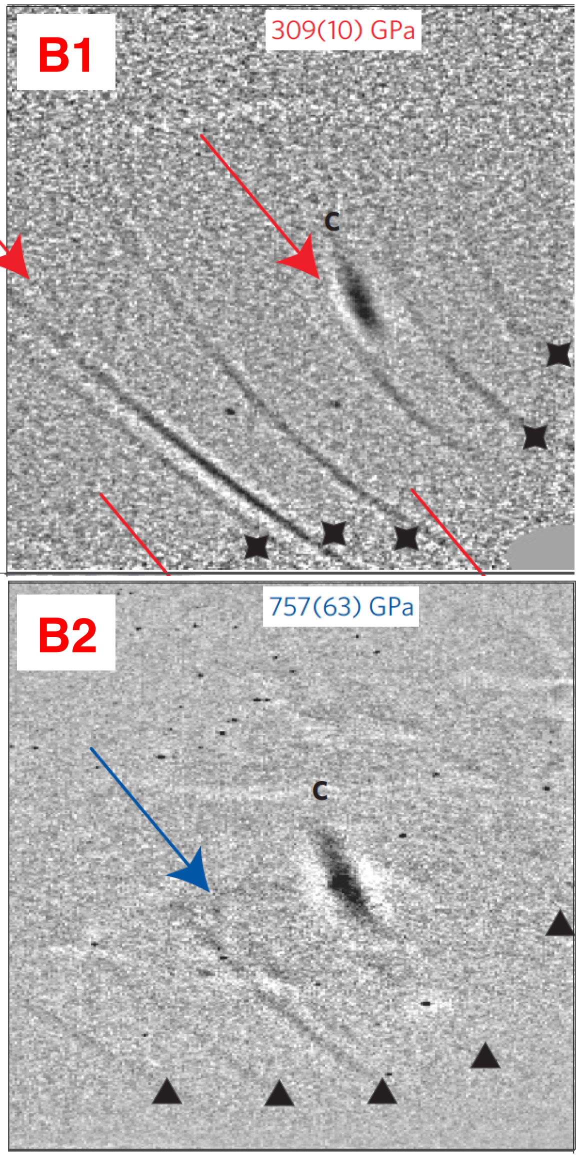


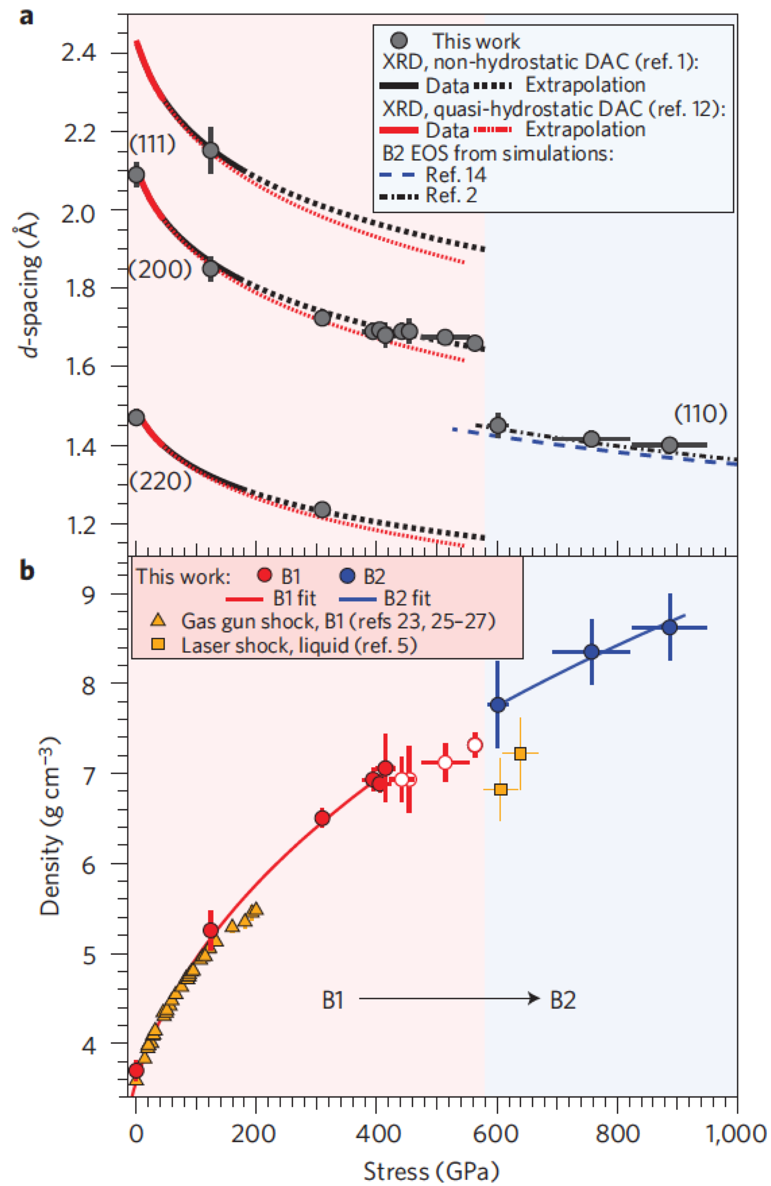
Rygg, et al., RSI, **83,** 113904 (2012)



De-warped image plate data

We observed the B1-B2 phase transition in MgO



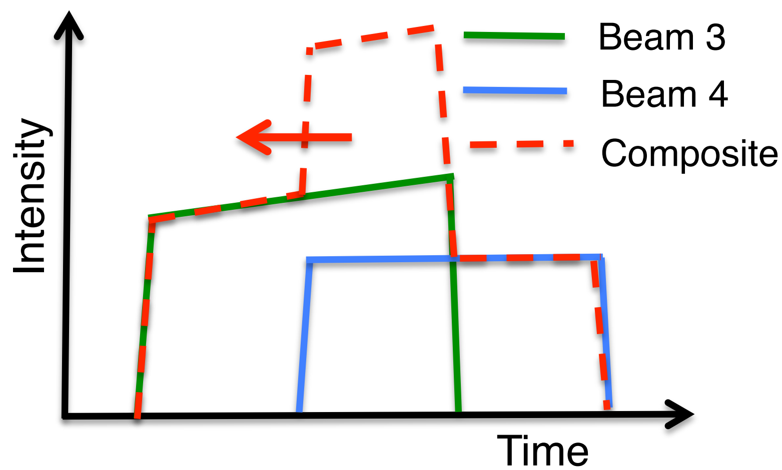


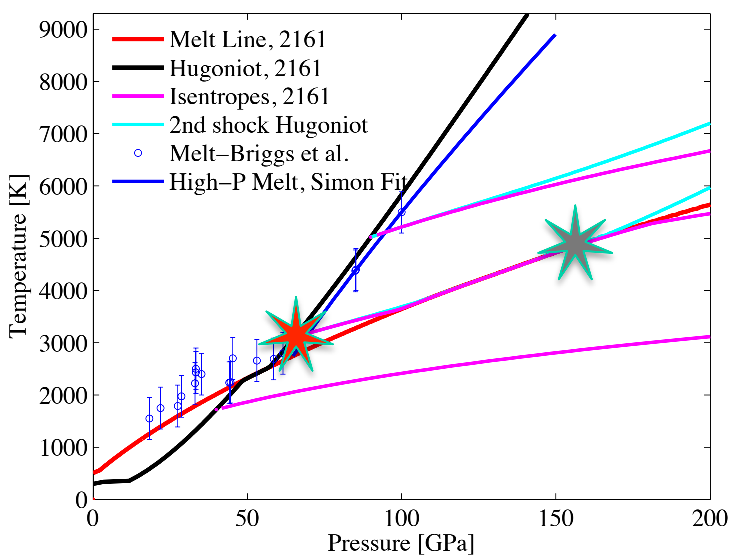
Coppari, et al. Nature Geoscience, 2013

1 Mbar = 100 GPa = 0.1 TPa

We have observed Shock-Melt – Refreeze for first time ever in Sn at Omega

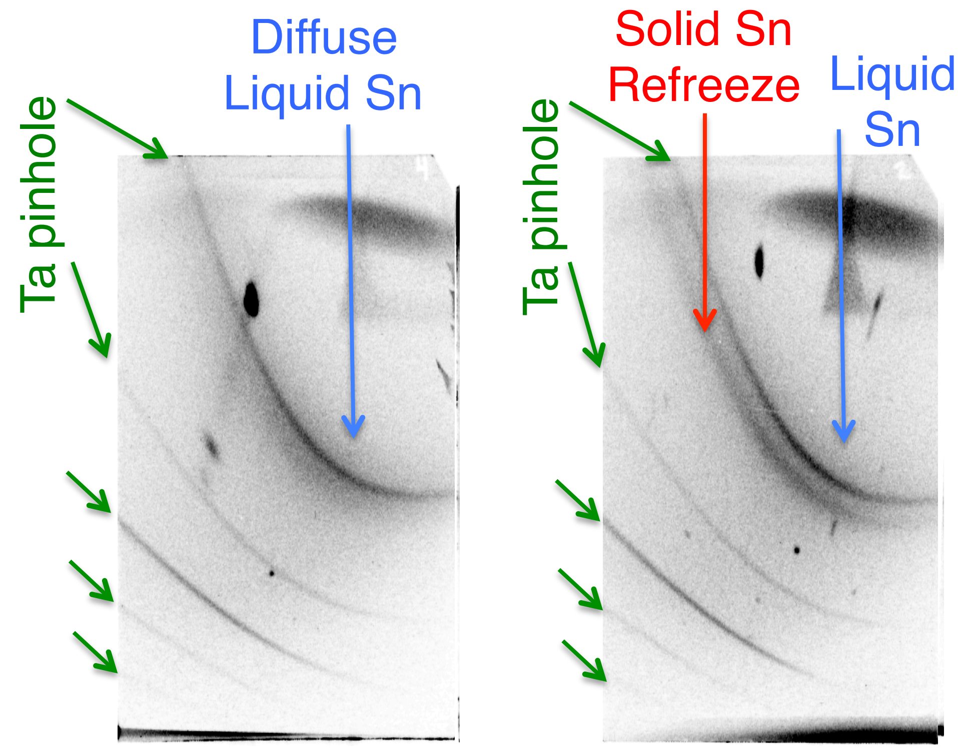
[May 28, 2014]





Shot 18450
Long Delay
=> All Liquid

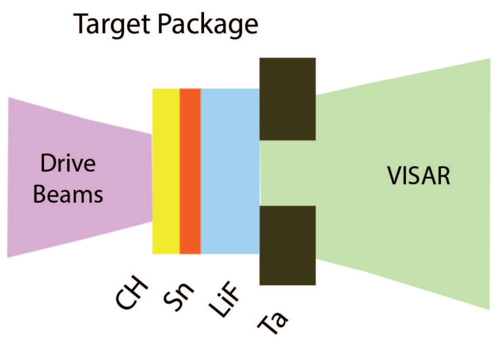
Shot 18452
Reduced Delay
=> Liquid + Refreeze

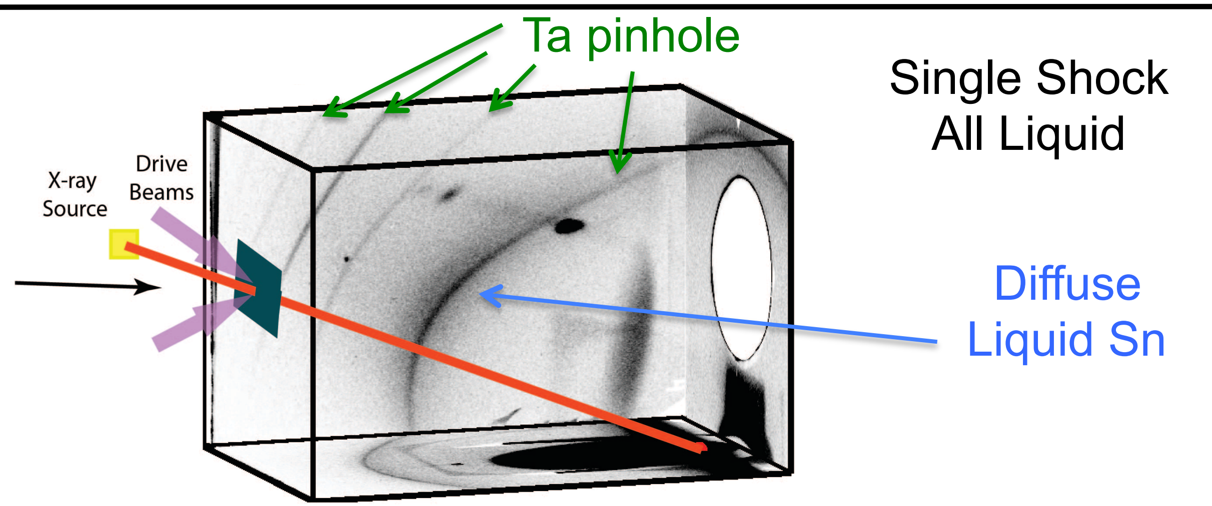


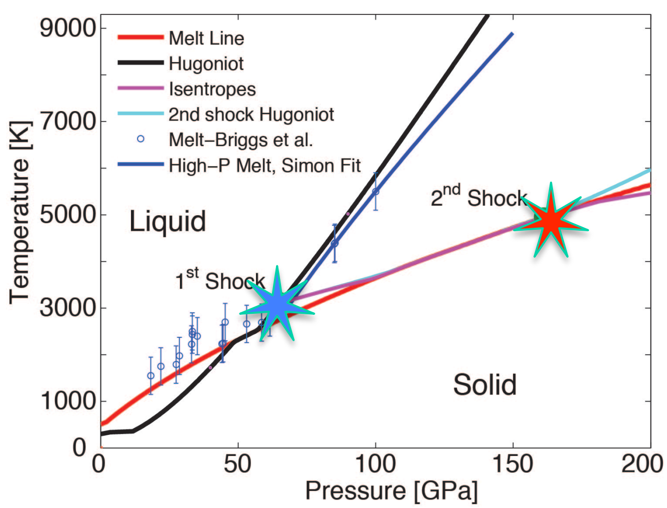
Rick Kraus, Federica Coppari

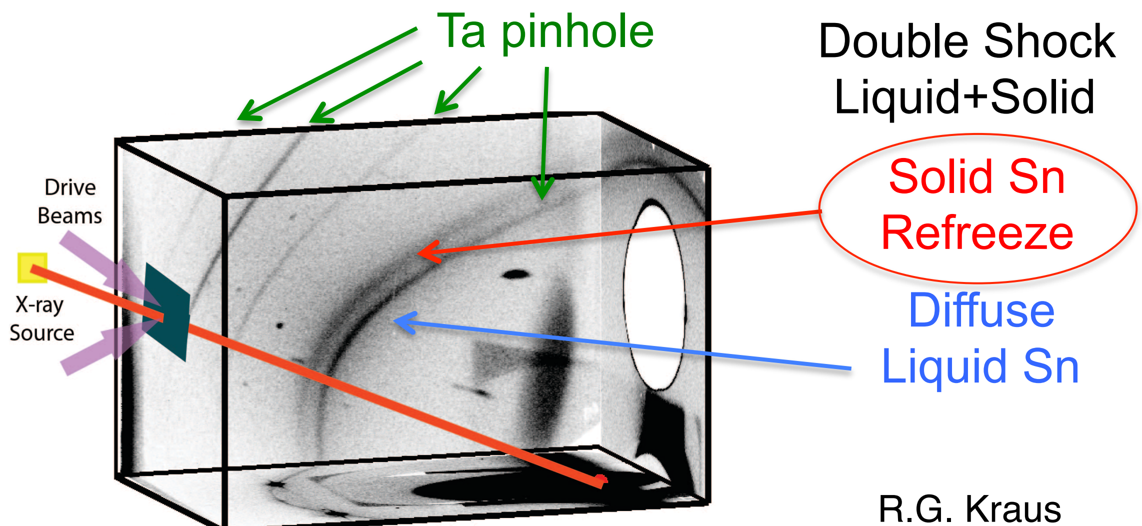
1 Mbar = 100 GPa = 0.1 TPa

Shock-Melt, Refreeze was observed for first time ever in Sn at Omega







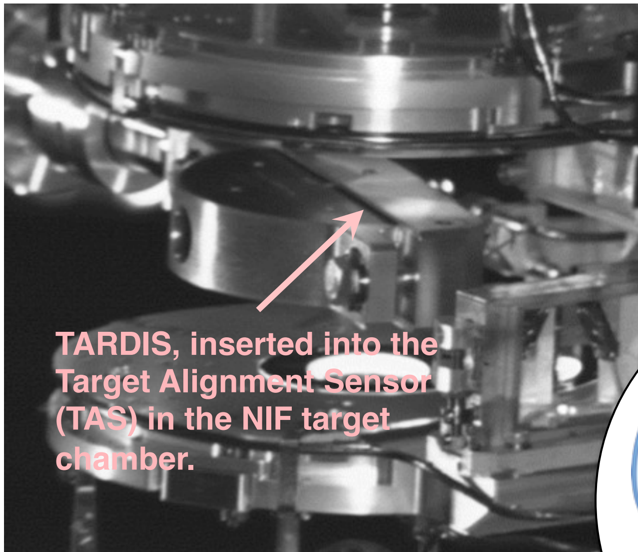


R.G. Kraus

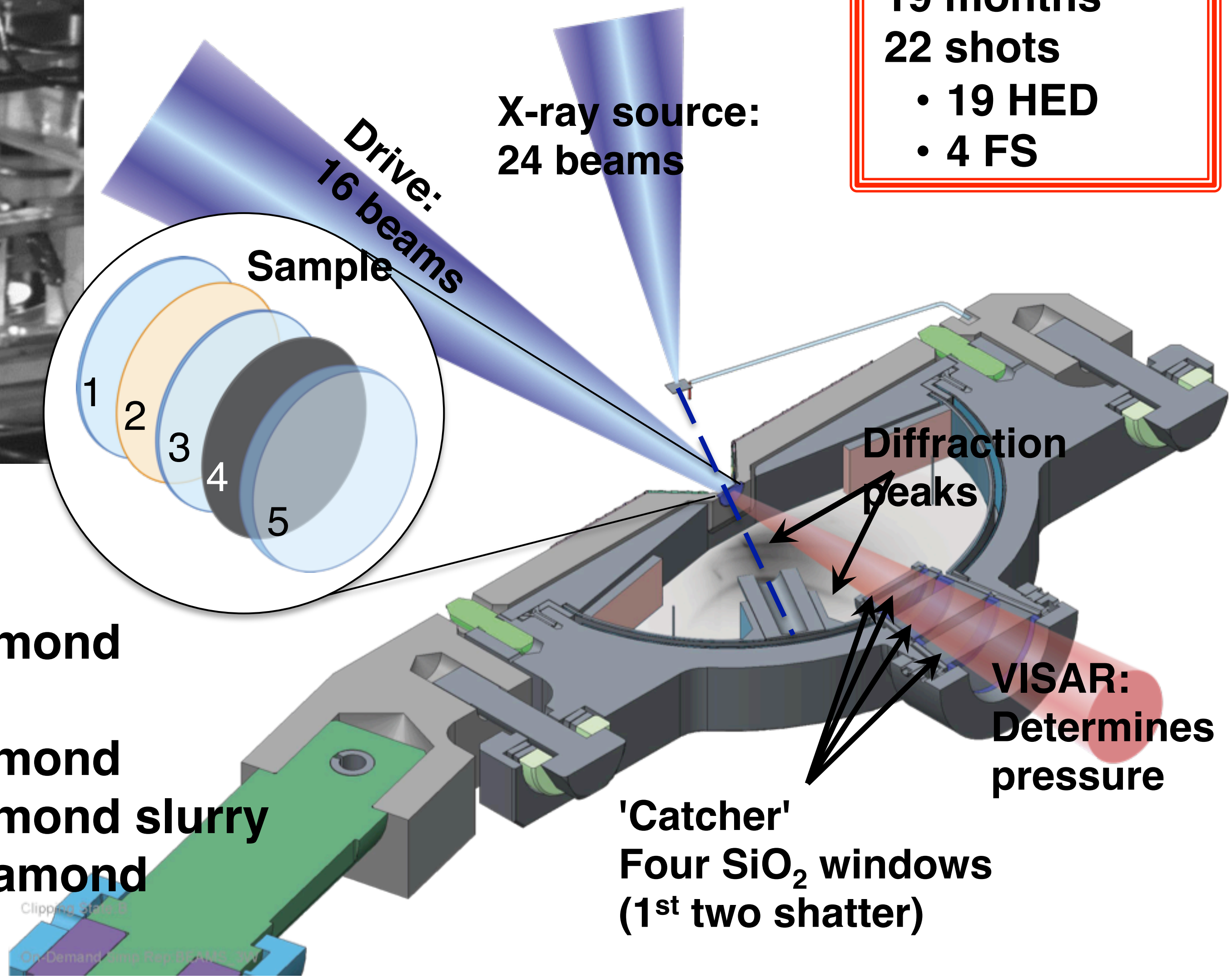
NIF Discovery Science campaign to measure Fe melt line from 5-20 Mbar (~4-20 M_E). Led by R. Hemley and R. Kraus, beginning in Oct.

1 Mbar = 100 GPa = 0.1 TPa

TARDIS: TARget Diffraction In-Situ diagnostic for x-ray diffraction experiments on NIF



19 months
22 shots
- **19 HED**
- **4 FS**

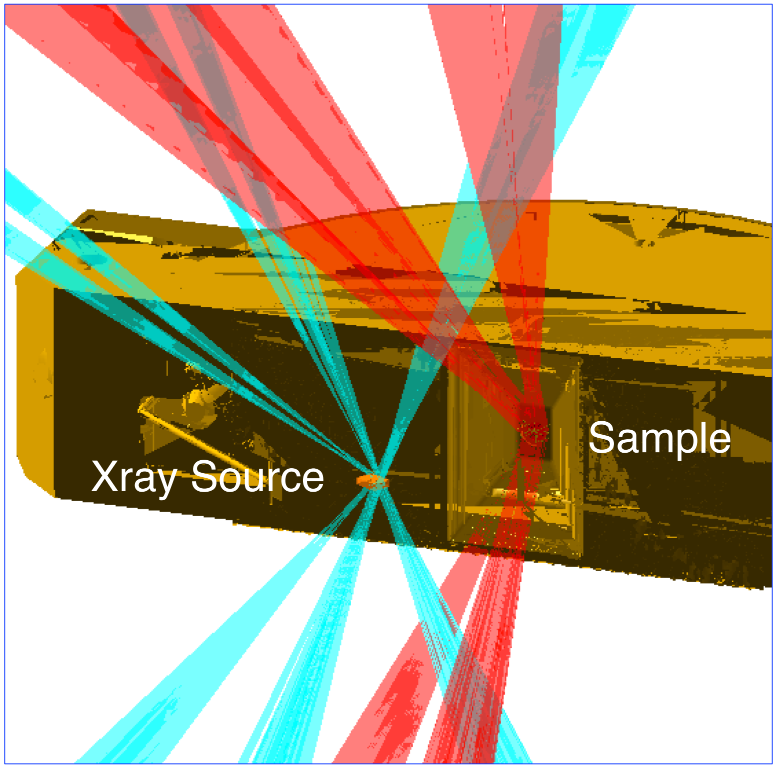


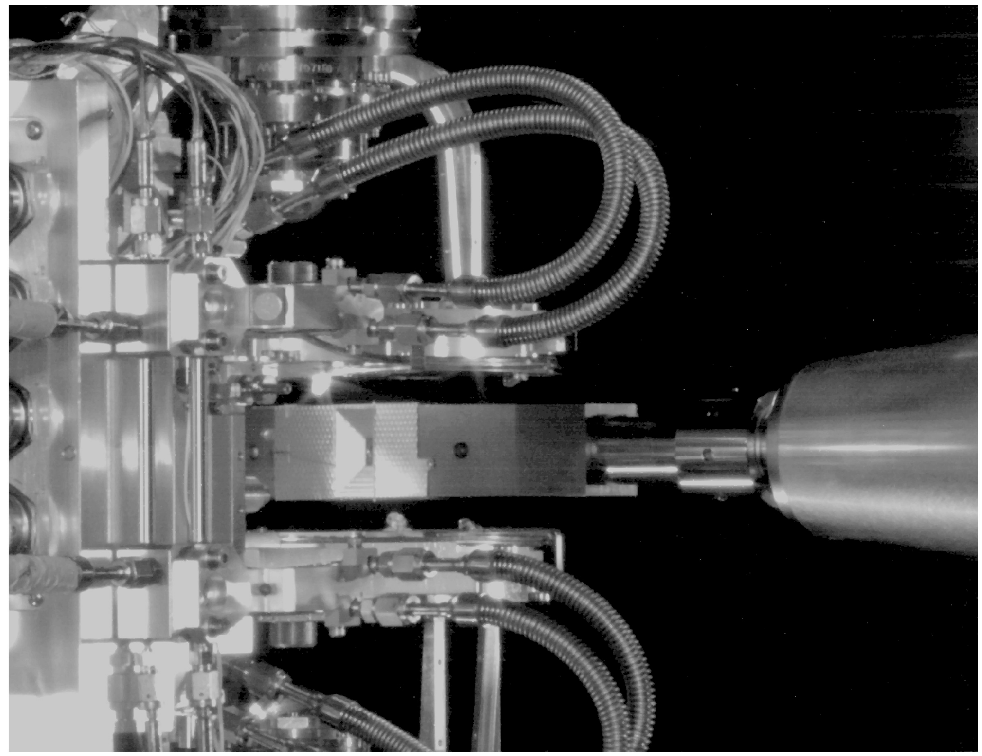
Sample:
1: 40 μm diamond
2: 2 μm gold
3: 40 μm diamond
4: 40 μm diamond slurry
5: 150 μm diamond

1 Mbar = 100 GPa = 0.1 TPa

This year we began angle-dispersive x-ray diffraction on the NIF

TARDIS = TARget Diffraction In Situ

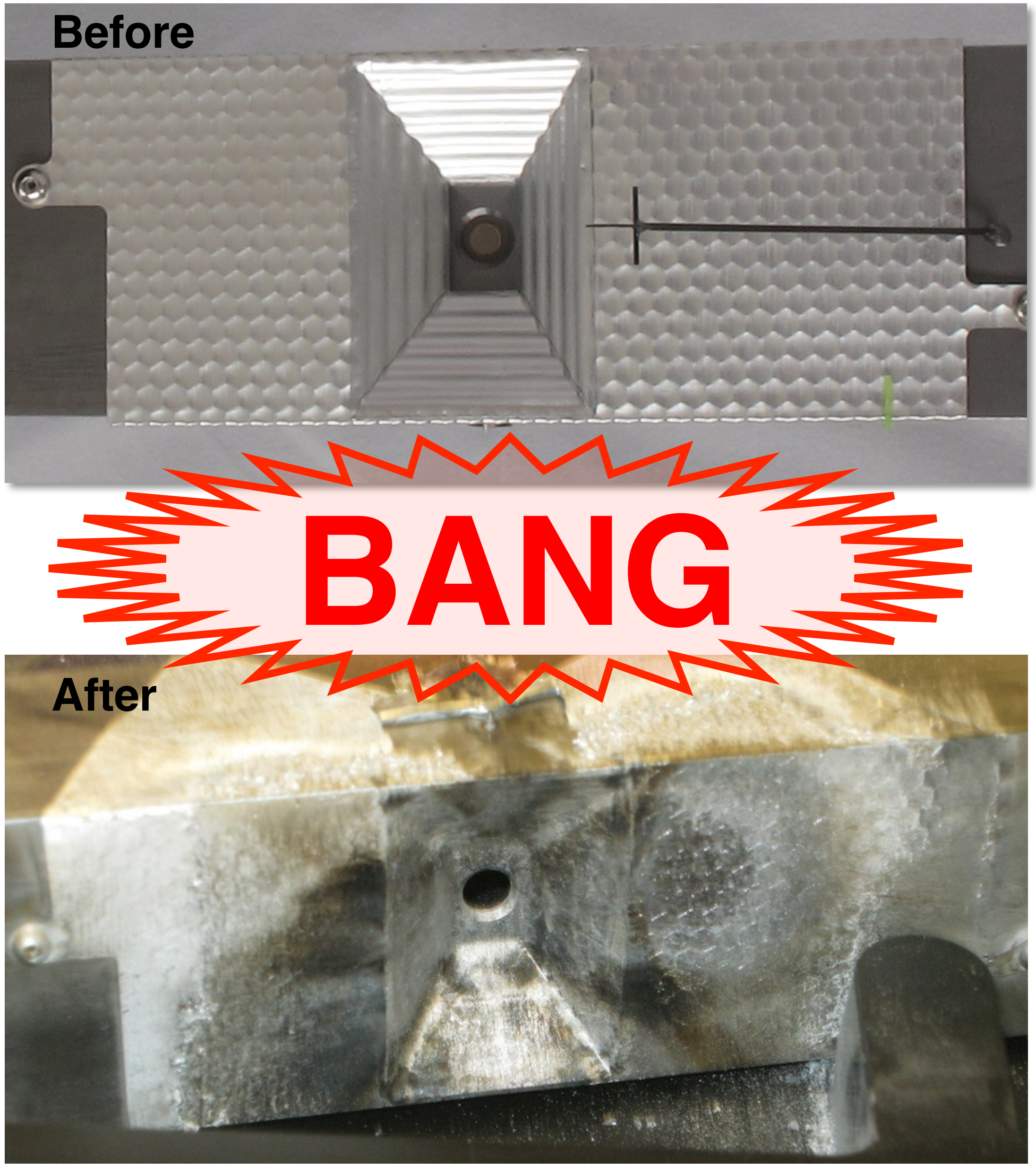




The TARDIS is a modified version of the PXRDIP used on Omega.

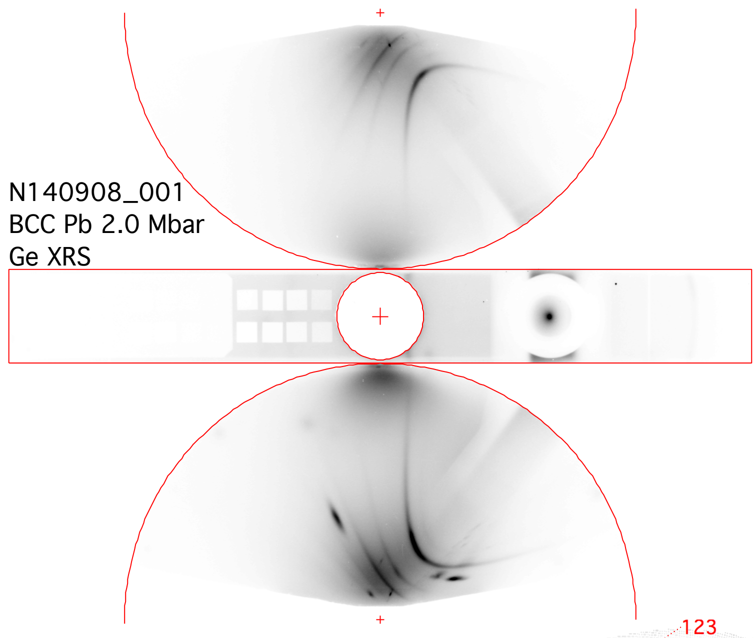
1 Mbar = 100 GPa = 0.1 TPa

Target sustains significant damage, but the support does not

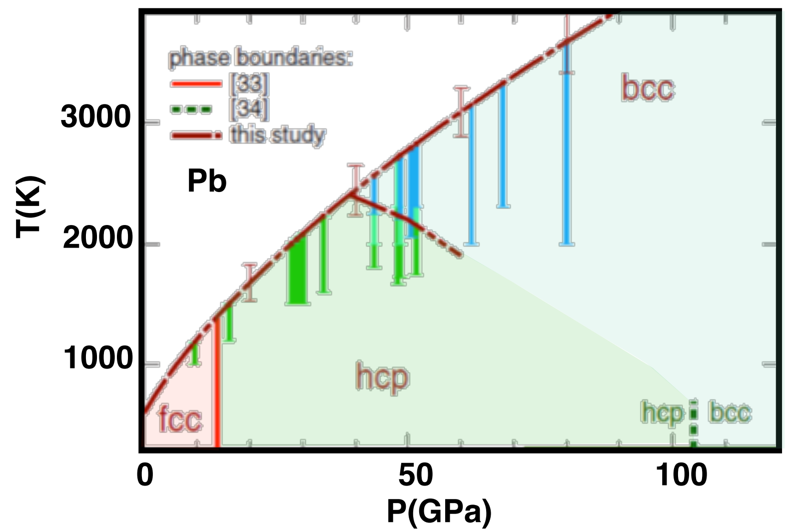


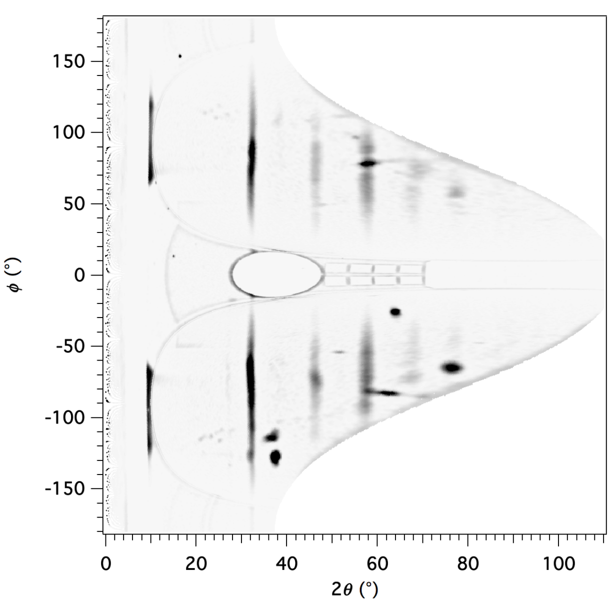
1 Mbar = 100 GPa = 0.1 TPa

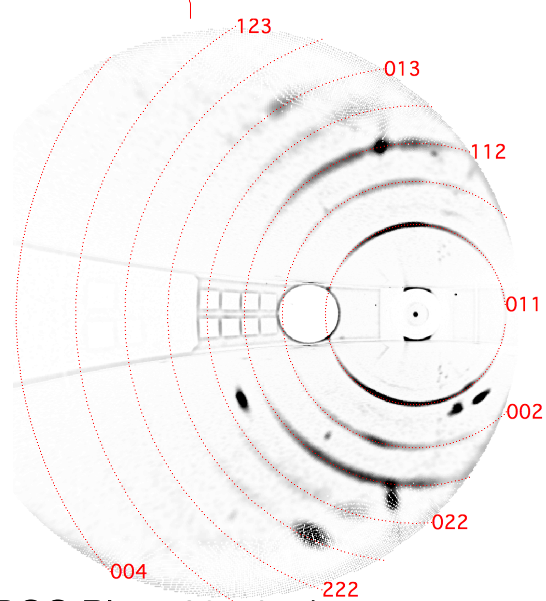
At least 5 BCC diffraction lines for Pb at 2.0 Mbar



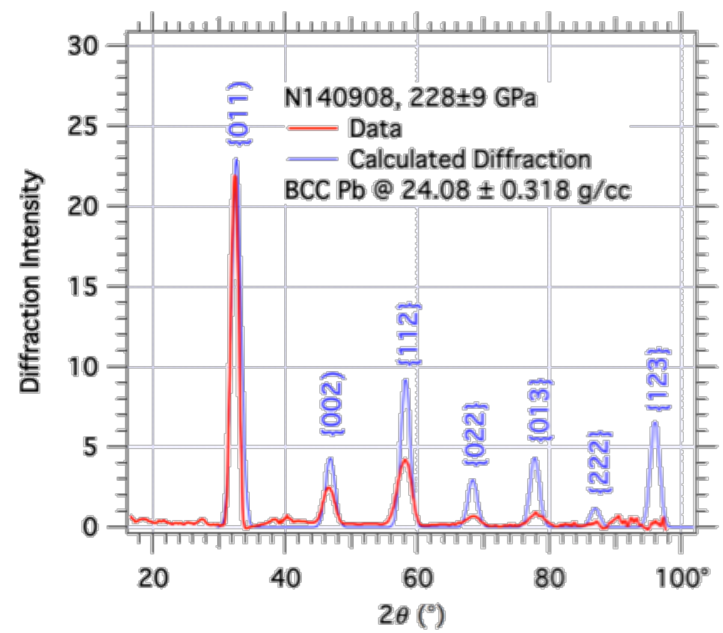
Pb Phase diagram [Dewaele, PRB (2007)]





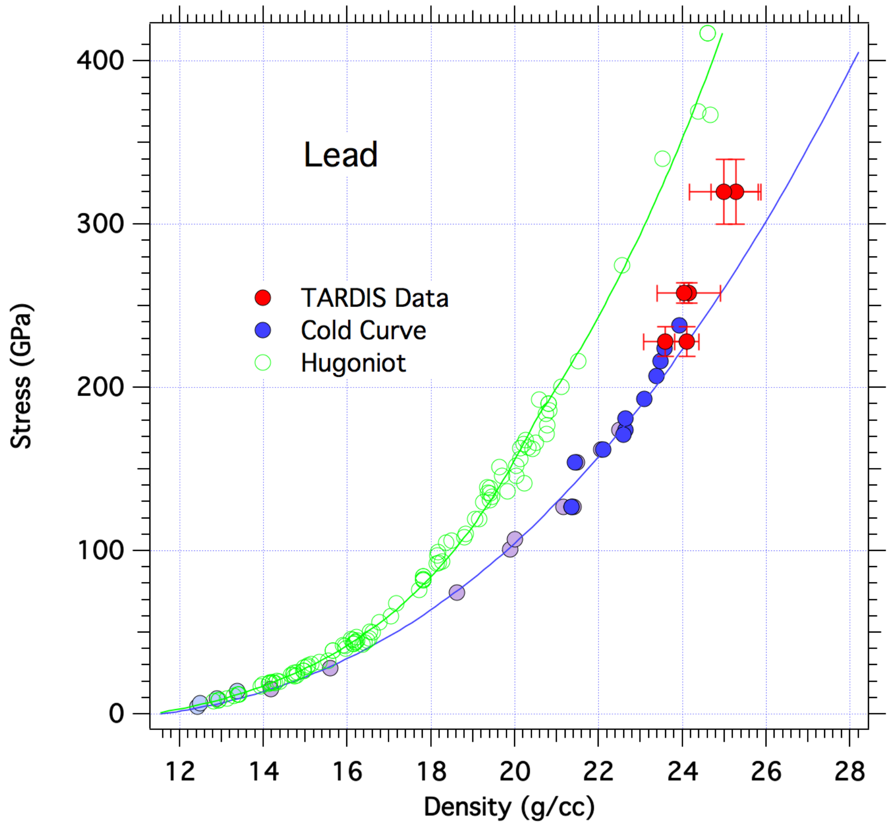


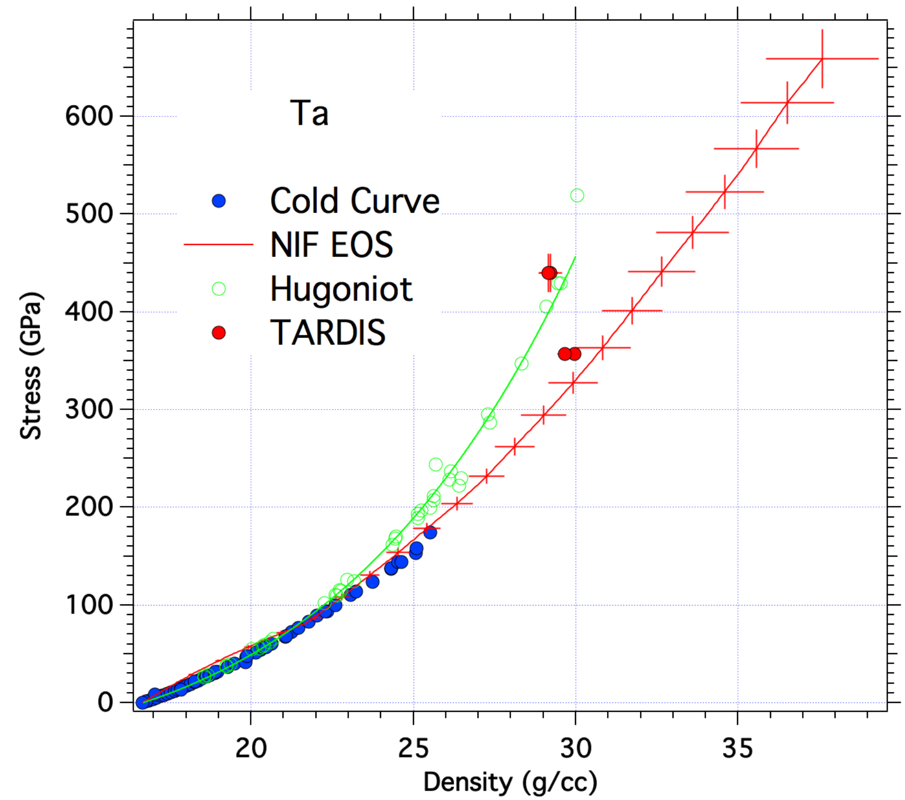
BCC Pb at 23.78 g/cc



1 Mbar = 100 GPa = 0.1 TPa

Preliminary Stress-Density Results



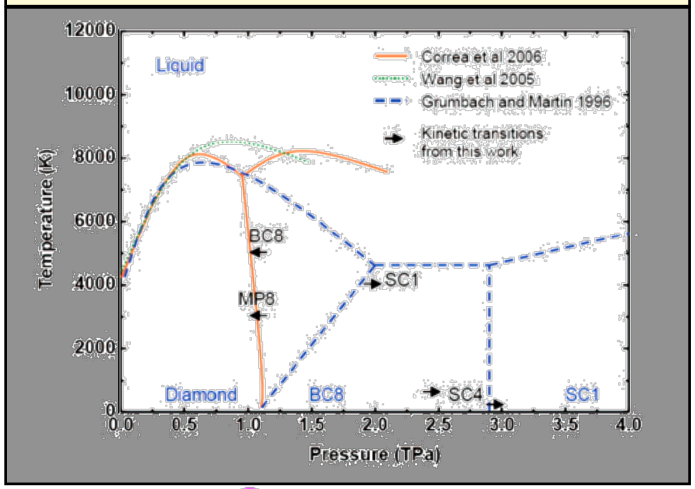


!!! Stress, Density, and Phase are very preliminary !!!

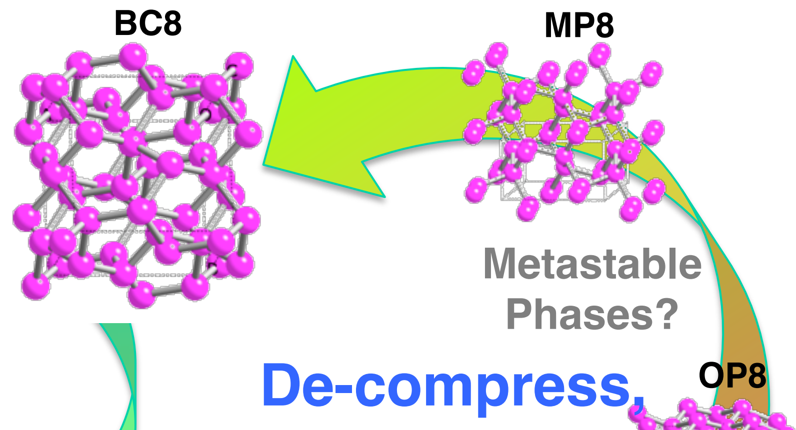
1 Mbar = 100 GPa = 0.1 TPa

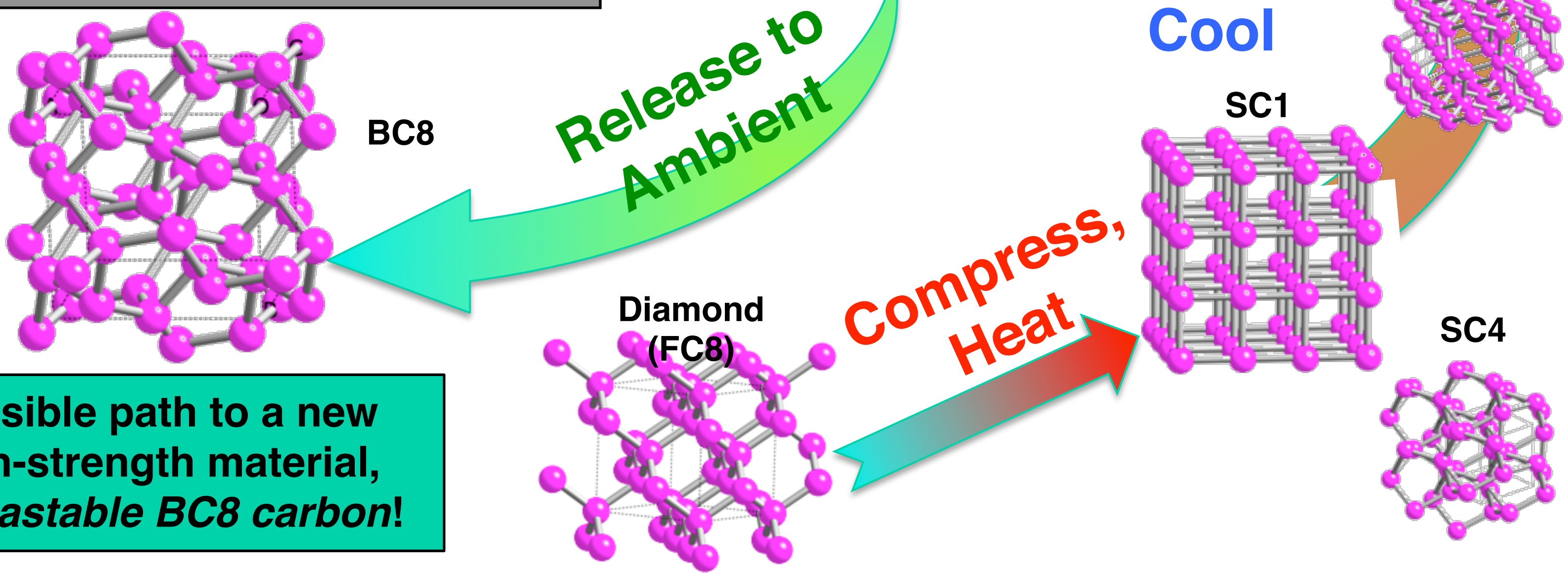
Current Fundamental Science on NIF campaign to try to locate BC8 phase of carbon

Carbon Phase Space



Sun, Klug, and Martonak, JCP 2009

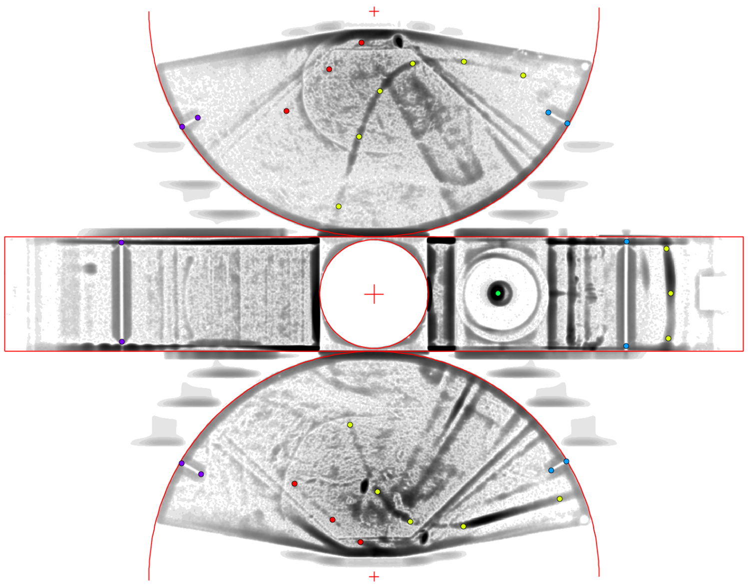


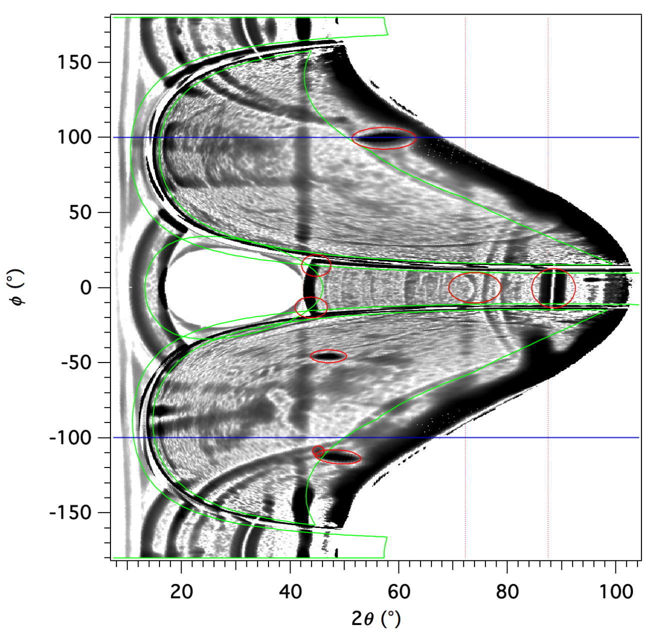


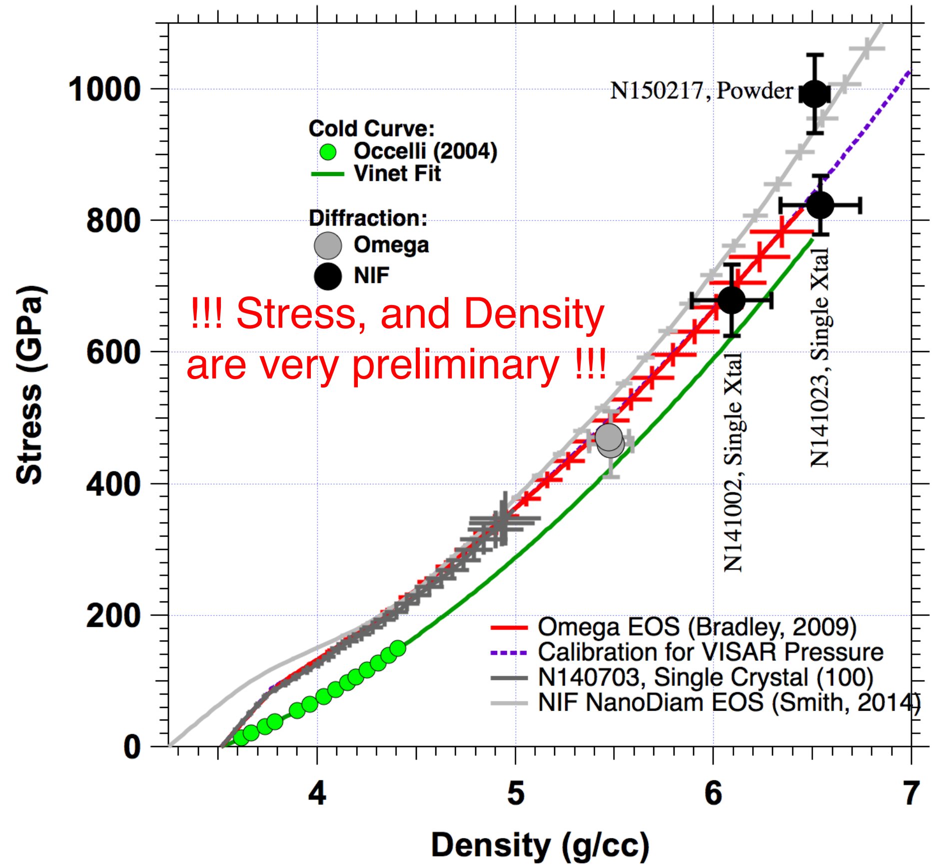
Possible path to a new high-strength material, *Metastable BC8 carbon*!

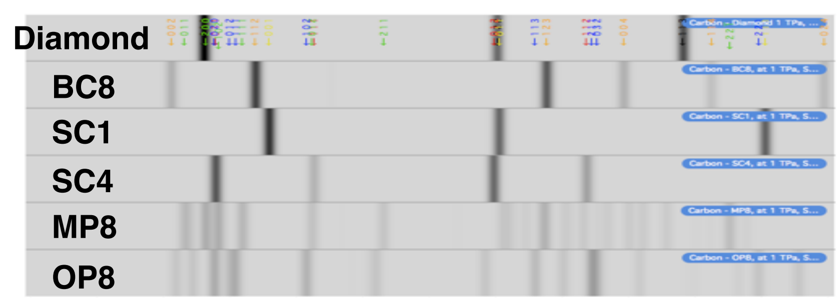
1 Mbar = 100 GPa = 0.1 TPa

We had only seen highly-structured diffraction from diamond. On Monday we saw power diffraction.









Diffraction of carbon structures at 1 TPa

1 Mbar = 100 GPa = 0.1 TPa

Outstanding Issues with Dynamic-Diffraction Experiments

Validate the accuracy of our stress determination

- Effect of strength in diamond is uncertain
  - Use different sandwich materials, e.g.: Diamond, LiF, MgO

Experimentally constrain the temperatures we reach

- Heating by: thermal conduction, plastic work, shock formation, etc.
  - Debye-Waller factor in diffraction
  - Debye-Waller factor in EXAFS
  - Thermal-expansion in diffraction

Explore systematics of rate-dependent phase transitions

- Simple structures may form more rapidly than complex structures
  - Explore phase diagrams on multiple platforms

Improve signal to noise ratios

- Lower ablation plasma and other background
- Use higher energy x-rays

Develop cheaper targets