Dynamic Compression of Planetary Materials at Omega and EP

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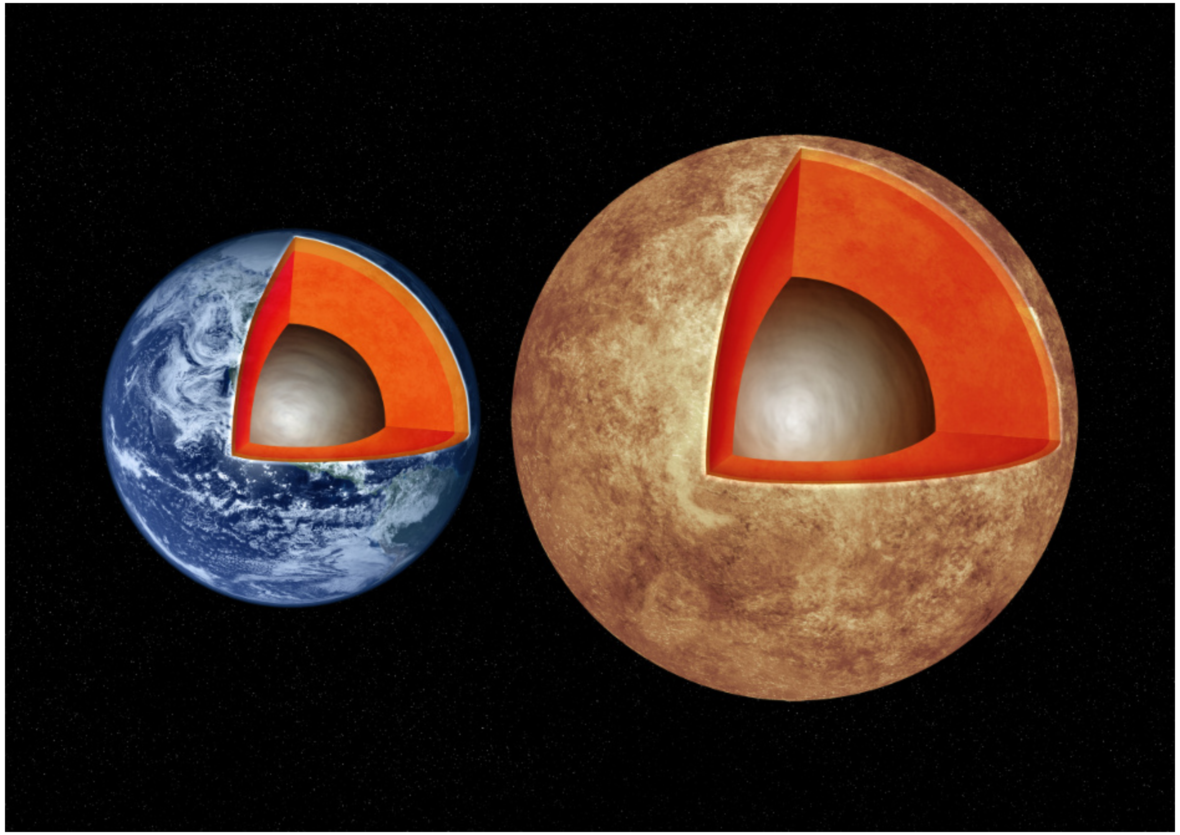

Omega Laser Facility Users' Group Workshop
April 26 2017

June Wicks, Princeton
Federica Coppari, LLNL
Rick Kraus LLNL
Dayne Fratanduono, LLNL
Jon Eggert, LLNL
Thomas Bohely, Rochester
Amy Lazicki, LLNL
Ray Smith, LLNL
Jue Wang, Princeton
Matt Newman, Caltech
Ryan Rygg, Rochester
Gilbert Collins, Rochester
Donghoon Kim, Princeton

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Laboratory for Laser Energetics
a unique national resource

Planetary Accretion and Early Solar System Evolution

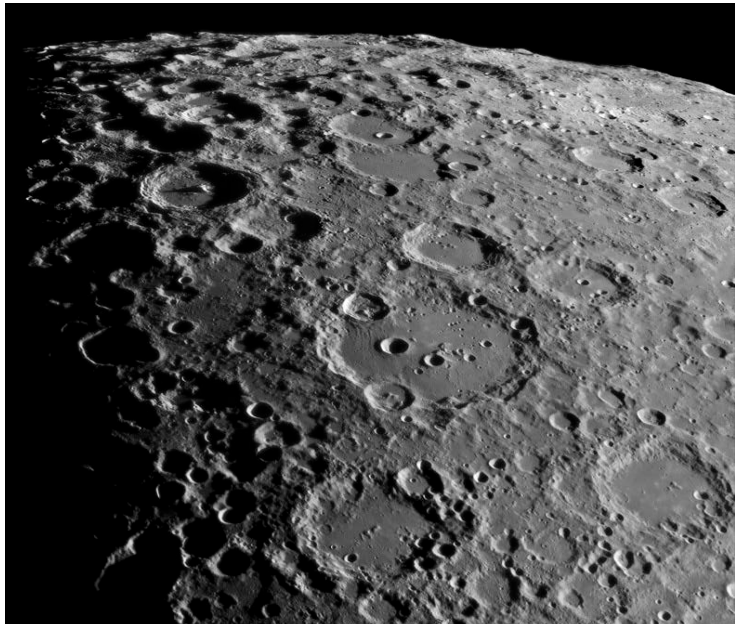
Accretion History

Chemical and Thermal Evolution of Planets

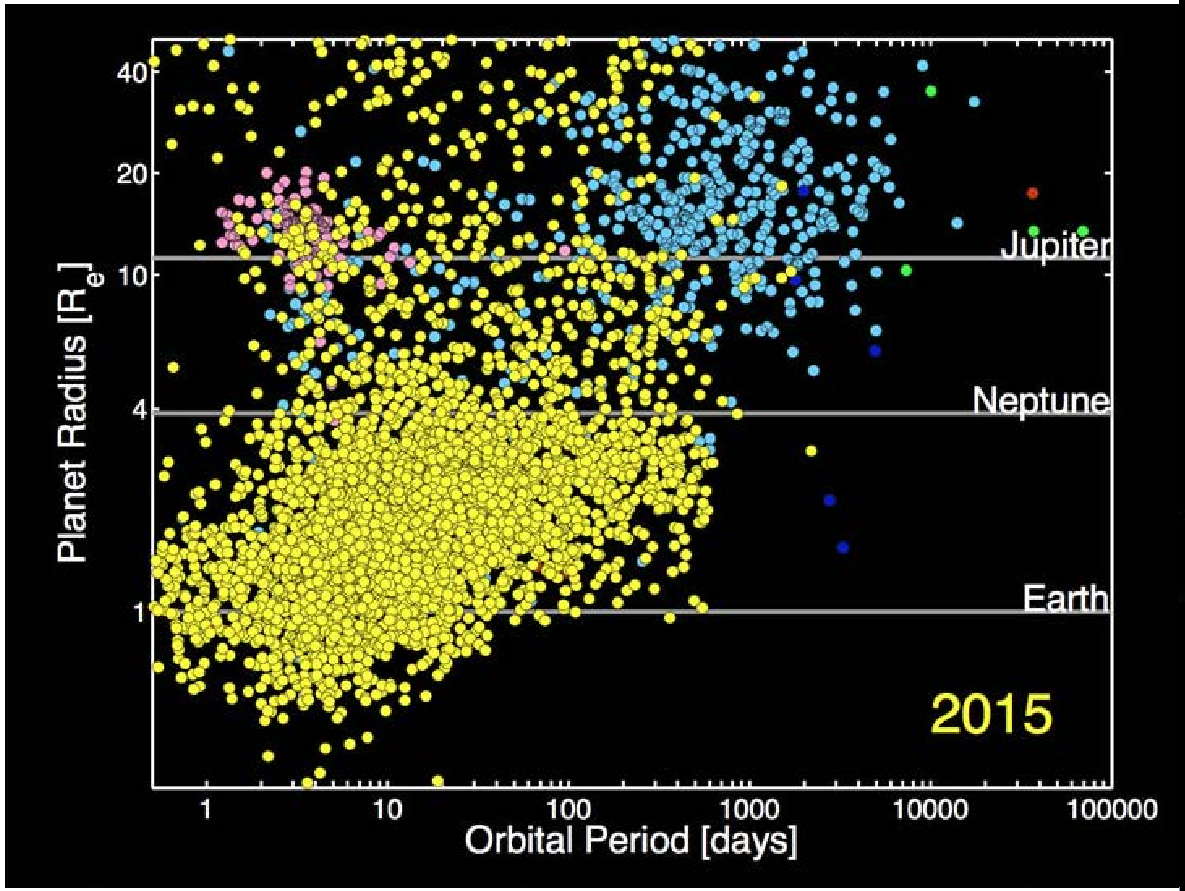
Differentiation and Melting

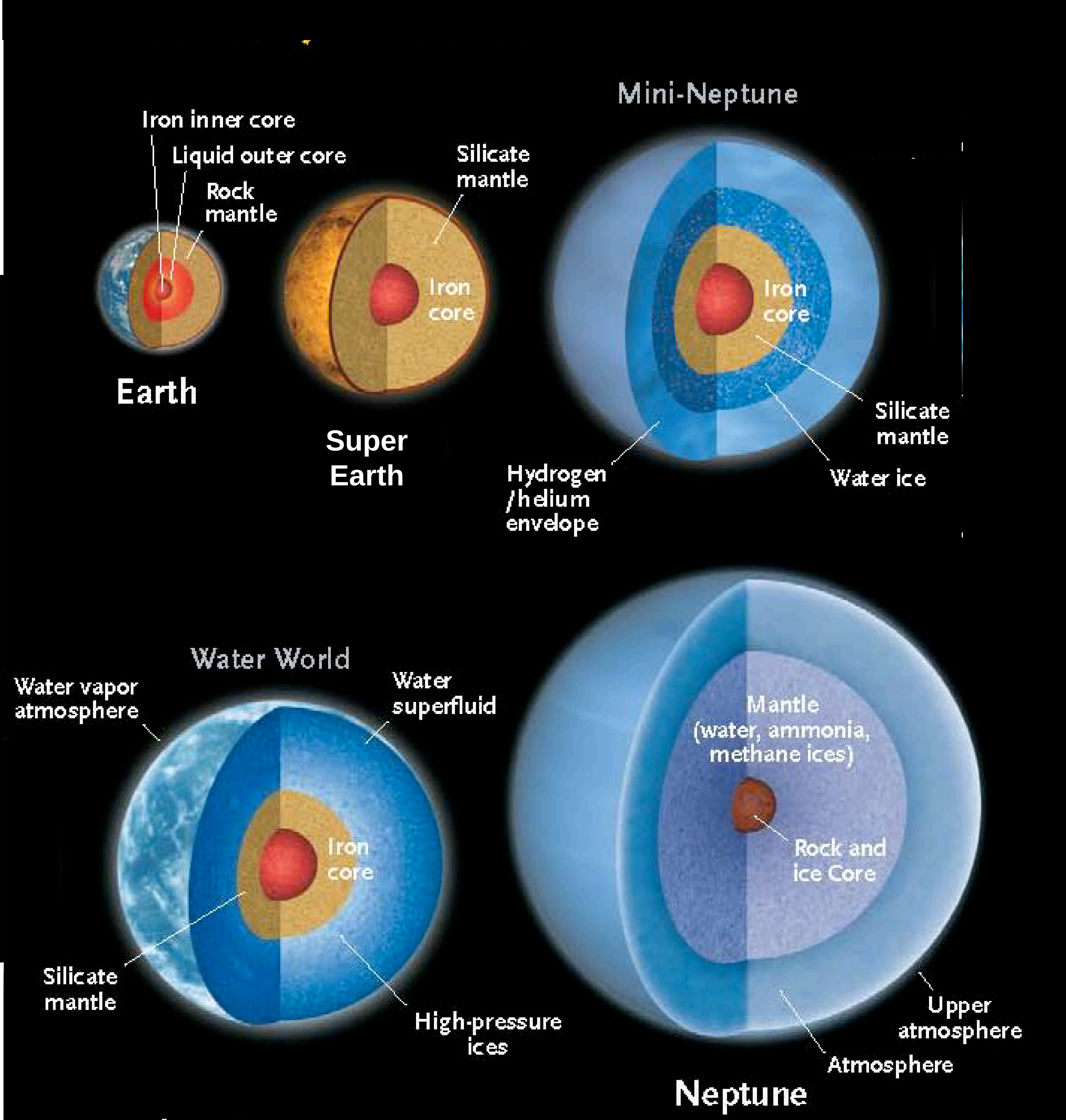
Formation of Atmospheres

Formation of Satellites



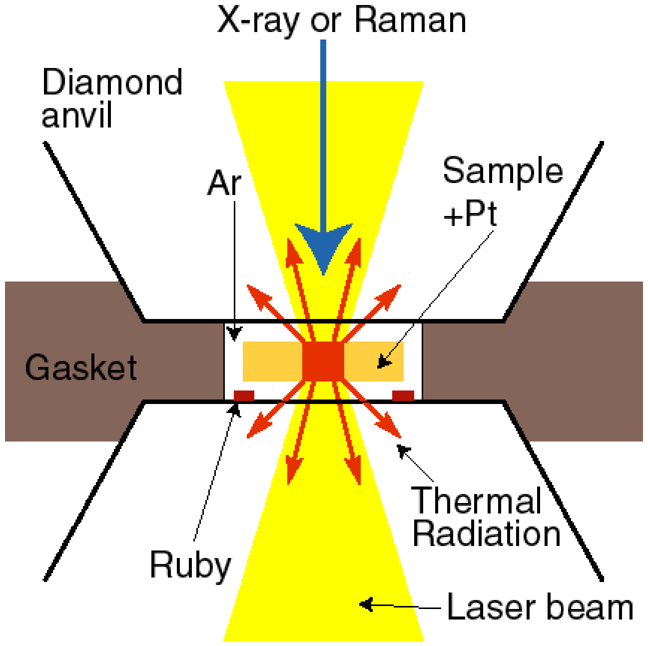
Extra-Solar Planets: Abundance of Super-Earths

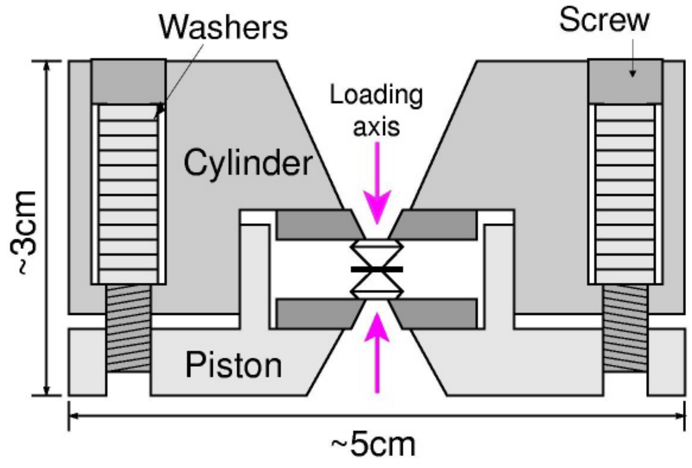




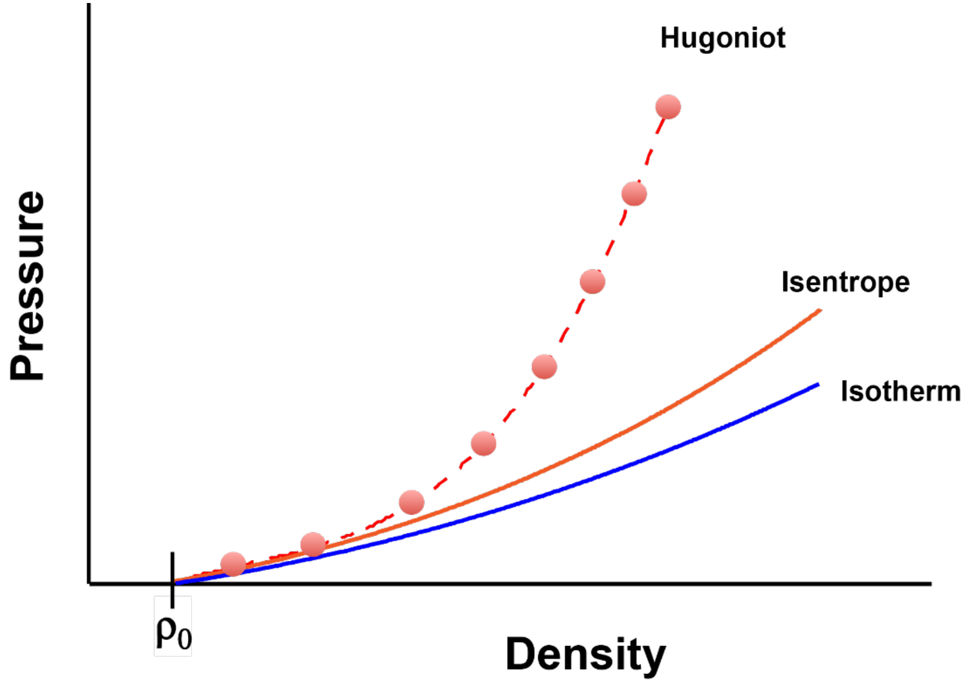
Standard Experimental Approaches

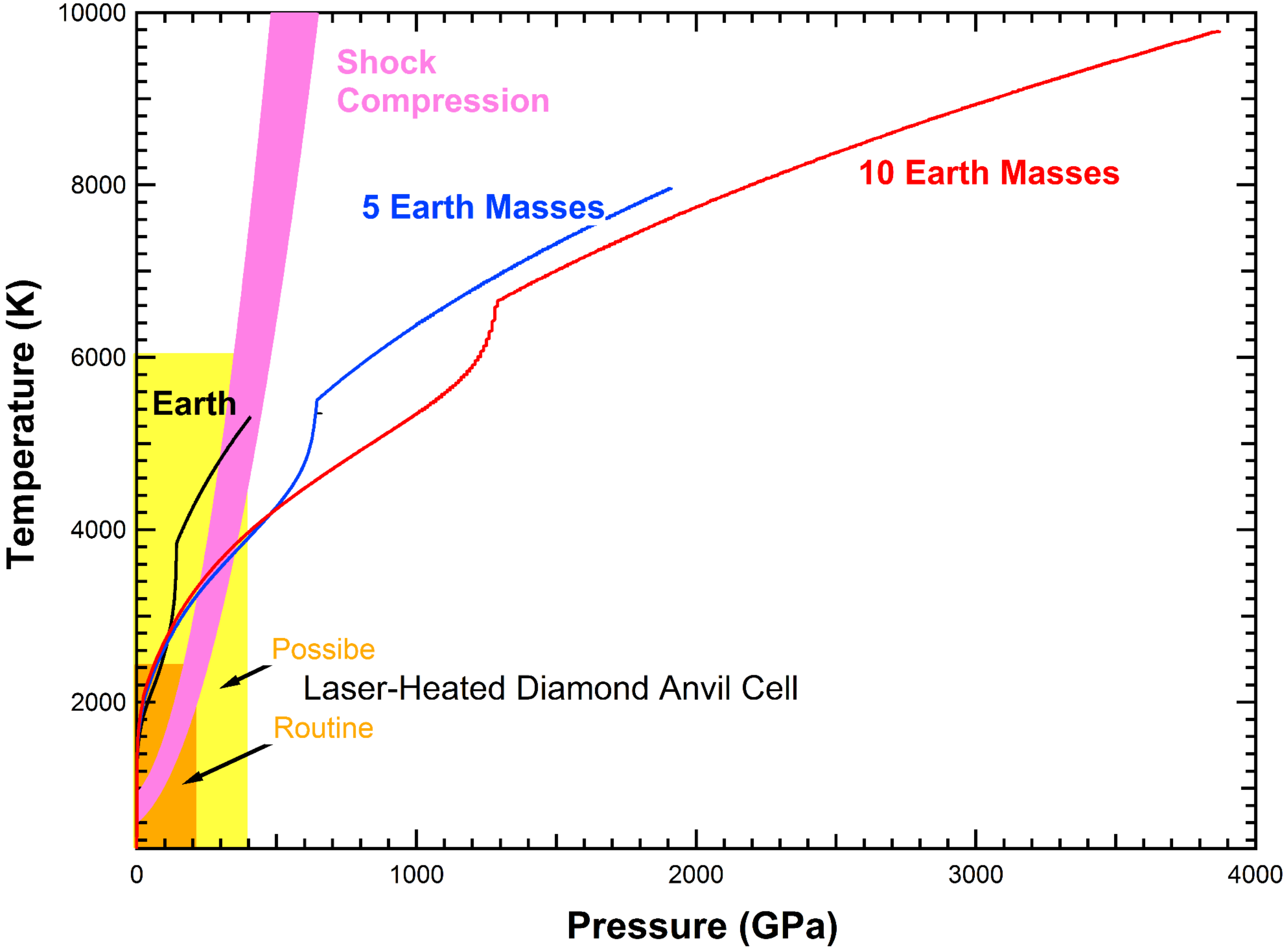
Diamond Anvil Cell





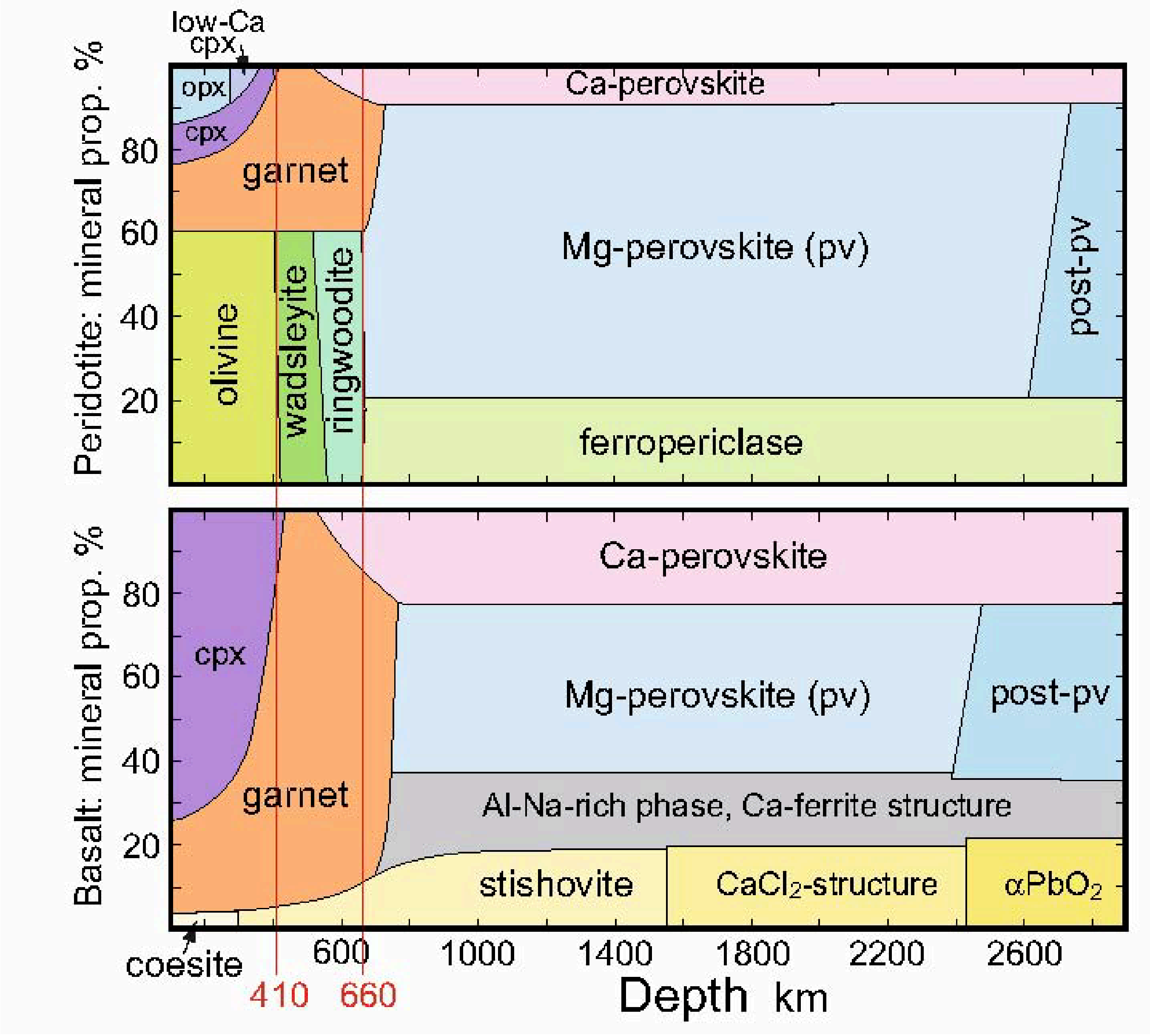
Gas Gun

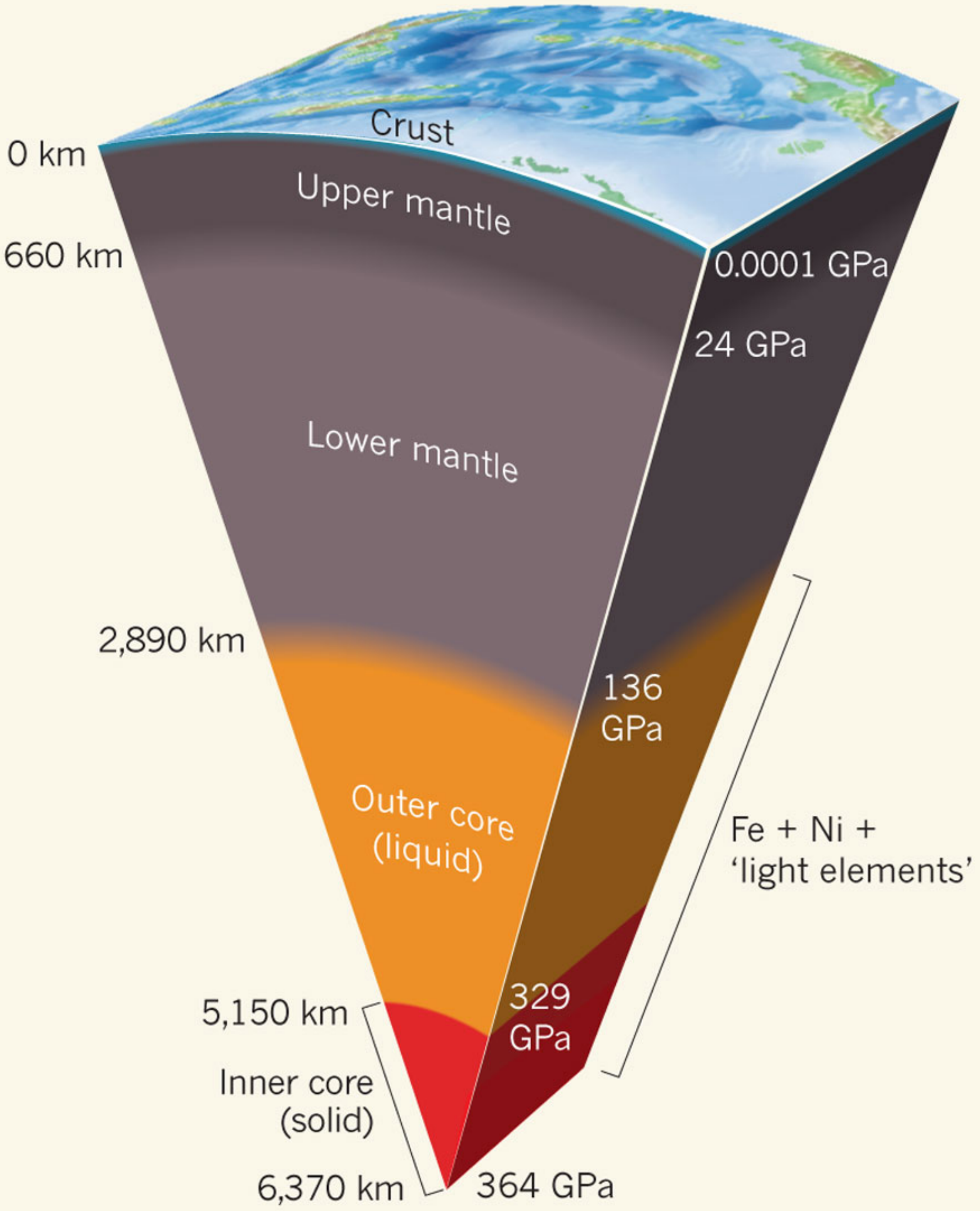




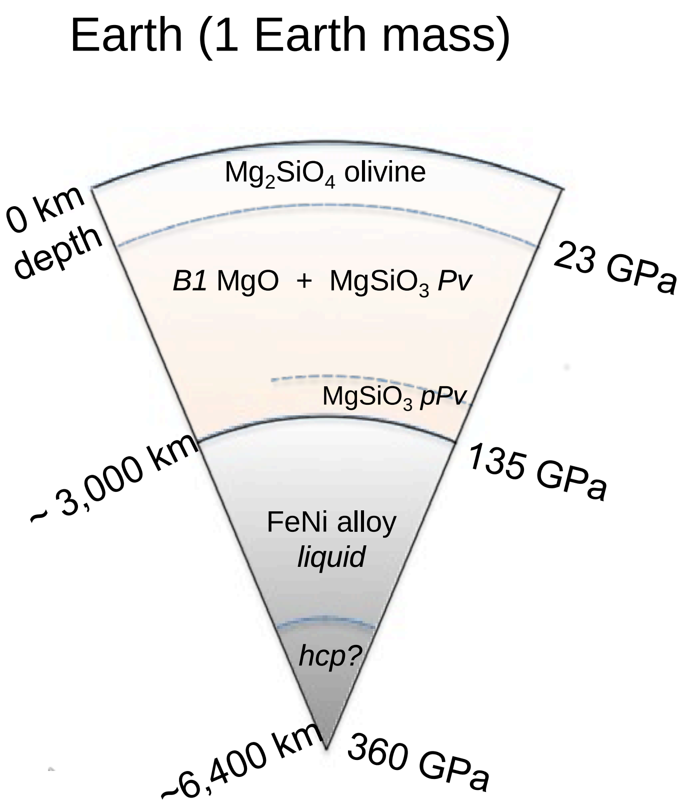
Shock
Compression
5 Earth Masses
10 Earth Masses
Earth
Possibe
Laser-Heated Diamond Anvil Cell
Routine
Temperature (K)
10000
8000
6000
4000
2000
0
1000
2000
3000
4000
Pressure (GPa)

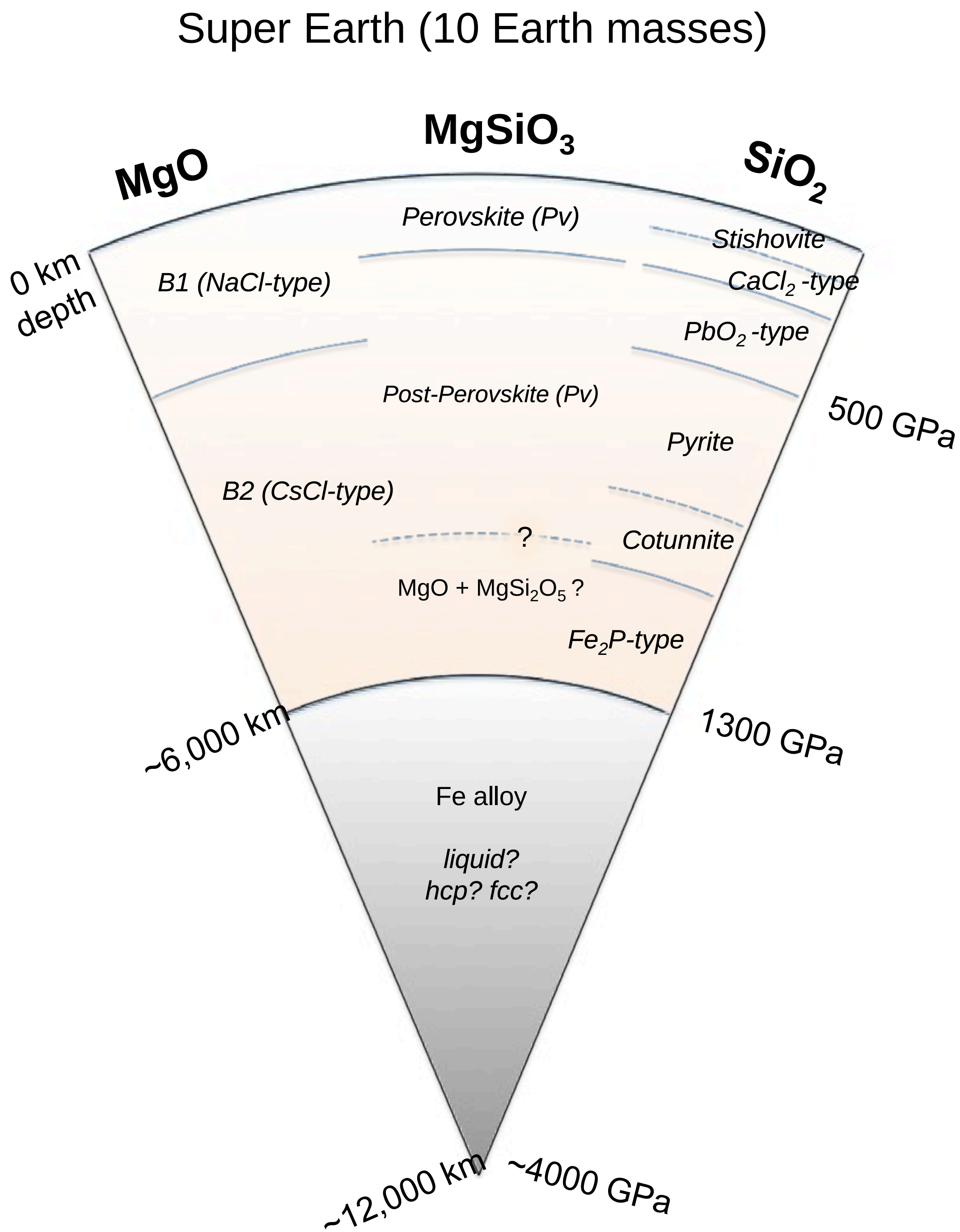
Earth Interior Structure and Mineralogy



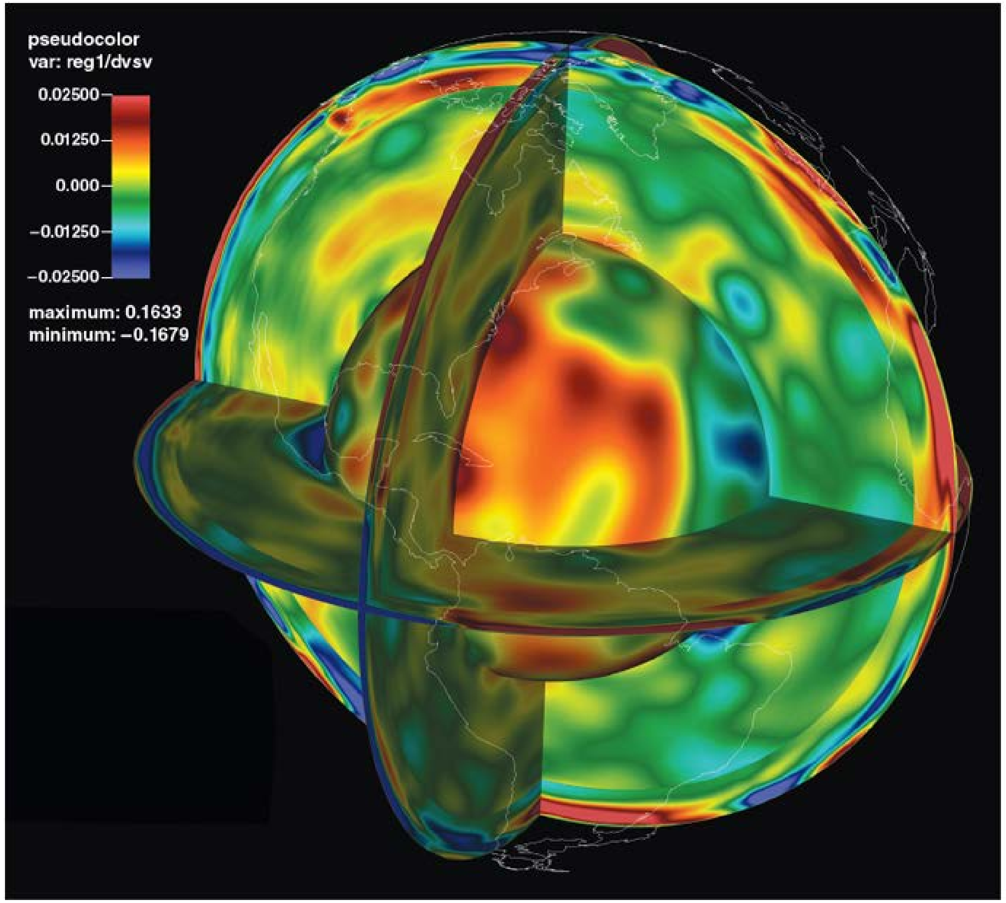


Earth vs Super Earth: Interior Structure and Mineralogy

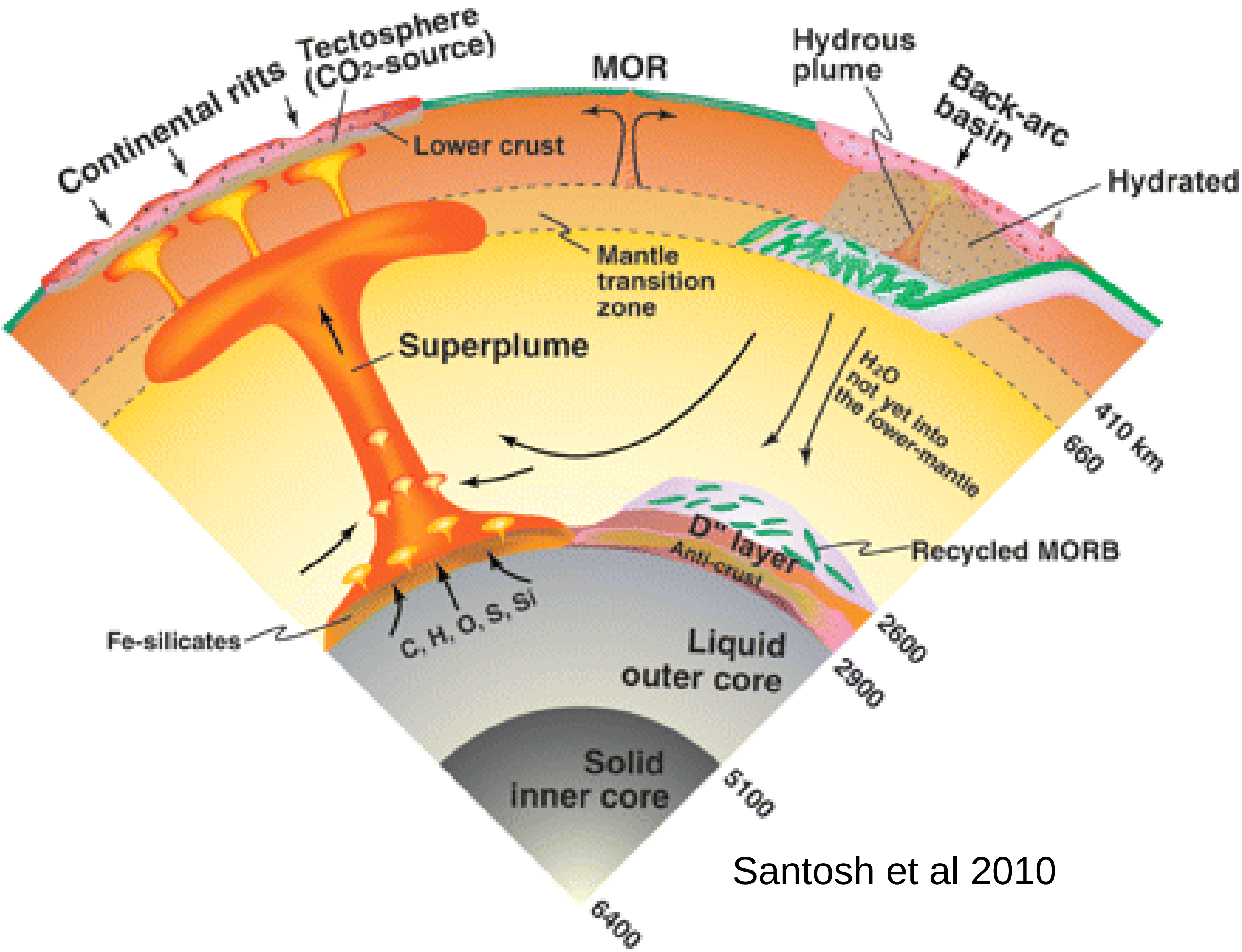




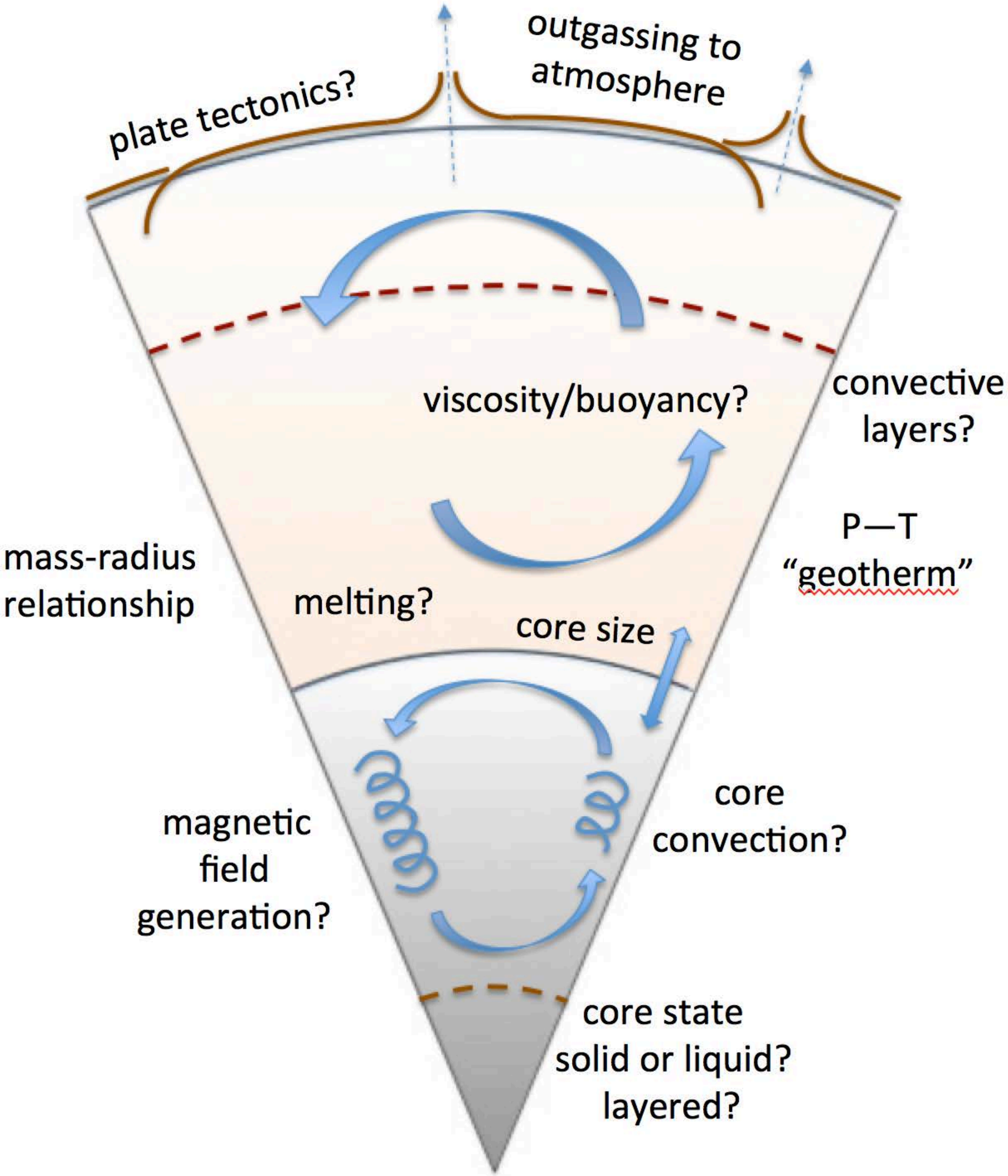
Earth Internal Dynamics



Tromp Group, Princeton



Santosh et al 2010



Interior Structure and Dynamics of Super-Earth Exoplanets

Mass-Radius Relationship

Internal Structure and Layering

Style of Mantle Convection

Plate Tectonics

Magnetic Field Generation

Experimental needs:

Crystal structure, equation of state, rheology, thermal expansivity, thermal conductivity

Effects of Pressure at the Atomic Scale

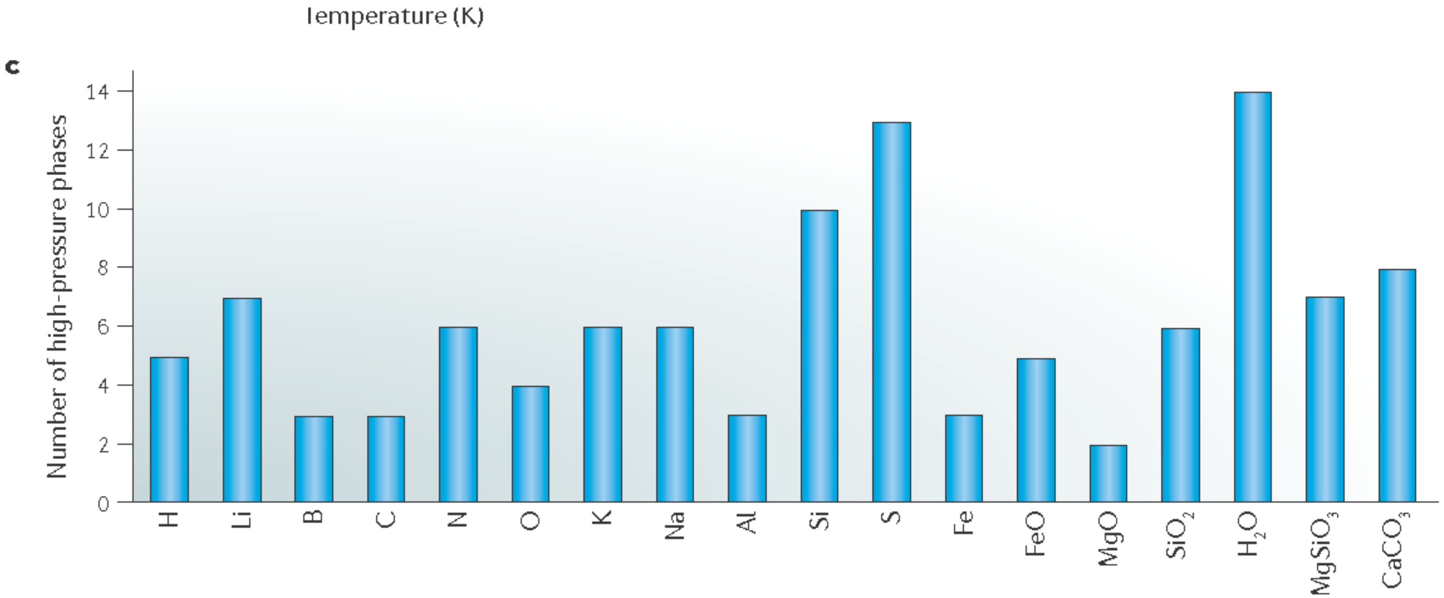
--Changing interatomic distances and bonding patterns (changing bond character and coordination, molecular → extended)

--Electron delocalization (band broadening, gap closure, metallization)

--Electron transfer among atomic orbitals (s→p, s→d, p→ d)

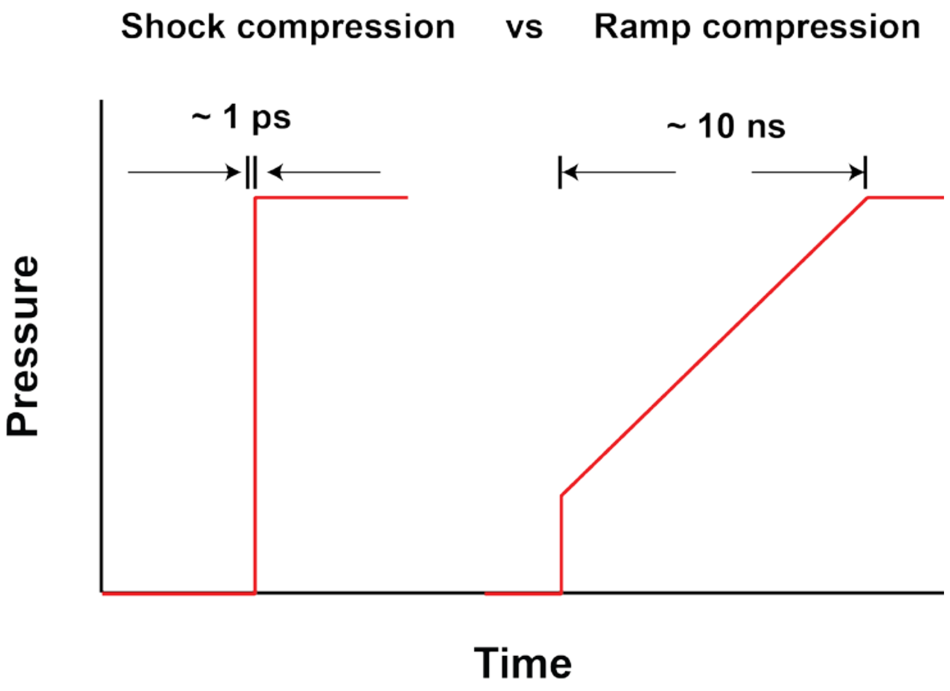
--Exotic charge redistribution (electrides)

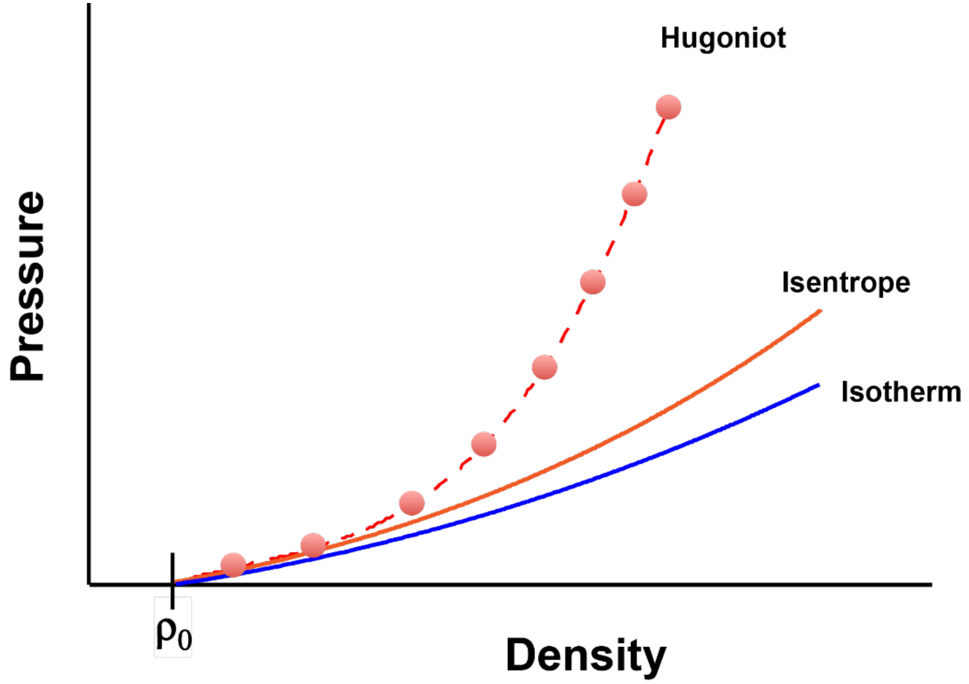
--Modifying the chemical identify of atoms (new periodic table, exotic stoichiometries)



Zhang et al., Nature Reviews: Materials, 2017

Dynamic Compression

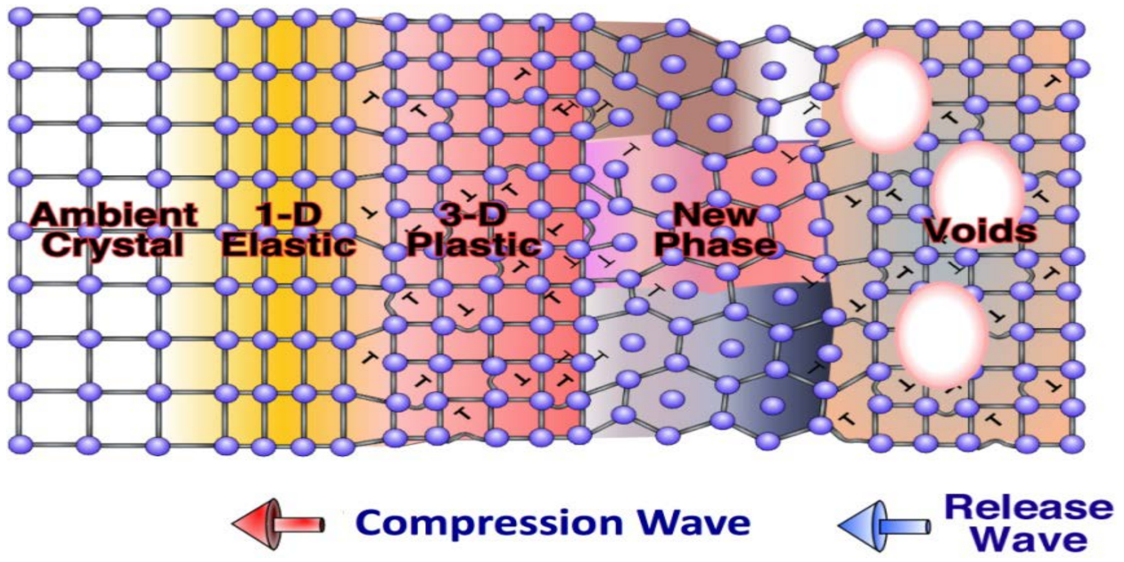




$$\frac{\rho}{\rho_0} = \frac{U_S}{U_S - u_p}$$

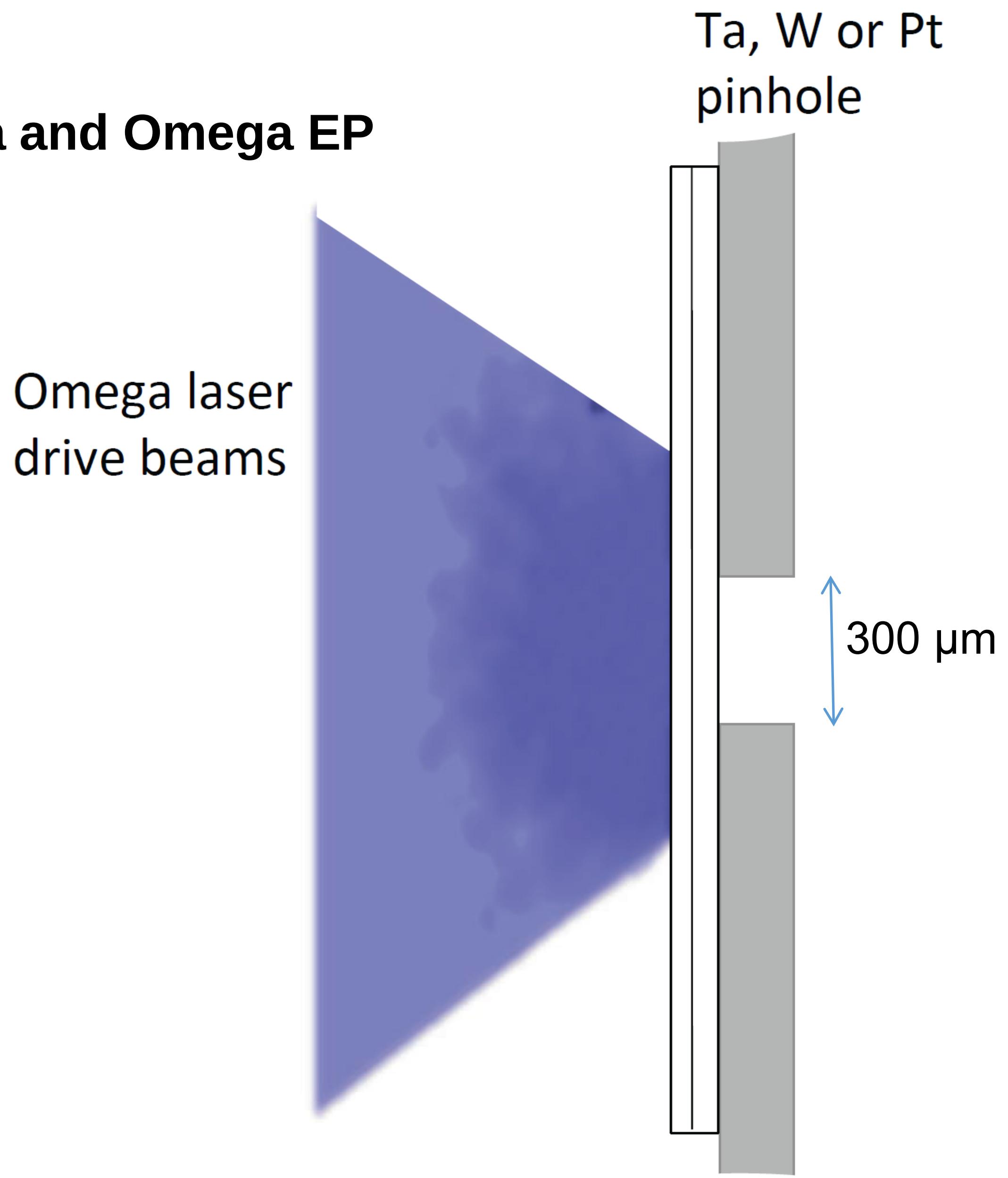
$$P = \rho_0 U_S u_p$$

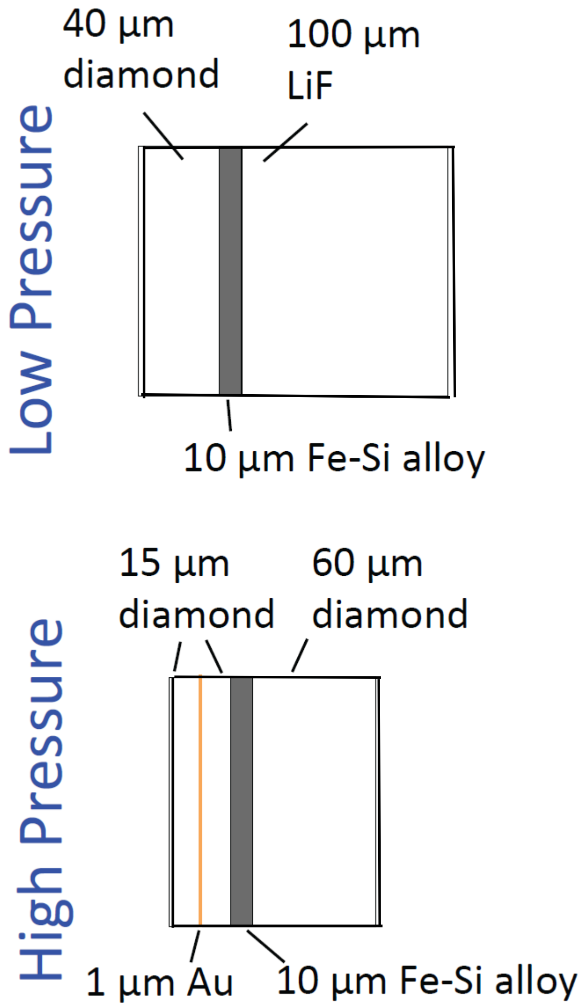
$$E_1 - E_0 = \frac{1}{2} P(V_0 - V)$$



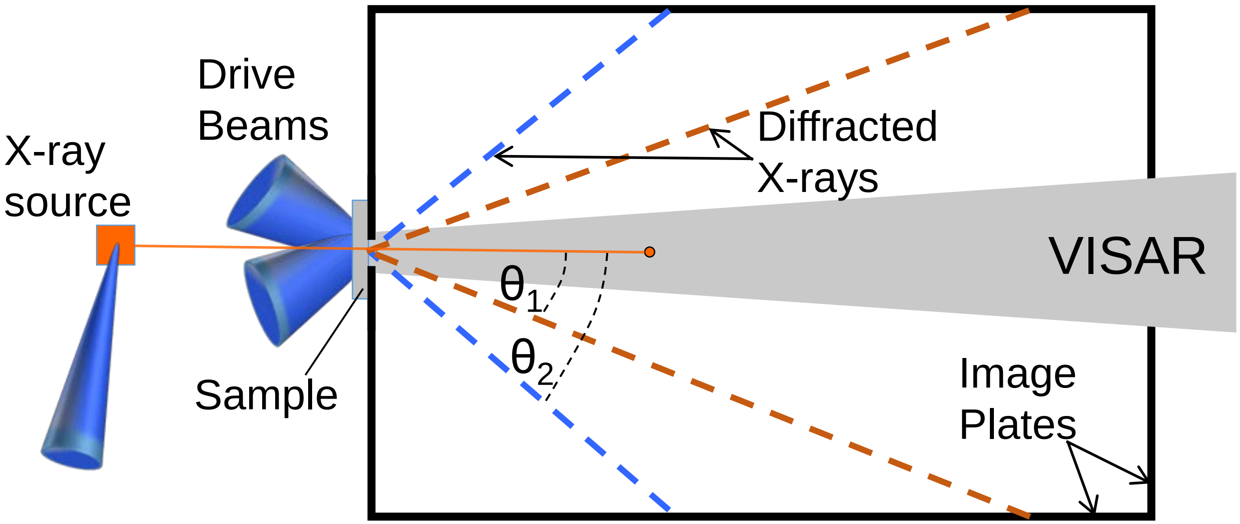
Pulsed X-Ray Diffraction Under Dynamic Compression: Target Package

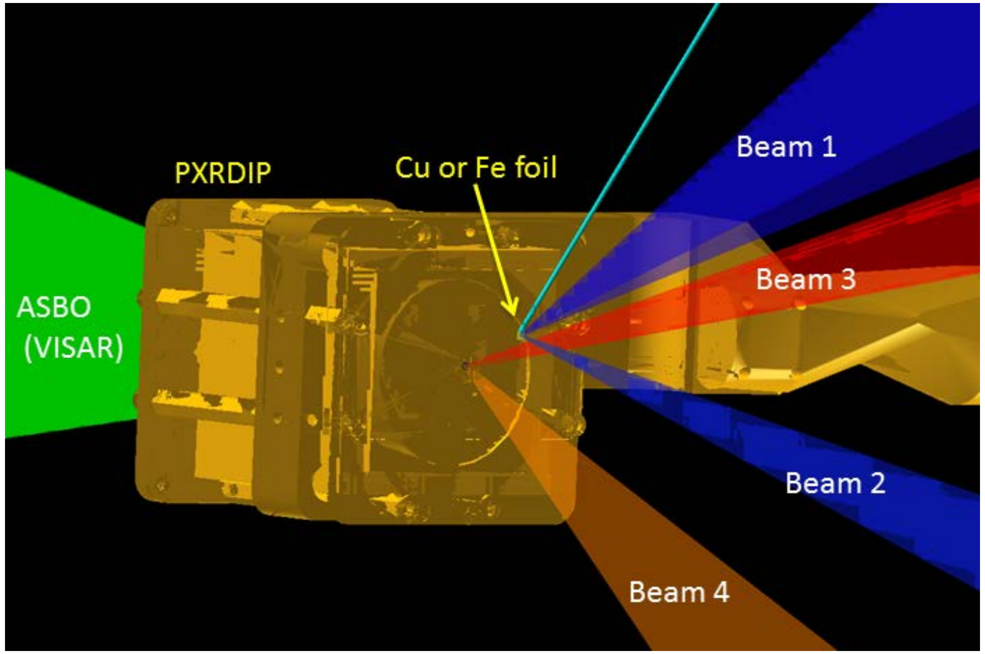
Omega and Omega EP



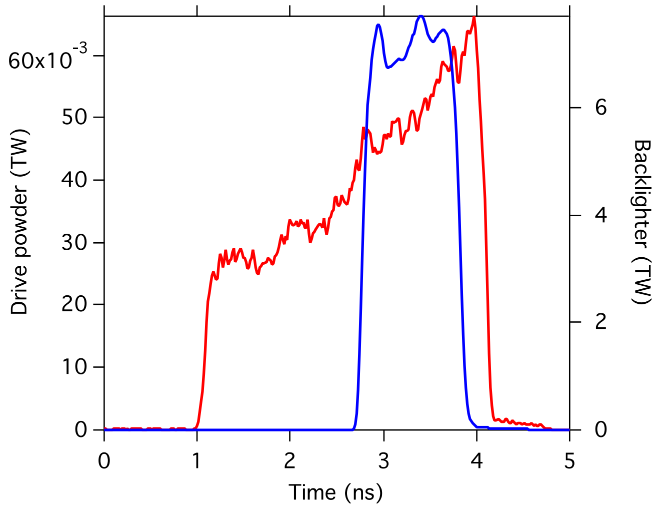


PXRDIP: X-Ray Diffraction Diagnostic

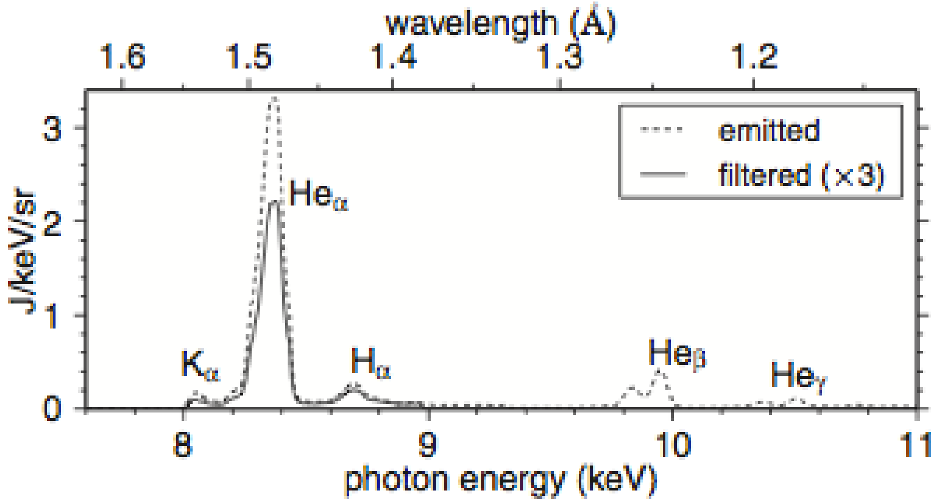




X-ray Source:
Quasi-monochromatic He_{α} x-rays generated with 1-ns laser pulse



X-Ray Energy Spectrum (Rygg et al., 2012)



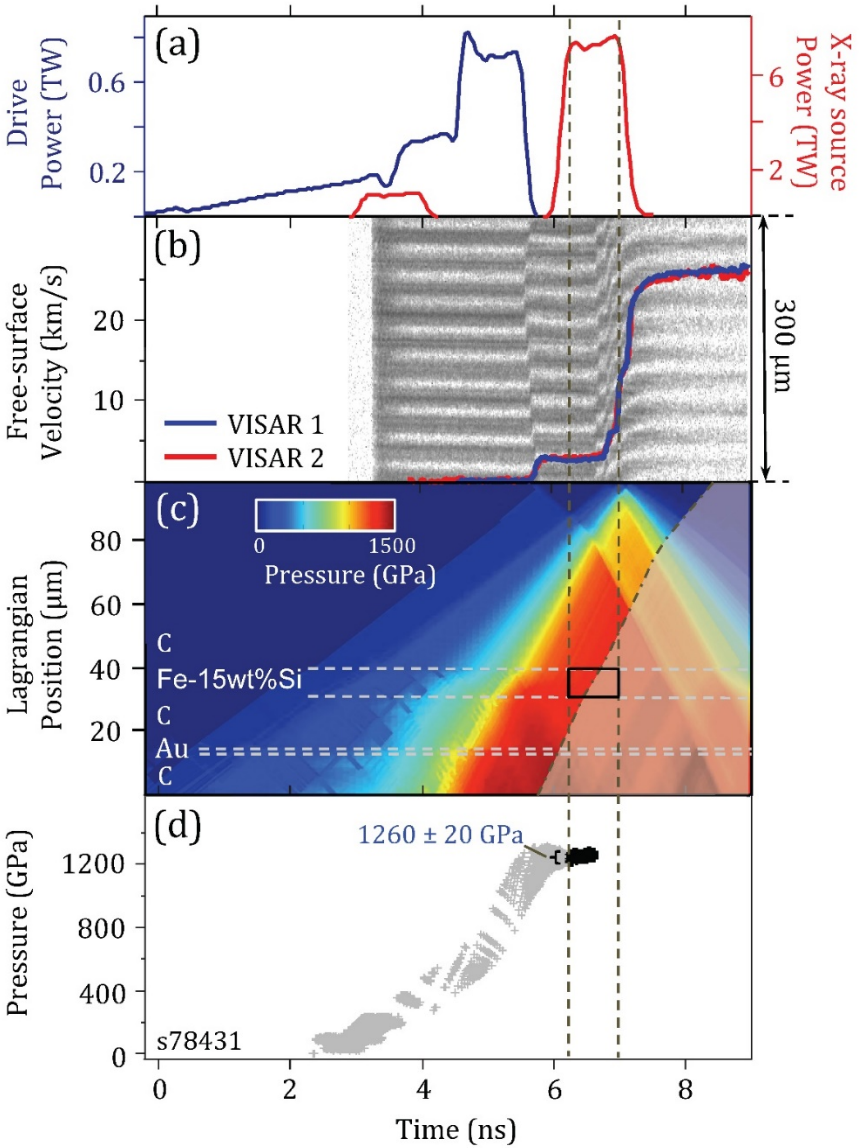
Laser Drive and Pressure Determination

Laser Drives

Interferometry

Hydrocode simulation
and
Characteristics analysis

Sample pressure



Thin sample (4 um thick) sandwiched between diamond layers

Several beams of Omega used to produce ramp loading. X-ray pulse generated using additional beams on a Cu, Fe, or Ge foil

Initial ramp pulse followed by 1 or 2 square pulses

VISAR used to record free surface velocity

Free surface velocity profile and (EOS) of diamond used to determine the stress state in the sample through the method of characteristics in which the equations of motion are integrated backwards in space and time

X-Ray Diffraction

$$n\lambda = 2d\sin\theta$$

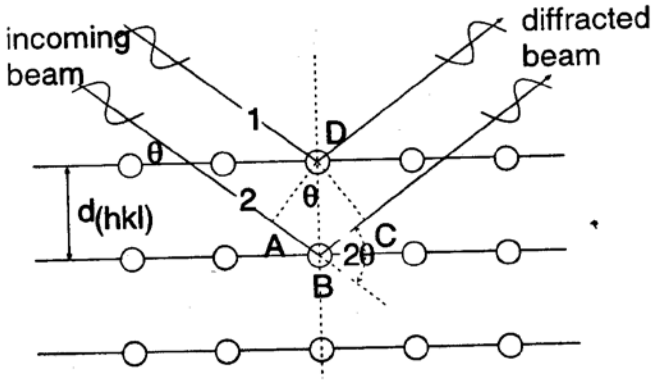
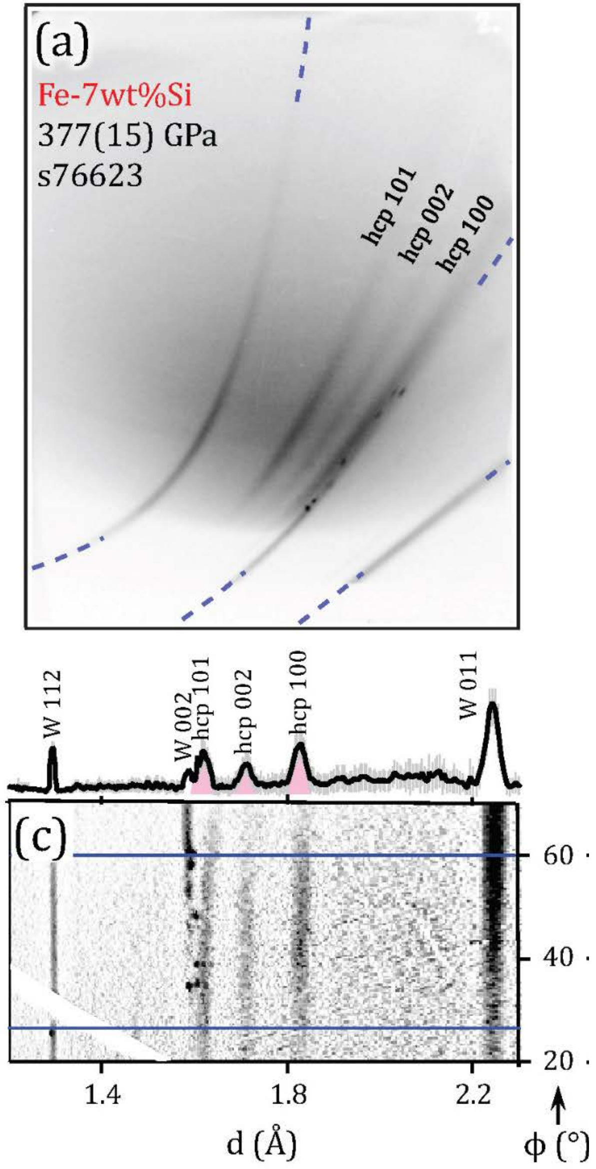
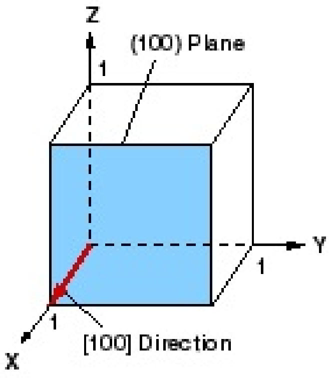
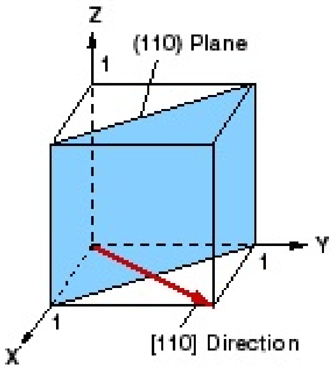


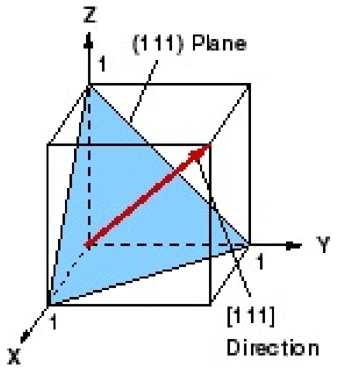
Figure 8 Bragg's law, assuming the planes of atoms behave as reflecting planes.

$$\frac{1}{d^2} = \frac{h^2+k^2+l^2}{a^2}$$

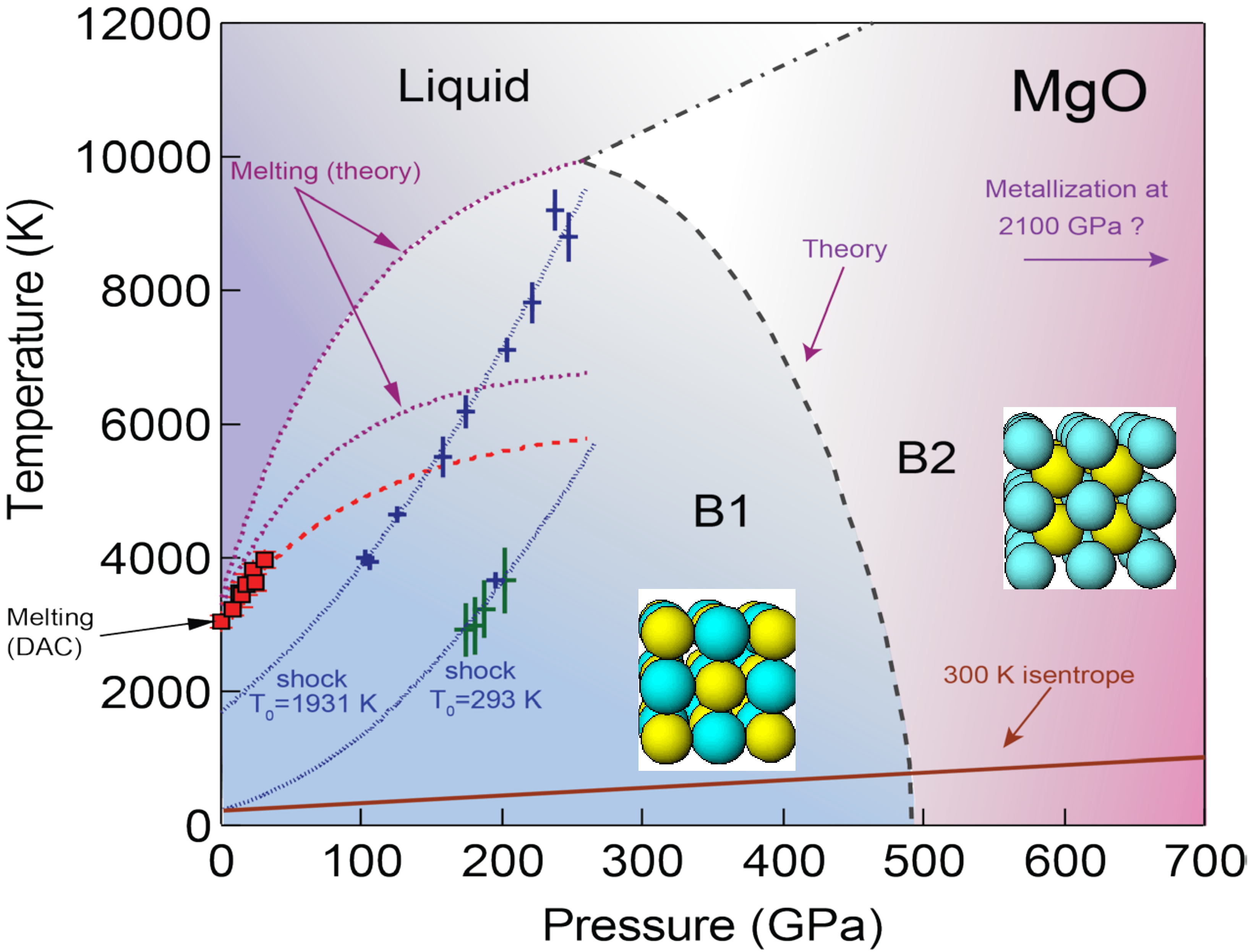




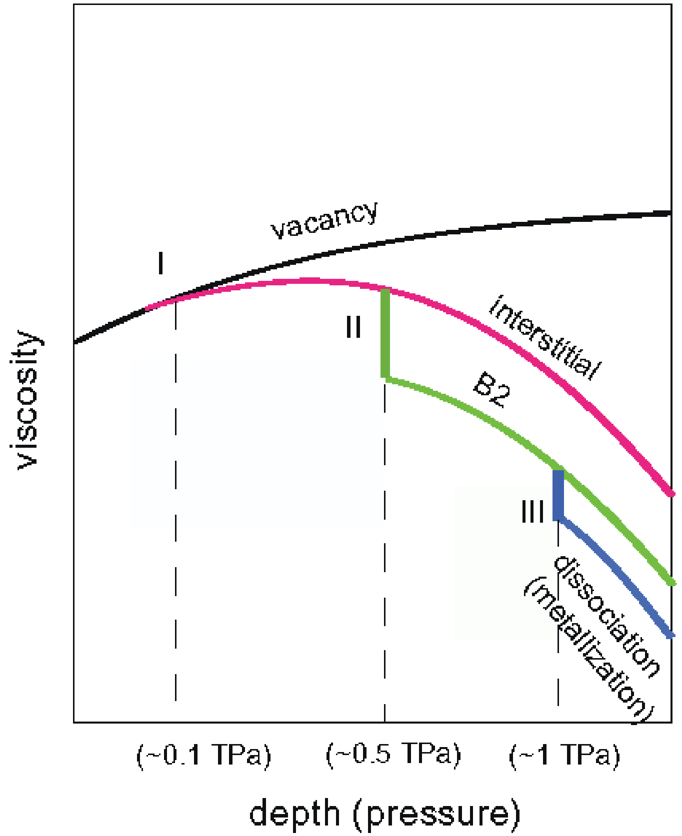




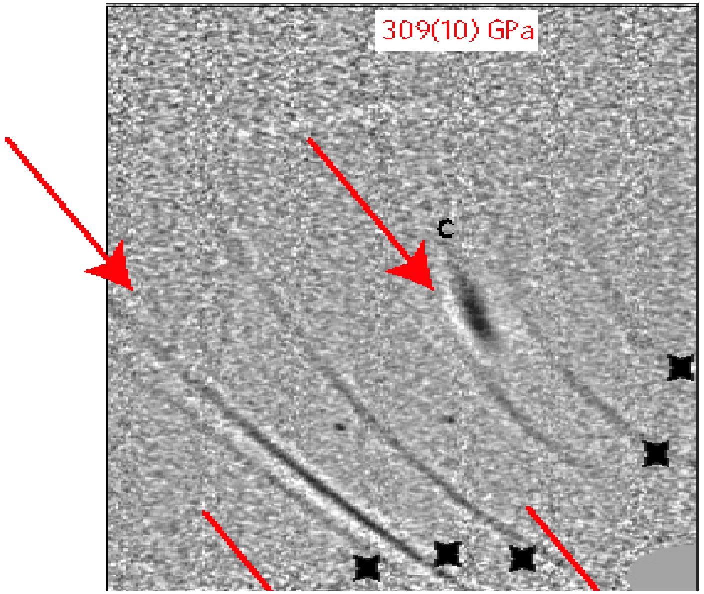
Ramp Compression of Magnesium Oxide (MgO)

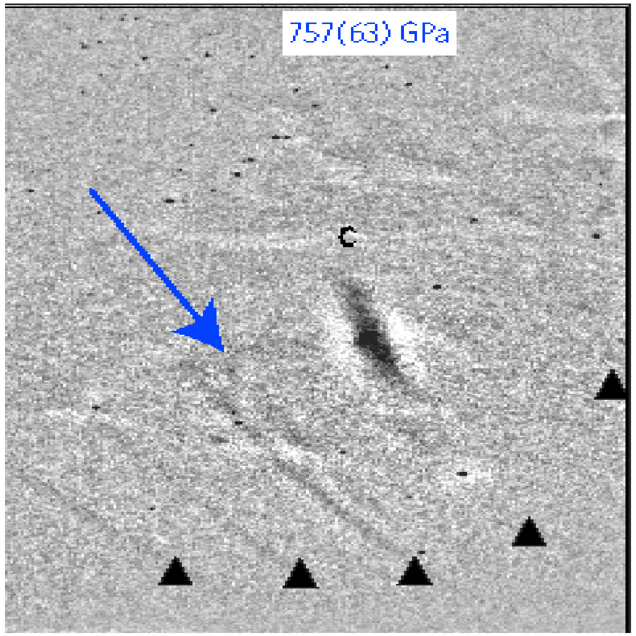


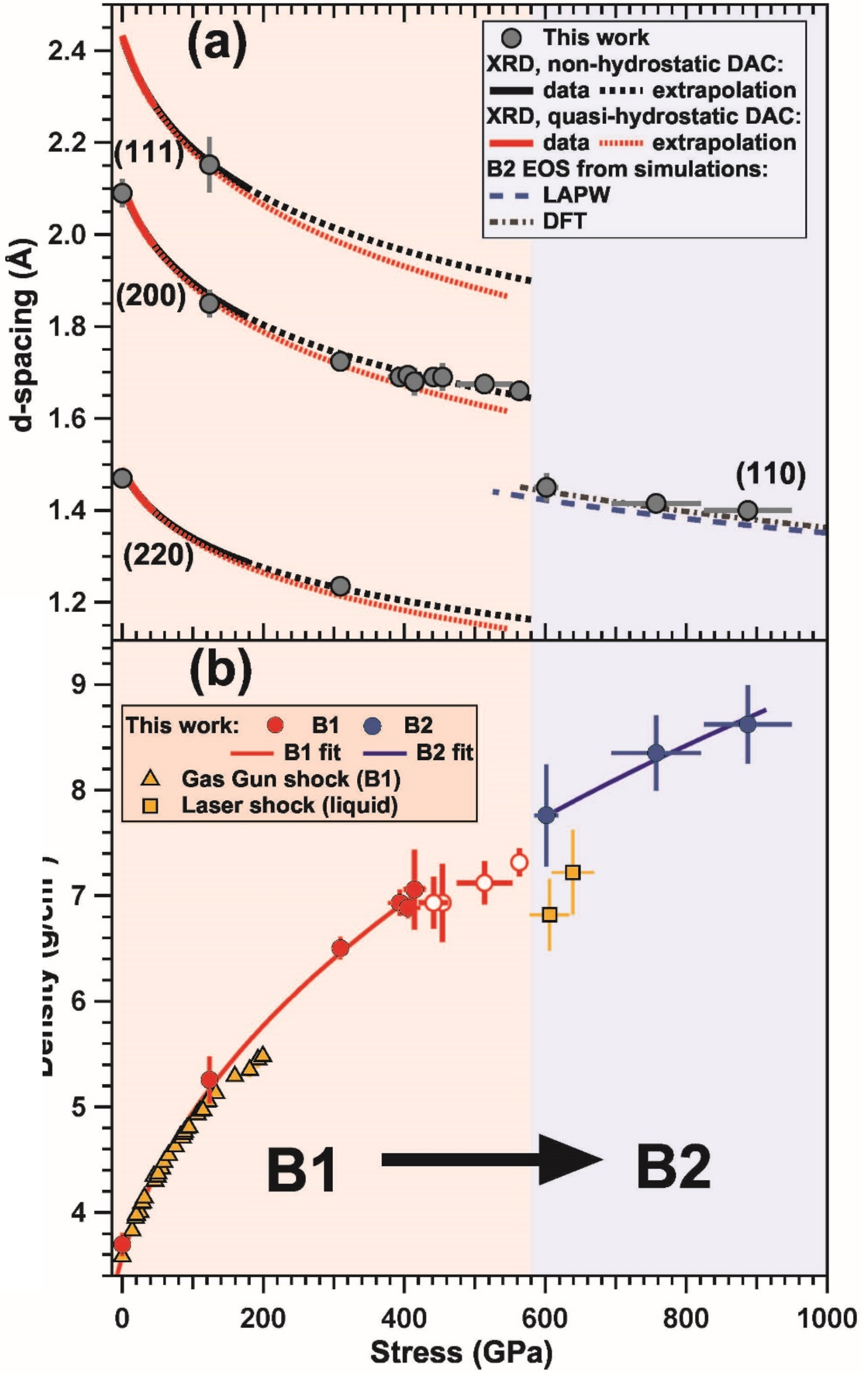
Viscosity change
in exoplanetary interiors
Due to B1-B2 transition?



Karato, 2011







Results

Phase transition near 600 GPa

High-pressure phase consistent with B2 structure

Diffraction data recorded to peak pressure of 900 GPa.

Rocky Exoplanets:
B2 MgO expected to be major phase in deep mantle

Coppari et al. *Nature Geosciences, 2013*

FY 15-16 Technical Advances at Omega and Omega-EP

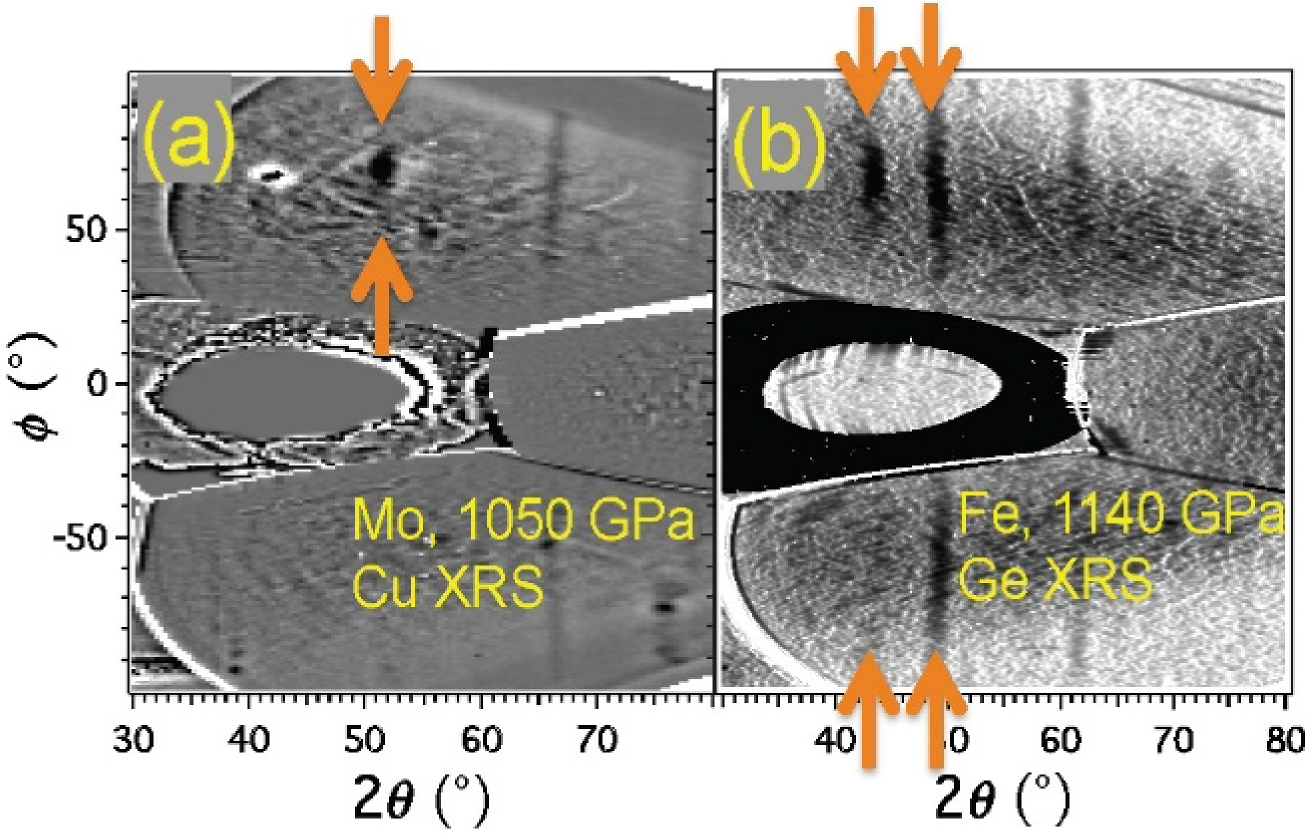
1. Development of high-energy Ge He_{α} source for greater spectral decoupling of backlighter and drive plasma X-rays resulting in improved SNR

2. Improved algorithms for background subtraction

3. Use of LiF windows for more precise pressure determinations

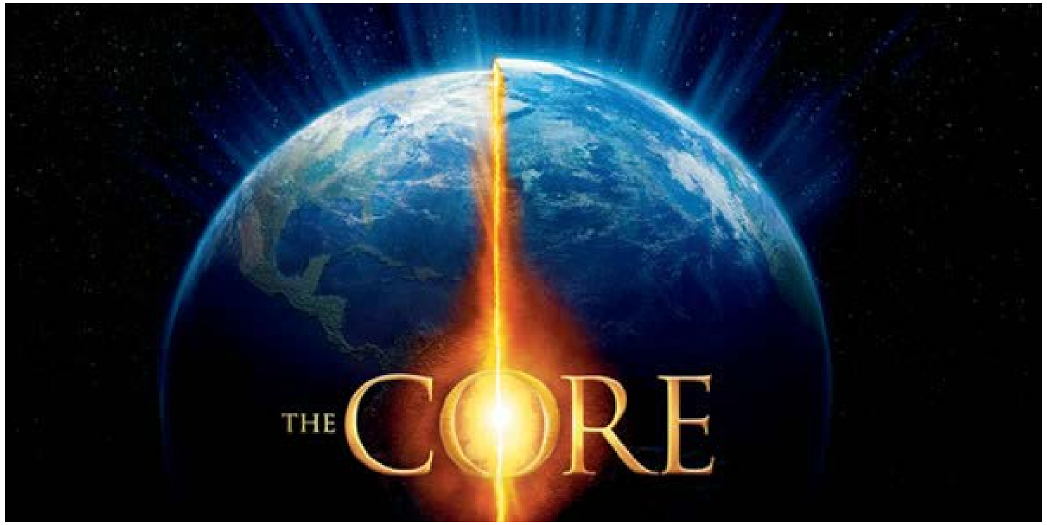
4. A backwards characteristics approach which models wave interactions through all sample layers

5. Use of hydrocodes to develop optimized laser pulse shapes to achieve a temporally steady shock wave



X-ray image plates showing enhanced signal quality using a Ge X-ray source and improved background subtraction

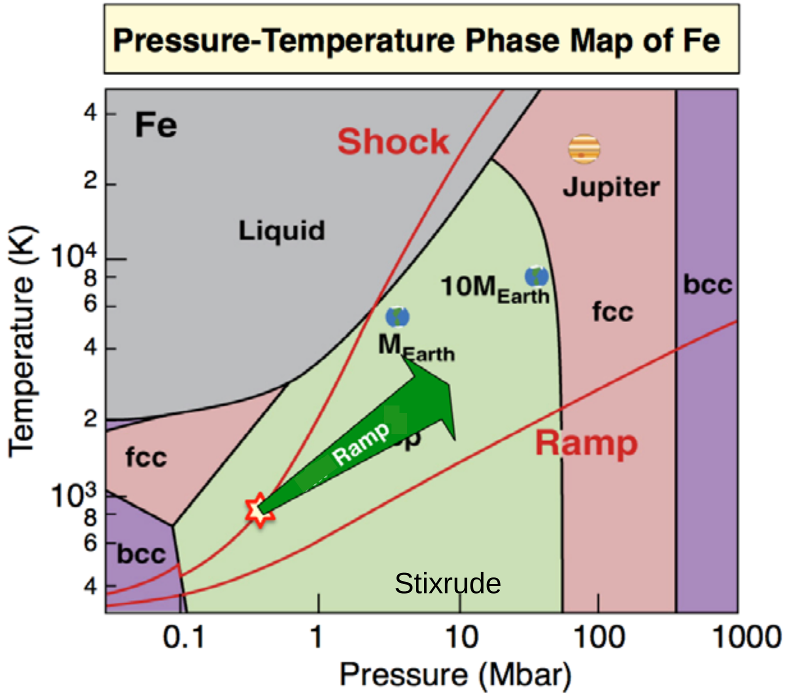
Planetary Cores:

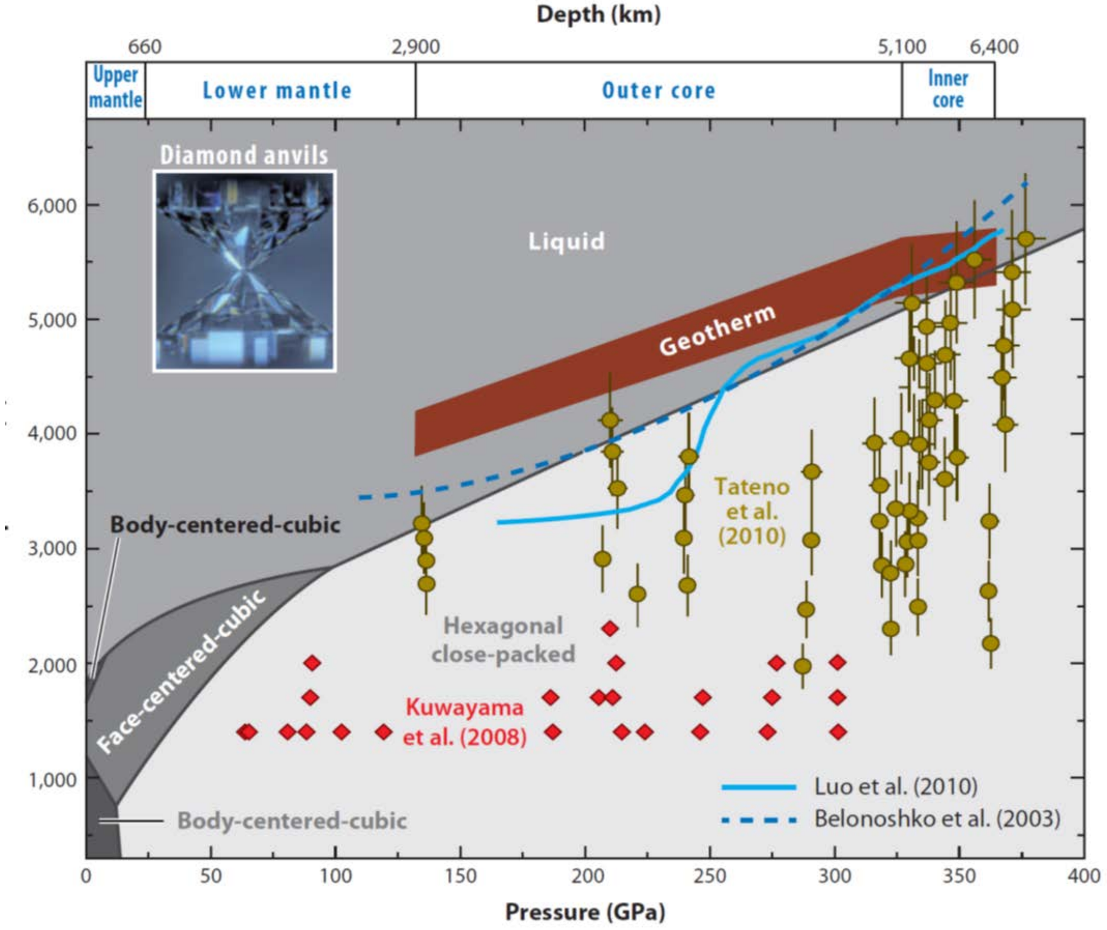


Crystal structure of Fe

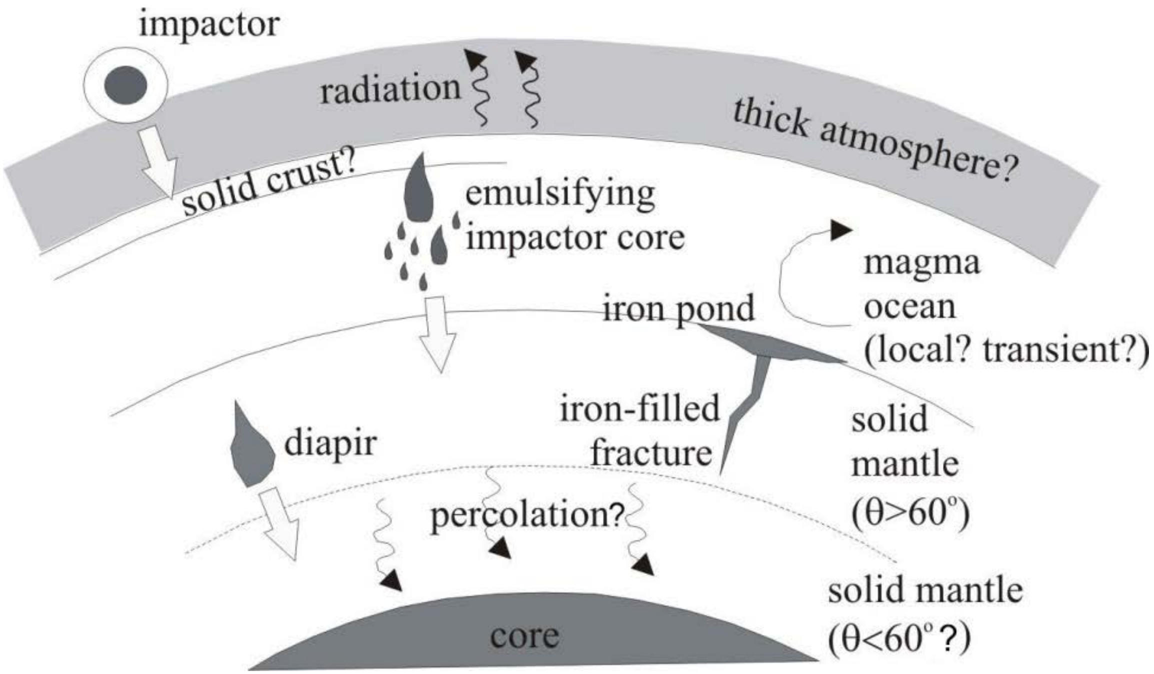
Effect of light elements

Melting curve

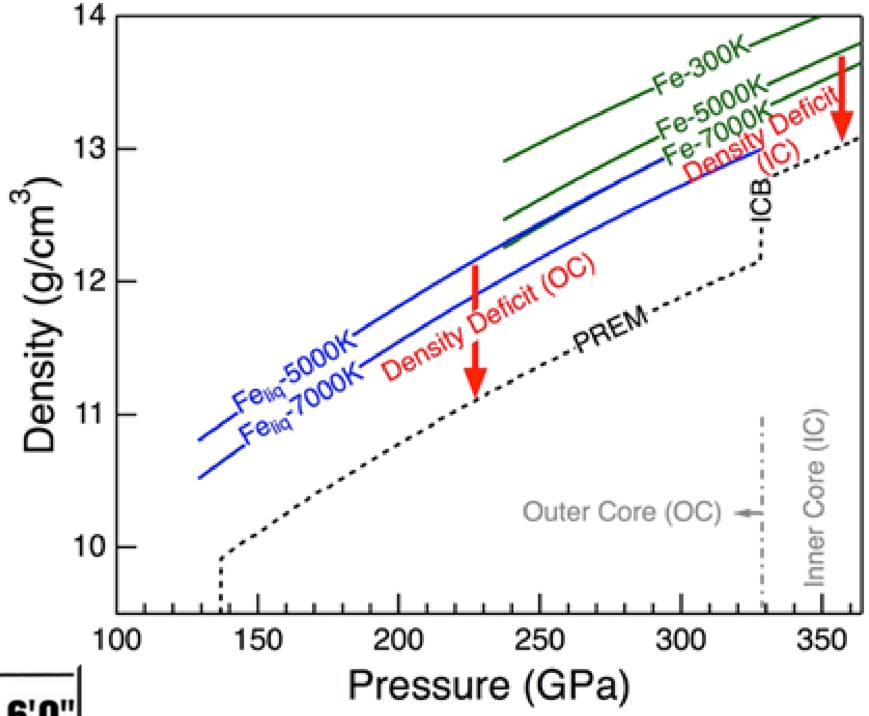


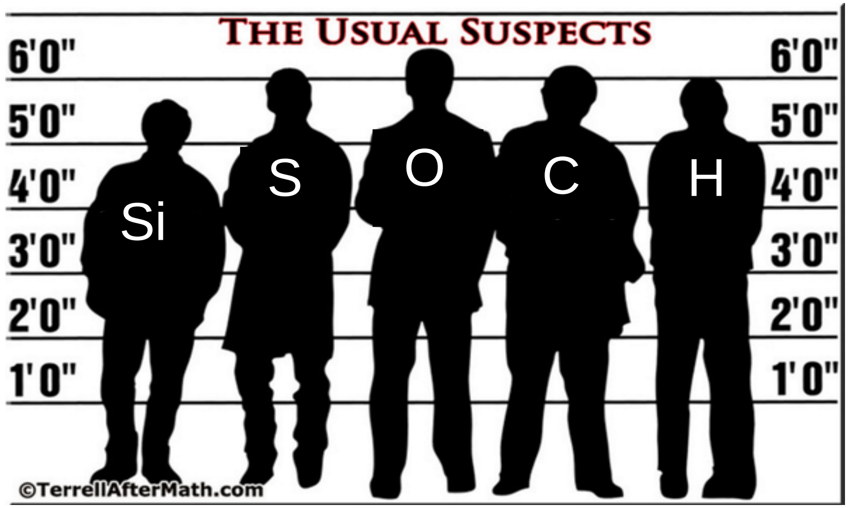


Earth Core Composition: Iron + ?

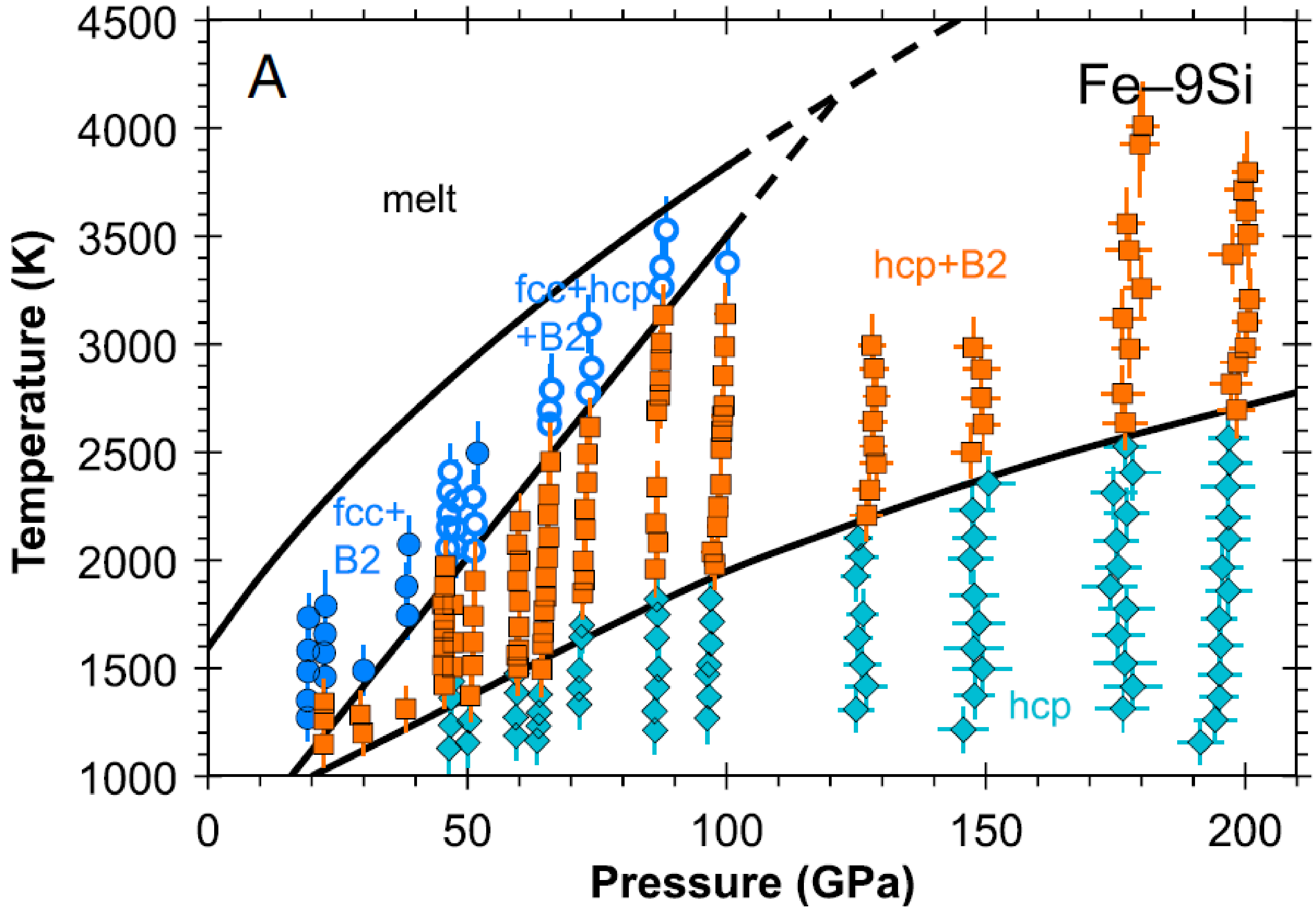


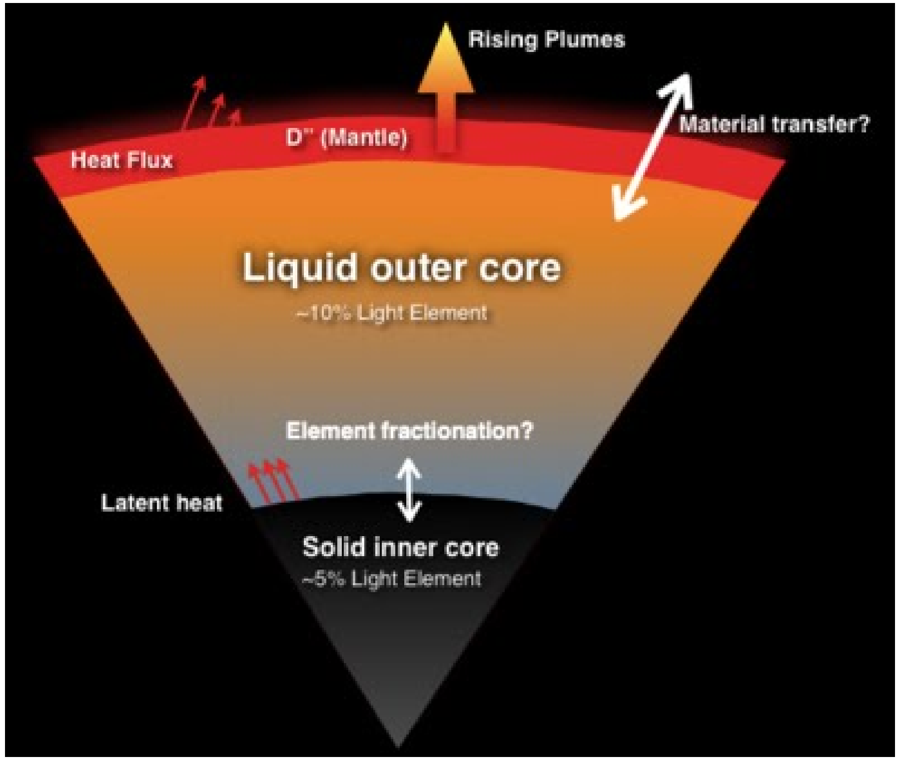
Rubie and Jacobsen, 2016





Iron-Silicon Alloys





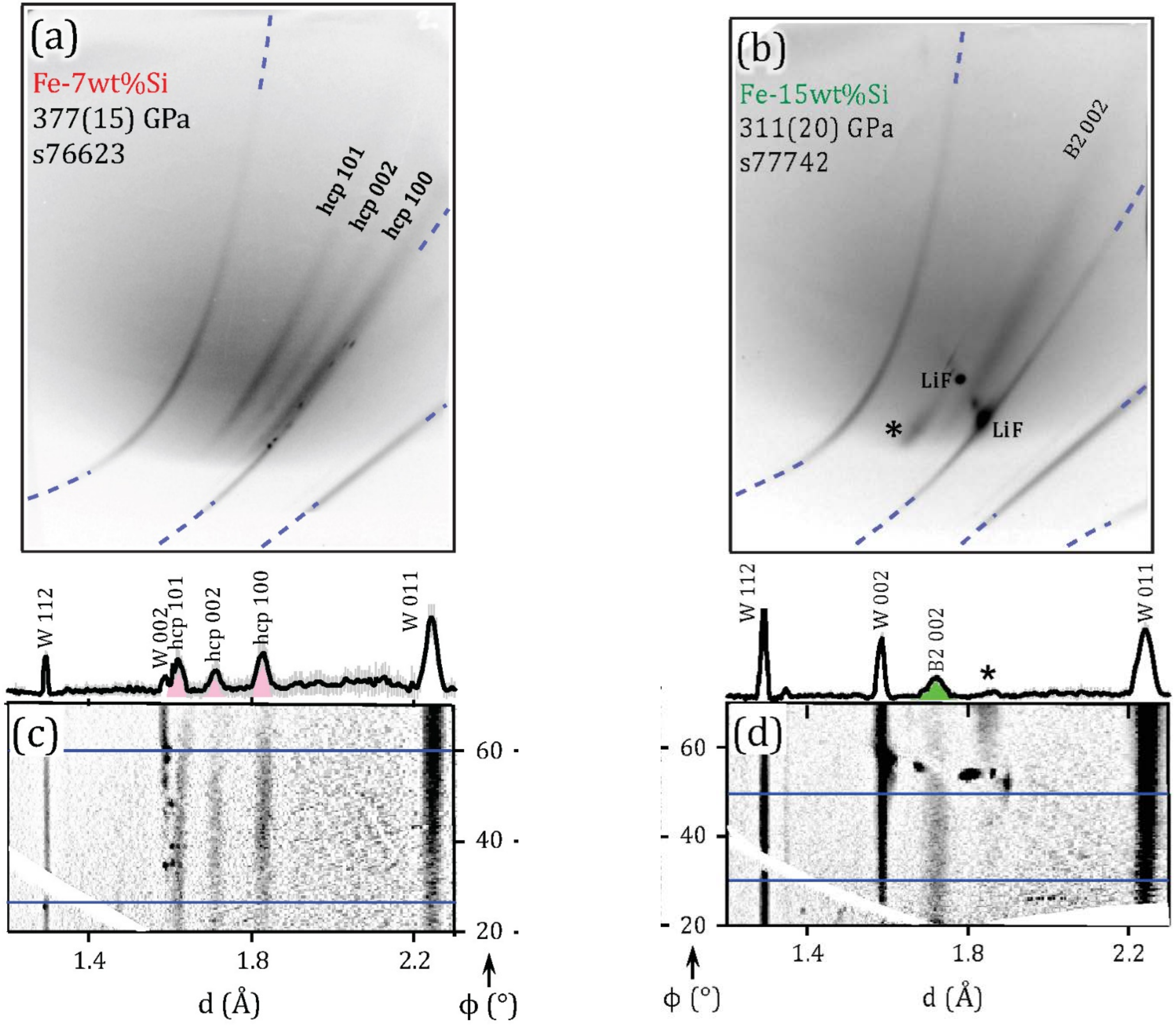
Core light element plays a role in mass-radius relation, density structure, core dynamics, and magnetic field generation

Fischer et al. 2014

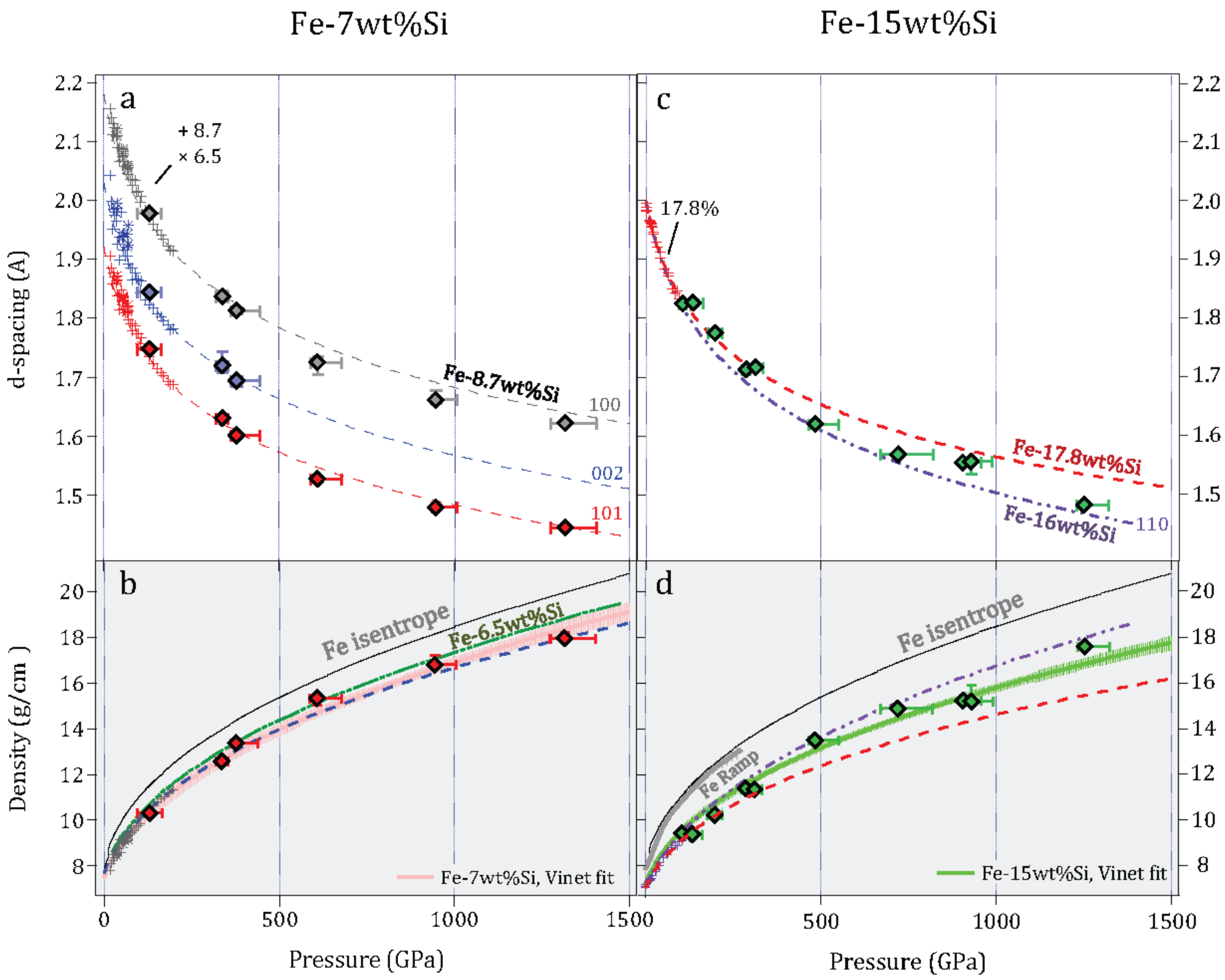
PXRDIP X-Ray Diffraction of Ramp Compressed Fe-Si Alloys:

Fe-7wt.%Si

Fe-15wt.%Si



Effect of Light Element (Silicon) on Structure and Density of Exoplanetary Cores



X-ray diffraction recorded to 1314 GPa

Achieved sample compression of 2.5x, extended pressure range by nearly a factor of 5

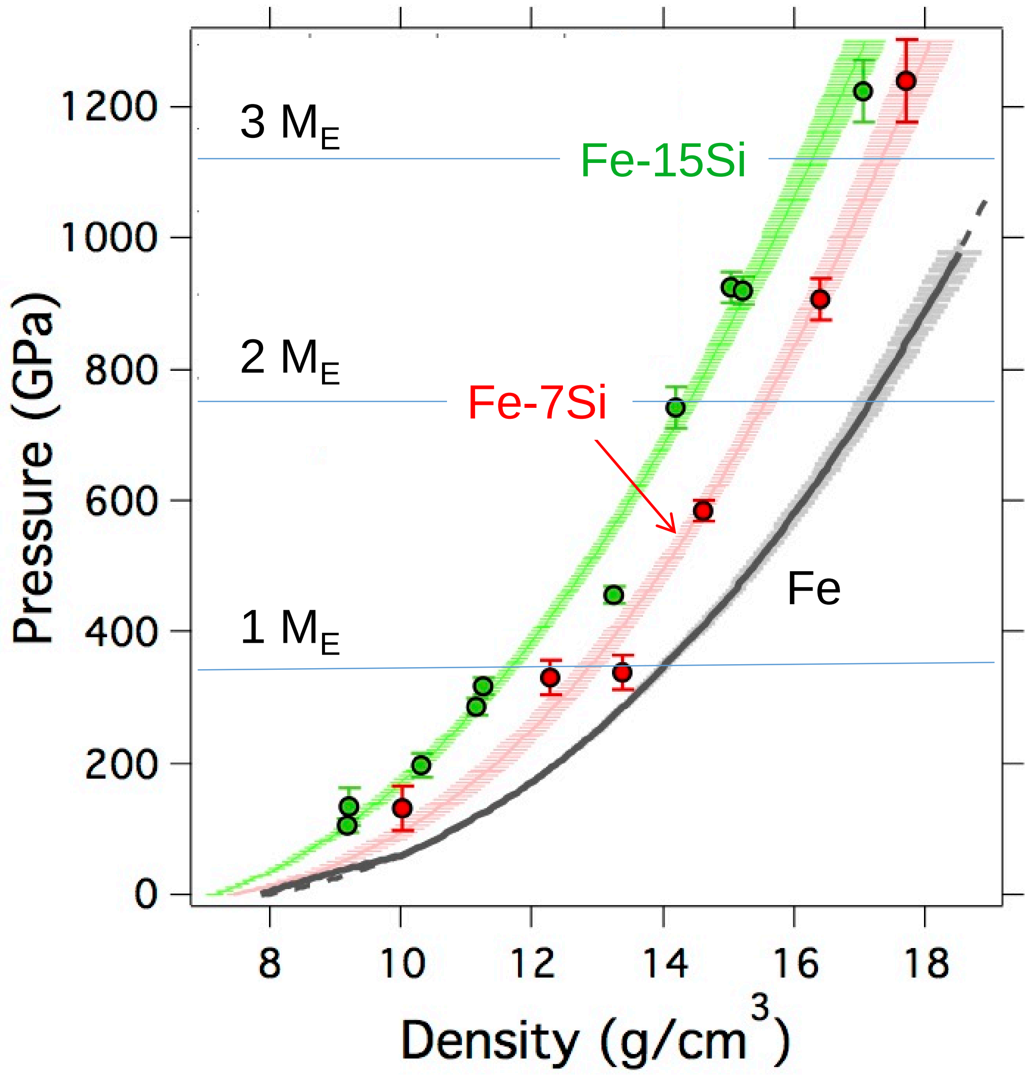
Crystal structure depends on Si content:

7wt% Si → HCP

15wt% Si → BCC

Wicks et al., in prep.

Density reduction of Iron at core pressures due to Si incorporation



Vinet Equation of state fits:

Parameter	Fe-7Si	Fe-15Si
V_0 (A^3)	11.166(4)	11.266(1)
K_0 (GPa)	168(56)	168(30)
dK_0/dP	5.49(9)	6.0(6)

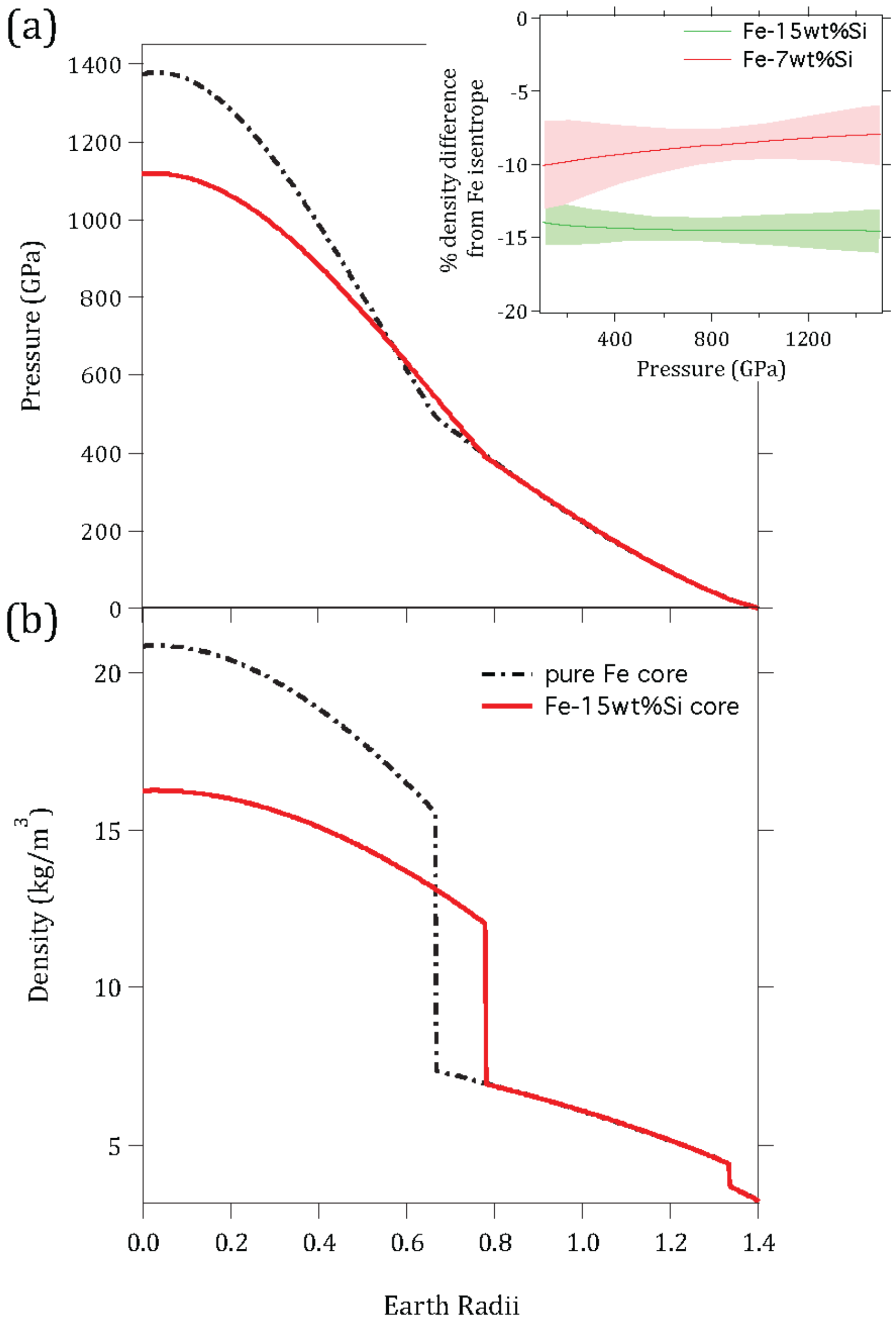
Density reduction relative to pure Fe:

Earth central pressure (363 GPa):
-10% (Fe-7Si) to -14% (Fe-15Si)

3 M_E planet central pressure (~1150 GPa):
-8% (Fe-7Si) to -14% (Fe-15Si)

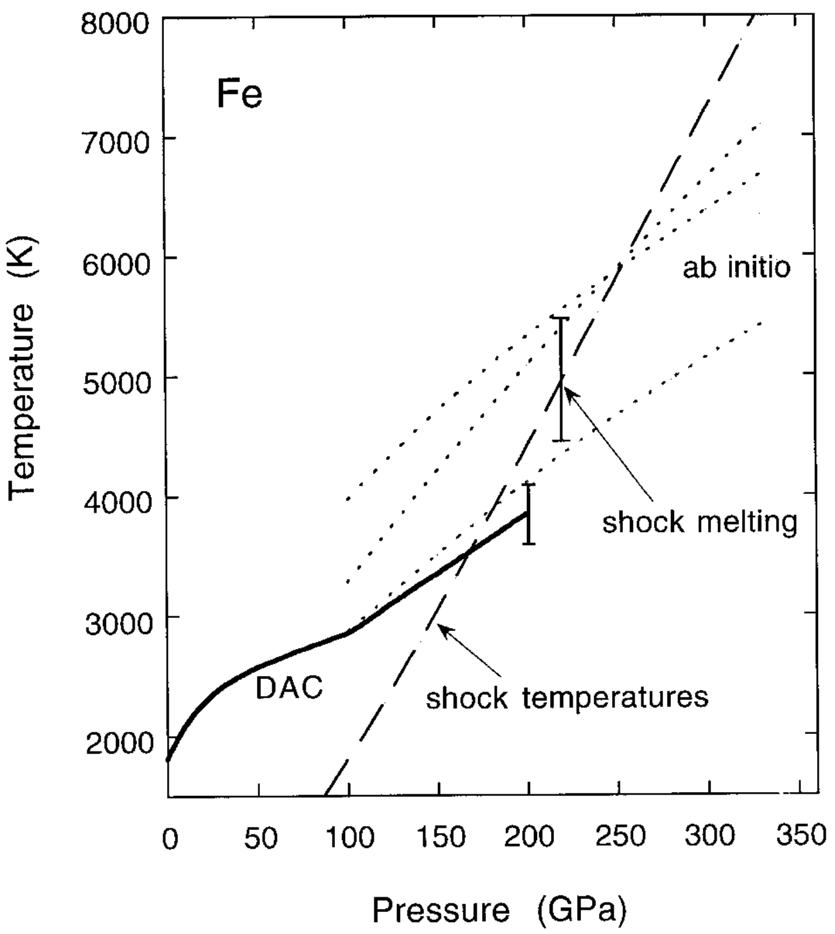
Exoplanet Example: Kepler – 10b

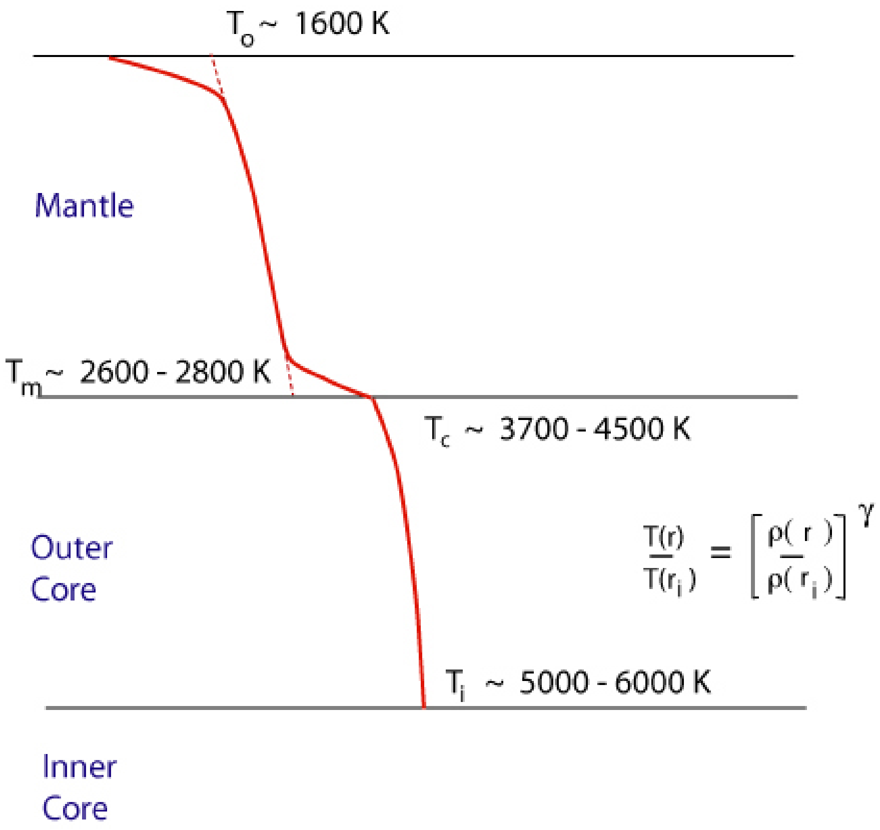
Mass = 3.33(49) M_E
Radius = 1.47(3) R_E
Orbital period = 0.84 days



Melting Curve of Iron: The Never-Ending Story?

Reinhard Boehler , Daniel Errandonea & Marvin Ross

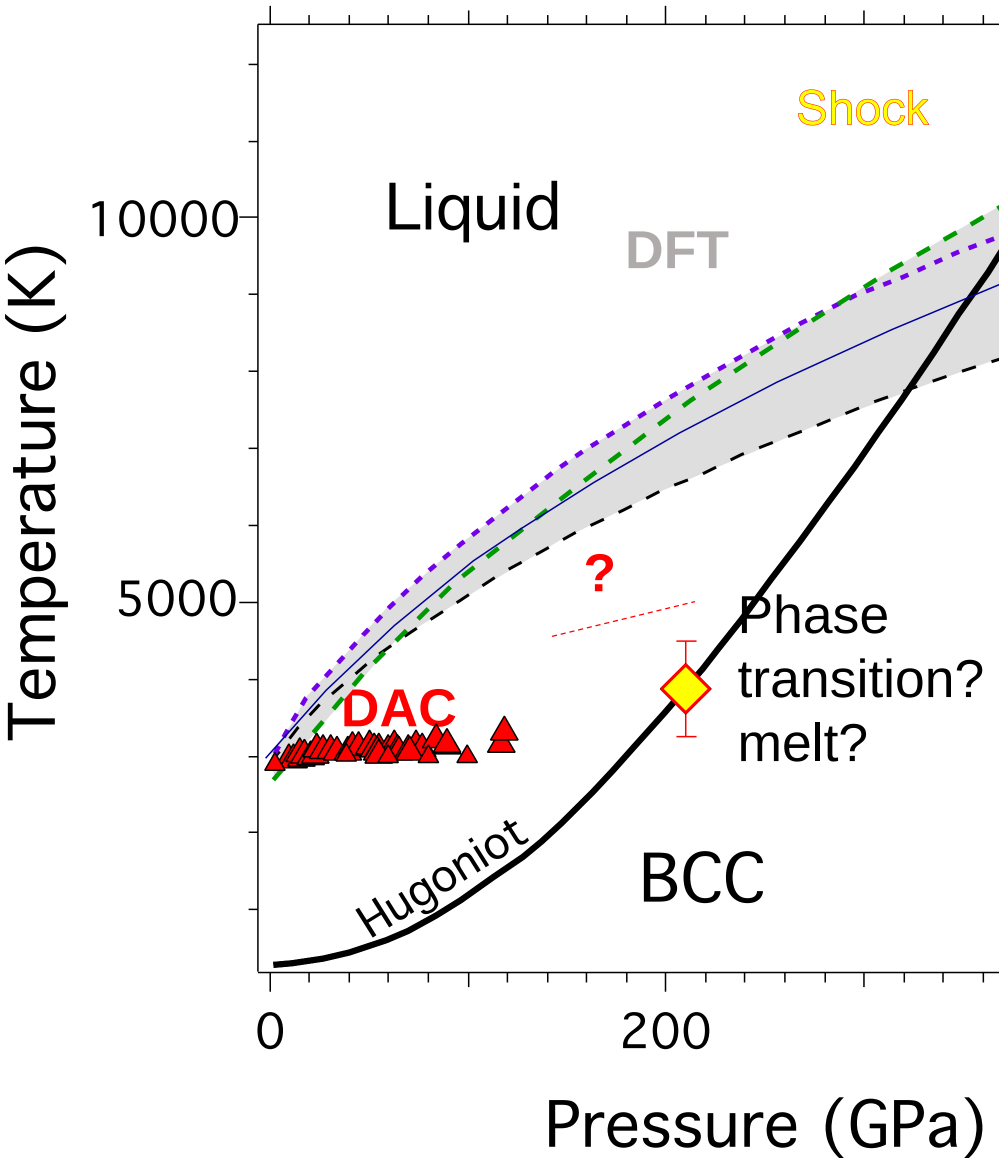


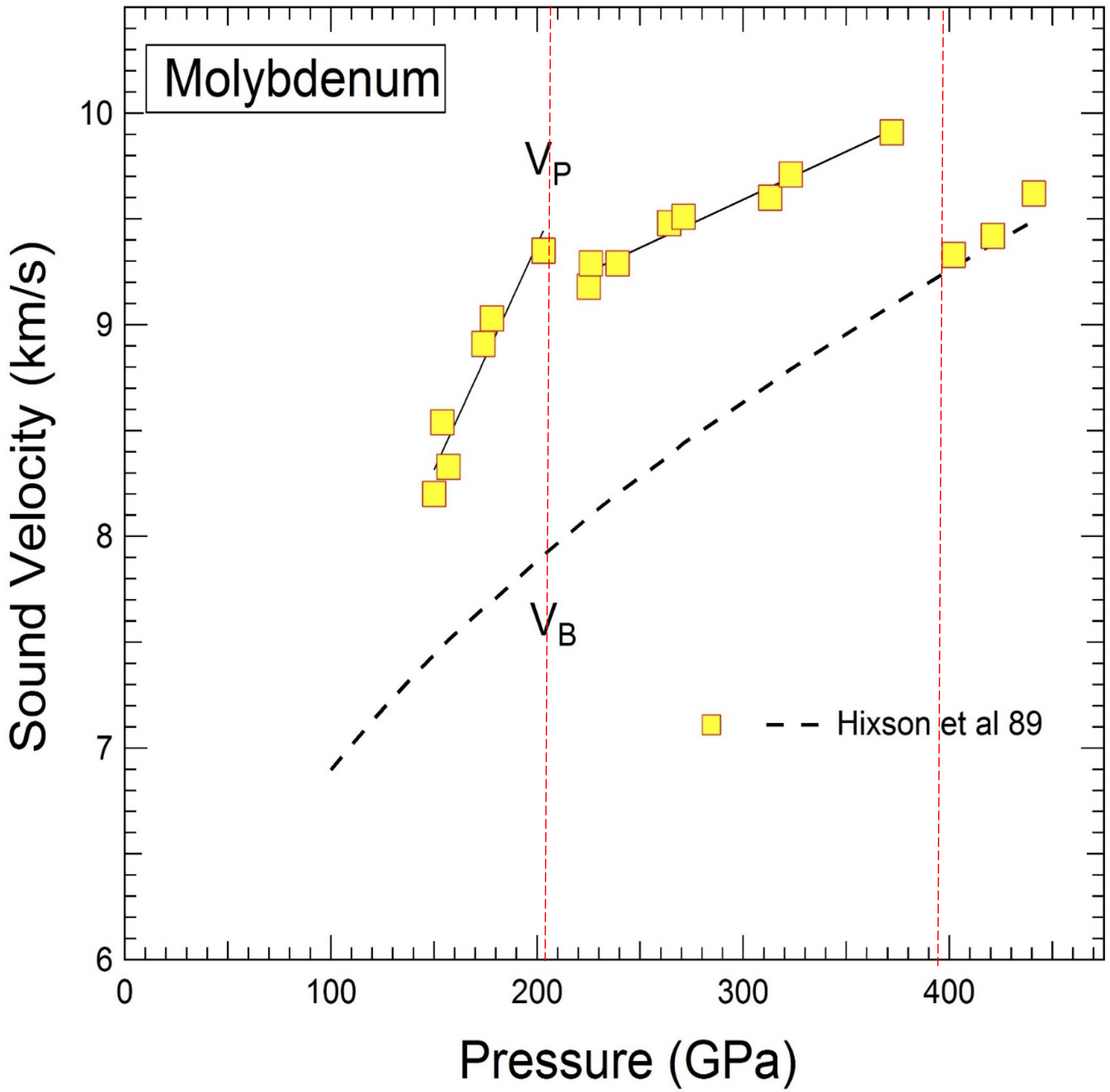


Iron melting at 330 GPa: Temperature reference at Earth inner- core outer core boundary

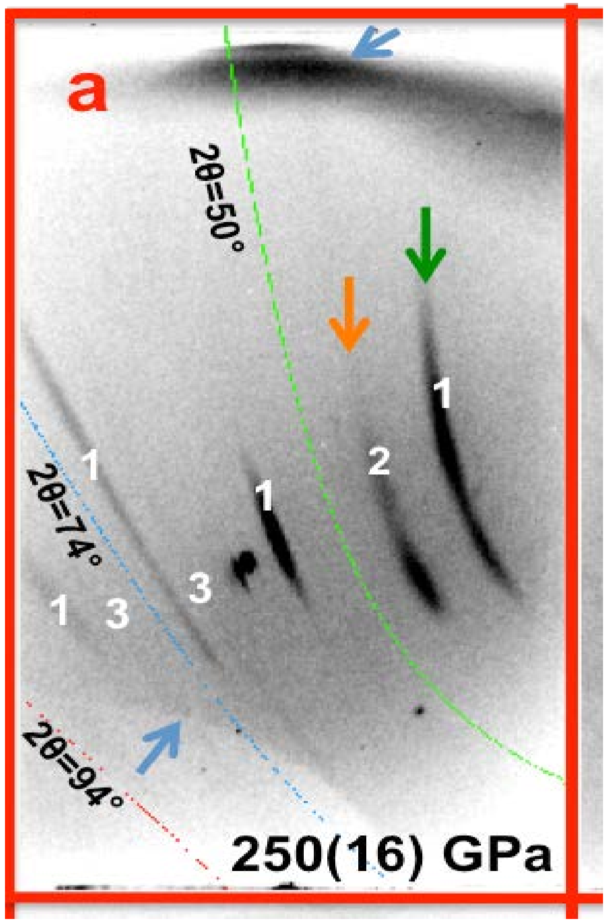
Adiabatic extrapolation across outer core gives temperature on core side of the core-mantle boundary

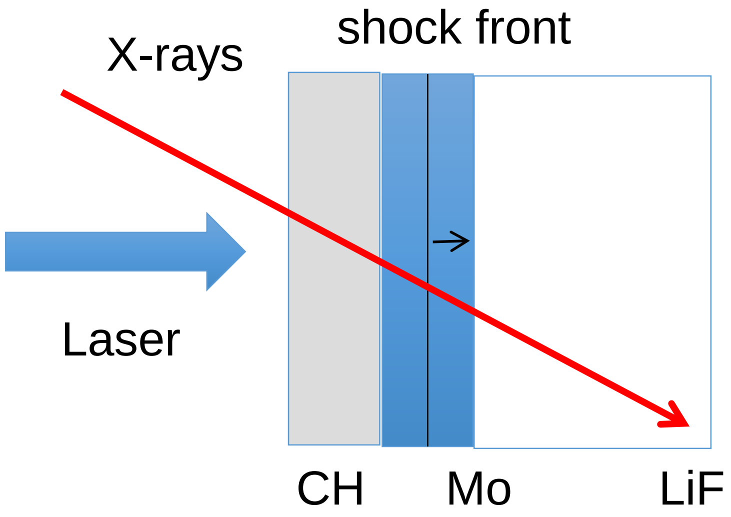
High-Pressure Melting: The Case of Molybdenum

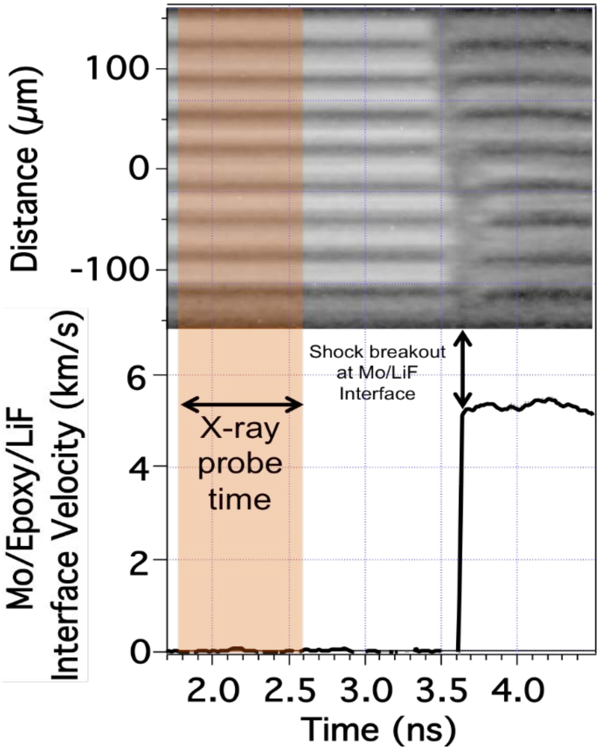


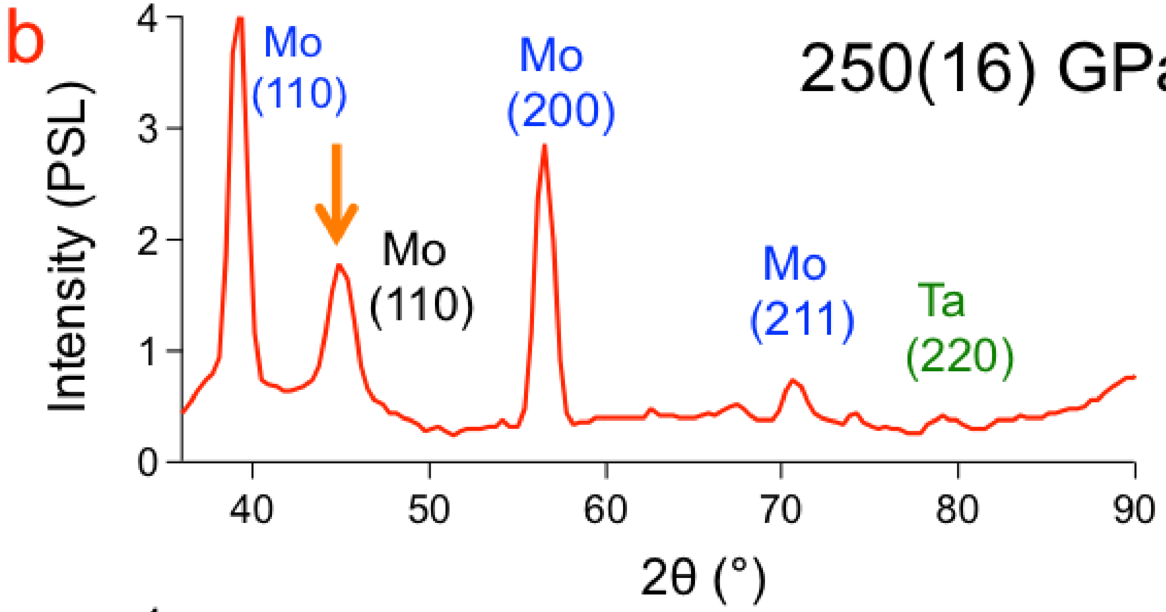


X-ray Diffraction of Shock-Compressed Molybdenum



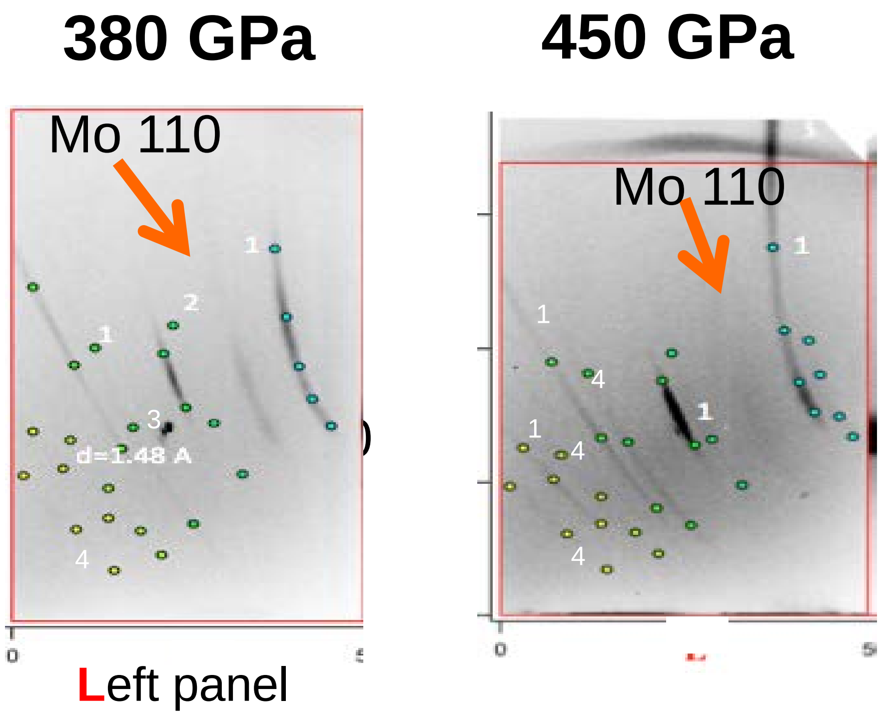


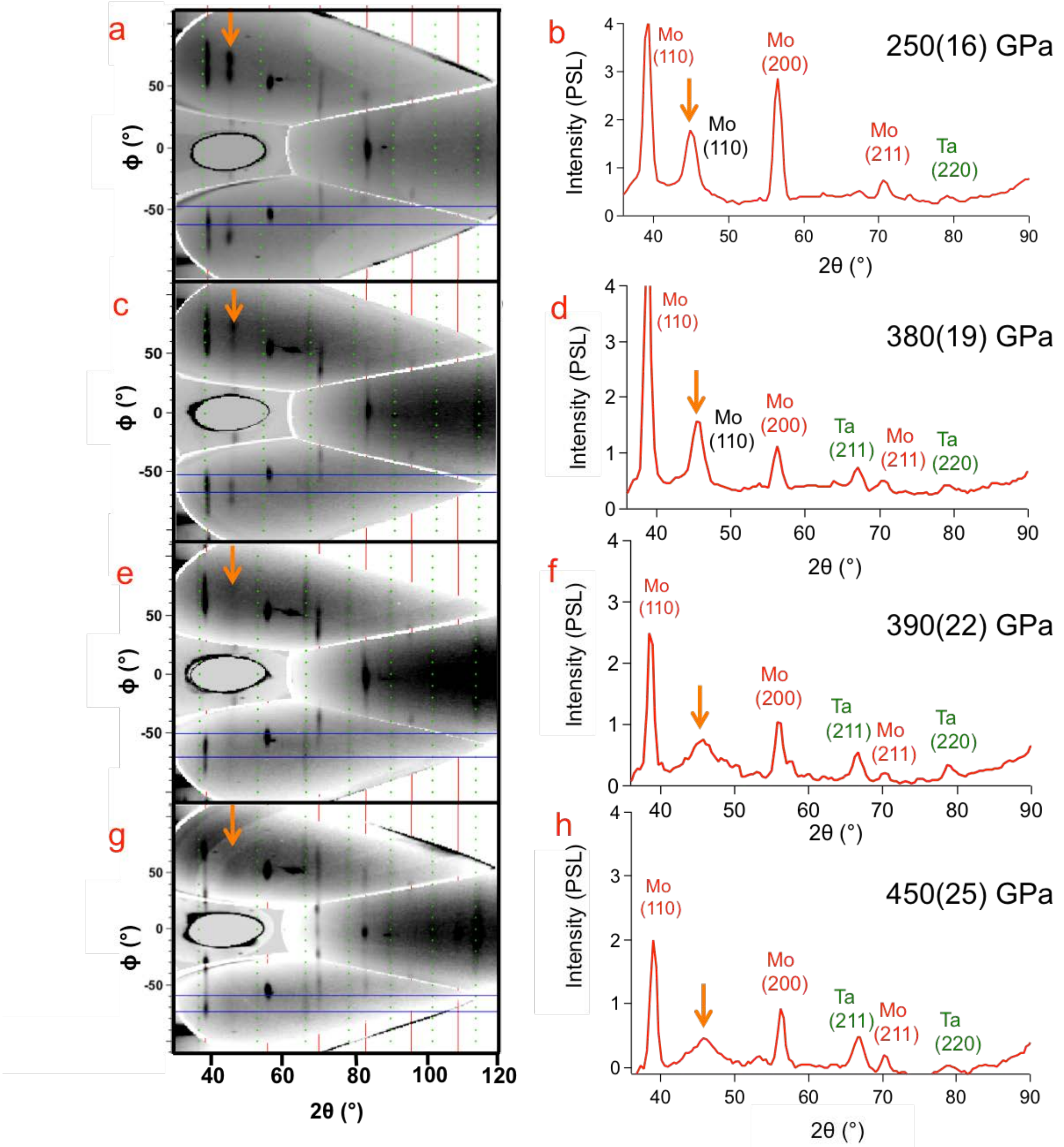




1. Uncompressed Mo; 2. Compressed Mo; 3. Uncompressed Ta

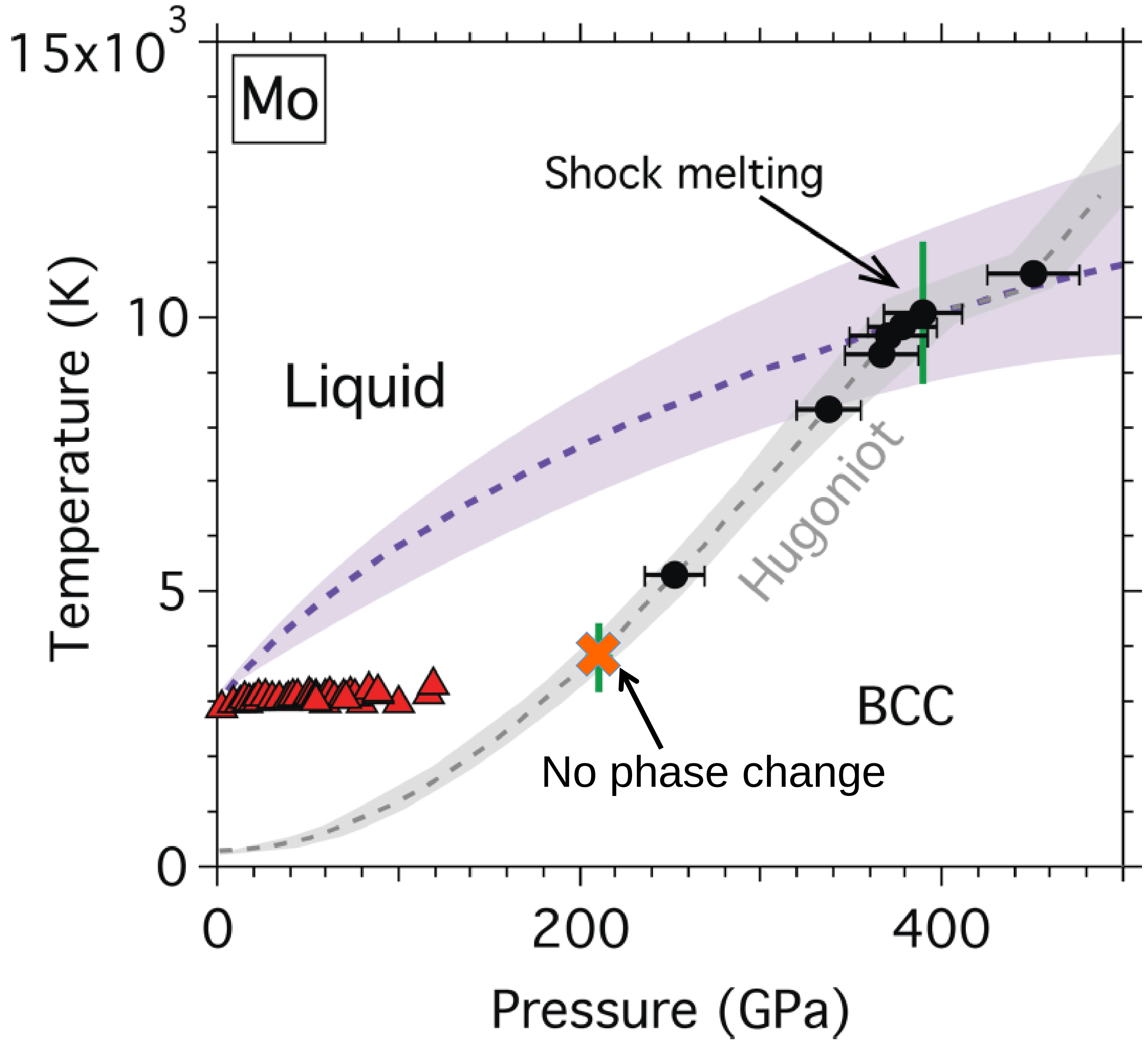
X-Ray Diffraction of Shock-Compressed Mo between 250 – 450 GPa





Wang et al., PRB, 2015

Molybdenum Under Shock Compression: Summary

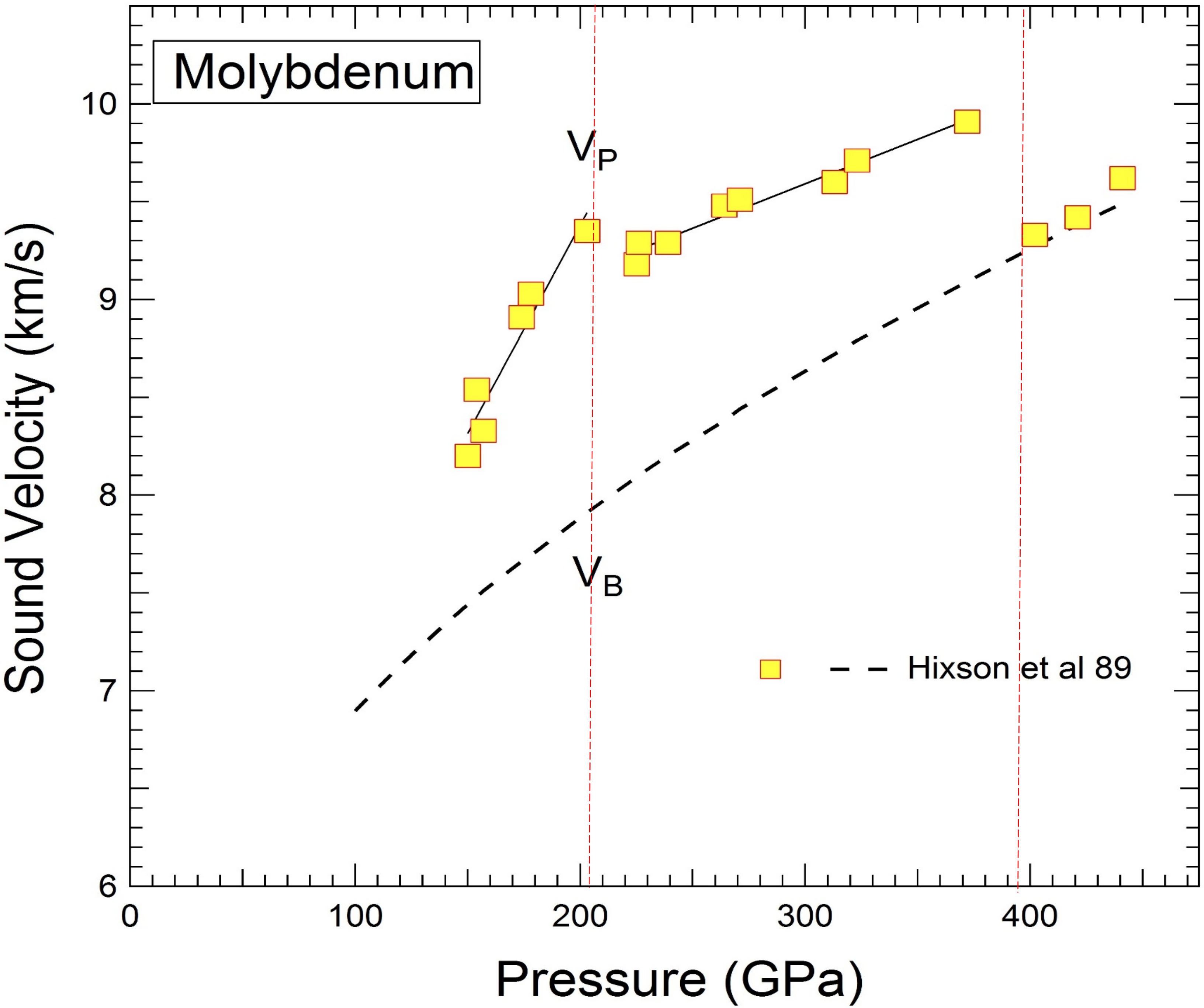


Molybdenum remains in the BCC structure until melting at 390 GPa

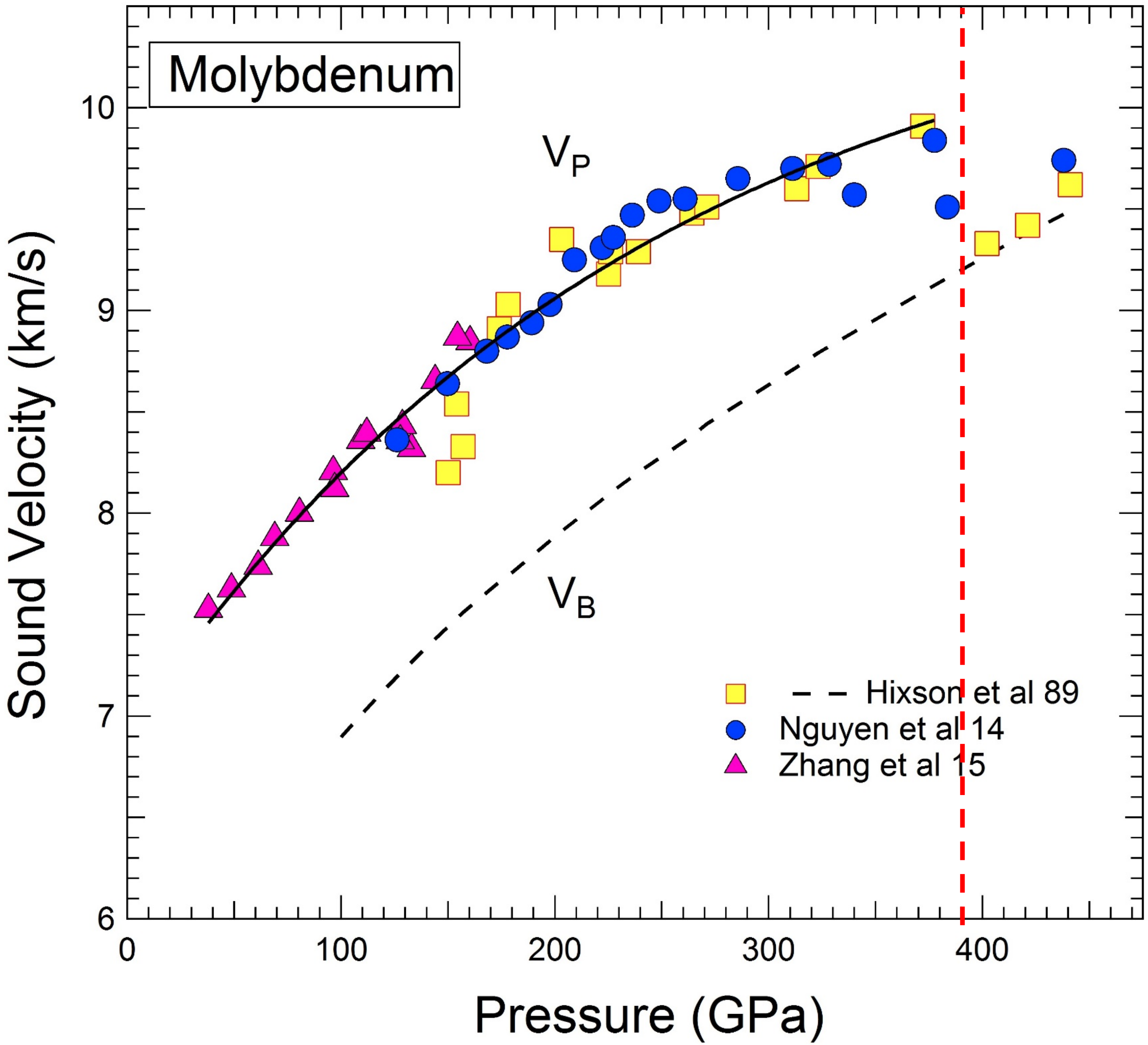
No phase transition at 210 GPa

Melting curve is steep, not shallow

Our results are consistent with latest DFT calculations including anharmonicity (Cazorla et al. 2012) and new Hugoniot sound velocity measurements

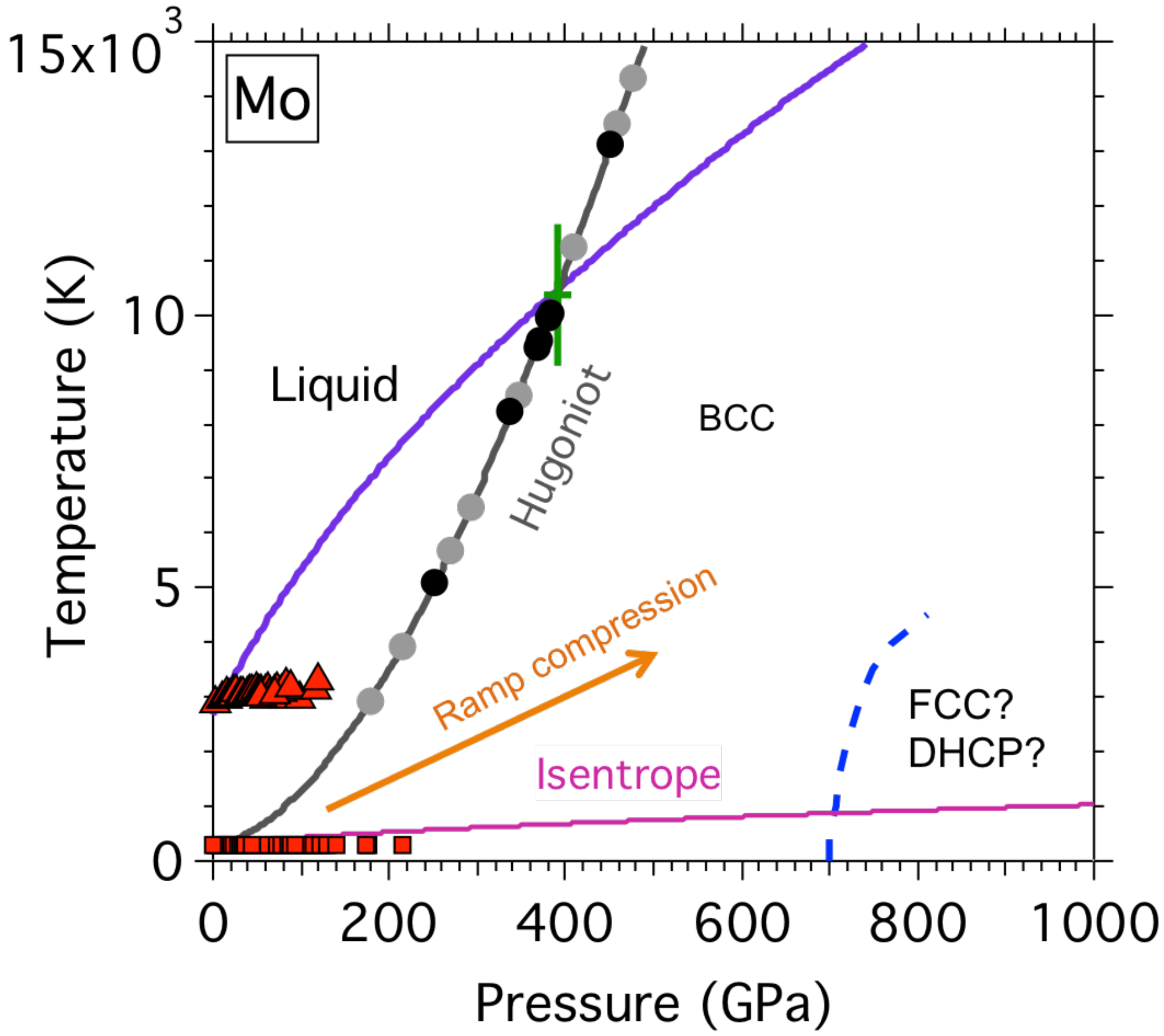


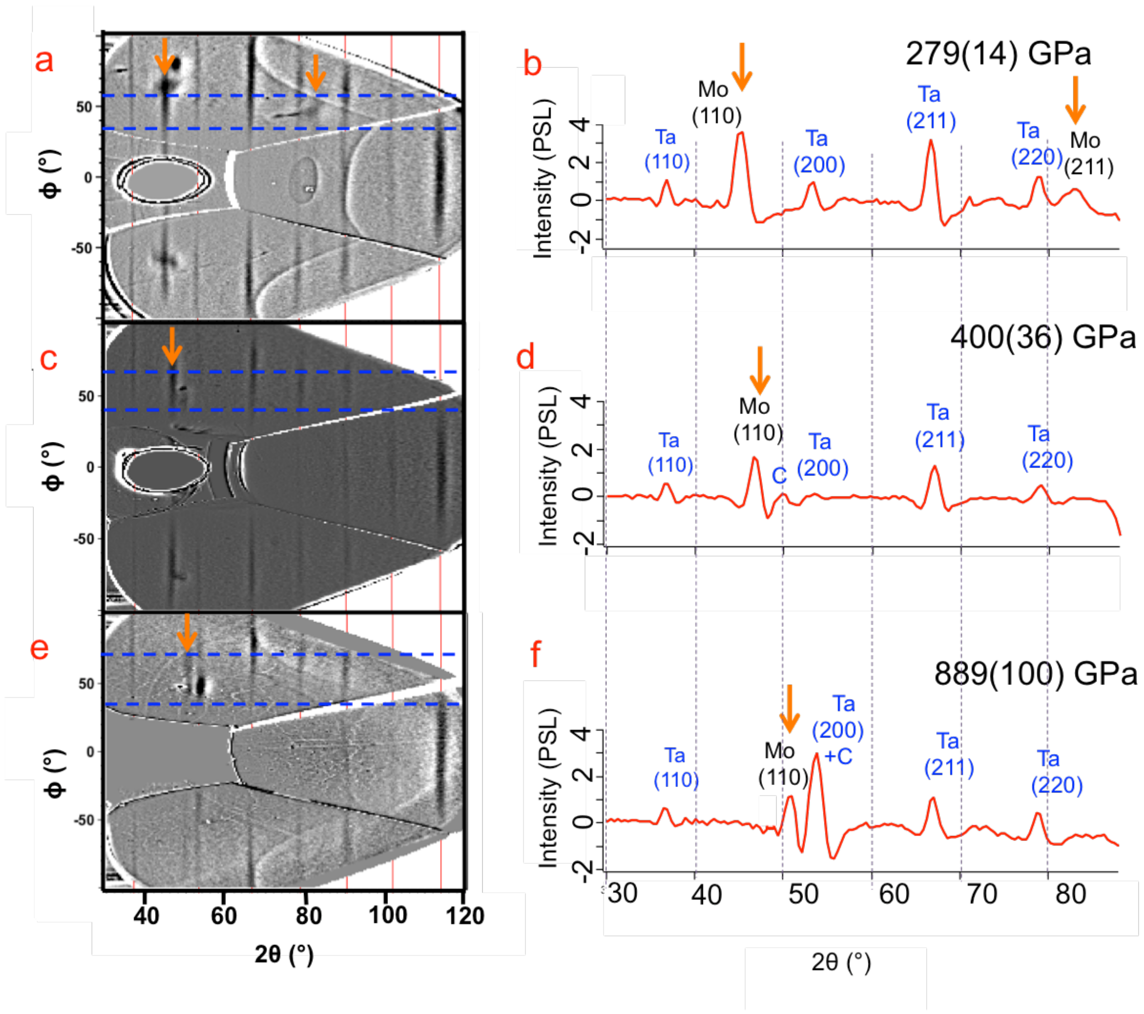
Molybdenum
Sound Velocity (km/s)
Pressure (GPa)
V_P
V_B
Hixson et al 89
10
9
8
7
6
0
100
200
300
400



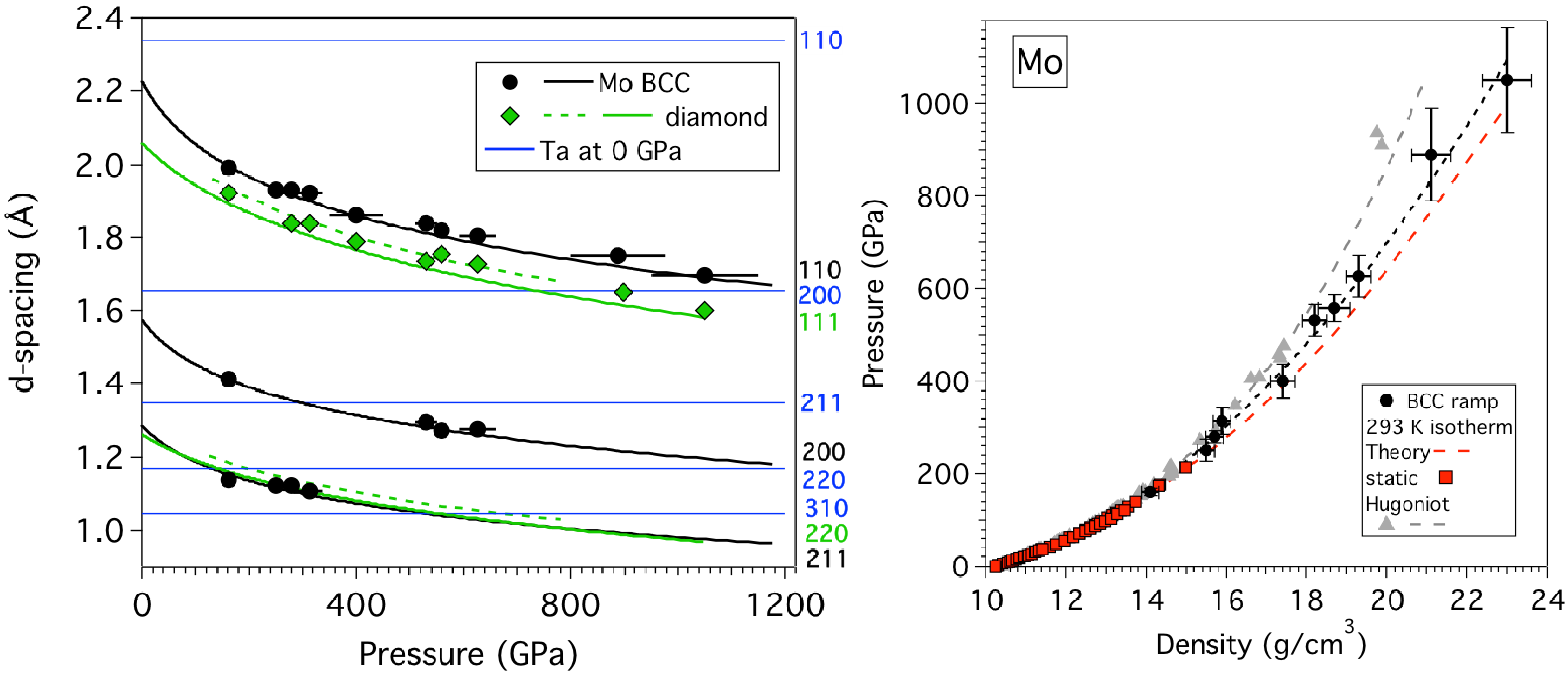
Molybdenum
V_P
V_B
Hixson et al 89
Nguyen et al 14
Zhang et al 15
Sound Velocity (km/s)
Pressure (GPa)
6
7
8
9
10
0
100
200
300
400

X-ray Diffraction Results from Ramp-Compressed Mo





BCC Molybdenum stable until 1050 GPa



Summary

Omega and EP provide unique capabilities to compress geological materials to conditions corresponding the deep interior of the Earth and extrasolar planets

Major Findings:

B1-B2 phase transition in MgO measured for the first time; Major structural feature in the mantle of super-Earth planets

Iron occurs in the HCP structure in super Earth planetary cores

The effect of Si on the density and phase of iron has been characterized up to 1300 GPa corresponding to expected central pressure of ~3.5 Earth mass planet

7 wt. % Si – HCP
15 wt.% Si -- BCC

The pressure-and density profiles of extrasolar planets are sensitive to light element core composition.

Shock melting of molybdenum has been detected, consistent with steep, not shallow, melting curve

Publications

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